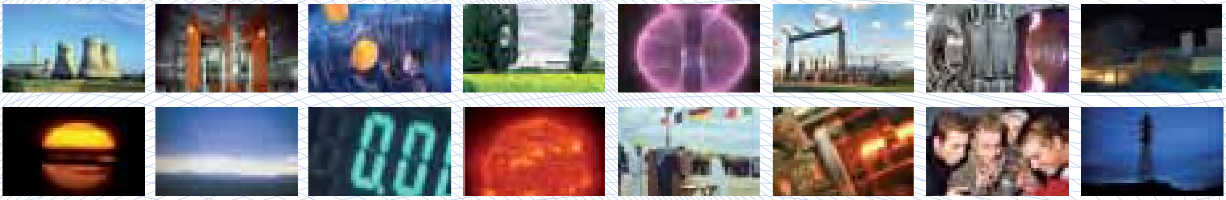

Focus On: JET

The European Centre of Fusion Research

Jan Mlynář

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Focus On: JET The European Centre of Fusion Research

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see the appendix of M.L.Watkins et al., “Overview of JET Results”, Proc. 21st IAEA Fusion Energy Conference,
Chengdu, China 2006

FOCUS ON: JET

PART I: FUSION BASICS

PART II: JET - THE JOINT EUROPEAN TORUS

PART III: HISTORICAL MILESTONES

Almost all stars, including our Sun, are powered by nuclear fusion reactions whereby hydrogen is converted into helium. The amount of energy released is unimaginable: only a negligible fraction falls on Earth and yet it has powered the water cycle, wind and life for billions of years. If we could imitate the Sun's processes on a human scale, we could use hydrogen (perhaps derived from ordinary water) as a virtually inexhaustible and extremely powerful fuel. Mastering fusion would resolve most of the energy issues of our present civilisation. The Sun's considerable gravitational forces confine its fusion reactions but unfortunately it is impossible to reproduce such forces here on Earth. The challenge is therefore to find and develop alternative techniques that would allow us to release fusion's considerable potential.

Even in the early stages of fusion research, physicists realised that in order to unlock fusion power, ionised gas (called plasma) needs to be controlled at hundreds of millions of degrees, at sufficient density and with good confinement of the plasma's energy. Many ingenious strategies have been developed to achieve the required target parameters, and steady progress has been made over the last 50 years. In the most successful approach, massive electric coils form strong doughnut-shaped magnetic fields to confine hydrogen plasma, which is heated to extreme temperatures of around 100 million degrees by electric currents, by microwaves and by energetic beams of hydrogen atoms. Today, the major fusion experimental facilities based on this concept operate very close to the conditions required to release immense fusion power. The Joint European Torus (JET) is at their forefront.

It was a great privilege for me to participate in work at JET, and I am happy I could contribute by spreading information of JET's mission and its results. From the beginning of my four-year "secondment" I have been a strong advocate of the role of JET's public website, **http://www.jet.efda.org**, and this booklet is a collection of articles that I managed to publish on the web during my stay at JET, in most cases being their main author. However, the articles could never exist in their present form without considerable input by co-authors, namely:

Clive Elsmore, the JET webmaster, **Chris Warrick**, the UKAEA Fusion Outreach manager, who is the main author of part 1 of the book; **Chris Gowers** and **Andrea Murari** (section 2.5), **Marco Wischmeier** and **Samuli Saarelma** (section 2.7), and **Giovanni Piazza** (section 2.10).

Support of the many JET scientists and engineers who found time to proofread the text also substantially improved the result. The concluding interview with John D. Lawson was organised by Jennifer Hay and edited by Nina Morgan. In the preparation of the images the articles benefited from regular professional help and advice from the staff of the JET Publications Services department, namely Stuart Morris, Chad Heys and Andy Cooper.

In our constant efforts to improve the public webpages I have also greatly appreciated the support of the EFDA-JET Close Support Unit led by Jérôme Paméla and, more recently, by Francesco Romanelli. I am also happy to say that a lot of encouragement and help came directly from the two consecutive heads of the Publications Office where I worked, Giuliano Buceti and Duarte Borba.

However, I am the only person to be blamed for any inaccuracy in the final articles, and I would greatly appreciate it if you could contact me concerning any corrections and comments.

The graphics of the present booklet are due to Matthew Banks who was on a student placement in the JET Publications Services department. I am sure that readers will appreciate his graphics layouts as much as I do.

Please take this booklet, which presents a collection of slightly modified JET web articles, as an invitation to regularly visit the JET website, **http://www.jet.efda.org**, where you can also find information on a more advanced level, as well as news concerning current developments in fusion research at JET and beyond. For further explanation of technical terms I would recommend searching a web resource such as **http://www.wikipedia.org**. Due to the origins of this booklet, it cannot be considered complete as several important pieces of the vast mosaic of JET research are inevitably missing. Indeed I hope that the tradition of the "Focus On" articles will continue on the JET website even after my departure. What I know for sure is that I will keep very good memories from this great four-year adventure. I am grateful to my family - that they were ready to come here with me and, eventually, to leave with me, which is perhaps even harder.

Culham, 8th March 2007
Jan Mlyná
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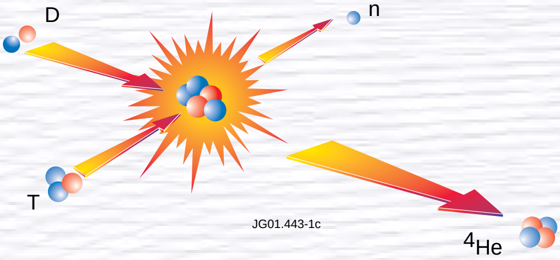
PART I:
FUSION BASICS

What is Fusion?

1.1

Nuclear Fusion is the process powering the Sun and stars. In the core of the Sun, at temperatures of 10-15 million Kelvin, hydrogen is converted to helium by fusion providing enough energy to keep the Sun burning and to sustain life on Earth.

A vigorous world-wide research programme is underway, aimed at harnessing fusion energy to produce electricity on Earth. If successful, this will offer a viable alternative energy supply within the next 30-40 years,with significant environmental, supply and safety advantages over present energy sources (see section 1.6).

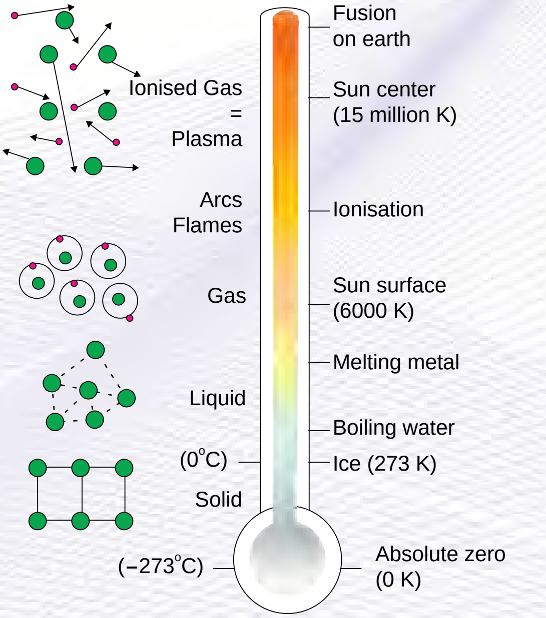


The energy released in fusion reactions is much larger than that for chemical reactions, because the binding energy that holds a nucleus together is far greater than the energy that holds electrons to a nucleus.

To harness fusion on Earth, different, more efficient fusion reactions than those at work in the Sun are chosen, those between the two heavy forms of hydrogen : deuterium (D) and tritium (T). All forms of hydrogen contain one proton and one electron. Protium, the common form of hydrogen has no neutrons, deuterium has one neutron, and tritium has two. If forced together, the deuterium and tritium nuclei fuse and then break apart to form a helium nucleus (two protons and two neutrons) and an neutron. The excess energy from the fusion reaction is mostly contained in the free neutron.

Fusion occurs only at very high energies (temperatures) on earth, temperatures greater than 100 million Kelvin are required. At these extreme temperatures, the deuterium - tritium (D-T) gas mixture becomes a plasma (a hot, electrically charged gas). In a plasma, the atoms become separated - electrons have been stripped from the atomic nuclei (called the "ions"). For the positively charged ions to fuse, their temperature (or energy) must be sufficient to overcome their natural charge repulsion.

In order to harness fusion energy, scientists and engineers are learning how to control very high temperature plasmas. Much lower temperature plasmas are now widely used in industry, especially for semi-conductor manufacture. However, the control of high temperature fusion plasmas presents several major science and engineering challenges - how to heat a plasma to in excess of 100 million Kelvin and how to confine such a plasma, sustaining it so that the fusion reaction can become established.



Plasmas occur at very high temperatures - the electrons are stripped from the atomic nuclei. (Image courtesy CEA, France)

Conditions of a Fusion Reaction

1.2

Three parameters (plasma temperature, density and confinement time) need to be simultaneously achieved for sustained fusion to occur in a plasma. The product of these is called the fusion (or triple) product and, for D-T fusion to occur, this product has to exceed a certain quantity - derived from the so-called Lawson Criterion after British scientist John Lawson who formulated it in 1955. (See section 3.5).

Temperature

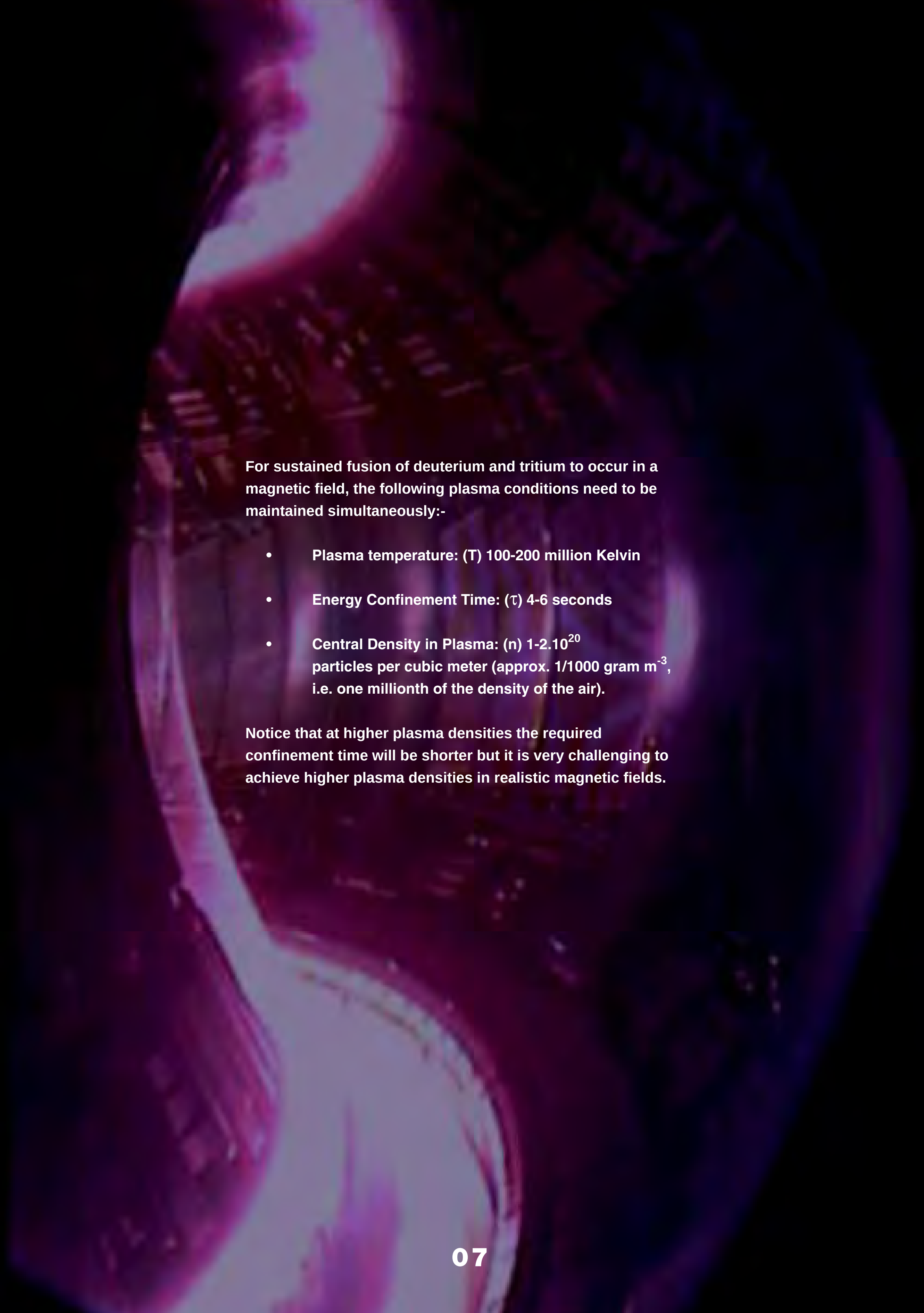
Fusion reactions occur at a sufficient rate only at very high temperatures - when the positively charged plasma ions can overcome their natural repulsive forces. Typically, in JET, over 100 million Kelvin is needed for the deuterium-tritium reaction to occur - other fusion reactions (e.g. D-D, D-^{3}He) require even higher temperatures.

Density

The density of fuel ions (the number per cubic metre) must be sufficiently large for fusion reactions to take place at the required rate. The fusion power generated is reduced if the fuel is diluted by impurity atoms or by the accumulation of helium ions from the fusion reaction itself. As fuel ions are burnt in the fusion process they must be replaced by new fuel and the helium products (the “ash”) must be removed.

Energy Confinement

The Energy Confinement Time is a measure of how long the energy in the plasma is retained before being lost. It is officially defined as the ratio of the thermal energy contained in the plasma and the power input required to maintain these conditions. At JET we use magnetic fields (see section 1.3) to isolate the very hot plasmas from the relatively cold vessel walls in order to retain the energy for as long as possible. The confinement time increases substantially with plasma size (large volumes retain heat much better than small volumes) - the ultimate example being the Sun whose energy confinement time is massive.



For sustained fusion of deuterium and tritium to occur in a magnetic field, the following plasma conditions need to be maintained simultaneously:-

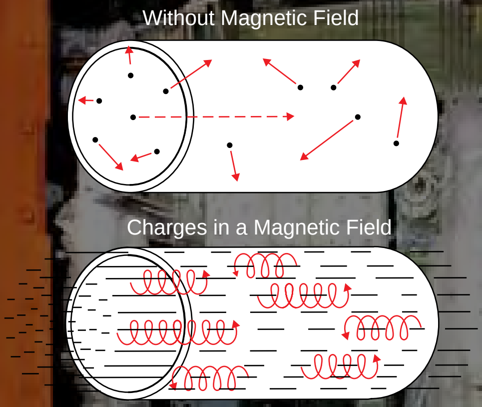
- Plasma temperature: (T) 100-200 million Kelvin
- Energy Confinement Time: (τ) 4-6 seconds
- Central Density in Plasma: (n) $1\text{-}2.10^{20}$ particles per cubic meter (approx. 1/1000 gram m^{-3}, i.e. one millionth of the density of the air).

Notice that at higher plasma densities the required confinement time will be shorter but it is very challenging to achieve higher plasma densities in realistic magnetic fields.

Magnetic Plasma Confinement and the Tokamak

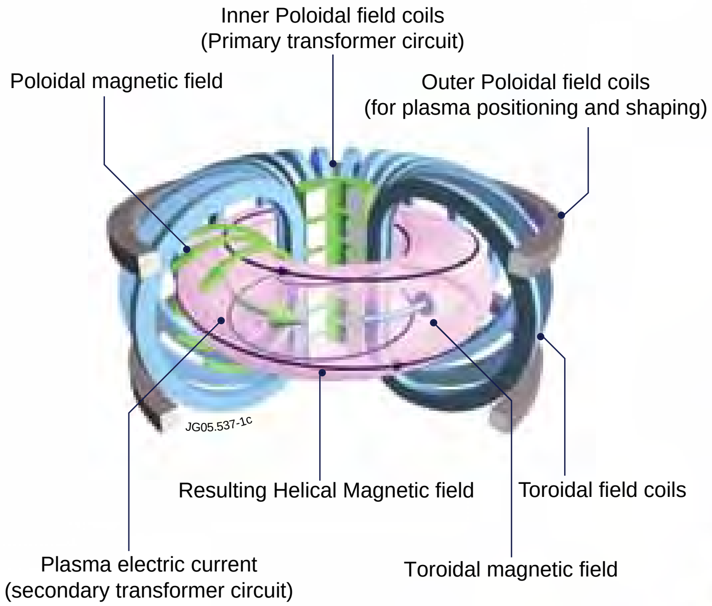
1.3

In a magnetic field the charged plasma particles are forced to spiral along the magnetic field lines. The most promising magnetic confinement systems are toroidal (from torus : ring-shaped, doughnut-shaped) and, of these, the most advanced is the Tokamak. Currently, JET is the largest Tokamak in the world although the future ITER machine will be even larger. Other, non magnetic plasma confinement systems are being investigated, notably inertial confinement or laser-induced fusion systems.



Charged particles spiral along the magnetic field lines

Since a plasma comprises charged particles : ions (positive) and electrons (negative), powerful magnetic fields can be used to isolate the plasma from the walls of the containment vessel, thus enabling the plasma to be heated to temperatures in excess of 100 million Kelvin. This isolation of the plasma reduces the conductive heat loss through the vessel and also minimises the release of impurities from the vessel walls into the plasma that would contaminate and further cool the plasma by radiation.



The principle magnetic circuits of a Tokamak

The Tokamak

In a tokamak, the plasma is heated in a ring-shaped vessel (or torus) and kept away from the vessel walls by applied magnetic fields. The basic components of the tokamak's confining magnetic fields are:

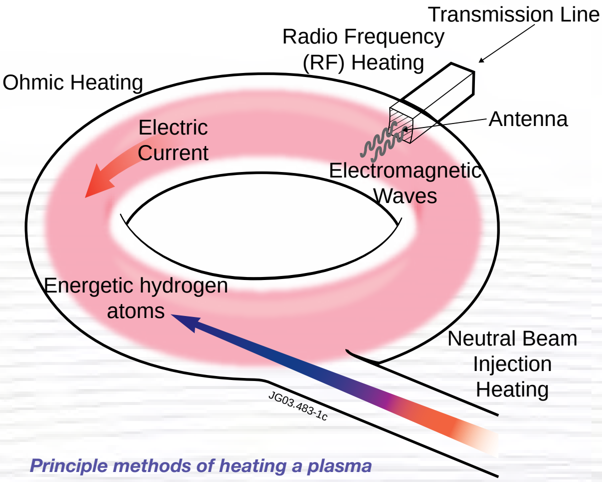
- The toroidal field with field lines circulating around the torus. This is maintained by magnetic field coils surrounding the vacuum vessel (see figure above). The toroidal field provide the primary mechanism of confinement of the plasma particles.

- The poloidal field with field lines circulating around the plasma cross section. It pinches the plasma away from the walls and maintains the plasma's shape and stability. The poloidal field is induced both internally, by the current driven in the plasma (one of the plasma heating mechanisms), and externally, by coils that are positioned around the perimeter of the vessel.

The main plasma current is induced in the plasma by the action of a large transformer. A changing current in the primary winding or solenoid (a multi turn coil wound onto a large iron core in JET) induces a powerful current (up to 5 millon Amperes on JET) in the plasma which acts as the transformer secondary circuit.

Heating the Plasma

1.4



Principle methods of heating a plasma

One of the main requirements for fusion is to heat the plasma particles to very high temperatures or energies. The following methods are typically used to heat the plasma, all of them are employed on JET:

Ohmic Heating

Currents up to 5 million Amperes (5 MA) are induced in the JET plasma - typically via the transformer. As well as providing a natural pinching of the plasma column away from the walls, the current inherently heats the plasma by energising plasma electrons and ions in a particular toroidal direction. A few MW of heating power is provided in this way

Neutral Beam Heating

Beams of high energy, neutral deuterium or tritium atoms are injected into the plasma, transferring their energy to the plasma via collisions with the plasma ions. The neutral beams are produced in two distinct phases. Firstly, a beam of energetic ions is produced by applying an accelerating voltage of up to 140,000 Volts. However, a beam of charged ions will not be able to penetrate the confining magnetic field in the tokamak. Thus, the second stage ensures the accelerated beams are neutralised (i.e. the ions turned into neutral atoms) before injection into the plasma. In JET, up to 23 MW of additional power is available from the Neutral Beam heating systems.

Radio-Frequency Heating

As the plasma ions and electrons are confined to rotate around the magnetic field lines (gyro-motion) in the tokamak, electromagnetic waves of a frequency matched to the ions or electrons gyrofrequency are able to resonate or damp their wave power into the plasma particles. As energy is transferred to the plasma at the precise location where the radio waves resonate with the ion/electron rotation, such wave heating schemes have the advantage of being localised at a particular location in the plasma.

In JET, eight antennae in the vacuum vessel propagate waves in the frequency range of 25-55 MHz into the core of the plasma. These waves are tuned to resonate with particular ions in the plasma - thus heating them up. This method can inject up to 20 MW of heating power.

Waves can also be used to drive current in the plasma by providing a “push” to electrons travelling in one particular direction. In JET, 10 MW of these so-called Lower Hybrid microwaves (at 3.7 GHz) accelerate the plasma electrons to generate a plasma current of up to 3 MA.

Self Heating of Plasma

The helium ions (or so-called alpha-particles) produced when deuterium and tritium fuse remain within the plasma's magnetic trap for a time before they are pumped away through the divertor. The neutrons (being neutral) escape the magnetic field and their capture in a future fusion powerplant will be the source of fusion power to produce electricity.

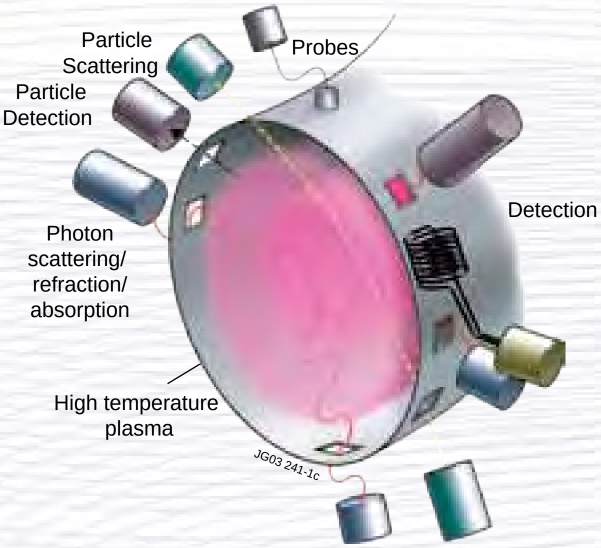
When fusion power output just equals the power required to heat and sustain plasma then a Breakeven is achieved. However, only the fusion energy contained within the helium ions heats the deuterium and tritium fuel ions (by collisions) to keep the fusion reaction going. When this self-heating mechanism is sufficient to maintain the plasma temperature required for fusion the reaction becomes self-sustaining (i.e. no external plasma heating is required). This condition is referred to as Ignition. In magnetic plasma confinement of the deuterium-tritium fusion reaction the condition for ignition is approximately six times more demanding (in confinement time or in plasma density) than the condition for breakeven.

For more details on plasma heating see section 2.4.

Measuring the Plasma

1.5

Measuring the key plasma properties is one of the most challenging aspects of fusion research. Knowledge of the important plasma parameters (temperature, density, radiation losses etc) is very important in increasing understanding of plasma behaviour and designing, with confidence, future devices. However, as the plasma is contained in a vacuum vessel and its properties are extreme (extremely low density and extremely high temperature), conventional methods of measurement are not appropriate. Thus, plasma diagnostics are normally very innovative and often measure a physical process from which information on a particular parameter can be deduced.



Some of the techniques used for measuring the properties of plasmas

Measurement techniques can be categorised as active or passive. In active plasma diagnostics, the plasma is probed (via laser beams, microwaves, probes etc) to see how the plasma responds. For instance, in inteferometers, the passage of a microwave beam through the plasma will be slowed by the presence of the plasma (compared to the passage through vacuum). This measures the refractive index of the plasma from which the density of plasma ions/electrons can be interpreted. With all active diagnostics, it must be ensured that the probing mechanism does not significantly affect the behaviour of the plasma.

With passive plasma diagnostics, radiation and particles leaving the plasma are measured - and this knowledge is used to deduce how the plasma behaves under certain conditions. For instance, during D-T operation on JET, neutron detectors measure the flux of neutrons emitted form the plasma. All wavelengths of radiated waves (visible, UV waves, X-rays etc) are also measured - often from many locations in the plasma. Then a detailed knowledge of the process which created the waves can enable a key plasma parameter to be deduced.

For more details see section 2.5.

"Thermonuclear fusion also bodes well for the future and could take over the reins from some existing energy sources towards the middle of the century."

Fusion as a Future Energy Source

1.6

Global demand for energy continues to grow year by year as the world population expands and society becomes more and more dependent on energy supplies. The need to find new sources of energy becomes increasingly important as environmental concerns mount over the emission of CO_2 from burning fossil fuels.

At a European level, future energy supply was discussed in an EU green paper published in 2000 - 'Towards a European strategy for the security of energy supply' and a progress report published in 2005. Of particular concern is the dependency Europe has on importing its energy from outside the EU (50% today and predicted to be 70% in 2030). The long term role of fusion is recognised in this report. 'Thermonuclear fusion also bodes well for the future and could take over the reins from some existing energy sources towards the middle of the century'.

At national, European and international levels, future energy supply is becoming one of the key issues. Fusion offers a valuable alternative in future energy mix scenarios.

Nuclear Fusion could play a role in electricity supply

The Way Ahead ...

The success of JET, in terms of optimising plasma stability and confinement, has led to the design of the next step device – ITER (see http://www.iter.org). ITER is an international collaboration with seven partners (EU, Japan, USA, South Korea, Russia, China and India) and is a more advanced, larger version of JET. It will be capable of producing 500MW of fusion power (ten times that needed to heat the plasma). In comparison, JET can only produce fusion power that is ~70% of the power needed to heat the plasma. After much political debate, the go ahead to build ITER at Cadarache in France was given in June 2005. ITER will take ten years to build and should operate from 2016.

The so-called fast track to commercial fusion power is a strategy designed to ensure that a demonstration fusion power station puts electricity into the grid in 30 years time. During the operation of ITER, a parallel materials testing programme will be undertaken - developing and assessing the materials needed for a powerplant. The experience from both these facilities will enable the first demonstration powerplant to be operational in ~ 30 years.

Advantages of Fusion

Fusion offers significant potential advantages as a future source of energy, as just part of a varied world energy mix.

Abundant fuels

Deuterium is abundant as it can be extracted from all forms of water. If all the world's electricity were to be provided by fusion power stations, present deuterium supplies from water would last for millions of years.

Tritium does not occur naturally and will be bred from lithium within the machine. Therefore, once the reaction is established, even though it occurs between deuterium and tritium, the external fuels required are deuterium and lithium.

Lithium is the lightest metallic element and is plentiful in the earth's crust. If all the world's electricity were to be provided by fusion, known lithium reserves would last for at least one thousand years.

The energy gained from a fusion reaction is enormous. To illustrate, 10 grams of deuterium (which can be extracted from 500 litres of water) and 15g of tritium (produced from 30g of lithium) reacting in a fusion powerplant would produce enough energy for the lifetime electricity needs of an average person in an industrialised country.

Inherent safety

The fusion process in a future power station will be inherently safe. As the amount of deuterium and tritium in the plasma at any one time is very small (just a few grammes) and the conditions required for fusion to occur (e.g. plasma temperature and confinement) are difficult to attain, any deviation away from these conditions will result in a rapid cooling of the plasma and its termination. There are no circumstances in which the plasma fusion reaction can 'run away' or proceed into an uncontrollable or critical condition.

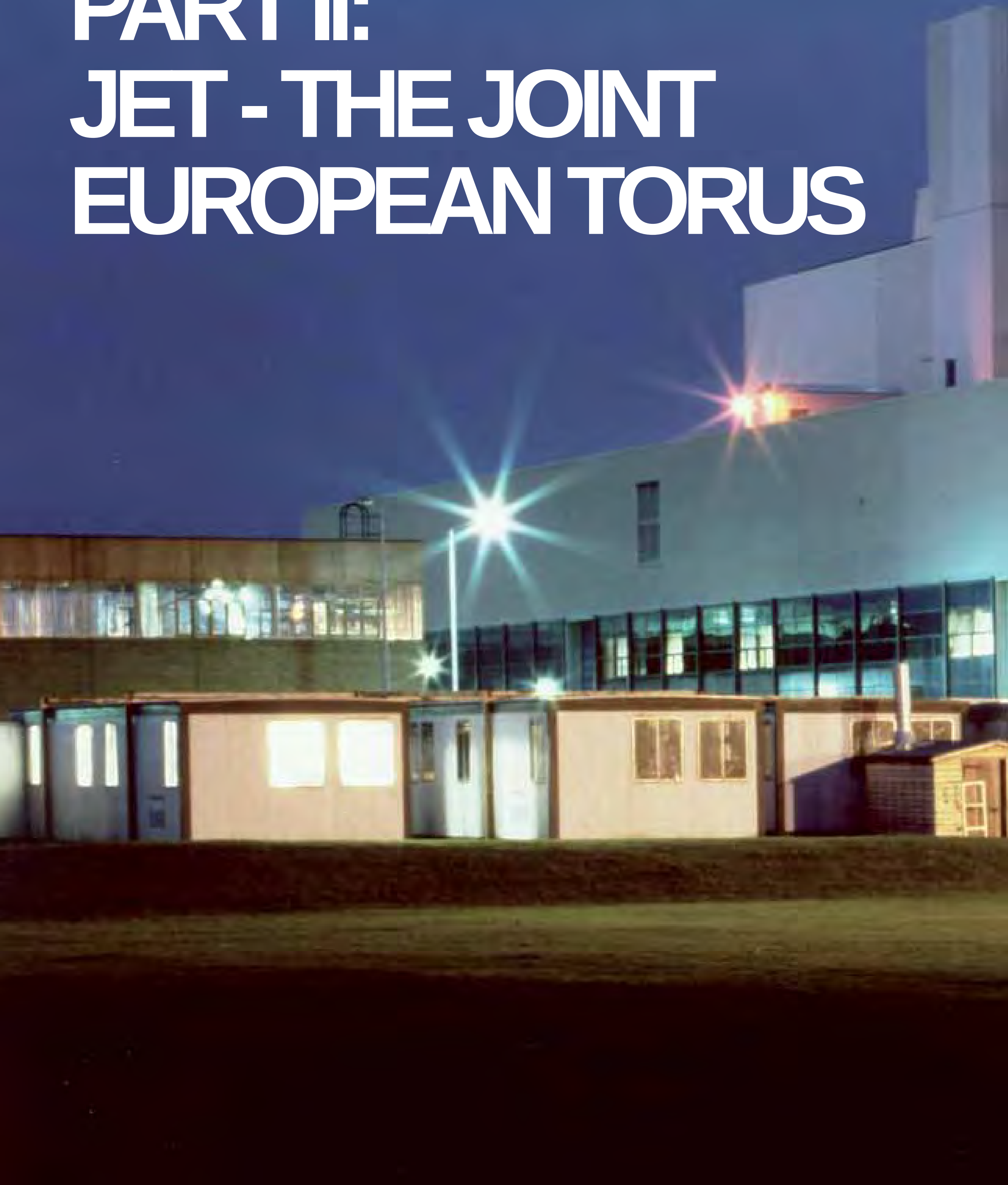
There is mounting concern that the emission of CO_2 *from burning fossil fuels is producing climatic change*

Enviromental Advantages

Like conventional nuclear (fission) power, fusion power stations will produce no ‘greenhouse’ gases and will not contribute to global warming.

As fusion is a nuclear process the fusion powerplant structure will become radioactive by the action of the energetic fusion neutrons on material surfaces. However, this activation decays rapidly and the time span before it can be re-used and handled can be minimised (to around 50 years) by careful selection of low-activation materials. In addition, unlike fission, there is no radioactive ‘waste’ product from the fusion reaction itself. The fusion byproduct is helium, an inert and harmless gas.

PART II:
JET - THE JOINT EUROPEAN TORUS



Description of the JET Tokamak

2.1

The JET machine is a large tokamak device of approximately 15 metres in diameter and 12 metres high. At the heart of the machine there is a toroidal (ring-shaped) vacuum vessel of major radius 2.96 metres with a D-shaped cross-section 2.5 metres by 4.2 metres. The linear dimensions of the plasma confined in this vacuum vessel are within a factor of two or three of those expected in a commercial reactor.

The toroidal component of the magnetic field on JET is generated by 32 large D-shaped coils with copper windings, which are equally spaced around the machine. The primary winding (inner poloidal field coils) of the transformer, used to induce the plasma current which generates the poloidal component of the field, is situated at the centre of the machine. Coupling between the primary winding and the toroidal plasma, acting as the single turn secondary, is provided by the massive eight limbed transformer core. Around the outside of the machine, but within the confines of the transformer limbs, is the set of six field coils (outer poloidal field coils) used for positioning, shaping and stabilising the position of the plasma inside the vessel, see Figure 2.

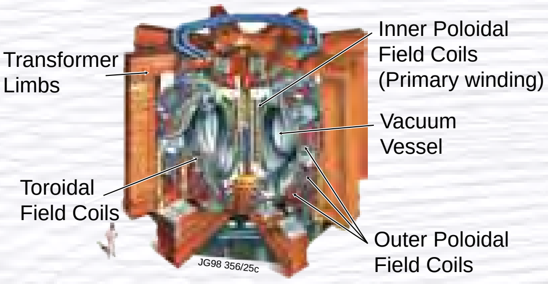


Figure 1: Cross-section of the Joint European Torus

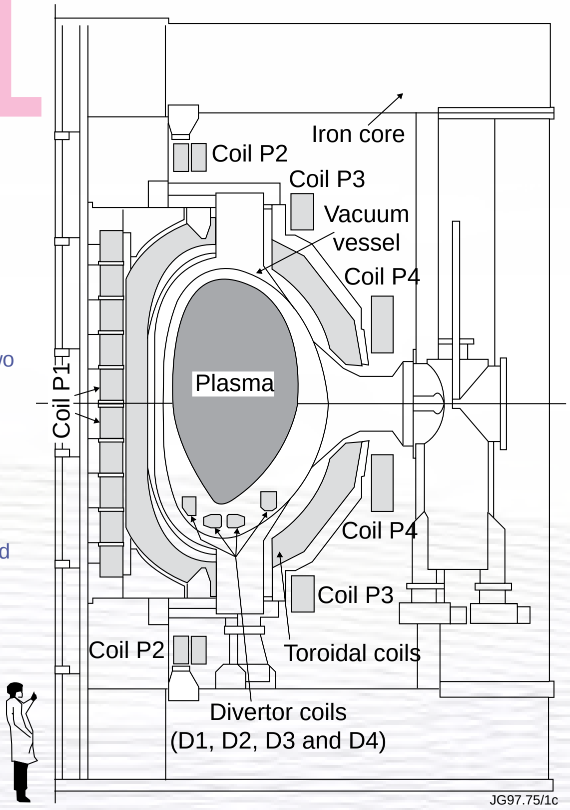
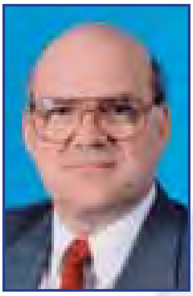


Figure 2: Vertical cross-section of JET showing the toroidal, poloidal and divertor coils.

During operation large forces are produced due to interactions between the currents and magnetic fields. These forces are constrained by the mechanical structure which encloses the central components of the machine.The use of transformer action for producing the large plasma current means that the JET machine operates in a pulsed mode. Pulses can be produced at a maximum rate of about one every twenty minutes, and each one can last for up to 60 seconds in duration. The amount of gas introduced into the vessel for an experimental pulse amounts to less than one tenth of a gramme.

“Without JET, ITER would not exist today.”

Prof Paul-Henri Rebut,
Former Chairman of JET Project Board,
Former Director of JET



JET parameters Plasma major radius	2.96 m
Plasma minor radius:	2.10 m (vertical) 1.25 m (horizantal)
Flat-top pulse length	20 – 60 s
Weight of the iron core	2800 t
Toroidal Field Coil Power (Peak On 13s Rise)	380 MW
Toroidal magnetic field (on plasma axis)	3.45 T
Plasma current:	3.2 MA (Circular plasma) 4.8 MA (D-Shape plasma)
Volt-seconds to drive plasma current	34 Vs
Additional heating power	30 MW

Figure 3: External view of the JET Torus

During experimental campaigns, JET operates in two shifts, from 06:30 to 14:30 and from 14:30 to 22:30. In total about 450 engineers and technical staff look after the smooth operation of the facility. On top of that, approximately five hundred scientists from across Europe (including Culham scientists) make up the rest of the team, contributing to the detailed definition of JET’s scientific programme and closely following the achieved results. Scientists from European fusion laboratories either collaborate at the JET site during their missions which can last from several days up to several years, or they may simply log in remotely, analyse data, discuss with their colleagues via email, phone or by teleconference, and ultimately publish scientific articles directly from their home laboratories.

> *“ Generating plasma conditions reminiscent of the sun requires a wide range of massive power supplies for heating and confining the plasma, and ultimately for igniting a burning plasma for electric power production in future fusion power stations.”*
>
> *Dr Alan Kaye,*
> *Former JET’s Chief Engineer*

Power Supplies

2.2

Energy needed to start fusion

Imagine you need to start a fire. Pretty simple with today’s technology, with a lighter or with matches, but quite difficult without. Still, humankind would not be able to produce lighters and matches without harnessing fire first. History shows that the early methods of starting fires were quite exhausting but, when successful, the effort was very rewarding.

In fusion research, we aim at releasing and controlling energy almost a million times more powerful than fire: the energy that drives stars. The task is at the very limits of present technology, but it is almost within our grasp. JET can achieve the extreme conditions (namely extreme temperatures) under which massive fusion energy can be briefly released. Let us take a look at the power sources needed to get us to this point....

Figure 1: Primitive methods of starting fires were energy demanding

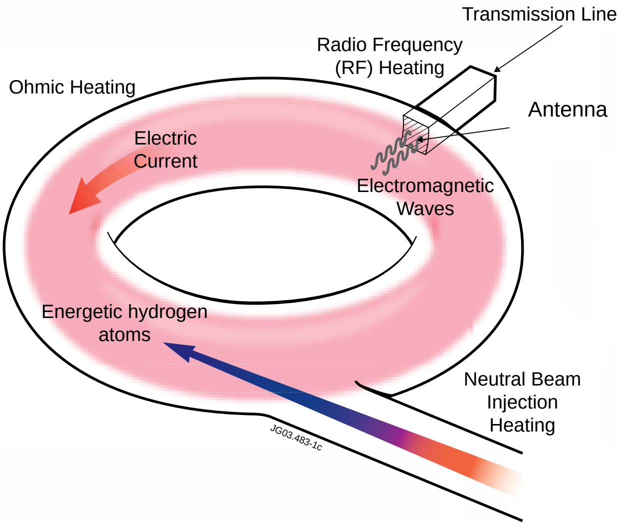


Figure 2: Plasma and its heating

JET is capable of producing hydrogen plasmas (completely ionised gas) with temperatures of hundreds of millions of Kelvins (or degrees Celsius). Obtaining such high temperatures requires extraordinarily powerful heating. Powerful heating is also needed to sustain these temperatures, otherwise the plasma would rapidly cool down due to inevitable heat losses via radiation and heat convection/conduction. Given that the temperature gradient from the vessel wall to the plasma centre is about one million degrees per centimetre, it is easy to see that the plasma can lose energy very quickly unless it is well insulated. Standard thermal insulation methods are totally inadequate so JET uses a magnetic confinement system to retain heat in the plasma by using magnetic fields to keep the plasma away from the vessel walls.

Plasma heating is not the biggest consumer of energy at JET. In reality, a significant amount of power is needed to feed the large coils (see figure 3) which produce the strong magnetic fields to keep the plasma under control and away from the vessel walls. Because the coils have resistance, the large currents in the coils cause them to heat and they need to be water-cooled as a consequence. The energy is mostly dissipated to atmosphere via special cooling towers. Some fusion experiments, like Tore Supra (France), LHD (Japan), EAST (China), Wendelstein 7-X (under construction in Germany), KSTAR (under construction in Korea) or the future ITER use superconducting coils that avoid this energy loss but at the cost of running them at very low temperatures, around -270 °C, using liquid helium.

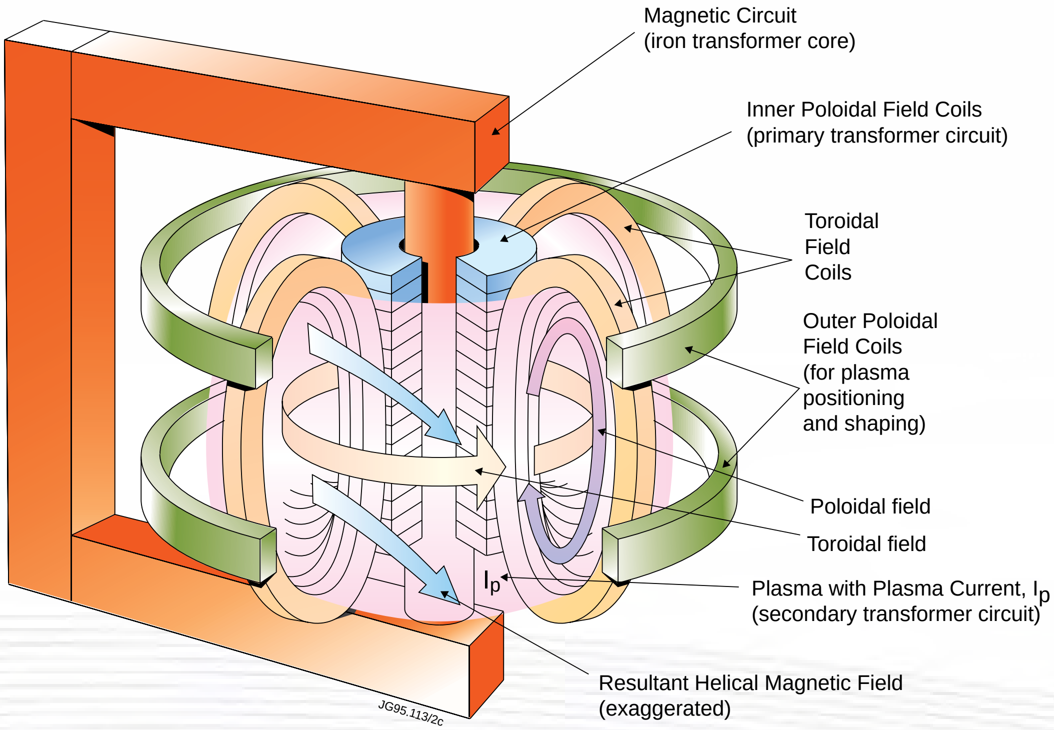


Figure 3: JET's coils and plasma

Every individual plasma experiment at JET (called a JET "pulse") lasts several tens of seconds and during experimental campaigns there are some 30 pulses a day. In other words, most of the JET power consumption is concentrated in short bursts, which is quite demanding on the electricity grid and on electrical engineering in general. Moreover, even during a single pulse, the power requirements are not constant – the pulse startup (magnetic field set-up and initial plasma heating) needs more power than the "plateau", the sustaining phase. The toroidal field coils (see figure 3) are the largest single load on JET. The poloidal field system, on the other hand, has complex switching and control requirements. After the plasma has been created, its position and shape is feedback-controlled by taking sensitive magnetic measurements and supplying additional power to the vertical and horizontal poloidal field amplifiers according to plasma behaviour.

As a comparison, the typical power of a central heating boiler in a family house is around 25kW (kilowatt = thousand watts). Running a JET pulse requires around 500 MW (megawatt = million watts) of power, of which more than a half goes to the toroidal field coils. Around 100 MW of power is needed to run the poloidal field system (ohmic heating and plasma shaping coils) and the rest (~150 MW) runs the additional heating sources (neutral beams and RF heating).

Of our plasma heating systems, the total input power to all the neutral beam heating systems can be up to 140 MW, and for the Ion Cyclotron Resonance Heating can be up to 90 MW. Additionally, the Lower Hybrid Current Drive system can support the JET plasma current, and the installed input power of this system is several tens of MW.

The energy conversion efficiencies of all heating and current drive systems limits the power that the plasma receives. The installed output power of the neutral beam heating system is 23 MW, and that of the Ion Cyclotron Resonance Heating is 32 MW of RF power. Lower Hybrid Current Drive can achieve 12 MW of microwave power. However in most JET pulses only part of these installed capacities is exploited, depending on experimental scenarios. Last but not least, the plasma also gets a few MW of power from ohmic heating, ie the heating due to electric current induced in the plasma by the inner poloidal coils. In total, JET plasmas usually consume a few tens of megawatts.

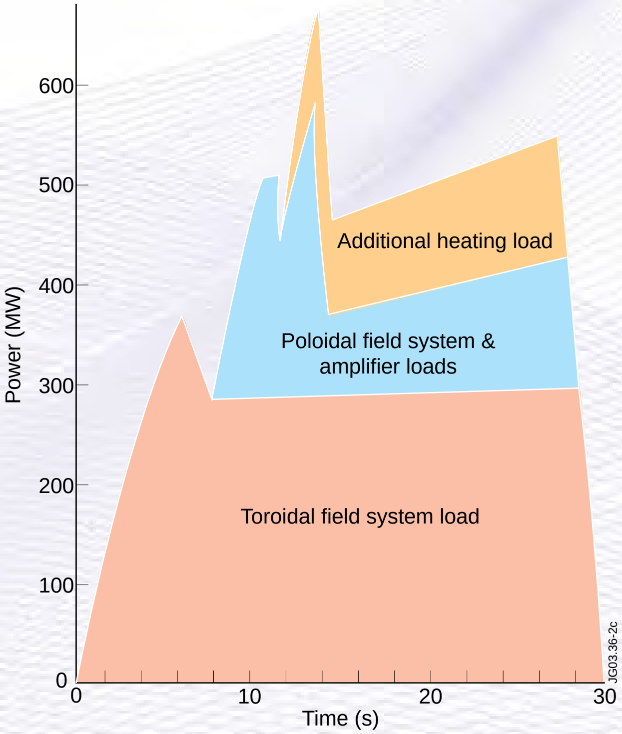


Figure 4 : JET's power loads

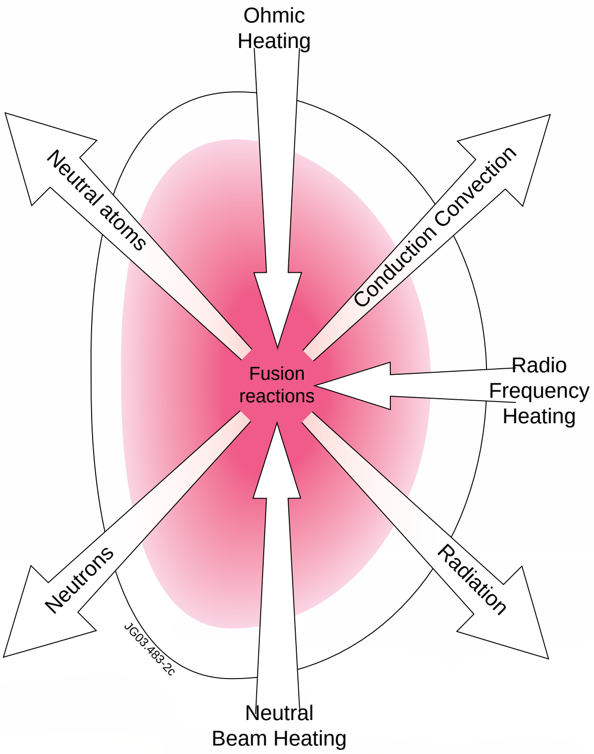


Figure 5: Plasma energy balance

The plasma accumulates only a fraction of the consumed energy. The rest leaks away via radiation, heat conduction and particle losses. The “energy confinement time” is a simple measure of our ability to reduce those leaks. The time is equal to the ratio between the total plasma energy (Joules) and the total heating power (Watts = Joules per second) needed to sustain such plasma energy. In the case of JET, the energy confinement time is usually close to one second. That is, with power consumption well above 10 MW, the total heat energy of the typical JET plasma is more than 10 MJ (10 million Joules). The heat energy of a hot truck engine is comparable to this number - but keep in mind that its weight and temperature differ a lot from the JET plasma. The latter weighs only tens of milligrams but is at a temperature of hundreds of millions of degrees.

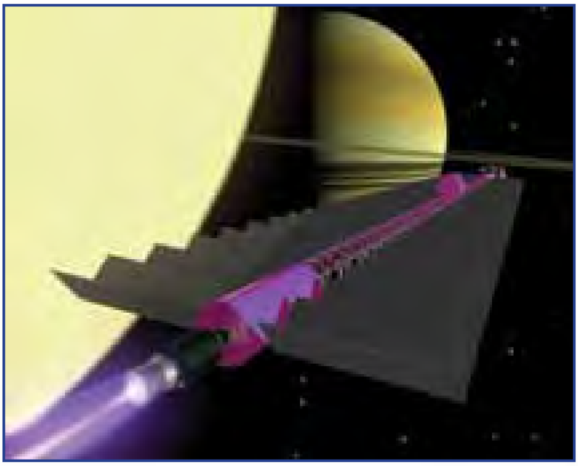


Figure 6: Fusion-powered spaceships are anticipated to explore outer Space (image courtesy of NASA)

Perhaps you may be thinking that JET's fusion research facilities are inefficient. That wouldn't be fair – they are efficient in their task, which is achieving the extreme conditions required to initiate fusion and producing plasmas on which to perform research. We are back to our first picture now: the priority of that Iron Age human was to start a fire, not to spare the energy of his body. In clear parallel to him, we are confident that our efforts will eventually pay off. In fact, we cannot imagine sustainable progress of humankind without first mastering fusion energy.

> *"Fusion power is likely to be our future and as JET is the key to this future also Power Supplies are the key to JET. The Power Supplies carry, condition and deliver the power lifeblood to the JET machine and the Flywheels are their heart."*
>
> *Alan Parkin,*
>
> *Head of JET Operational Support Group*

JET's Flywheels

In summary, the JET power supply system has an installed capacity approaching 1400 MW (MW = megawatt = one million watts), a significant proportion of the maximum output of a large power station. However, not all of the installed capacity is necessary when an experiment is run - the different systems rather serve as a portfolio of many options on how we may produce various plasma conditions. Even more importantly, most of the power requirements are concentrated into short time periods of plasma pulses, followed by much longer quiet periods of machine cooling and data processing. This interval can be used to accumulate stored energy on our research site, thus providing a powerful local source that can considerably reduce the national grid load during the subsequent plasma pulse.

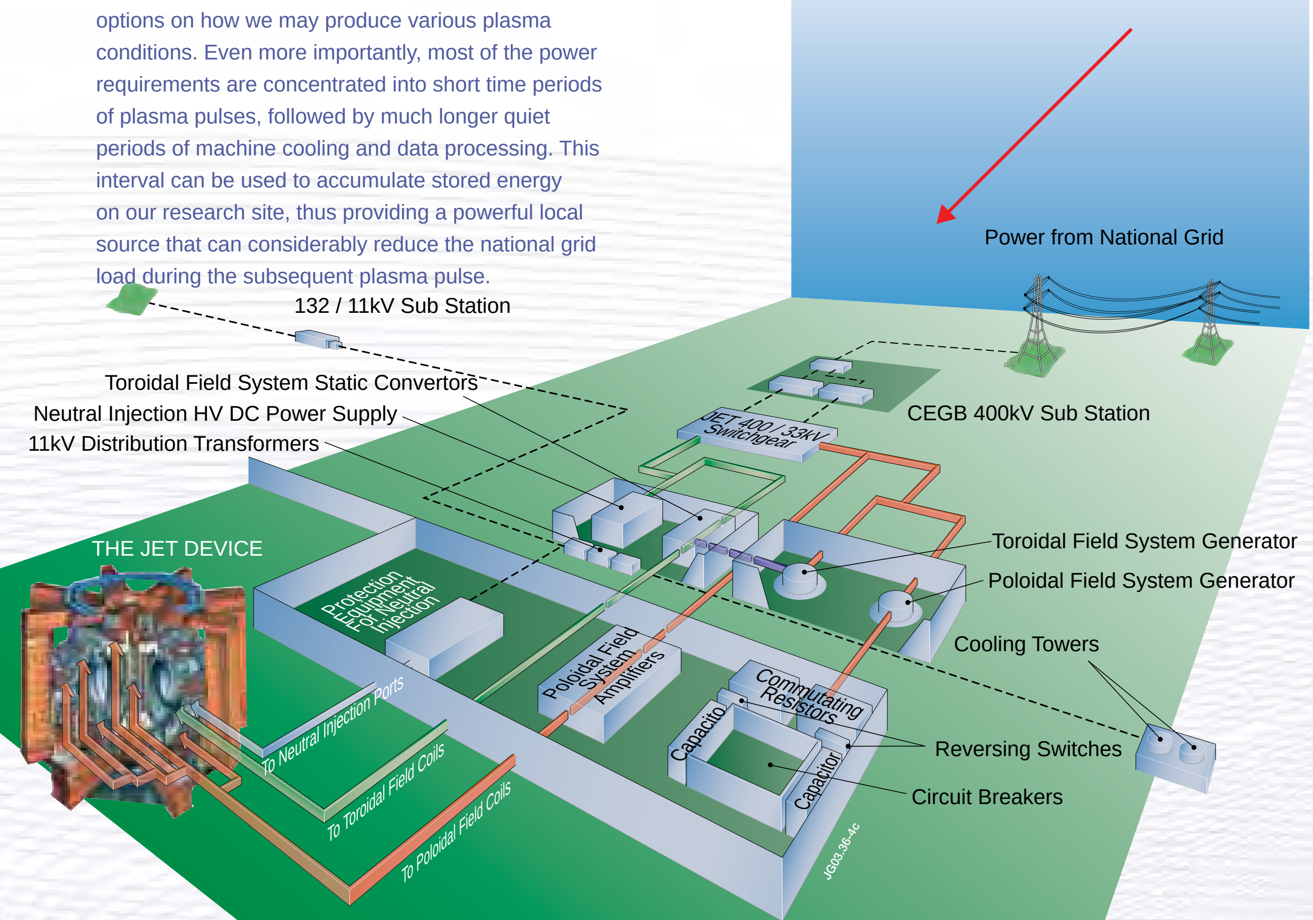


Figure 7: JET power supplies and their connection to the National Grid (The arrow shows camera position in the next photograph)

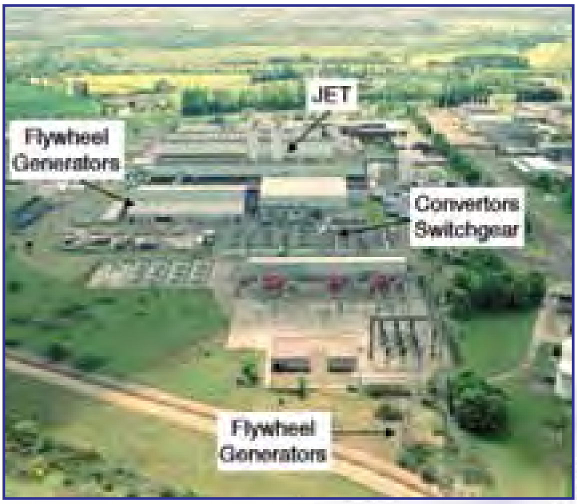


Figure 8: A birds eye view of the JET Power Supplies

Two methods of energy storage are applied in fusion research facilities. Large banks of capacitors are used on small and middle-sized machines with short (flash-like) experimental pulses. On big machines, energy may be stored using massive flywheels. JET, a large tokamak with pulses extending 20 seconds and more, is an obvious candidate for the flywheel solution.

Each JET pulse consumes around 10 GJ (GJ = gigajoule = one thousand million joules) of energy, with the peak power requirements exceeding 1000 MW. This amount of power cannot be taken from the UK National Grid so two massive flywheel generators are used to supply the additional energy needs. The rotating part (rotor) of each generator is 9 metres in diameter and weighs 775 tons (!), much of which is concentrated on the rim to form a large flywheel.

For experts - the total moment of inertia is 13.5 million kg.m^2 per flywheel!

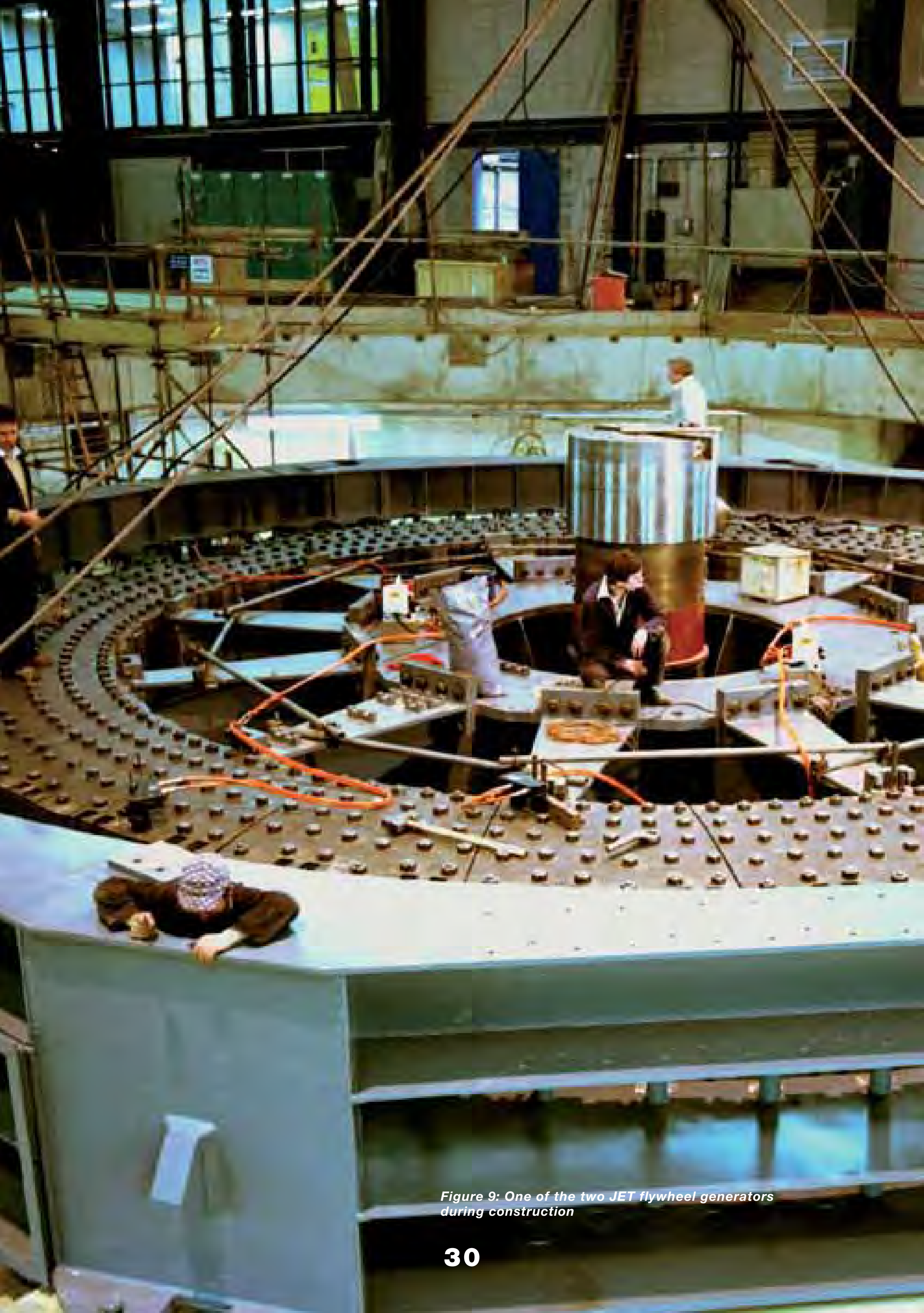


Figure 9: One of the two JET flywheel generators during construction

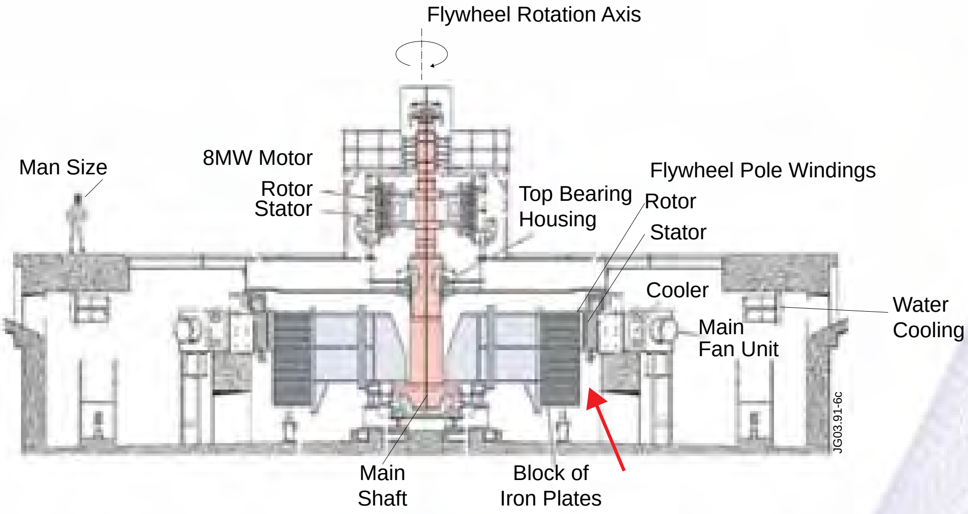


Figure 10: Side-view of the complete generator (the arrow shows camera position in the next photograph)

Before each pulse the flywheel is accelerated by its 8.8 MW electric motor - even high-speed trains like Eurostar or TGV have less powerful motors...

Each flywheel can be spun up to 225 rpm (3.75 Hz) so that the edge of the flywheel rotates at the speed of 380 km/h (236 mph)! That is where the rotor carries the pole windings. Positioned as closely as possible to these rotating windings are stationary pole windings mounted on the stator, which is the fixed cylindrical construction around the flywheel.

When power is needed for a JET pulse, the rotor pole windings are energised. In other words, electric current is sent to the rotor windings so that they start producing a strong magnetic field. The magnetic field immediately interacts with the stationary windings. According to the laws of electrodynamics, the stationary windings start producing massive electric power at the expense of the kinetic energy of rotor gyration: magnetic forces act as a powerful brake that slows the flywheel down to approx. 112 rpm.

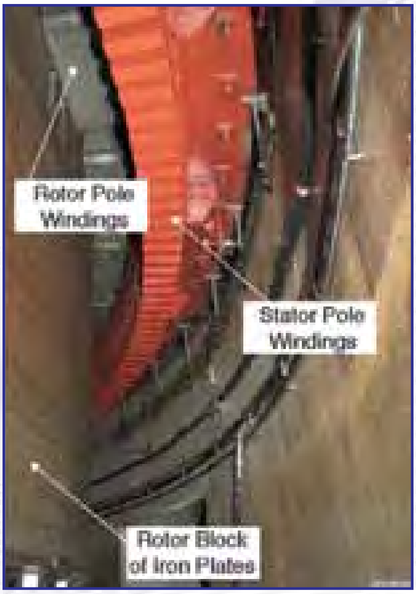


Figure 11: Inside the generator: Stator and rotor pole windings

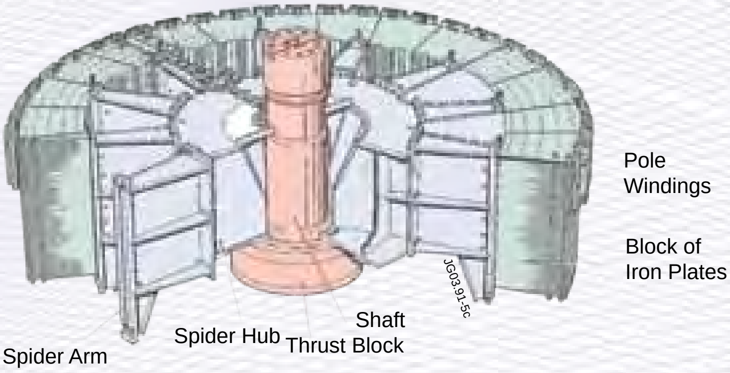


Figure 12: Sectional view of a flywheel rotor

Figure 14: 90° Panoramic view of the Didcot Power Plants and JET (5 km apart)

The remaining power required during the pulse - namely part of the toroidal coils' consumption and all the additional heating - is obtained directly from the national grid. Again, semiconductors (diodes and thyristors) must be used to convert the grid AC power into a dynamic DC form suitable for JET. The power used for pulsed operation is supplied from the 400 kV grid. In addition, continuous electrical power is provided by two 132 kV supplies to run the ancillary equipment.

An important advantage of the Culham site for the JET facility has been the vicinity of the Didcot Power Plants. This huge enterprise with coal power plant and combined cycle gas power plant, with total installed electric power of 3400 MW, is located only some 5 km (3 miles) away from JET.

However, when the UK public's electricity consumption hits a peak, the National Grid operator can quickly inhibit the pulsed operation of JET in order to prevent overload of its power plants. Our scientists, being naturally very curious people, have tried to find out when these periods of "JET blackouts" are likely to occur. To our surprise, the intervals of TV advertising spots that are broadcast in the middle of highly popular programmes (eg Coronation Street, football finals etc) are common causes of delays in JET's evening operations. Presumably adverts cause millions of viewers to switch on their kettles all at the same time!

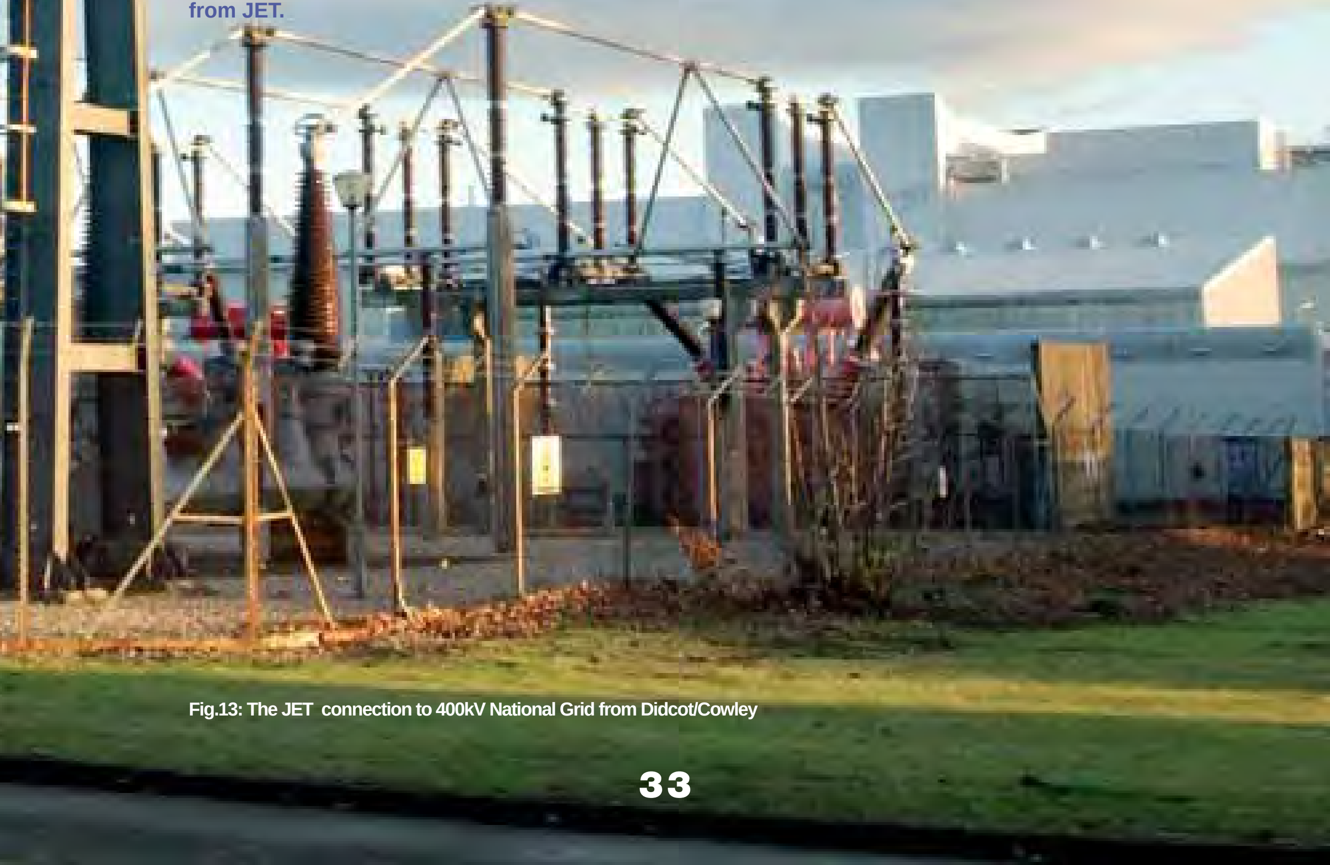


Fig.13: The JET connection to 400kV National Grid from Didcot/Cowley

"What comes to your mind if you hear someone say, "The Shut-Down is over: they restarted the pumping today!"? Perhaps you think of a water circulation pump like the one at home in the central heating system, an oil impeller like the one in your car, or maybe a vacuum pump similar to the roughing pumps you used in project work at university. Actually the pumping referred to is the set of large turbopumps mounted on the torus that produce the ultra-high vacuum needed for the tokamak to operate, but of course JET includes a wide variety of pumps in its plant, many of them of colossal capacity compared to those more familiar examples."

Tom Todd,

Chief Engineer

Cooling System and Vacuum Pumping

2.3

A newcomer to JET can get easily confused when pumping systems are discussed. Indeed, there are two large and completely different pumping systems, both quite impressive and deserving respect for their technology and performance: the cooling system of the JET machine (fluid pumping), and its vacuum system (gas pumping).

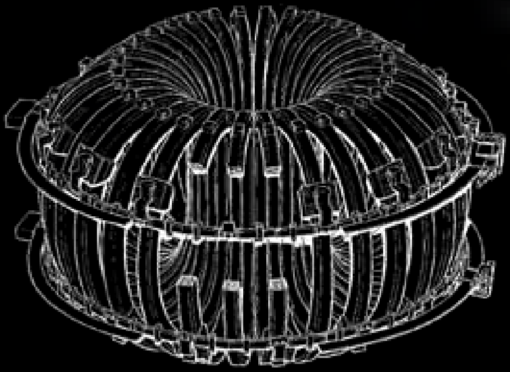


Figure 1: JET's toroidal field coils.

Cooling the JET machine

As mentioned in the previous section, most of the electrical power consumed by JET is transferred into heat. The main reason for this is that all of JET's massive coils which produce the strong, plasma confining magnetic fields are made from copper - and even though copper is a very good conductor, it still has a small resistance to the electric current. At very high electric currents, needed to achieve the strong magnetic fields, this resistance causes significant heating in all of JET's coils. They must be continuously cooled down to prevent overheating of the facility.

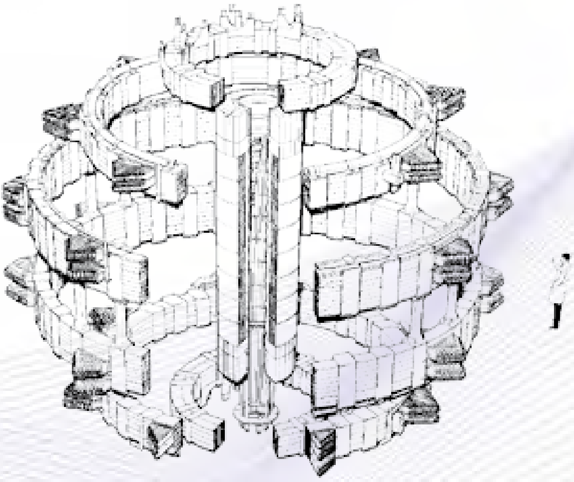


Figure 2: JET's poloidal field coils.

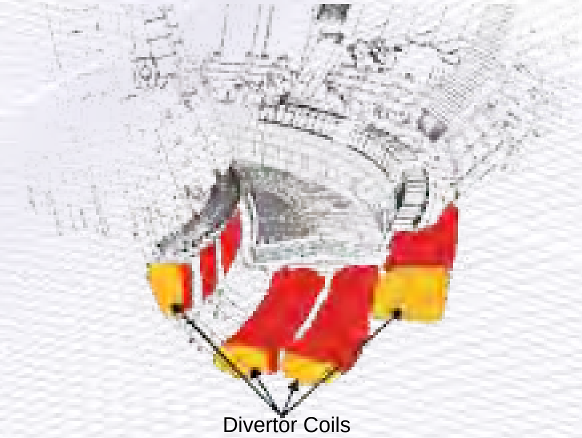


Figure 3: JET's divertor coils (in-vessel cross-section)

Figure 5: Toroidal field coils cooling pumps

Figure 6: Poloidal field coils cooling pumps

Figure 7: JET's cooling towers during major maintenance work in 2004

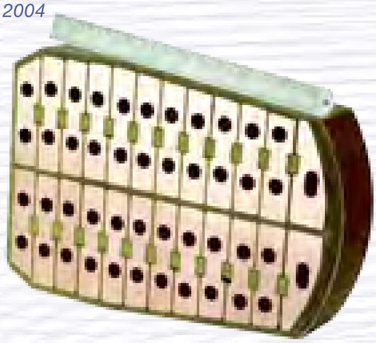


Figure 4: Photo of the JET toroidal coil in cross-section showing holes where the cooling liquid circulates

Apart from the toroidal and divertor coils, all of JET's coils are cooled by forced circulation of water. The cooling water needs ongoing effective demineralisation and deionisation in order to keep its conductivity very low. Therefore, a special water treatment facility has been installed at JET. However, in the event of leaks, the water becomes re-ionised and conductive after a short period, so that it can cause electrical short-circuits. That is why the most vulnerable toroidal and divertor coils use a special cooling liquid known as Galden HT55, a non-flammable heat transfer fluid that maintains its high resistance under all conditions.

Tens of powerful pumps that force the circulation of the water and Galden can be found just below the JET Torus Hall, in its basement area. It is an extremely noisy environment during JET operations! Deionised water and Galden circulate in closed loops and exchange their heat with the main water circuit in heat exchangers that are situated next to the pumps and look like large engine radiators. The main water circuit then carries the excess heat to JET's four cooling towers, each with a two speed fan. Although these towers are very small in comparison to the cooling towers of nearby Didcot Power Plant, they still have a significant capacity of 4 x 35 MW (million watts) corresponding to 4 x 1000 m3 (one million litres) of water per hour cooled down from 50 °C to approximately 20 °C. Next to the towers are five large pumps which drive the water circulation in the main circuit - one per tower, the fifth is spare – each with 200 kW power and operating on 3300 Volts. An additional booster pump supports the water flow at the far end of the main circuit.

Figure 8: 3 MW chiller unit

During the plasma discharge, when large electric currents flow in the coils to generate the magnetic fields, the temperature of the coils increases sharply. After the discharge their temperature slowly decreases to the level at which the next discharge is feasible. Overheating of the JET coils is the main limiting factor for the duration of the JET discharges. A typical JET plasma discharge lasts for 20 seconds - but it can be longer (even 60 seconds) when lower magnetic fields are required. The cooling system has been designed so that after each discharge the facility can be cooled down in 15 minutes, to match the similar time intervals required to spin up the flywheel generators (see the previous section) and to download and save all data acquired from the JET diagnostic systems.

To further boost the performance of JET - whenever high magnetic fields or long discharges are required - two massive 3 MW chillers (large refrigerators) have been installed on site (see figure 8). When operational, these chillers are connected to the heat exchanger of the Galden-cooled units (toroidal field coils and divertor coils), replacing the main water circuit. The chillers can push the temperature of the Galden fluid down to 12 °C.

The JET magnetic field coils are not the only reason why a substantial cooling system is required on site. Other major "customers" of the system are Neutral Beam Injectors, principally for their ion dumps and deflection magnets (see section 2.4), and the JET flywheel generators. In addition, many minor systems need to be connected to the cooling pipework, including the air conditioning plant, cryogenic plant (see below) and individual plasma diagnostics (see section 2.5).

Item	Water flow from the main circuit	Secondary circuit fluid	Flow and pressure in the secondary circuit	Pumps (numbers and power)
Toroidal field (TF) and divertor coils (Div)	800 m^3/h	Galden	TF : 900 m3/h at 7 Bar(g) Div : 22 m3/h at 22 Bar(g) max	TF : 4 x 55kW Div : 2 x 11kW & 2 x 18kW
Poloidal field coils (including transformer coils)	600 m^3/h	Deionised water	Coil 1: 120 m3/h at 12 Bar(g) Coil 2: 725 m3/h at 10 Bar(g) Coils 3 and 4: 360 m3/h at 5.5 Bar(g)	Coil 1 : 1 x 45kW Coil 2 : 3 x 200kW Coils 3 & 4 : 2 x 55kW
Neutral beams	800 m^3/h	Deionised water	Beam dump: 2000 m3/h at 6 Bar(g) Injectors: 440 m3/h at 10 Bar(g)	1 x 320kW and 1 x 30kW 1 x 132kW and 1 x 4kW
Flywheel generators	1050 m^3/h	–		
Air conditioning	100 m^3/h	–		
Cryogenic plant	80 m^3/h	–		
Other	56 m3/h	–		

Table.1: JET's main cooled items

Figure 9: Neutral beam injector box cooling pump (in foreground) and the high voltage supply leads of the beam accelerators (in background)

In order to achieve much longer plasma discharges, recent and future fusion facilities (including ITER) have to be equipped with superconducting magnetic field coils. A beneficial side-effect of this important upgrade is that power consumption of the superconducting coils is negligible compared to copper coils. However, there is a price to pay. Not only is the production of the superconducting coils very expensive, but - more importantly - a sophisticated liquid Helium cooling system to maintain very low temperatures (about -268 °C) in the coils will be required, otherwise the phenomenon of superconductivity (complete disappearance of electric resistance) would not occur. Therefore, building and operating a superconducting facility means opting for a considerably more complicated undertaking. It can be said that at JET, the copper coils were chosen for the sake of simplicity in the 1970s, when JET was an unprecedented technological step as it was. Nevertheless, notice that even in ITER an extensive water cooling system will be required to support, for example, operation of its cryoplant and its neutral beam injectors.

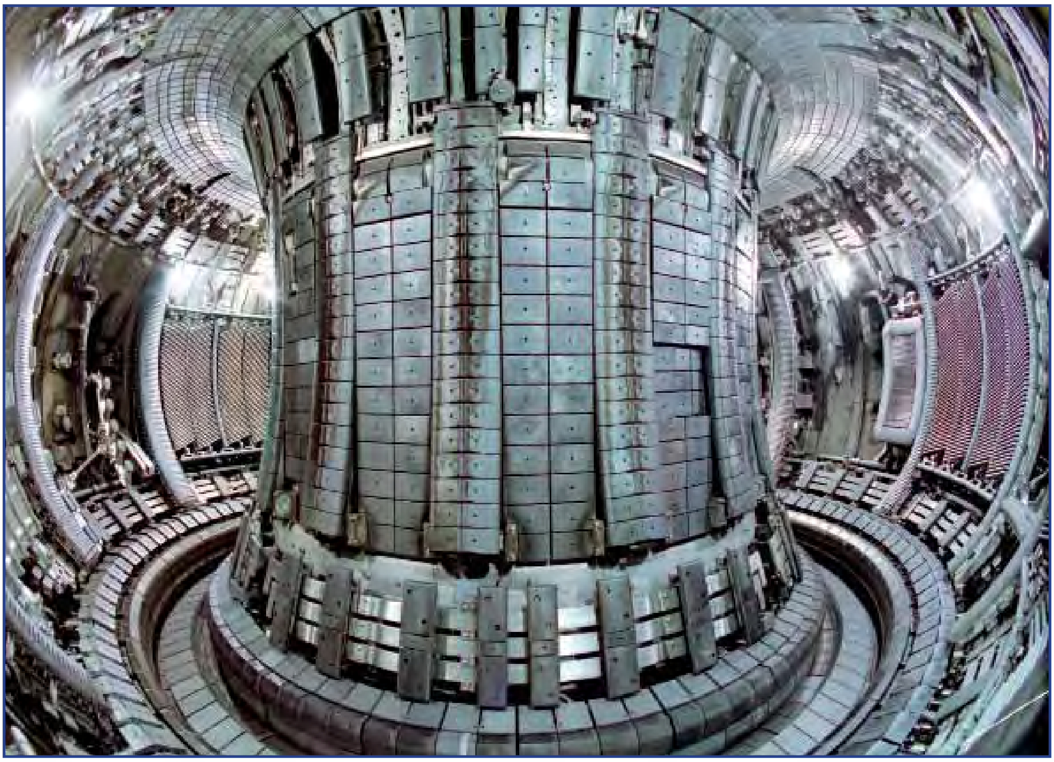


Figure 10:View inside the JET vacuum vessel

Vacuum Pumping of the JET Torus

The other major pumping system is the JET Vacuum System. It is responsible for pumping out gas from the large volume of the JET torus - the doughnut-shape vacuum vessel in which plasma discharges take place. The total vessel volume to be pumped is more than 200 m^3 - similar to the volume of an average apartment!

Why is this vacuum pumping required? The densities of the hydrogen plasma that can be confined by magnetic fields are very low, about one million times lower than the density of air. Even a much smaller amount of non-hydrogen elements remaining in the vessel (e.g. nitrogen or oxygen from the air) would considerably damage discharge performance.

During JET's shutdown periods, however, the vessel is vented to air allowing maintenance and new installations. Therefore, after each shutdown, all air must be thoroughly pumped out. The working gas for the plasma experiment - usually deuterium (heavy hydrogen isotope), occasionally protium (common light hydrogen isotope), helium and, in special campaigns, tritium (superheavy hydrogen isotope) - are puffed in just before and during the plasma discharge according to the real-time plasma control requirements (see section 2.6). In addition, JET plasmas can be "fuelled" by Neutral Beams and by pellets, i.e. by small capsules of frozen deuterium fired right into the hot plasma core. These working gasses are sometimes complemented by precisely defined minuscule amounts of impurities to diagnose the plasma parameters.

In order to keep plasmas as clean as possible, the vacuum system pumps the JET vessel continuously, even during the plasma discharge. The continuous pumping has negligible influence on plasma fuelling (i.e. on supplying the working gas), because at very low densities the fuel gas expands immediately to the whole vessel. The gas influx is electrically neutral, therefore not guided by the magnetic field. Plasma exhaust, to the contrary, is guided by magnetic fields towards the bottom of the JET vessel, to the divertor (section 2.7), where it is continuously collected by dedicated cryopumps (see below).

JET is unique in the world as a fusion research experiment able to work with tritium, and, as a consequence, it has to be operated with all precautions required for active isotope handling. All the gases that are pumped from the vessel must go through a dedicated pipeline to the Active Gas Handling System (see section 2.10). In this system, chromatography and cryodistillation processes allow for safe separation and storage of the different isotopes from the pumped gases - namely of tritium (active), deuterium and helium (stable). This procedure is required at all times, even when JET is not operating with tritium, as traces of tritium continuously desorb from the vessel structure into the main pumped volume.

Figure11: Dr N Holtkamp (centre), the ITER Principal Deputy Director General, visits the Active Gas Handling System at JET (April 2006)

JET can achieve a very good level of vacuum, up to a millionth of a millionth of the density of air (in technical terms, the final pressure of impurities can achieve up to 10^{-9} mbar, that is 10^{-7} Pa). The procedure required to achieve and maintain that good vacuum is actually quite complicated, and several techniques must be employed.

Turbomolecular Pumps

First, a medium-level vacuum is achieved by pumping directly from the Active Gas Handling System. When the pressure in the vessel goes down below 1 x10^{-2} mbar , four large turbomolecular pumps are switched on. These turbine pumps, which rotate at ~33,000 rpm (550 revolutions per second!) and have a pumping capacity for nitrogen of 2000 litres of gas per second each, operate continuously and effectively to produce a very low gas pressure in the vessel. The vessel is further pumped by the cryopumps in the divertor region (see below) and JET would not be routinely operated with the cryopanels warm. With the pumped divertor panels at helium temperature a well conditioned torus will typically be pumped to ~1 x 10^{-8} mbar. Several smaller turbomolecular pumps are installed to maintain vacuum in some of the JET diagnostic systems.

Figure 12: Turbomolecular pump at JET and its turbine rotor

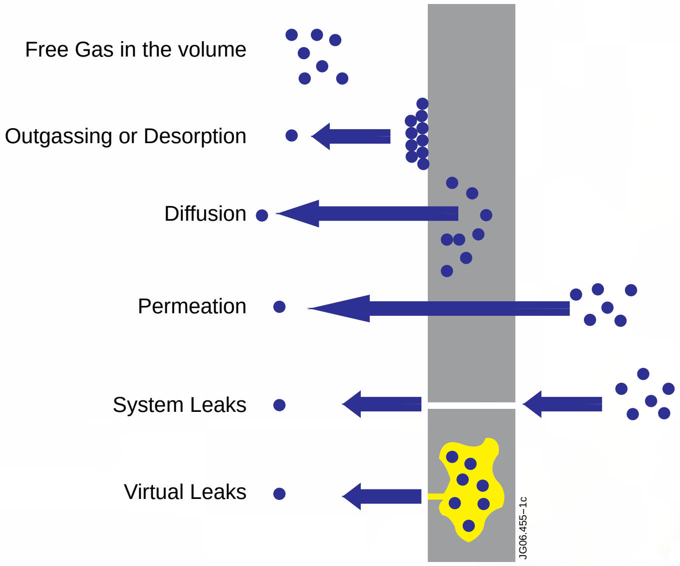


Figure 13: Diagram of gas load in a vacuum system

Cryopumps

At several specific regions of the JET facility, a very high pumping speed is required: in the Neutral Beam Injector box, where it is necessary to prevent the gas flow from the beam neutraliser into the plasma, in the divertor region at the bottom of the vessel, where the plasma exhaust is directed by magnetic field lines, but also in the Lower Hybrid Current Drive system (section 2.4) and in the deuterium pellet source. Very fast pumping in these regions is achieved by cryopumps - large surfaces that are at extremely low temperatures. On these surfaces nearly all gases immediately freeze and collect as frost. The only troublesome gas at JET which does not freeze is helium. In order to cope with helium at JET, argon frosting can be applied in the Neutral Beam Injector box. The six cryopumps at JET have the following pumping speeds (in litres per second) :

6,000,000 l/s in each of the two Neutral Beam Injectors,

130,000 l/s (total) in the Torus Divertor Region - two separate pumps,

50,000 l/s in the Lower Hybrid system,

10,000 l/s in the Pellet Centrifuge.

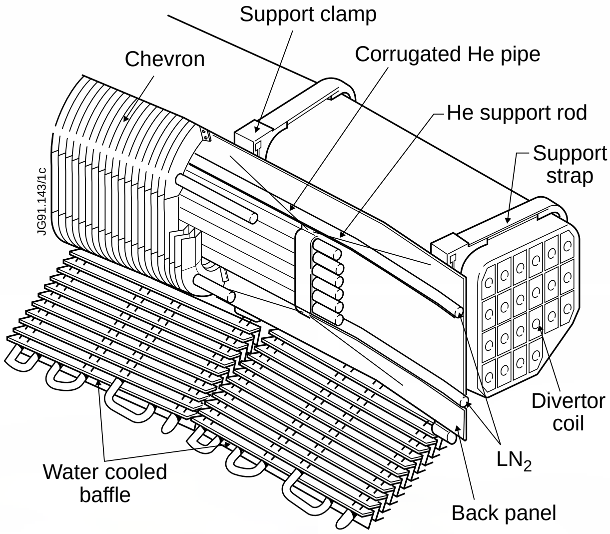


Figure 14: Section of the Divertor

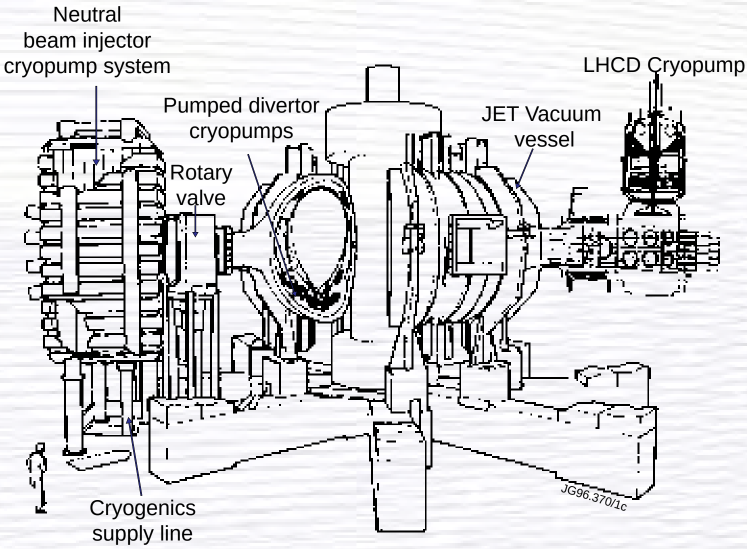


Figure 15: Cryopumps at JET

Figure 16: Valves controlling distribution of liquid gases at JET cryoplant (Photo: L.Antalova and J.Polverini)

Figure 17: Cryopump for the Neutral Beam Injector box

During operation, the JET cryopumps are cooled down to -269 °C (4 K) by liquid helium that is supplied from the JET cryoplant. In order to maintain the required amount of liquid helium for the facility, the JET cryoplant has a helium liquefier, an extreme member of the broad family of high capacity refrigerators. During JET operations, the JET's helium liquefier unit - with two main compressors and several ancillaries - needs around 1 MW power continuously in order to produce about 8,000 litres (i.e. one tonne) of liquid helium per day.

Unlike the turbo molecular pumps, the cryopumps have limited operation times – they collect pumped gas on their surfaces that needs to be removed periodically. The procedure, known as regeneration, consists of the controlled heating of the cryopumps: the gas evaporates from the cryopumps and is pumped out from the vessel by the turbo pumps. Obviously, regeneration can only be undertaken when there are no experiments - at JET it is typically done weekly on Saturdays, or overnight in case more frequent regeneration is required.

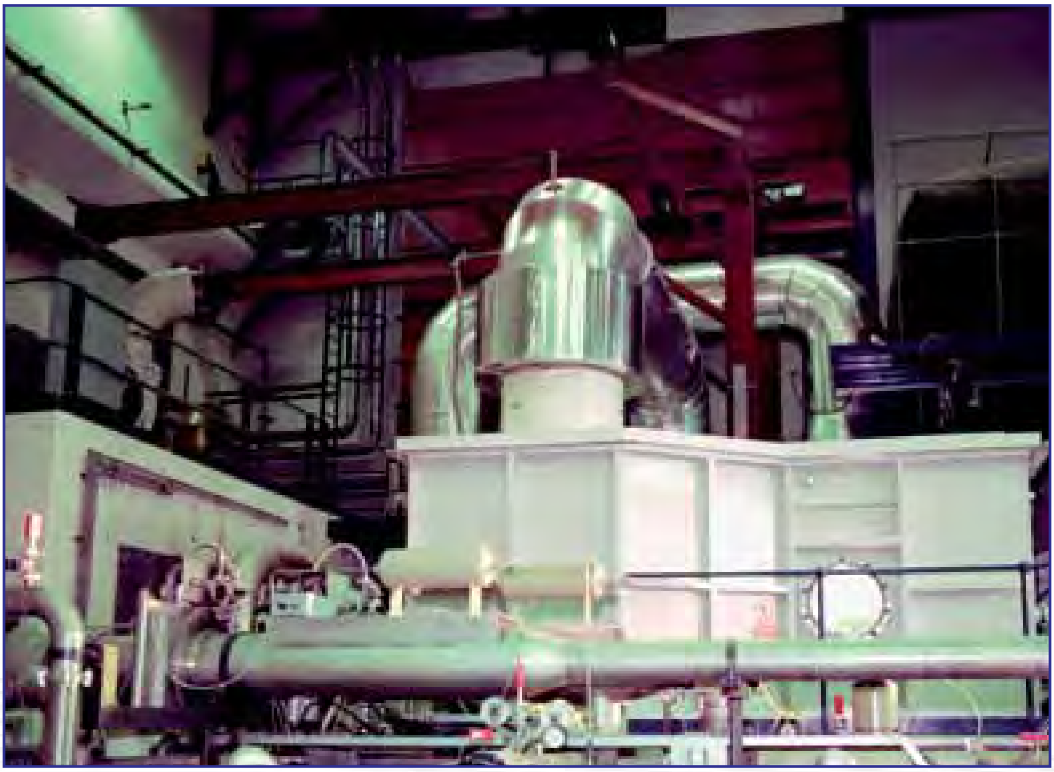


Figure 18: The gas baking system at JET

JET Vessel Baking

The structure of the JET vacuum vessel is quite complex, with a large number of components and materials. Only vacuum-safe materials may be accepted for new installations, which do not evaporate and do not easily absorb and release gases. Even then, pumping the vacuum vessel to a very good vacuum (very low pressure) is not straightforward, namely because the gas molecules tend to “hide” - adsorb on the surfaces of the solid state materials of the vessel. A very basic and efficient method to release the gas molecules from their hiding places is material baking. At JET, the whole structure of the vacuum vessel can be baked at up to 320 °C, and the baking system keeps the JET vessel hot continuously (even during plasma experiments), usually at about 200 °C. As a matter of fact, JET cannot be operated without baking - this is because its thermal expansion moves it free from the packing blocks.

The JET vessel baking is driven by two systems: hot gas and electrical. To allow for the hot gas baking, the JET vacuum vessel was built in two layers so that the baking gas can circulate in their interspace. Helium, which is used as the baking gas, runs in a closed loop – from the JET vacuum vessel to a massive blower (280 kW electric motor) that forces 22 m^3 of the gas every second through heat exchangers (total 780 kW of heating power) and back into the interspace of the double-layer vacuum vessel. To also sustain the baking process on vessel components which project from the doughnut-shape vessel, (eg the diagnostic windows), the electrical baking system was installed. This complementary system consists of hundreds of electrical heaters mounted directly onto the outside surface of the vessel components.

Discharge Cleaning

Vessel baking is a key tool in the "first wall conditioning", which is necessary in order to achieve high plasma purity, however its effect can be boosted if, in parallel, the inner surfaces are bombarded by charged particles. While by keeping materials hot we can "shake out" the gas particles adsorbed to surfaces, by bombarding the surface the particles get "kicked out". In most tokamaks, including JET, the walls are conditioned by baking combined with the effect of particle bombardment using "cold" gas discharge known as glow discharge as well as "hot" plasma discharges – hence the term "discharge cleaning".

Figure 19: Glow discharge during tests of JET's discharge electrode

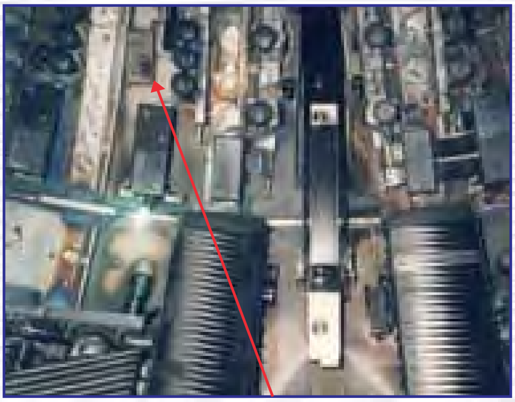


Figure 20: Electrode of the glow discharge system inside the JET vessel

At JET, a glow discharge can be struck in the whole volume of the vacuum vessel either in deuterium, or in helium. Sometimes, though rarely, a hydrogen glow can be performed. Deuterium glow cleaning is more chemically reactive than helium, for example it reacts with oxides attached to the wall, releasing heavy water. Helium glow cleaning acts mainly by the electric charge of the glow particles. The glow discharge can be switched on continuously in the JET vessel - more than 24 hour continuous glow discharge cleaning in deuterium followed by a similarly long glow discharge cleaning in helium is not exceptional after long shutdowns. During experimental campaigns, an overnight glow discharge cleaning may be requested to improve the first wall condition. The glow discharge cleaning is typically run once a week after regeneration of the pumped divertor helium panels.

High temperature plasma discharges themselves act as a rather efficient tool to further clean the first wall from adsorbed atoms and molecules, as the plasma particle energies (i.e. velocities) are much higher in hot plasmas than in the glow discharge. For fusion experiments this is an adverse effect, as it increases the amount of impurities in the plasma. However, after a shutdown it is a common practice to run a few standard, scientifically uninteresting plasma discharges prior to the actual research with "tuned up" discharges. In any case, there are many other reasons for doing so: other systems, including power supplies, real-time control and plasma diagnostics, need a few simplified plasma discharges after each shutdown, to be recommissioned.

Beryllium Evaporation

Last, but not least, the first wall conditioning process is usually complemented with a technique that can deposit a microscopic layer of a suitable light element on the first wall. The layer helps to keep good vacuum conditions, in particular by gettering oxygen. Many tokamaks use boron in a glow discharge process known as boronisation. JET, the only fusion facility worldwide to do so, has opted for beryllium in-vessel evaporation. This conditioning technique is typically applied once a week, often just after the glow discharge cleaning.

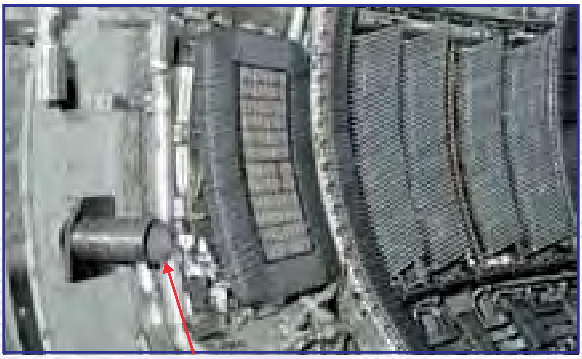


Figure 21: Beryllium evaporator inside the JET vessel, next to a microwave antenna

JET's unique beryllium handling capability is of an extreme importance today, as the design of the next step facility, ITER, relies on a beryllium first wall. Consequently, JET is being prepared to accept a large and challenging project, the replacement of the present Carbon Fibre Composite first wall by a beryllium first wall, which is planned for 2008-9, see section 2.11.

> *“JET’s powerful additional heating systems allow us to heat plasma, drive plasma current, and provide us with the key tools to optimise the plasma performance”*
>
> *Jean-Marie Noterdaeme,*
>
> *senior scientist,*
> *Task Force Heating*

Plasma Heating and Current Drive

2.4

The goal of fusion research is a “burning plasma” - fully ionised gas self-sustained in an extreme state by power released from fusion reactions of its atomic nuclei. The burning plasma would then provide a new powerful, clean and safe source of energy. To achieve this, we need to overcome two major challenges. First, to ignite the plasma, temperatures in the order of hundreds of millions of degrees centigrade must be reached i.e. the plasma must be heated sufficiently. The second, more difficult challenge, is to sustain the plasma at these temperatures by confining and controlling it in order to maintain its density and ensure that it does not suffer excessive heat losses (see part 3.5).

Figure 1:Nuclear Fusion is the driving force of all stars including our Sun

Figure 2: Electricity can produce heat and magnetic forces

Tokamaks (a family of fusion research devices, to which both JET and the future burning plasma experiment ITER belong, see section 1.3) utilise an ingenious scheme that addresses both challenges at the same time: a huge electric current is induced in the plasma to heat it and to complement the confining magnetic field. The electric current produces heat thanks to the ‘Joule Effect’, a phenomenon familiar to us in everyday items such as electric ovens, irons or light bulbs (Fig.2). In these household appliances the electric current usually does not exceed a few Amperes. Electric currents can also produce strong magnetic fields, an effect which is used in, for example, magnetic cranes, and in fact in all electric motors. Hundreds or even thousands Amperes of electric current can flow in industrial electromagnets. However, in a large tokamak like JET, we may induce millions of Amperes into a plasma in order to heat and confine it.

Ohmic Heating

The tokamak concept is a breakthrough in plasma research, but not a complete solution. At millions of degrees and above, plasma is conducting electricity far too well, with very little resistance - which also means with not enough heat produced by the Joule Effect. The unit of electric resistance is the Ohm, so plasma physicists usually say ‘Ohmic heating is ineffective at high temperatures’ where the word ‘high’ refers to the hundreds of millions of degrees required for burning plasmas. In order to attain the target temperatures some sort of ‘additional heating’ is required to supplement the ‘Ohmic heating’ (as a matter of fact, eventually the ‘additional heating’ plays a dominant role). Neutral particle beams (‘NB Heating’) and resonant electromagnetic waves (‘RF Heating’) can do this job.

Furthermore, tokamaks cannot maintain a continuous electrical current in the plasma and this limits the concept of complementing the magnetic field, see Fig.3. Tokamaks have a transformer-like electrical setup, with plasma that acts as a single secondary loop - and no transformer can provide continuous direct electric current in its secondary circuit. An additional ‘current drive’ is to be provided if we wish to confine burning plasma continuously. Electromagnetic wave current drive offers a possible solution.

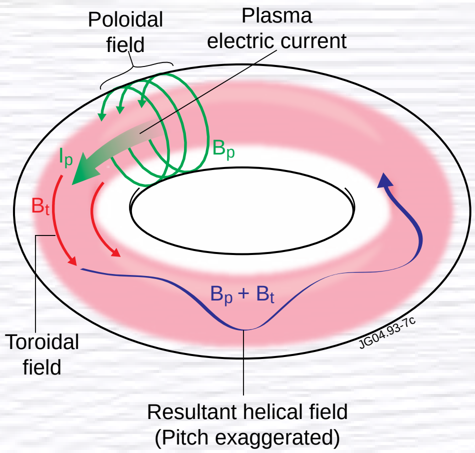
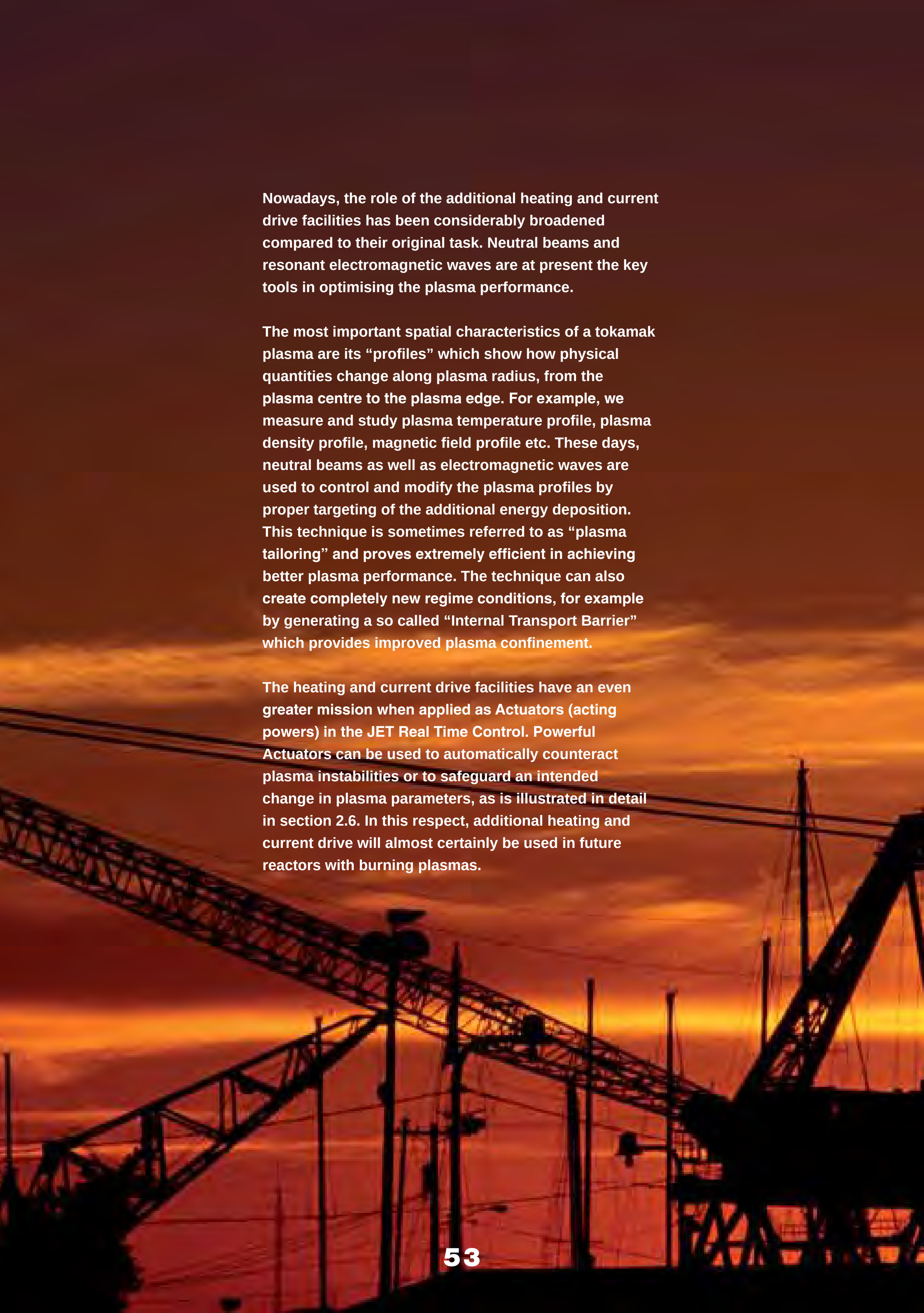


Figure 3: Magnetic fields in tokamak - toroidal is generated by external coils, poloidal by electric current in plasma

Nowadays, the role of the additional heating and current drive facilities has been considerably broadened compared to their original task. Neutral beams and resonant electromagnetic waves are at present the key tools in optimising the plasma performance.

The most important spatial characteristics of a tokamak plasma are its “profiles” which show how physical quantities change along plasma radius, from the plasma centre to the plasma edge. For example, we measure and study plasma temperature profile, plasma density profile, magnetic field profile etc. These days, neutral beams as well as electromagnetic waves are used to control and modify the plasma profiles by proper targeting of the additional energy deposition. This technique is sometimes referred to as “plasma tailoring” and proves extremely efficient in achieving better plasma performance. The technique can also create completely new regime conditions, for example by generating a so called “Internal Transport Barrier” which provides improved plasma confinement.

The heating and current drive facilities have an even greater mission when applied as Actuators (acting powers) in the JET Real Time Control. Powerful Actuators can be used to automatically counteract plasma instabilities or to safeguard an intended change in plasma parameters, as is illustrated in detail in section 2.6. In this respect, additional heating and current drive will almost certainly be used in future reactors with burning plasmas.



Neutral Beam Injection (NBI)

A widespread technique of the additional plasma heating is based on the injection of powerful beams of neutral atoms into ohmically pre-heated plasma. The beam atoms carry a large uni-directional kinetic (motional) energy. In the plasma, beam atoms loose electrons due to collisions, i.e. they get ionised (electrically charged) and as a consequence are captured by the magnetic field of tokamak. These new ions are much faster then average plasma particles. In a series of subsequent ion-ion, ion-electron and electron-electron collisions, the group velocity of beam atoms is transferred into an increased mean velocity of the chaotic motion of all plasma particles. The action is similar to the opening break in the game of pool, when a fast motion of one billiard ball can cause the seemingly chaotic motion of all billiard balls. However, the world of plasma particles is inconceivably small, and many billions of particles are in play. We 'the giants' sense an increase in their chaotic motion as an increase in temperature. In other words, a neutral beam heats the plasma - and that is what we desire!

Figure 4: Assembly of one of the sixteen ion sources for the JET NBI system

In fusion experiments, the neutral beams are usually formed by atoms of hydrogen isotopes (hydrogen, deuterium or even tritium at JET). Notice that we always speak about a ‘Neutral beam’ and its ‘atoms’. Indeed, the beam needs to consist of neutral atoms (as opposed to electrically charged ions) otherwise it could not penetrate the strong magnetic field that confines fully ionised plasmas. The energy of the beam (corresponding to the velocity of its atoms) must be sufficient to reach the plasma centre - if the beam atoms were too slow, they would get ionised immediately at the plasma edge. At the same time, the beam is supposed to have power enough to deliver significant amounts of fast atoms into plasma, otherwise the heating effect would not be noticeable. At JET, the beam energy is 80 or 140 keV, corresponding in the case of deuterium beam to 2800 or 3600 km/s which is approximately five times faster than the mean velocity of the ions in a JET deuterium plasma. The total power of beam heating at JET is as much as 23 MW (million Watts). With this power, the number of beam atoms per second corresponds approximately to 10% of the total number of JET plasma ions.

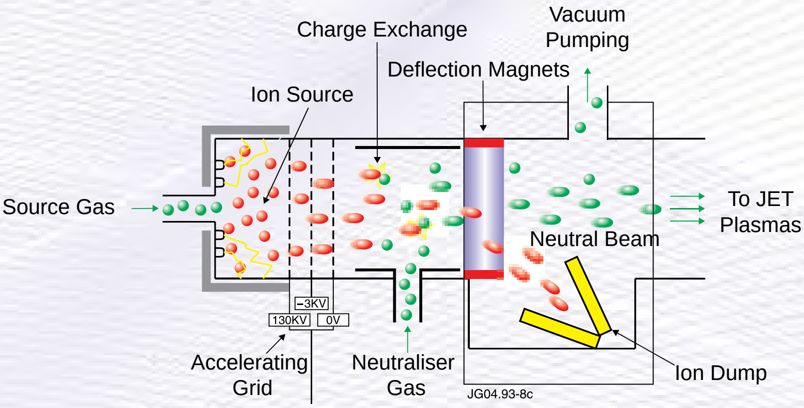


Figure 5: Scheme of the NBI principle: ions in red, neutral atoms in green

Figure 6: Ion dump of the JET Neutral Beam Injector

It is not at all straightforward to generate powerful neutral beams of very fast atoms, see Fig.5. The only way to form the neutral beam is to produce large amounts of ions first, then to accelerate the ions in a strong high-voltage electric field and finally to neutralise the accelerated beam. The accelerated ions get neutralised in charge-exchange interactions with a gas cloud, however, some leave the cloud still in a charged state. These residual fast ions must be deflected by a dedicated electromagnet to a cooled ion dump that can withstand heavy ion bombardment, see Fig.6. Last but not least, powerful vacuum pumping (described in section 2.3) must assure that practically no slow atoms from the neutralising gas cloud can diffuse as far as to the plasma chamber, so that the fast neutral atoms have free access to burst into the plasma. This technology works well but is still being refined in order to increase the reliability, purity and efficiency of the neutral beam.

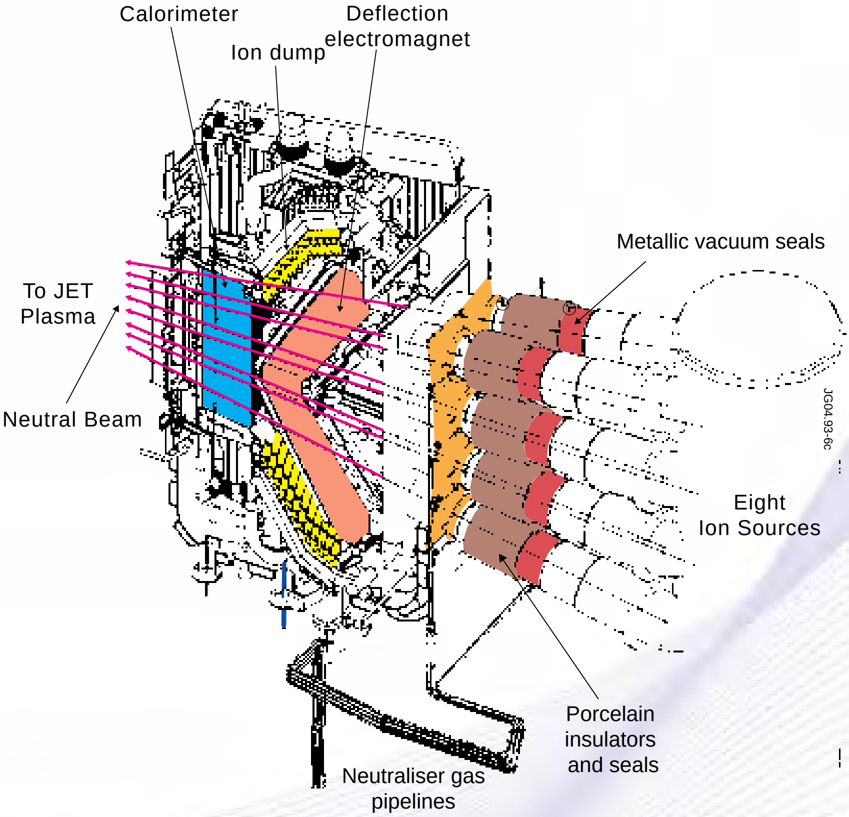


Figure 7: One of two identical NBI systems at JET

Figure 8: Installation of NBI at JET

Plasma and Electromagnetic Waves

Plasma is an intriguing state of matter. Being formed by charged particles (ions and electrons) it is affected by long-range electric and magnetic forces. As a consequence, plasma - and specifically magnetically confined plasma - can host an extremely rich mix of oscillations and plasma waves, covering sound, electrostatic, magnetic and electromagnetic waves. Depending on local plasma parameters, plasma waves can propagate, get dumped (absorbed), be reflected or even converted to different plasma waves.

In general, plasma waves carry energy, so that wave absorption involves energy transfer. Their energy is then in most cases converted to an increased mean velocity of the chaotic motion of particles, i.e. to higher temperature of the absorbing medium. Wave absorption is extremely efficient if the wave frequency is resonant with some of the fundamental oscillations of the medium. However, significant heating can occur even at non-resonant frequencies - witness the widespread everyday use in microwave ovens where magnetron devices produce electromagnetic waves which heat by cyclically turning over the water molecules in food, rather than resonating with them.

Figure 9: Leaves as well as solar panels can convert energy of electromagnetic waves coming from the Sun (ie sunlight) into other forms of energy

Ion Cyclotron Resonant Heating

(ICRH, also known as RF Heating)

In magnetically confined plasmas, particles (ions and electrons) rotate around magnetic field lines – see Fig.10 – with frequencies that depend only on three quantities: charge and mass of the particle, and magnetic field strength. Other parameters like temperature or density play no role at this 'cyclotron' frequency. Therefore, if an electromagnetic wave with cyclotron resonant frequency is launched into the plasma, all the targeted particles (defined by mass and charge) are heated, provided that the magnetic field complements the resonant condition. In tokamaks, the magnetic field decreases with distance from the tokamak major axis. This allocates the resonant region to a narrow vertical layer, thus giving us a simple control over deposition of the cyclotron resonant wave.

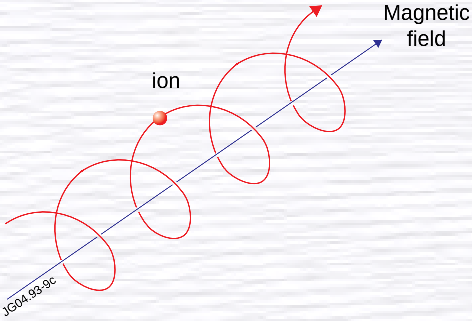


Figure10: Cyclotron motion of a plasma ion around a magnetic field line

To accommodate complicated wave propagation rules, multiples of the base cyclotron frequency, called 'higher harmonics' are mostly applied in practice. The effect of higher harmonic resonance relies on space variations in the wave intensity, so that such a resonance is stronger for particles with larger orbits. That is, higher harmonic heating is more significant for fast particles than for slow particles, which introduces temperature dependancies as well as distortion in thermal distribution due to the heating.

Ion cyclotron resonant heating (ICRH) is routinely applied on JET. It is resonant with the second harmonic (i.e. double) frequency of ion gyration of main JET plasma ions (deuterium) or with a base frequency of gyration of a minority species (e.g. tritium, helium...). The available resonant frequencies at JET are in the range of 23-57 MHz (megahertz, or million of oscillations per seconds) which correspond to length of the vacuum electromagnetic wave from 13 m (at 23 MHz) down to 5 m (at 57 MHz). This is a “shortwave” frequency, which is not very popular in the air due to many fades, blackouts and interferences (the FM radio frequencies are just a bit higher, around 100 MHz). In total, the installed power of JET ICRH system is as much as 32 MW (megawatts = million watts), and in practice only part of this potential is sufficient for the JET experiments. This is a huge power compared to radio or TV broadcast, where a 50 kW (kilowatts = thousand watts) transmitter is already considered as a powerful one.

Figure 11: ICRH wave generators at JET

Figure 12: ICRH transmission lines (Photo: J.Polverini and L. Antalova)

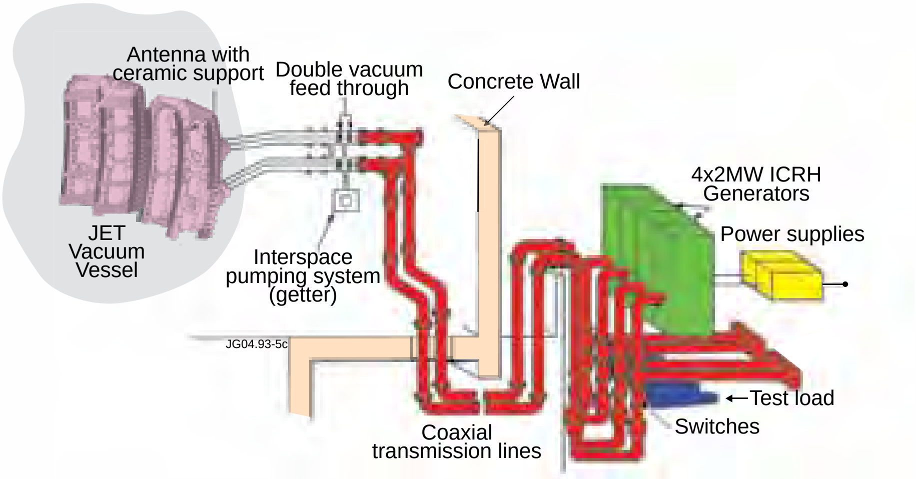


Figure 13: Schematic of the ICRH system at JET

Amplifier chains generate the ICRH electromagnetic waves, each chain with a powerful (2 MW output) tetrode tube in final stage. Transmission lines that conduct ICRH waves from the generators to the JET tokamak are low loss coaxial cables. Coaxial cables consist of a conducting outer metal tube enclosed and insulated from a central conducting core. Such cables are generally used in any high-frequency transmission - e.g. signal from the TV aerial or satellite dish is transferred to the TV set by a coaxial cable. However, at JET due to high powers involved the ICRH output coaxial cables look rather like ‘pipelines’ with 20 cm diameter of the outer metal tube, see Fig.12. Several hundreds meters of these transmission lines are installed at JET. The transmission lines terminate in 4 ICRH antennas that are installed within the JET inner wall and that are slotted in the front. Each antenna consists of four conductors (straps), see Fig.14, and each strap is fed by a separate generator. The ICRH electromagnetic waves cannot propagate in the JET vessel vacuum (their wavelength being too long) so that the antenna must be as close to the plasma as possible.

For information, there is a similar technique called electron cyclotron resonant heating (ECRH) but we do not use it at JET. The principle is based on the fact that electrons, being several thousand times lighter than ions, have much higher cyclotron frequencies. In tokamak plasmas the required ECRH frequencies are in the order of 100 GHz (gigahertz = billions of cycles per second, corresponding to vacuum wavelength in the order of a few millimeters only) which is more challenging for the wave generation and transmission. These frequencies are also used in some modern radar applications. However, the power of such devices is negligible compared to ECRH requirements. ECRH targets plasma electrons only, and the heat transfer from electrons to ions is relatively slow. The advantages of ECRH are that its waves can propagate in vacuum and that they can be steered with high precision. ECRH is installed on some other large tokamaks such as JT-60U in Japan, DIII-D in USA and ASDEX-U in Germany.

Figure 14: LHCD and ICRH antennas in JET vaccum vessel (LHCD grill in frame in left, next to it four slotted launchers of ICRH

Lower Hybrid Current Drive (LHCD)

There are many other resonant frequencies in tokamak plasmas but experiments have found some to be inefficient or impractical while others simply cannot penetrate through the plasma edge region. Two of the candidate frequencies are "hybrid", so called because they result from force interplay between electrons and ions, so that their frequencies lie between ion cyclotron and electron cyclotron ones. Although the lower hybrid frequency can get into the plasma, unfortunately it has an inefficient heating effect. Nevertheless another significant application of lower hybrid frequency has evolved: the corresponding lower hybrid wave can drive electric current thanks to the fact that it has an electric component parallel to magnetic field lines.

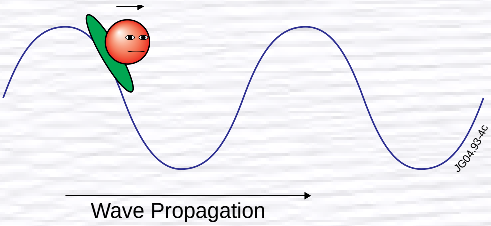


Figure15: A charged particle can increase its velocity by "surfing" on an electromagnetic wave

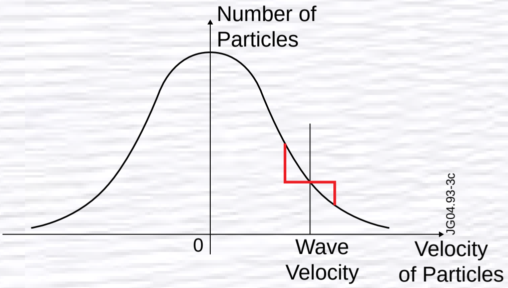


Figure 16: As a consequence of the particles "surfing" on the wave, the thermal distribution of the particles changes as the red line shows. The assymetry in velocity distribution causes a net electric current to appear

One would perhaps expect that the very rapidly alternating electric field of electromagnetic waves could not generate a constant electric current, but this common sense proves to be false. Plasma electrons with thermal velocities slightly slower than the wave propagation velocity can actually “surf” on the uprising electric potential and thus increase their velocity in the direction of the wave, Fig.15. It is also true that any electrons which are slightly faster than the wave will be slowed down. However, the thermal distribution of velocities causes there to be fewer faster particles, Fig.16. Consequently, there are more electrons which are accelerated rather than decelerated so that in total a net electric current appears. Though the effect looks minute on the electron velocity distribution, in terms of electric drag it is significant.

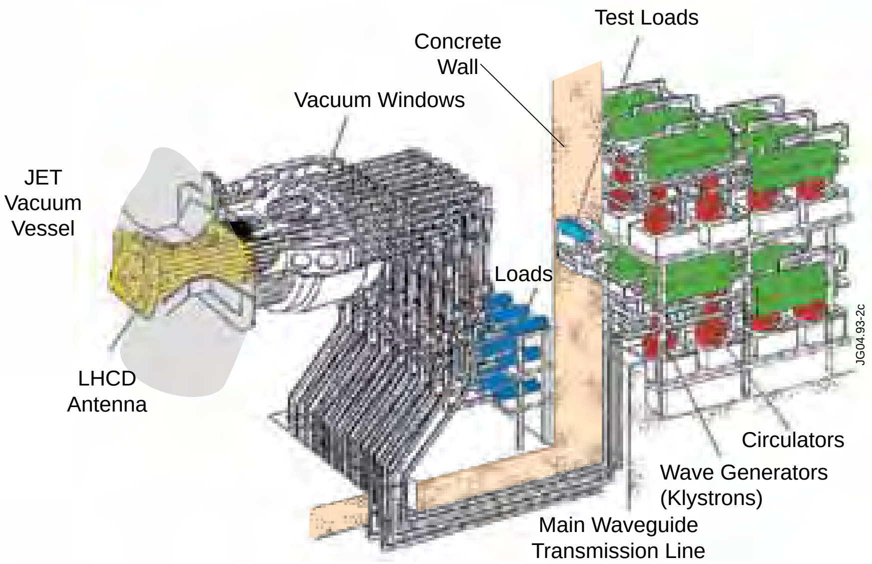


Figure 17: Schematic of the JET LHCD system

Figure 18: Completion of the LHCD antenna known as "multijunction grill"

Figure 19: Connection of the LHCD waveguides to the JET vacuum vessel

At JET, Lower Hybrid Current Drive system work at frequency 3.7 GHz (gigahertz = billions of cycles per second) which correspond to wavelength of 0.1 m in vacuum. The frequency belongs to called L-band used e.g. by satellite broadcast. The LHCD installed capacity at JET is 12 MW (million watts) of additional power. Thanks to this system, electric current of several MA (million Amperes) can be driven. The electromagnetic wave is generated in klystrons - tubes that can produce the above frequencies by resonant modulation of an electron beam. At JET, 24 klystrons are installed in 6 independent modules. The electromagnetic wave is then transmitted to the LHCD antenna by a complex system of waveguides. Waveguides are hollow rectangular metallic conductors with cross-section size that corresponds to the transmitted wavelength. The LHCD antenna is of a very sophisticated design, called "mult junction grill" in order to allow for a correct phasing of the wave before it is launched into the plasma (see Fig.18). The correct phasing of LHCD waves is hampered by propagation in vacuum, therefore it is required that LHCD antenna is mounted directly in the JET inner wall, as close to the plasma as possible.

Figure 20: The JET's new ITER-like ICRH antenna during inspection

For the first burning experiment, ITER, a complete portfolio of all efficient methods of plasma heating and current drive is likely to be adopted, with the expected total output power over 100 MW. JET is the closest tokamak in plasma size and shape to ITER, so it is natural that JET's heating and current drive facilities are widely involved in experiments relevant to ITER. The proposed ITER "plasma scenarios" are optimised on JET by accurate profile tailoring as explained in the introduction. In 2007 a new "ITER-like" ICRH antenna (Fig. 20) is to be installed as a major JET enhancement in order to validate the new concept of robust, stable ion cyclotron wave emission suitable for the harsh conditions of the future burning plasmas of ITER.

"The challenge of characterising extreme conditions of nuclear fusion plasmas both spatially and temporally has inspired JET to produce an impressive array of diagnostic techniques. Drawing from fields as diverse as neutronics, spectroscopy, lasers and microwaves, JET is a leader in the art of measurement."

Dr Andrea Murari,
Task Force Leader ,
Diagnostics

Plasma Diagnostics

2.5

In fusion research, plasma heated to hundreds of millions of degrees needs to be confined well enough at sufficient density. The task of diagnosing such a plasma, of measuring its characteristics, is therefore not straightforward! Consider how you would measure, for example, inner plasma temperature. One cannot simply put a sensitive element inside the hot plasma - not only it would sublimate, but more importantly, the experiment would be lost as the plasma would cool down and become impure. What can be done then? Firstly, one can simply try and observe the plasma from the outside, applying as many different methods as possible and exploiting a great variety of physical phenomena, ranging from atomic effects and nuclear reactions to radiation propagation and electromagnetism. Quite a few tricky computing methods (including tomography, better known in its medical applications) provide information about plasma internal properties purely from external measurements. Secondly, one can send a tiny harmless probe into the plasma, like a beam of atoms, laser light or a microwave radiation, and observe its behaviour in the hot plasma. In both cases, a good understanding of the physics underlying the measurements is essential to get sensible results.

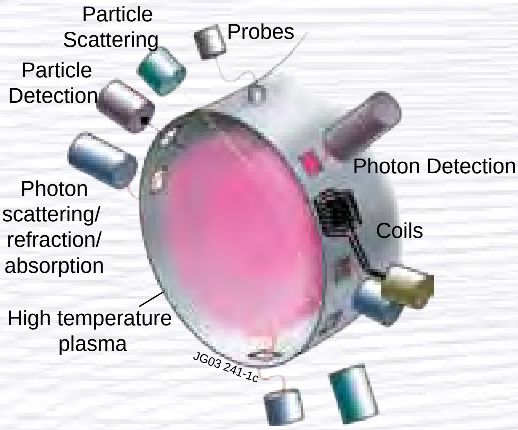


Figure 1: Methods of plasma observation

JET has the most complete set of diagnostics for reactor grade plasmas in the world, with unique capabilities in measuring the thermonuclear fusion products, ie the fast neutrons, gamma rays and alpha particles (both confined and lost). As it is the only tokamak facility that can use all hydrogen isotopes, absolutely unique diagnostics are also required to measure the plasma isotopic composition. Other major goals of the JET diagnostics are common to big fusion experiments: to determine plasma temperature and density, to measure plasma particle and radiation losses, to find out the magnetic topology and to observe plasma flows and fluctuations. The specificity of JET, in this case, consists of providing conditions for these measurements that are closest to a reactor environment. Below are a few important examples of the diagnostic methods applied at JET.

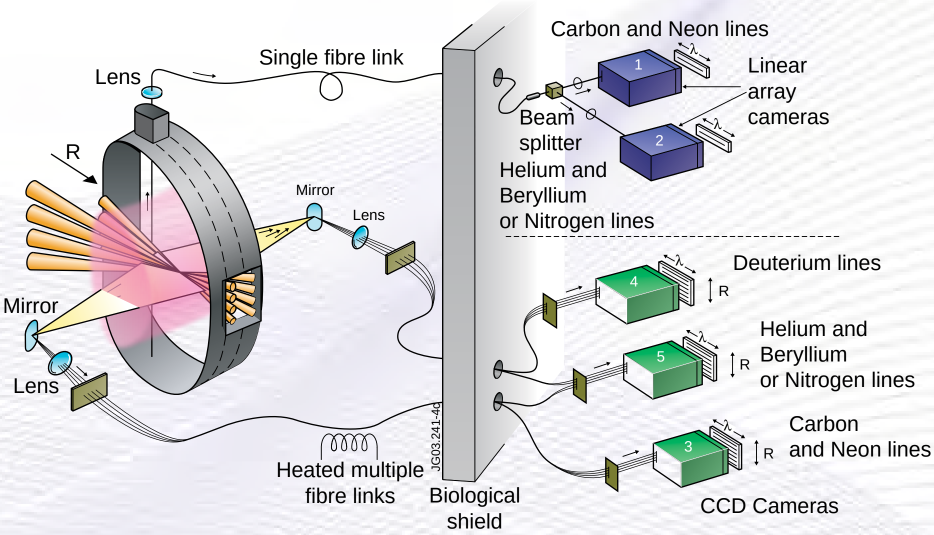


Figure 2 : Charge exchange spectroscopy

Diagnostics using the Neutral Beam

We human beings have lots of experience in observing visible light - that is, the electromagnetic radiation emitted by atoms. But no light comes from the hot core of tokamak plasmas as proper atoms are extremely rare there - at these temperatures almost all of them are decomposed to nuclei and free electrons (atoms become fully ionised). One of our essential diagnostic tools is charge exchange spectroscopy which relies on importing atoms into the hottest plasma regions. At JET, a neutral beam heating system launches billions of billions of neutral atoms into the plasma at extremely high velocities. In collisions with the hot plasma they rapidly loose their electrons, quite often by passing them to plasma nuclei (hydrogen ions) or to heavier nuclei ('impurity' ions, see figure 3). Although the ions will soon loose the electrons in subsequent collisions, they can shine light in the meantime! By observing the characteristics of this very distinct light from impurity ions we can tell (thanks to the Doppler effect, see below) what the temperature of the plasma ions is and what direction of flow the plasma has. Even more importantly, these data can be resolved to a precision of one centimeter as the light originates only in regions very close to the neutral beam.

What is a Doppler effect? It is a shift in the observed frequency of a wave (electromagnetic or sound) which occurs when the source and observer are in motion relative to each other. The frequency increases when the source and observer approach one another and decreases when they move apart. Given chaotic thermal motion, the combined Doppler effect of many moving atoms results in the broadening of the spectral line, i.e. of the light frequency which characterises the radiation of the atoms. The higher the temperature, the faster the atoms move and the bigger the Doppler effect. Consequently, the width of a spectral line can serve as a measure of plasma temperature.

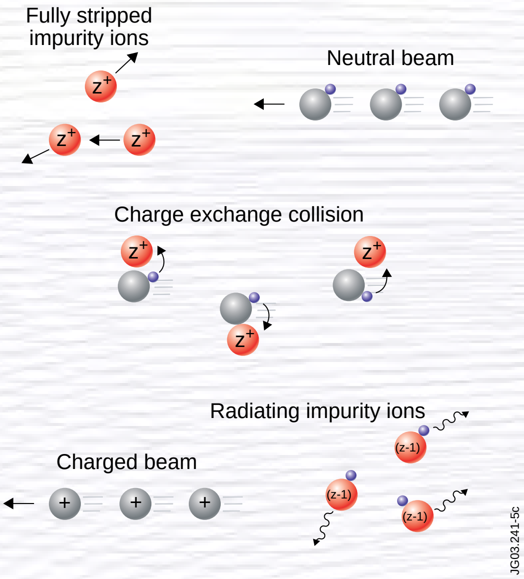


Figure 3: Principal scheme of charge exchange

The neutral beam atoms themselves emit light that can be measured separately, as the Doppler effect at the velocity of beam atoms causes a distinct shift in the frequency (that is in colour) of their light. Moreover this radiated light has specific features due to the fact that the beam atoms cross very rapidly through a strong magnetic field - its characteristic spectral lines are split and polarised. By measuring these features we can determine the direction of magnetic field lines even inside the hot plasma! The technique, called Motional Stark Effect Spectroscopy, (figure 4) is quite challenging but vital as the plasma confinement depends so much on the exact topology of the magnetic field, and the topology depends on electric currents in the plasma. JET is developing a real-time control system based on data from these measurements, see section 2.6, so that we can correct the magnetic topology in real time by changing currents in JET's external coils and/or the plasma heating parameters. Similar feedbacks from other diagnostic systems (e.g. Polarimetry) have already resulted in an improvement of JET plasma confinement.

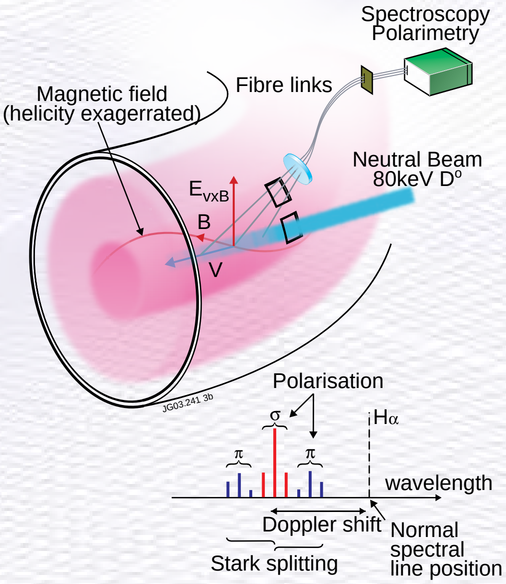


Figure 4: local magnetic field measurements by Motional Stark Effect (MSE)

LIDAR

Normally a light ray cannot be seen unless it hits your eye, but with dust or mist in the air, one can spot it from the side too by the scattering of light. When an intense laser beam is sent into plasma, its light will get scattered on free electrons. The analysis of the scattered laser light is essential in determining local density and temperature of plasma electrons. This diagnostic technique is used worldwide. However, at JET it has been combined with the principle of radar, and this approach – known as LIDAR for LIght Detection And Ranging - is also the best candidate for future reactor designs.

The LIDAR – Thomson Scattering diagnostic (see Fig. 5) measures the plasma electron temperature and density. In the JET plasma the temperature of the electrons can range from about 2 million Kelvin near the edge to over 200 million Kelvin in the centre. One way to measure such high temperatures is to shine an intense laser pulse into the plasma and to detect the back-scattered light from the electrons. Notice that the classical theory of the scattering of electromagnetic radiation by a charged particle was developed by Joseph John Thomson (1856-1940, an English physicist generally credited as the discoverer of the electron), and that is why the phenomenon is known today as “Thomson scattering”.

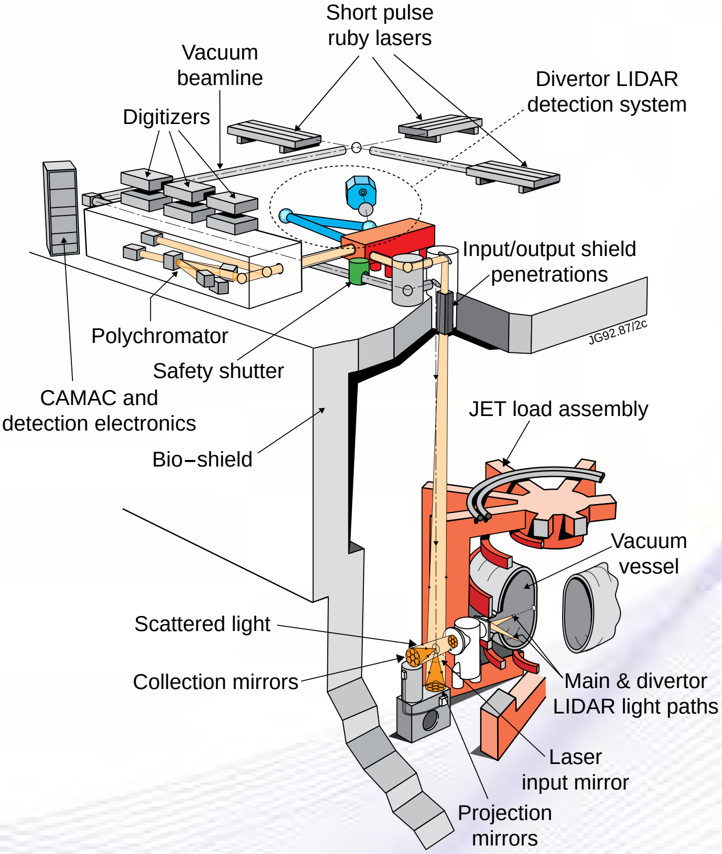


Figure 5: JET's LIDAR – Thomson Scattering Diagnostic

This diagnostic has the advantage that it is non-perturbative but it is technically challenging to implement and operate. At JET we run two such LIDAR diagnostics - the "Core" system looks at the bulk of the plasma, and the "Divertor" system looks at the edge plasma.

The monochromatic laser light is scattered and doppler shifted by the fast moving plasma electrons producing a broad spectrum of scattered light, see Fig. 6.

By measuring the width of this scattered spectrum the velocity distribution and hence the electron temperature (T_e) can be determined and by measuring the total intensity (i.e. the area of the spectral peak) of the scattered light the density of the electrons (n_e) can be deduced. This is the basis of the Thomson scattering technique.

At JET we also want to know how the temperature and density vary across the plasma. To get this information we send a short laser pulse (0.3 nano-seconds duration which, at the speed of light, is only 10 cm long) across the plasma diameter. By using a fast detection and recording system, we can observe its progress by capturing the changes in the back-scattered spectrum. We can then analyse these changes as the pulse passes from the relatively cool edge, through the hot core and out again through the opposite plasma edge. Since we know by the time of flight, or LIDAR, principle where the laser pulse is in the plasma at each instant, we can compute from the instantaneous scattered spectrum the local values of temperature and density in the plasma, ie. from the time of flight of one laser pulse through the plasma we can obtain the temperature and density variations across the whole diameter (that is, the density and temperature profiles).

This is the basis of the Core LIDAR-Thomson scattering diagnostic which we have developed at JET. We use a 1 J ruby laser (wavelength 694 nm) as the light source pulsed at four times a second, and for detection we have six microchannel plate photomultipliers (rise time 0.3 ns) each connected to fast data storage (1 GHz sampling). The scattered spectrum is dispersed into the six detection channels using a set of dielectric edge filters which act together to make a high throughput spectrometer. All the sensitive equipment is located outside the biological shield in the JET roof laboratory, only the large and relatively simple input and collection optics assembly is required to be located next to the JET machine.

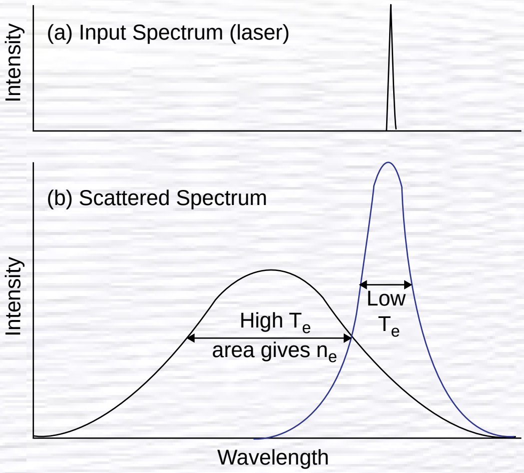


Figure 6: Input and scattered spectra

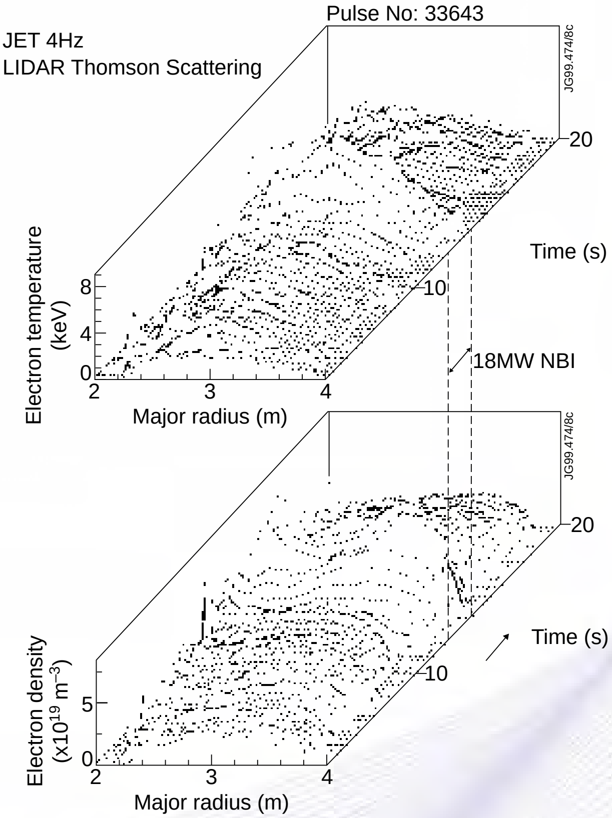


Figure 7: Time evolution of the temperature and density plasma profiles

The result obtained by firing the laser several times during a JET plasma pulse is shown in figure 7. The changes in the temperature and density profiles due to 18 MW of Neutral Beam heating are clearly seen.

A second LIDAR system, the Divertor diagnostic, operates on the same principle but has a 3 J laser with a pulse repetition rate of 1 Hz (one per second). It uses four photomultipliers and detection channels.

Passive diagnostic systems

The above described systems can be categorised as active, for they measure response of the plasma to a probe (neutral beam or laser). The passive diagnostics systems measure radiation and particles emitted by the plasma itself. In this case, it is typically more difficult to understand spatial characteristics of the observed plasma.

A single vertical cross-section of the plasma is sufficient to learn about the state of the whole plasma volume as the cross-section does not vary significantly around the tokamak, in its toroidal direction. As a matter of fact, any local disturbance is immediately spread along the magnetic field lines - plasma particles move freely in this direction. Consequently, only very few fast diagnostic systems (eg magnetic diagnostics) monitor the toroidal irregularities. On the contrary, it is essential to measure the plasma's vertical cross-section in as much detail as possible, to determine plasma profiles in the direction perpendicular to the toroidal magnetic field. The limiting factor in this is the number and position of available ports (windows into the plasma). Due to this limitation, a number of diagnostics have very similar geometrical set-ups e.g. the JET gamma-ray profile monitor (figure 8), the soft X-ray diagnostics and the JET system of bolometers that measures total plasma radiated power.

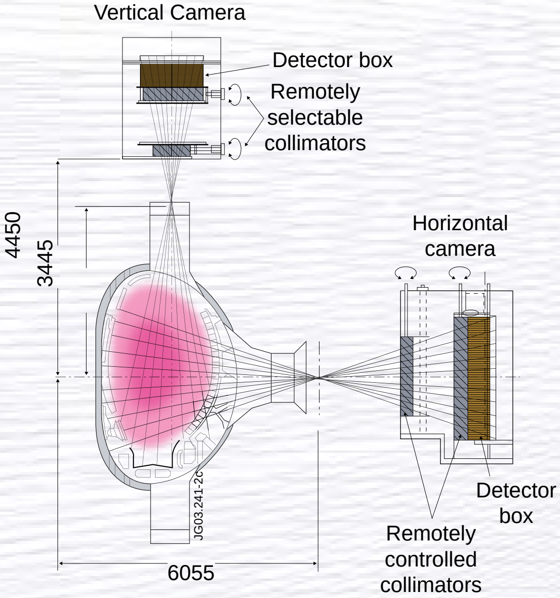


Figure 8: Neutron / gamma profile monitor at JET

The neutron and gamma-ray profile monitor represents just one of tens of passive diagnostic methods applied at JET. The monitor has two cameras that allow observations of plasma radiation from ten horizontal and nine vertical directions. In this way we can localise the source of the radiation, in this case the neutrons produced by fusion or gamma-rays produced by nuclear reactions. The latter can serve us to trace the presence of fast-ions, in particular helium nuclei (alpha particles).

With increasing confidence in the plasma stability control, fusion research can concentrate on another stepping stone: the power exhaust and plasma-wall interactions (ie interactions of plasma with the vessel's inner surface). Consequently a lot of effort is invested in plasma edge diagnostics. Besides traditionally efficient tools like electrical (Langmuir) probes, neutral particle analysers, infrared cameras and dedicated spectral measurements, new methods are being developed and used at JET. Among the most innovative and successful are the quartz microbalance monitors (figure 9) which permit the measurement of the minute erosion and deposition on wall materials. Thanks to these measurements we can rapidly progress towards better plasma configurations to produce lower wall erosion.

Figure 9: Quartz microbalance

At JET, signals from all diagnostic systems are digitised and stored in a central database. The sampling frequencies depend on the requirements of the diagnostics and vary from a few measurements per second up to about one million per second. In total, several billion readings of diagnostic data are recorded per JET pulse, each reading with 12 or 16 bits. In other words, every JET pulse produces a few GBytes of raw diagnostics data, so that as much as 100 GBytes are stored daily. Most of the data need further processing - this is done automatically where possible by dedicated computer codes, but in many cases human intervention and/or data validation is required. The processed data are stored separately from raw data. All data are accessible to all scientists on the JET site and, moreover, any scientist from any Association of the European Fusion Development Agreement (EFDA) can work with the data from her/his home institute via the technique of Remote Access. Many Associations and Contractors continue to develop new diagnostics for JET or upgrade the present ones, see section 2.9. At the same time, JET serves as a unique test bed for the development of diagnostics for the future fusion reactor machine, ITER.

Figure 10: JET Control Room

Diagnosing fusion plasmas involves many of the most advanced measurement techniques of physics and electronic engineering. There are more than fifty different approaches applied at JET and this explains why hundreds of scientists worldwide are so passionate about the performance of JET diagnostics. Nuclear fusion in general and JET in particular are the main driving forces behind the development of specific measuring techniques like fast neutron/gamma spectrometry and high energy active spectroscopy. Moreover, notice that the diagnostics of a fusion plasma operate on a quite realistic scale. Therefore, these measuring techniques can be relevant for practical applications and can potentially create interesting spin-offs.

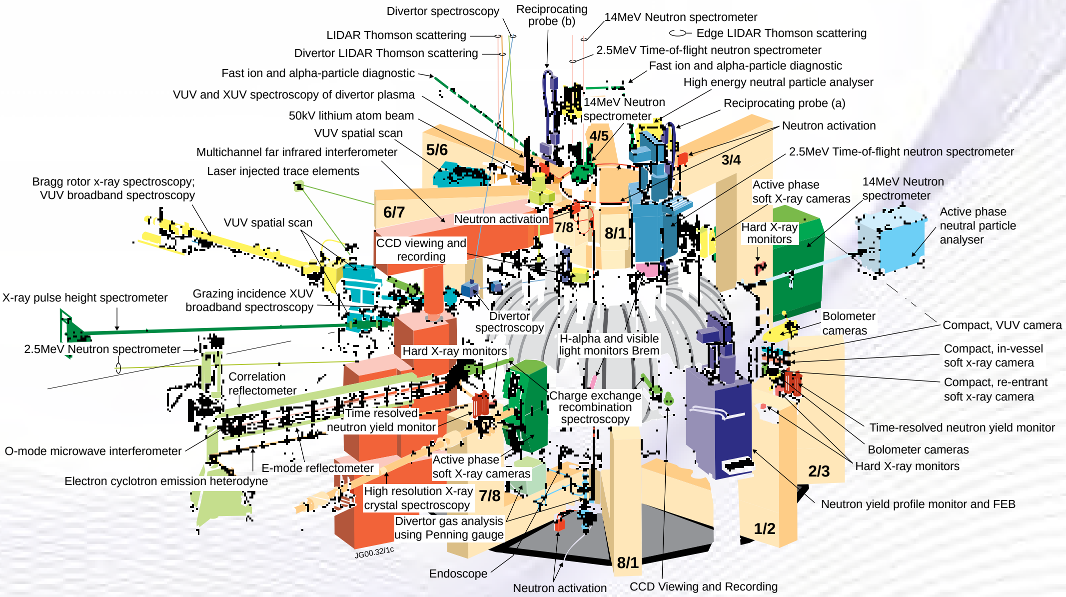


Figure 11: Overview of JET diagnostics

"JET is developing new real-time techniques for measuring and controlling fusion plasmas to maximise performance and minimise internal disturbances. Real-time control will be essential for future long-pulse reactors such as ITER."

Rob Felton,
Real Time Measurement and Control Systems Manager

Real Time Control of JET Plasmas

2.6

If JET had live news reports, this might be a typical broadcast during a JET pulse:

"The high temperature plasma is evolving correctly, confined by the magnetic fields of the JET machine. Now powerful microwaves and particle beams are being switched on to increase the temperature of the plasma up to hundreds of millions of degrees! At this moment, we can see fusion reactions occurring. Oh! what's that? What has happened? There was a flash in the plasma but the machine has brought it under control again! From the experts at the control desk I understand there was a sort of fast growing perturbation in the magnetic field. Quite unpredictable they say, like turbulence in the air. But even before we spotted the danger, JET's automated systems had recognised it and reacted: the heating was switched off briefly until the perturbation vanished. Look, there are even more fusion reactions now than before!"

During the early years of fusion research, the parameters of high temperature plasmas were severely limited by the design of the experimental facility and its power sources. The experimental scenario was ‘hard-wired’, including some basic real-time feedback features, and used elementary electronic control over a few key parameters. The output data were usually shown on oscilloscope screens and photographed. Advances in computing in the eighties enabled experimental scenarios to be ‘pre-programmed’ and the resultant data to be stored digitally for subsequent analysis. The very fast response of today’s computing and control systems allows us to move towards extensive real-time control and data analyses. The real-time tools are enabling us not only to precisely tailor key plasma parameters and keep them under control, but also to run several consecutive experiments within a single plasma discharge. This latter feature is very significant now that JET’s plasma discharges may last tens of seconds - and in future superconducting facilities where plasmas could potentially extend over tens of minutes.

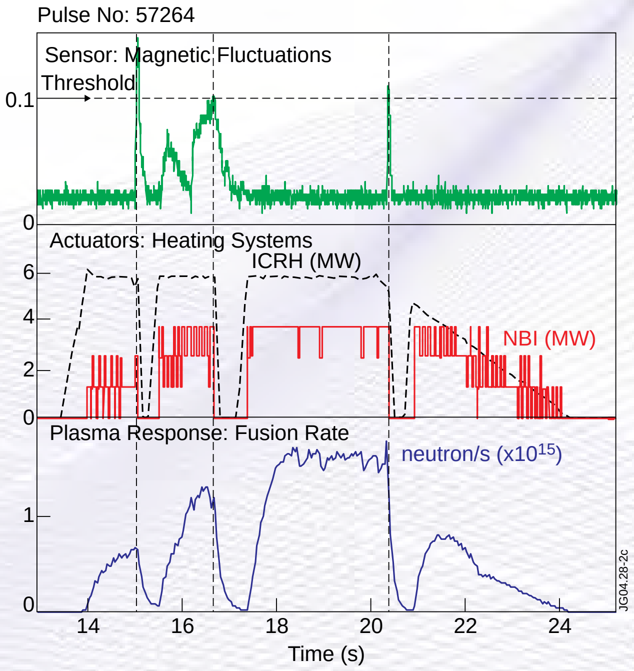


Figure 1: The above ficticious report is based upon this real JET pulse.

In principle, real-time control allows instantaneous modification of actions according to changes in observations. There are many examples of real-time control in nature - response to light is an elementary example. Pursuing a moving target is another example, requiring much more sophisticated real-time control. Indeed, your brain and arm are performing a quite complex feedback process when you move a mouse to position the cursor on your PC screen.

What is the correct way of designing a real-time control system in the technical world? A very general outline is given in the figure 3. A Sensor measures the changes in a control parameter over time. Some control parameters, e.g. magnetic field perturbation, correspond directly to experimental measurements. Others, e.g. normalised plasma pressure, require the sensor signal to be calculated from several independent measurements - just like the post-pulse physics analysis, except that the sensor signal is needed in real time. This is quite challenging in terms of both hardware and software performance.

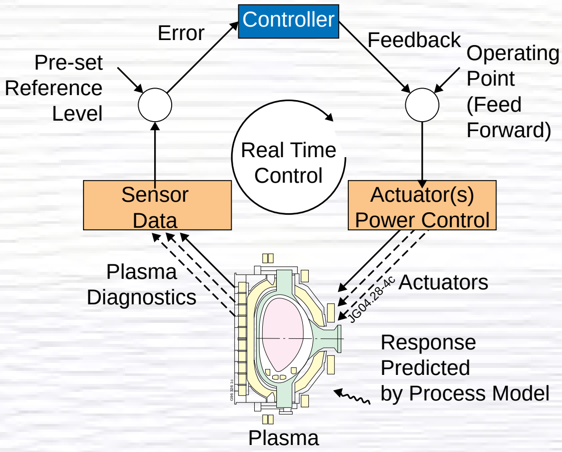


Figure 3: Basic elements of Real Time Control design

Figure 2: An experiment control room 40 years ago - lots of knobs and chart recorders

Real-time feedback control is achieved by comparing a sensor signal to a desired reference value that is pre-set within the experiment scenario. The difference between the two - the Error - serves as an input to the Controller. The Controller can rapidly modify performance of the Actuators (every 10 milliseconds at JET) in order to minimise the Error.

The relationship between the action of the Actuators and the Sensor measurements (the system response) is not straightforward. Indeed, the plasma behaviour can be quite complex and involve many disturbances. A process model is needed to predict the response but process models based on plasma physics equations alone cannot yet fully predict plasma behaviour. Consequently, dedicated experiments are run to help to identify plasma responses so that a reliable process model can be implemented. Also worthy of note are the disproportionate levels of power required to drive the actuators and the response measured by the sensors: while the former is in the order of millions of watts at JET, the latter is often less than milliwatts, which means that the power scale differs for more then nine orders of magnitude.

In the previously mentioned example of computer mouse control, the mouse cursor position is sensed by your eyes, the target area is the Reference, your brain is the Controller and your arm the Actuator. Instead of the plasma environment there is a mouse, computer and monitor between the Actuator (arm) and the Sensor (eyes), with a much more predictable behaviour.

Actuators must be designed so that they have enough power to change the quantities measured by sensors, but possibly without modifying other characteristics of the system. The Controller, on the other hand, should be designed so that it can respond to Errors within an appropriate time, usually referred to as a deadline. In today's plasma physics, the Controller commonly consists of a PID (Proportional-Integral-Derivative) element as used in many industrial process controllers, eg in chemical plants. However, more sophisticated controllers based on multiple-input multiple-output models, state-space models, and neural networks are being developed.

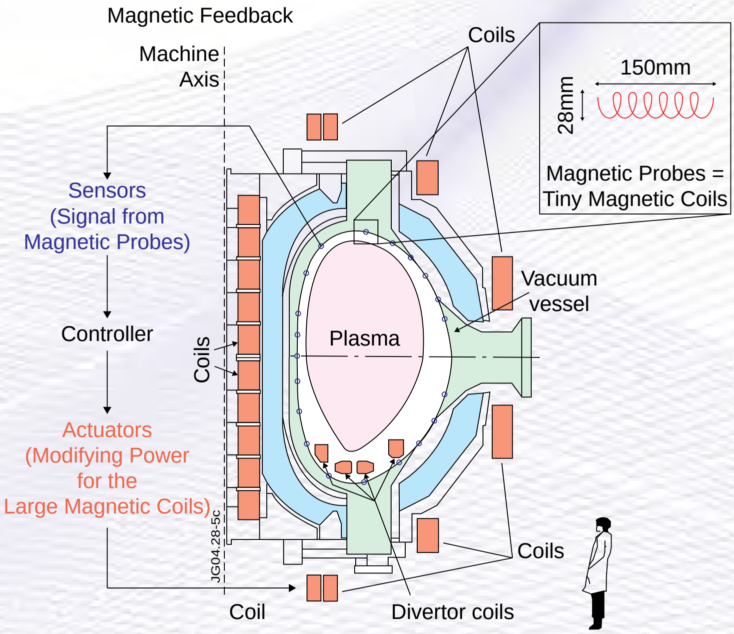


Figure 4: Principle of Real Time Control of Magnetic fields at JET.Note: Large Coils are wound around the machine axis

Figure 5: Laser Interferometer : measures refractive index for plasma density control.

In magnetic confinement fusion research, the earliest examples of real time control were in the sensing and control of the magnetic fields used to keep the very hot plasma away from the vessel walls. Feedback stabilises the confining magnetic fields, counteracting plasma forces that randomly disturb the configuration. The magnetic field is monitored by tiny magnetic probes and from their data the plasma boundary position is calculated. The distance of the plasma boundary from points within the vacuum vessel produces a Sensor measurement. The Controller takes the Errors in these distances and drives large poloidal coils (the Actuator) to correct the magnetic fields, see Fig.4. Scientists realised in the early sixties that without this feedback control, high temperature plasmas would never survive for more than a few tens of milliseconds. Of course, the feedback at that time was completely hard-wired and analogue (ie based on resistive, inductive and capacitive elements and amplifiers, not on digital processors).

Further real time control appeared a bit later - a feedback control based on plasma density. Precise fuelling of high temperature plasmas is essential to keep an optimal plasma density, but it is very difficult to predict how much fuel will be required because of gas absorbed into, or released from, the walls and materials within the tokamak chamber. Therefore, the most reliable method to keep plasma fuelling within the required limits is to use a real time control of the fuelling valve (the Actuator) based upon the density measurements (the Sensor). This density feedback was quite a technological milestone for fusion research as there is no diagnostic signal that directly corresponds to plasma density. This had to be calculated from measurements of the plasma refractive index (Fig.5).

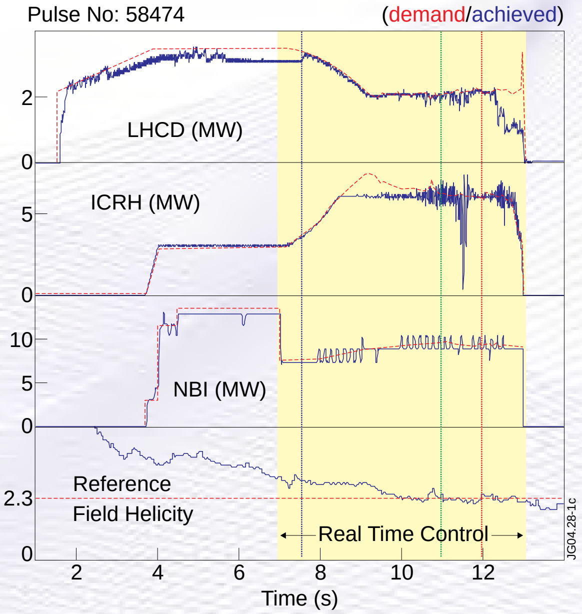


Figure 6: Several Actuators can be used to Real Time Control of the Magnetic Field Helicity at JET

Figure 7: Part of the Real Time Measurement and Control System showing the analysis computers and an ATM network switch

Today, powerful digital data acquisition systems allow us to implement a wide range of real time controls and JET is at the forefront of this progress. For example, we can control in real time the gradient of plasma temperature from the edge to the centre of the plasma, and how it evolves in time. The same can be also done for magnetic field helicity, see Fig.6. This allows us to control particle transport barriers that significantly reduce losses of heat and thus improve plasma confinement. Concentration of different chemical elements in the plasma or occurrences of regular magnetic structures can also be influenced in real time. Additionally, there are event-driven controls that can immediately modify heating and/or fuelling in response to fluctuations in magnetic fields or excessive radiative losses from the plasma (as in the Figure 1).

JET makes real-time measurements of neutrons, magnetic flux, plasma temperature, density, helicity, X-ray, UV, visible and IR radiation, etc. We do real-time analysis of magnetic fields, confinement, spectral lines, chemical composition, and profiles of temperature, density and current. There are over 500 signals involved, updating every few milliseconds! We use an ATM computer network, see Fig. 7 (like telephone companies use in their backbone exchanges) to deliver sets of signals (datagrams) from each source to the appropriate destinations.

Figure 8: Neutral Beam Injector - JET's most powerful Actuator

Magnetic coils, gas valves, Neutral Beam injectors (NBI, Fig.8), pellet injectors, Ion Cyclotron Resonance Heating (ICRH) and Lower Hybrid Current Drive (LHCD) microwave systems can all act as Actuators in JET. In other words, their performance can be modified in real time in response to instantaneous measurements and calculations. By combining these Actuators, a large variety of plasma scenarios can be tuned and stabilised. Thanks to this feature, JET can drive experiments starting from basic physics studies (with very simple and symmetric plasma set-ups) through to identity/similarity experiments which model other facilities, up to reactor-like (ITER-like) high power plasma scenarios. Notice that in identity/similarity experiments, JET can - thanks to its real time capacities - mimic plasma conditions of other magnetic fusion facilities (eg the German ASDEX-U, Japanese JT-60U or American DIII-D) and thus confirm and even enhance their results.

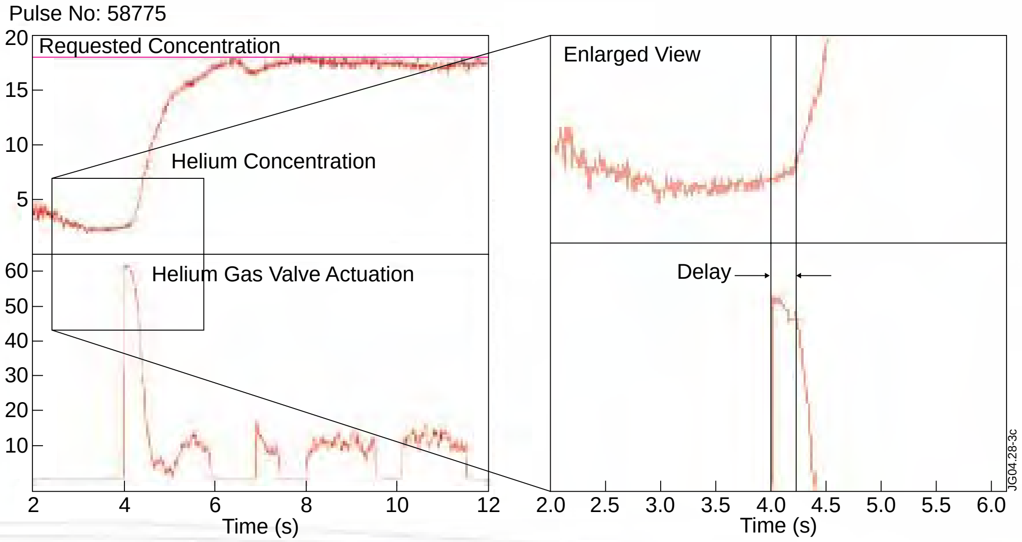


Figure 9: Real Time Control of Helium concentration: the Process has its own delays which the Controller has to anticipate

In most of the above applications, the real-time control must be fast enough to keep up with the plasma evolution. That is, the response time of the feedback system is a critical parameter. In our scheme, it is the process model that indicates the allowable delay for the response time. When exceeded, the control is lost. Even worse, some actuators might produce effects which cause operational delays. For example, exaggerated gas influx can aggravate the vacuum properties of the vessel.

Some plasma processes such as the diffusion of helium (see Fig.9) are quite slow (in the order of a few hundred milliseconds) and do not require rapid response times. Others are much more rapid, for example the magnetic perturbations which can evolve in only a few milliseconds. The latter are thus quite demanding on the electronics of the real-time hardware, namely on the high-power electronics that drive the Actuators.

Fortunately, in general, with bigger fusion facilities the allowable time delay increases, and at the same time computer technology keeps evolving. It is thus probable that in future fusion reactors plasma will be controlled in real-time by very sophisticated methods and algorithms. The precise tailoring of the key plasma parameters in both space and time will play a crucial role in developing a continuous and economic source of fusion energy.

Lower hybrid current drive (LHCD) Waveguides at JET

> *"The boundary edge is where the stellar world of hot plasmas meets the earthly world of cold solids. Understanding the complex interaction of these two worlds is essential for operationg a fusion reactor successfully."*

Wojtek Fundamenski,
Deputy Leader,
JET Task Force E (Exhaust)

Plasma Edge

2.7

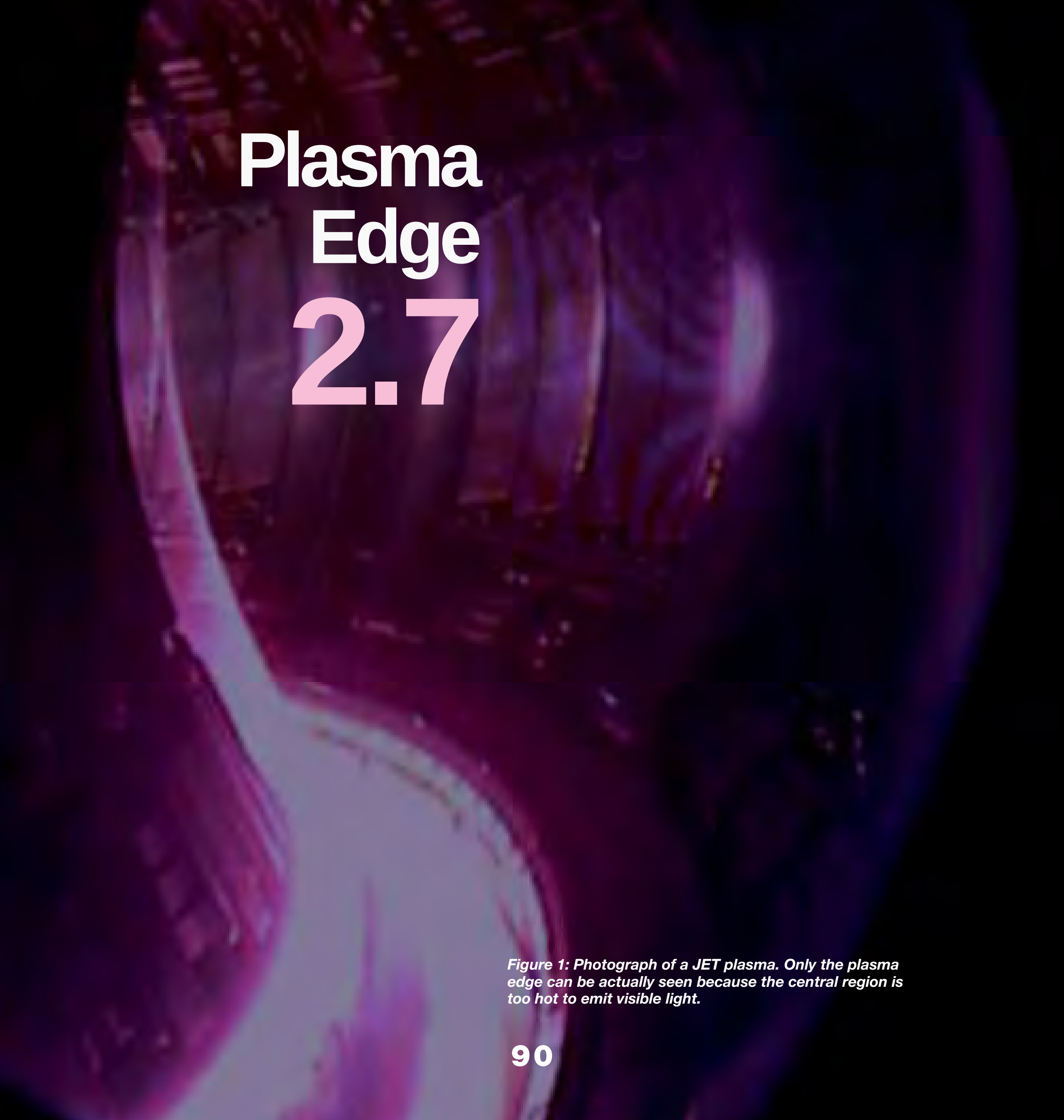


Figure 1: Photograph of a JET plasma. Only the plasma edge can be actually seen because the central region is too hot to emit visible light.

In order to protect the vital fusion processes in a burning plasma from the cold reactor components (and vice versa), considerable effort is invested into researching the plasma edge.

At JET, the distance from the plasma core (at hundreds of millions degrees Centigrade) to the first wall (i.e. to the plasma-facing tiles at several hundreds of degrees) is about one metre. In order to increase the volume in which fusion reactions take place the geometry of the plasma has been designed in such a way that in reality most of the temperature drop from the core plasma to the walls of the vessel occurs over the last few centimeters. This means that in this region the temperature may decrease by several tens of million degrees per centimetre! By comparison, the gradient within a candle flame, from wick (cool) to flame outer (hot), is of the order one thousand degrees per centimetre.

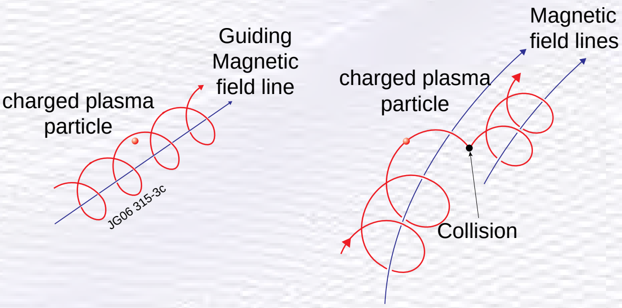


Figure 2: Charged particles in a magnetic field spiral around the "guiding" field line (left). In a collision the guiding field line is changed (right)

The plasma is composed of electrically charged particles, electrons and ions. Such electrically charged particles have the natural property of following magnetic field lines as shown Fig. 2. The field lines may be imagined as strings along and around which charged particles move. Some of these magnetic field lines intersect the solid materials of the vessel at some location. Charged plasma particles that happen to be on such field lines are therefore guided into collisions with the first wall and deposit their energy onto the plasma-facing material. In plasma physics, such a terminal field line is called "open". Open field lines are found at the edge of the plasma close to the walls. In contrast, deeper inside the JET torus, the field lines run around the "doughnut" in never-ending loops, without ever encountering any solid material. They form so called "closed" field lines. In an idealized scenario, plasma particles are safe from collisions with the first wall as long as they are guided along these closed field lines - see Fig. 3. However, there are processes that force plasma particles to leak out from the confined volume, which is the volume entirely filled by closed field lines: particles diffuse across the magnetic field. As can be seen from Fig. 2, particles may leave the confined volume simply due to the fact that their orbit around each field line has a finite radius. Furthermore they can "jump" from one guiding field line to another due to collisions with other plasma particles (Fig. 2) or due to fluctuating electric fields causing so called turbulent cross-field transport (turbulent transport is a hot research topic across different disciplines in physics, see section 2.8). Because of complex instabilities, in addition to the above mentioned mechanisms, plasma particles can be ejected out of the region of closed field lines in big quantities during bursts, commonly called Edge Localised Modes (ELMs), that will be discussed later in this section. However, as the mechanisms that are responsible for transport across the field lines are slower than the particle mobility along the lines, the torus, with its doughnut-shaped geometry and closed field lines, is currently the most successful design for plasma confinement.

Introducing the Plasma Edge

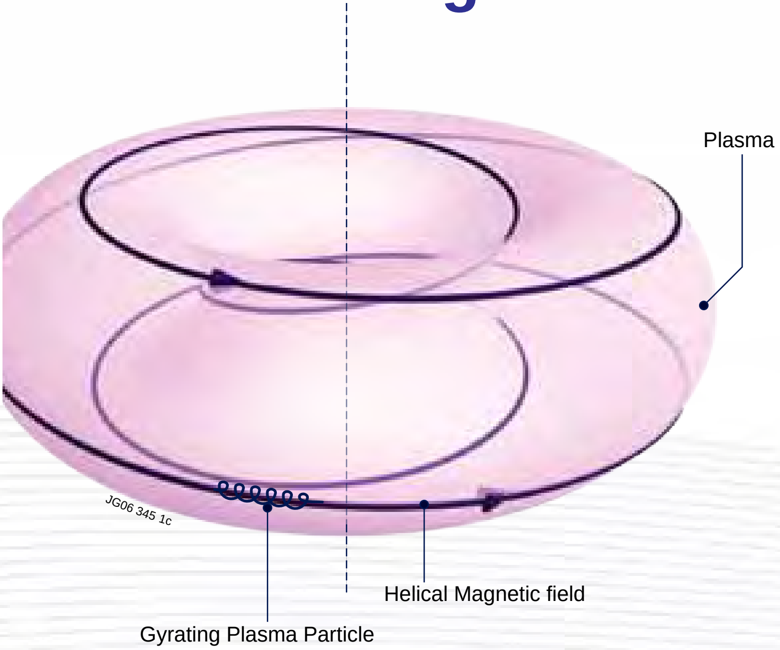


Figure 3: In a torus, plasma particles spiral along closed field lines until they leave these through cross field transport

It may seem ideal to totally avoid the presence of open field lines by building a fusion reactor with a wall perfectly aligned with the closed magnetic field lines. As shown previously, transport across the magnetic field exists by default and this therefore wouldn't prevent plasma reaching these walls. Furthermore, such a simple solution is technologically not realistic. Any imperfection in the shape of the plasma facing wall and/or in the geometry of the magnetic field lines would result in some field lines intersecting the solid walls - they'd break "open". In addition, as the plasma itself contributes to the establishment of the total magnetic field (due to its nature of comprising moving charged particles) it is not possible to keep the field geometry under stringent control. Not to mention that one wants to diagnose the plasma and needs observation ports along the wall. In brief, plasma particles eventually collide with the first wall at arbitrary locations and the particle and energy confinement inside the closed field lines is not perfect. In order to overcome this problem the researchers have opted for a design with a set of well defined open field lines between the first wall and the confined plasma. This constraint resulted in the constitution of a whole branch of fusion research, the physics of the plasma edge, which studies phenomena related to the existence of the open field lines at the edge of the confined plasma volume.

The edge of the plasma is a region between solid materials in the vessel walls, and the main plasma volume, called the core region with closed field lines. In a fusion reactor the plasma edge may be imagined as a protective skin: its properties control the power and particle exchange between the burning plasma (the plasma core) and the vessel walls. It must be pointed out that there is a strong interplay between the behaviour of the plasma edge and the interactions of this plasma with the first wall. They affect each other through various processes that occur on the walls themselves due to contact with the plasma or inside the volume of the plasma edge as a result of these plasma-wall interactions, that will be detailed later in this section.

The Concept of Limiters and Divertors

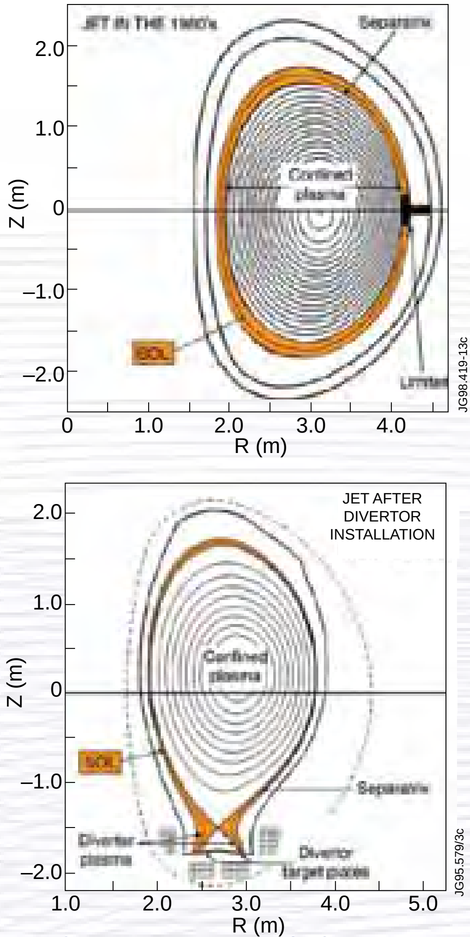


Figure 4: Schematics of the limiter (top) and the divertor configurations (bottom). A vertical cross section of the tokamak torus is shown (compare with Fig. 5)

As we have learned so far, particles are confined to a certain degree within the volume composed of closed field lines. Those that escape this region are called plasma exhaust. The border of the confined region is known as the Last Closed Flux Surface (LCFS) or separatrix, while the term Scrape-Off Layer (SOL) designates a narrow region (usually only a few cm wide) outside this border. The SOL may be imagined as the region where the plasma is essentially scraped off from the core plasma. Here the magnetic field lines are open, and direct the plasma exhaust into a defined region where the exhaust particles are allowed to collide with the wall and much colder neutral gas (the phenomenon of plasma detachment, as described below).

There are two ways by which the last closed field line can be delimited, see Fig. 4. In the simplest and historically earlier option the confined region is “limited” by inserting a barrier a few cm into the plasma. This is called a limiter and essentially it was there to protect the walls from the hot core plasma. Though successful to some extent, it had two major disadvantages: Firstly, material released by impact of the plasma on the limiter could penetrate straight into the core and degrade its properties. Secondly, in a reactor it would not be possible to pump away the “ash” (helium resulting from fusion reactions and diluting the core plasma) in a sufficiently efficient manner.

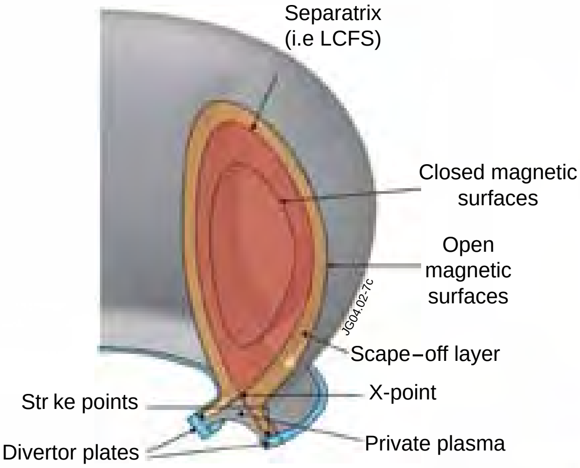


Figure 5: Geometry of a toroidal magnetic field with a divertor

Therefore a more sophisticated solution was developed about 25 years ago, using a modification of the magnetic field lines at the plasma edge, so that the field lines of the SOL are diverted into a dedicated region where the plasma exhaust ends up in collisions with the wall (the target plates) or with gas. This is shown in Fig. 4 (bottom) and Fig. 5, with the diversion of the field lines at the bottom. This latter configuration, called a divertor, has proven in experiments to be significantly more advantageous.

Pros and Cons of the Divertor Concept

Originally the main purpose of limiters and divertors was to separate plasma from the first wall and improve the performance of the tokamak. Particles enter the SOL only by cross-field transport which, as we have learned, is small compared to transport along the field lines. Therefore as a particle moves radially outward from the SOL towards the wall the number of particles “running” along each field line diminishes, as there are less and less that can diffuse into the field lines radially, being transported away along the field to the “targets”. In its simplest form this results in an exponential decay of the temperature and density of the plasma. The result of this is that the heat and particle fluxes onto the walls become sustainable for the wall materials. (Similar conditions exist in neon light bulbs, which everybody knows work well.) Most particles and nearly all of the power entering the SOL are immediately guided along the open magnetic field lines to the limiter or the targets of the divertor. Wherever the plasma impinges onto material wall surfaces impurities from these walls are released.

However, divertors have several important advantages over limiters:

- The materials facing the exhaust plasma are not in any direct contact with the main (confined) plasma. Consequently tokamaks with divertor plasmas have lower levels of impurities in the core plasma. As a result they tend to achieve much higher temperatures in the core, increasing the probability for fusion reactions.

- So called high confinement modes (or H-modes) can be achieved nearly exclusively in the presence of divertors. In the H-mode a barrier against cross-field transport is created that significantly reduces the diffusion of particles into the open field lines thereby increasing the density and temperature of the core plasma. The H-mode was discovered by pure serendipity in 1982, while operating the German ASDEX tokamak with a divertor configuration (see section 3.9). Despite much progress having been made over the past two decades in the description of the H-mode, an understanding of the basic mechanisms that lead to an H-mode, which are likely to include phenomena of the edge plasma, still remains unclear and is a major topic of fusion research around the world.

- As will be explained below, the path of the exhaust particles along a field line from when they enter the SOL along the separatrix to the divertor targets, known as the connection length, can be very long (~30 m in JET and ~150 m in ITER). Depending on the plasma conditions along the separatrix this can be long enough for the plasma to cool down so far that the plasma electrons and ions recombine to neutral atoms before even reaching the solid surfaces. These neutral particles create a “cloud” of gas in the divertor region (see “divertor detachment”).

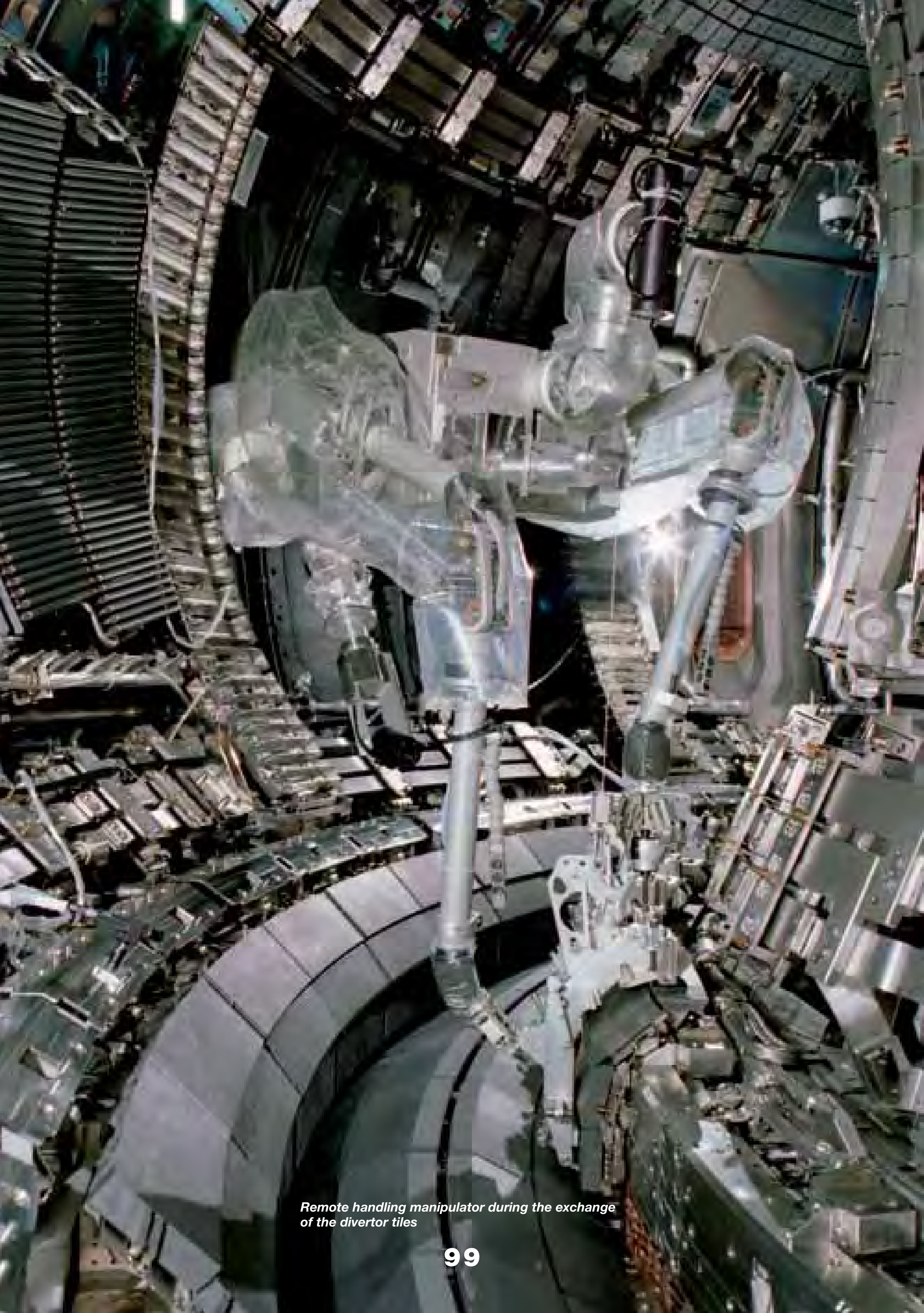
- With a neutral gas developing in the divertor region, high enough gas pressures can be achieved such that pumps (at JET, powerful divertor cryopumps, see section 2.3) are able to remove the now cold plasma exhaust from the tokamak. Such removal of the exhaust is crucial for the functioning of a reactor as this exhaust contains the fusion “ash” helium, which, if not pumped away, would dilute the fuel to such an extent that a burning plasma would not be sustainable anymore.

As the most expensive units of a tokamak are the magnetic field coils, the volume inside such coils in which fusion reactions can occur needs to be maximised to make fusion cost efficient. In this respect the introduction of a volume for the divertor in which no fusion reactions can occur is a major drawback as it increases the costs for a reactor compared to a limiter (but at least it works!).

Why is the Connection Length So Long?

For reasons of stability, in a tokamak the closed magnetic field lines (i.e. field lines entirely immersed in the plasma, see above) do not wind around the torus in simple circles. Instead they have to be imagined as follows: each field line is a very long and thin string that covers, at certain distance from the plasma centre, the surface of the doughnut entirely. This is achieved by tilting the field lines by a small angle as shown in Fig. 3. This angle is called the pitch, Fig. 6. When the pitch angle is set properly, the field line winds around the doughnut without ever reaching its point of departure, so that after many revolutions a single field line can cover almost the entire doughnut-shaped surface. Open field lines (i.e. magnetic field lines in the SOL) must be tilted as well, indeed, the pitch angle cannot change abruptly. Therefore, each particle entering the SOL may have to do several revolutions around the torus before reaching the targets of the divertor. The path is longest for particles residing in the immediate proximity of the separatrix. In fact the X-point in Fig. 5 represents the perpendicular projection of a field line with a zero pitch (a horizontal circular field line) so that charged particles in its vicinity follow trajectories with an extremely low pitch. Therefore these particles can undergo many collisions before reaching the target plates, strongly altering the plasma properties along these field lines.

Figure 6: Near the plasma edge the magnetic field line pitch can be very low. The pitch angle is typically a few times smaller than in the image above



Remote handling manipulator during the exchange of the divertor tiles

Modes of Divertor Operation

- Sheath Limited. Let us define the region of the SOL adjacent to the confined region **upstream** and the target plates **downstream** (following the flux of plasma exhaust along the open magnetic field lines). When the connection length between the upstream and downstream locations is rather short and/or the plasma density in the SOL is low (e.g. when the core plasma density is low), then the temperature drop along a field line is negligible. In this case, all the power entering the SOL reaches the solid surfaces, namely the divertor target plates. The power deposition is highly localised close to the divertor strike points (i.e., the intersection of the separatrix with the divertor plates, see Fig. 5).

  When plasma is in contact with a solid surface then so called “Debye sheath” forms. Heat transfer across this sheath between the plasma and the wall must be proportional to the product of the particle flux and plasma temperature. Therefore the heat that can be transported along the field lines is limited by the heat that can cross the sheath. That is why this regime is named “sheath limited”. As a consequence, the plasma temperature and particle flux in front of the target will increase until the sheath can transport the entire power that enters the SOL, resulting in high temperatures and heat loads on the target. In practice this mechanism excludes the Sheath limited regime from being relevant for a future fusion reactor.

- High Recycling. When the density in the SOL is increased then the plasma flux to the targets increases. As charged particles of a plasma impinge on the solid first wall they recombine on its surface or inside the bulk material to form neutrals which may subsequently be released from the first wall back into the plasma. This process is called recycling. With increasing plasma density more and more neutrals are released from the target plates and penetrate into the SOL – the recycling becomes high. The neutrals are ionized in the plasma of the SOL which removes energy from the SOL in the volume not far from the target. Consequently the temperature along the field line drops. The temperature is further decreased if impurities are present in the SOL, enhancing radiative losses and so cooling down the divertor plasma. The difference between upstream and downstream temperatures may be also increased by extending the connection length between the two regions.

  In the high recycling regime the pressure, being proportional to the product of plasma temperature and density, remains constant along any given magnetic field line connecting upstream and downstream locations. That is, the density of the plasma gets high in front of the targets where the temperature is low. If the plasma and the target material are composed of chemically active species, these may even react with each other leading to the further release of impurities into the SOL, enhancing the above cycle with increasing core plasma density.

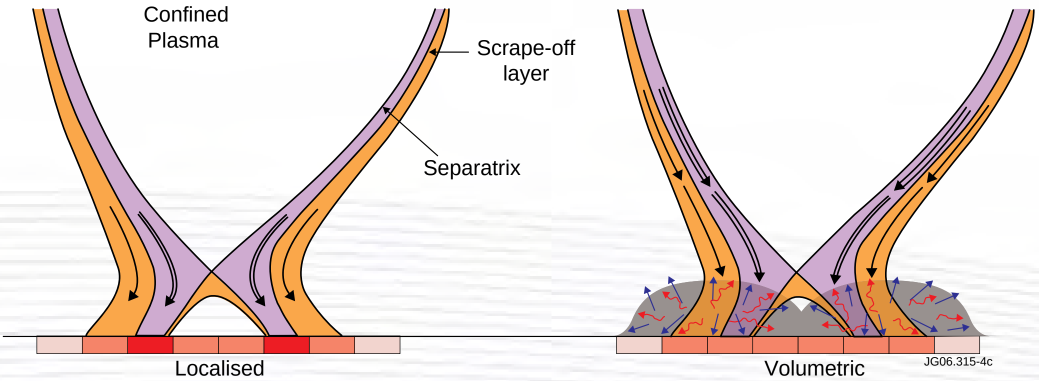


Figure 7: Localised and volumetric losses of plasma energy in the divertor region (long black arrow – plasma flux in the SOL, blue arrows – neutral atoms, red arrows – radiation)

The volumetric radiation in front of the targets reduces the power flux to the material surfaces and thereby increases the lifetime of the divertor plates - see Fig. 7. With the neutrals being ionized in front of the targets, the main particle sources of the SOL are now the target plates and no longer the particle flux across the separatrix as it would be in the case of the sheath limited regime – the difference denotes the high recycling regime. However, the only source of power for the SOL remains the plasma power losses across the separatrix!

- Divertor Detachment. With further increase of the plasma density the amount of charged particles that reach the divertor plates falls to negligible levels. As the density is increased more impurities are released by plasma facing components that raise the radiation levels. For tokamaks where the walls of the divertor are made of materials that do not radiate efficiently enough, impurities can be puffed i.e. “seeded” into the divertor for obtaining the required radiation and thus cooling of the divertor volume. This method is known as impurity seeding. As the temperature in the divertor decreases over a large volume, electrons and ions can recombine to form neutrals volumetrically. This process is amplified by the presence of those neutrals that, recycled at solid surfaces, now act as a “break” for the plasma that flows towards the targets through friction. They increase the time that the charged particles have for recombining, making this process more likely to happen. When this occurs in large quantities the measured particle flux at the target plates drops by more than an order of magnitude. Neutral atoms transport the residual power and as they are not bound by magnetic field lines, they can deposit power and particles over broad areas reducing the peak values to acceptable levels for materials to sustain the bombardment - see Fig. 7.

  This regime is known as the plasma (or divertor) detachment as ideally the plasma becomes completely detached (separated) from any solid surface. Plasma detachment allows higher operating temperatures upstream. Due to the high neutral particle densities/pressures established in the divertor volume in front of the pump ducts, the pumping of the helium ash becomes more efficient. And due to the negligible plasma influx onto material walls the production of impurities may be reduced.

Expected Divertor Operation in Fusion Reactors

As we have seen, divertor detachment is very advantageous for handling the exhaust power and fusion ash, sparing the divertor targets from unacceptable localised power loads and removing the Helium exhaust. However, in experiments it can sometimes be challenging to stabilize detachment on both targets when plasmas become fully detached. Here fully detached means that the plasma detaches along the entire target surface. Under these conditions large volumes of the divertor are cold and neutrals have a long lifetime (i.e. average time that a neutral particle doesn't get ionised) allowing them to penetrate into the confined region. The influx of neutral particles and, in particular, impurities into the confined plasma causes high radiation levels from this region, which may result in the thermal instability of the whole plasma. The phenomenon that leads to such instabilities is known as MARFE (Multi-faceted Asymmetric Radiation From the Edge) and needs to be avoided - see Figs 8 and 9.

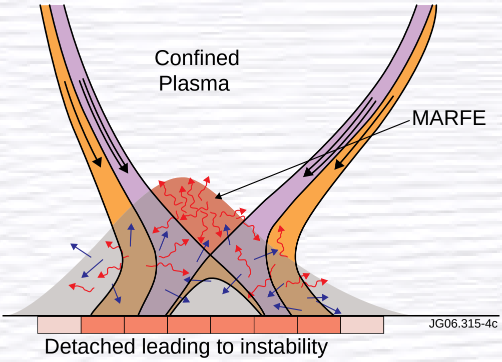


Figure 8: Schematics of the divertor MARFE (blue arrows – neutral atoms, red arrows – radiation)

In current normal tokamak operation (and also for the future ITER machine) it is planned to run the divertor in the so called partially detached regime, Fig. 10. In this regime usually the plasma at the inner target (the target on the left side of the images at smaller radii) is still completely detached; whilst at the outer (right) target it is only partially detached. This means that it is not detached along the entire target but only in those regions where the connection length is longest, thus close to the strike point. Further out it remains in the high recycling regime such that neutrals cannot leak in large quantities into the SOL outside of the divertor. It has been found and extrapolated for ITER that such a degree of detachment is sufficient for handling the power load and it is best for the performance of the SOL. It also reduces the risk for a MARFE, by limiting the size of the cold cloud of neutrals in front of the target plates, as shown in Fig. 10.

Computer models are used to predict and interpret the complex behaviour of the SOL and divertor plasma, thus also those of JET and ITER. These models are very complex and include many different processes. Whilst providing a reasonably reliable qualitative interpretation of the plasma edge behaviour they often fail to predict dependable numerical values (see section 2.8). For example, it is not definite whether ITER will achieve plasma detachment naturally or whether impurity seeding will be required. It is thus one of the tasks of the researchers concerned with edge physics to further develop the models for the edge and improve their accuracy against existing experiments such as JET.

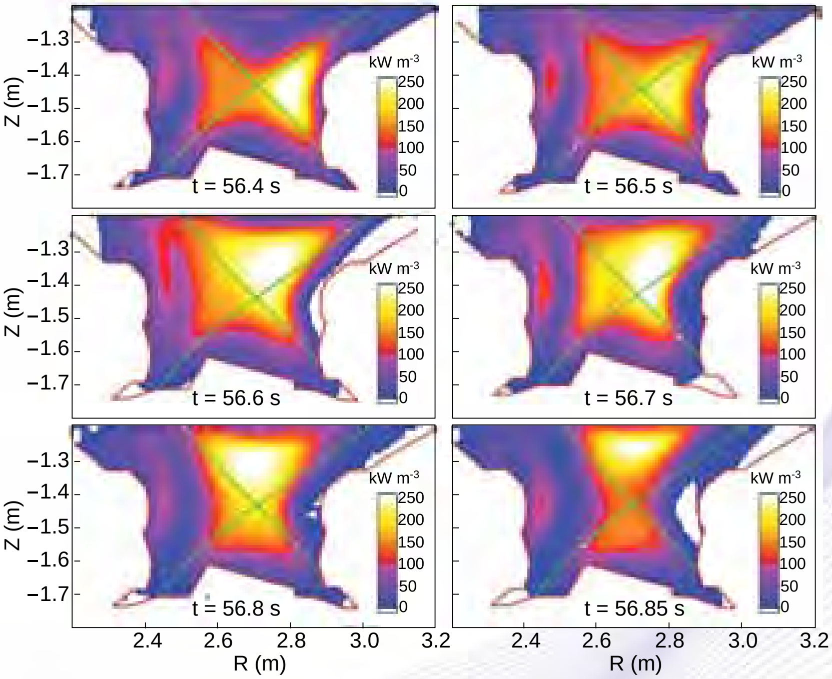


Figure 9: Occurrence of MARFE as observed by the JET bolometry diagnostic system

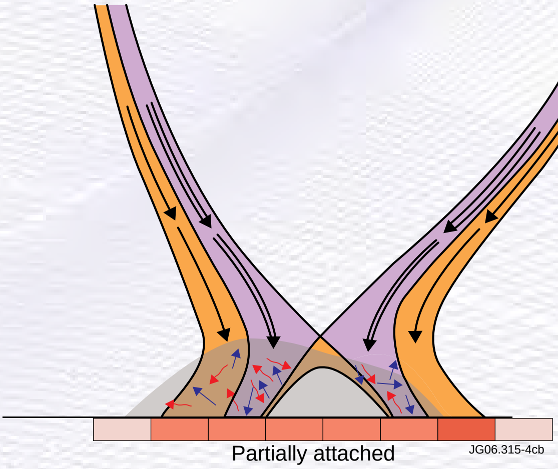


Figure 10: Size of the gas cloud can be efficiently controlled when plasma is just partially detached (blue arrows – neutral atoms, red arrows – radiation)

Edge Localised Modes (ELMs)

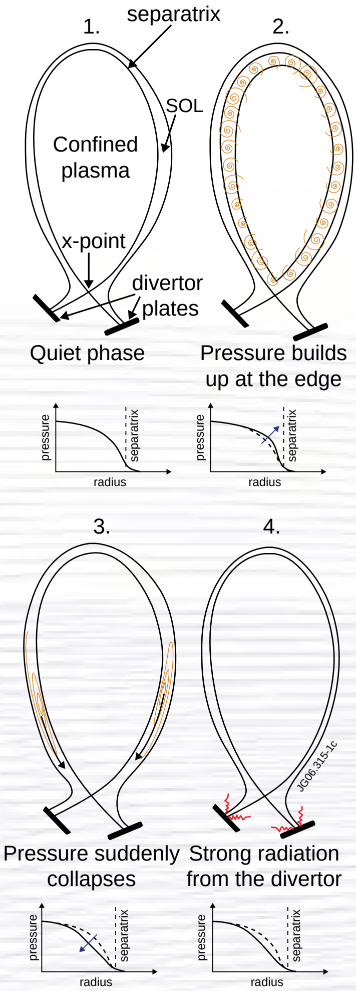


Figure 11: Time development of an ELM crash.

Edge Localised Modes (ELMs) are repetitive bursts of the edge plasma. Because of their periodicity (albeit irregular), one way to imagine the ELM phenomenon is to picture a single ELM cycle. The most rapid changes occur during an ELM crash which is usually significantly shorter than the time between the ELMs. Fig. 11 shows the evolution of a plasma during an ELM. The plasma cross-section and the radial plasma pressure profile (i.e. plasma pressure as a function of distance from the plasma centre) are shown at four different time points during an ELM crash.

The first column of Fig. 11 corresponds to the situation before the ELM crash. The plasma is stable and has a steep pressure gradient at the edge. The gradient is maintained by the edge transport barrier that is always associated with the high confinement mode (H-mode) of tokamak operation.

The second column shows the onset of an ELM, which can be imagined as an onset of many small turbulent eddies at the edge due to the pressure gradient having exceeded a critical value for stability. The instability is not necessarily triggered by the pressure itself, but, for instance, by the so called “bootstrap current”, an electric current driven by the pressure gradient.

In the third column, the edge plasma is lost to the Scrape-Off Layer (SOL) where it flows along the magnetic field lines towards the divertor.

The lost plasma ends up on the divertor plates producing the distinctive peak in the D-alpha radiation (visible light emitted by excited atoms of deuterium fuel) as indicated in the fourth column.

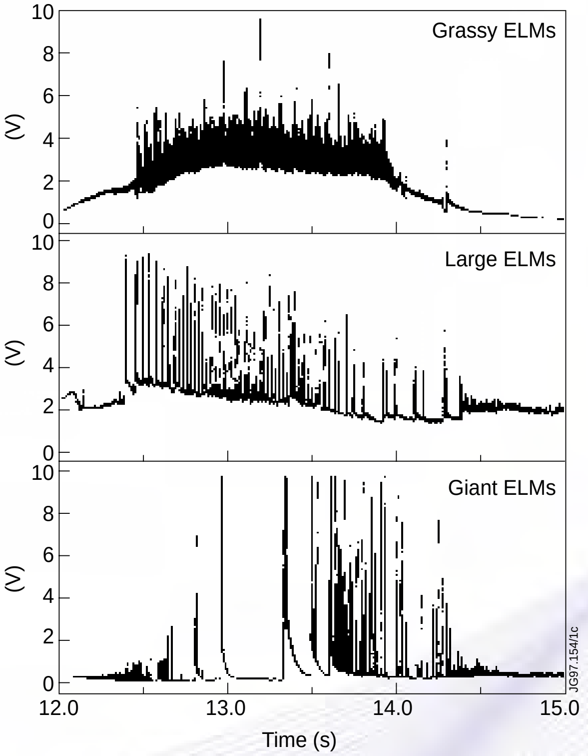


Figure 12: ELMs can be observed in the plasma edge as repetitive peaks e.g. in light intensity or in voltage measured at an electric probe

ELM activity may evolve as shown in Fig. 12. The short, intense heat load on the plates causes erosion of the divertor materials. During the instability, the edge pressure gradient is reduced until the plasma becomes stable again. Then the pressure gradient starts recovering to the level where it reaches the stability limit so that another ELM occurs. If the conditions stay constant, the cycle can continue indefinitely. Depending on the ELM type and the details of a plasma device, each ELM removes 1 - 7 % of the plasma energy and particles.

ELM Classification

Another way to examine ELMs is to study the global behaviour of the plasma during ELMs. While some of the features are common to all ELMs, there are also distinctive differences as shown in Fig. 12. Consequently, it has become standard to use the following classification of ELMs:

- Type I ELMs: The D-alpha radiation shows large isolated bursts and, therefore, Type I ELMs are also called ‘large’ or even ‘giant’ ELMs. The plasma edge is close to the theoretical (“ideal ballooning”) stability limit or even beyond it. The instability is pressure driven, and as the heating power is increased, the ELM repetition frequency also increases. The degradation of the plasma confinement is smaller than with other ELM types.

- Type II ELMs: These are observed only in strongly-shaped plasmas, i.e. with high elongation and triangularity of plasma cross-section. Also the plasma density needs to be rather high. The magnitude of the ELM bursts is lower and the frequency is higher than that of type I ELMs, while the confinement stays almost as good. Sometimes, type II ELMs are called ‘grassy’ ELMs.

- Type III ELMs: The bursts are small and frequent. Therefore, another name for type III ELMs is ‘small’ ELMs. The instability is driven by electric current, and appears when plasma resistivity is rather high (i.e. edge temperature rather low). The ELMs repetition frequency is found to decrease with the increasing heating power. The plasma confinement is degraded more than with other ELMs.

In the presence of the edge transport barrier, i.e. in the tokamak H-mode operation, ELMs are instrumental for maintaining a stable density of confined plasma. In other words, without ELMs the plasma density in the H-mode increases above the overall stability limit, leading to sudden loss of the plasma confinement in a major instability called plasma disruption. However, two ELM-free operating modes with stable density have been observed in high confinement mode (H-mode) of the tokamak operation:

- The U.S. Alcator C-MOD tokamak exhibits an “Enhanced D-Alpha” mode or EDA. In an EDA, while the plasma behaves as in the ELMy H-mode (steady-state density achieved, no accumulation of impurities), there are no periodic bursts of plasma, but the D-alpha-radiation remains at an increased level throughout the EDA period. The particle and energy confinement is reduced in comparison with a real ELM-free H-mode.

- In the U.S. DIII-D tokamak, with neutral beams injected in the direction opposite to the plasma current and with a large distance between the plasma and first wall, low density H-modes have been observed and named “quiescent H-mode”. In this mode the ELMs become suppressed, and replaced by harmonic oscillations in the plasma edge. The oscillations are a sign of turbulent transport that keeps the particle transport high. Consequently, the plasma density does not increase as in a normal ELM-free H-mode which would normally lead to a disruption. From the fusion reactor operation point of view, the drawback of the quiescent H-mode is that it leads to accumulation of impurities into the core plasma.

In order to decrease the divertor erosion and, at the same time, maintain a good control of the pressure profile, several methods of ELM suppression are considered at present. The two most promising approaches are the following :

- Pace making of ELMs by injecting small pellets of frozen fusion fuel into the plasma edge at a high frequency, see section 2.11.

- Plasma edge ergodisation by resonant perturbations of the magnetic field. Studies at the DIII-D tokamak demonstrated an unexpectedly strong ELM suppression via resonant magnetic field perturbations. This is considered to be a very promising result for a reactor-relevant operation. However, both its understanding and its validation on other tokamaks is still at an early stage (in 2006).

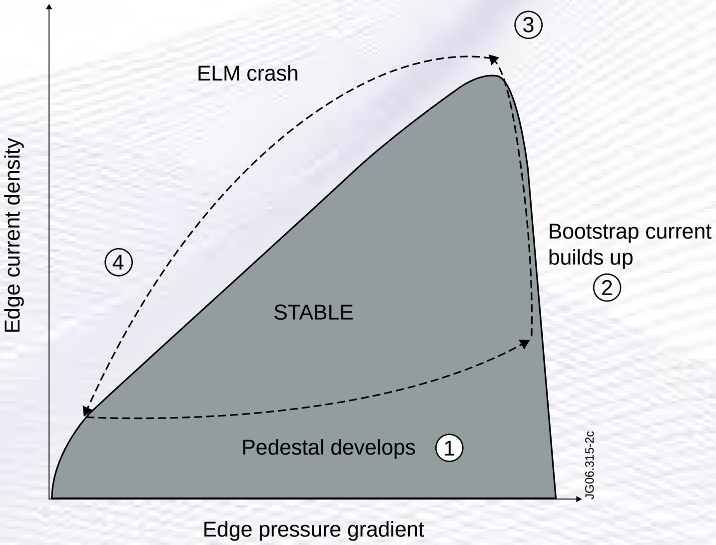


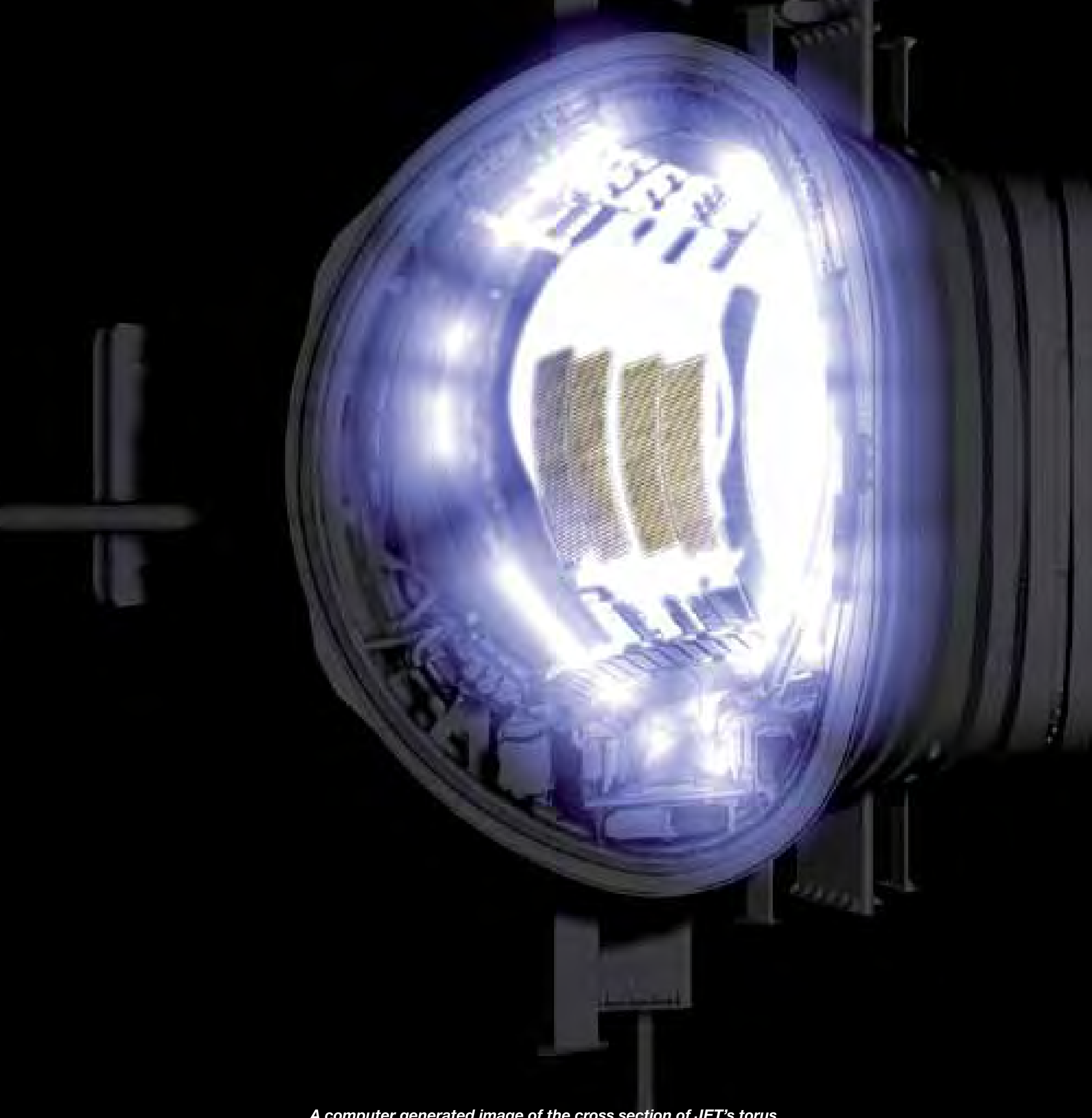
Figure 13: Model for the ELM mechanism as proposed in article "Magnetohydrodynamic stability of tokamak edge plasmas" by Connor, J.W., Hastie, R.J., Wilson H.R., Miller, R.L., published in Physics of Plasmas Vol. 5 (1998) page 2687.

ELM Model

Several models for ELMs have been suggested. Most models use plasma instabilities to explain ELM behaviour of plasmas. The plasma goes through a cycle where it is destabilized and then stabilized again. The following model has been suggested for the type I ELM cycle, see Fig. 13.

The ELM cycle starts with a low pressure gradient as a result of the previous ELM crash that has removed the edge pressure “pedestal”. Due to the edge transport barrier, the edge pressure pedestal develops quickly (1). The growth of the pedestal stops at the so called “ballooning stability” limit (2). Due to the pressure pedestal, the above mentioned bootstrap current - which is proportional to the pressure and temperature gradients - starts to grow. Eventually, the bootstrap current destabilizes an effect known as “ideal peeling” which leads to an ELM crash (3) and the loss of the edge pressure pedestal (4). The cycle then restarts from the beginning.

For general information on plasma modelling see section 2.8.



A computer generated image of the cross section of JET's torus

Plasma-Wall Interaction

In magnetic confinement fusion devices, plasma facing components are subject to heat and particle fluxes that strike the first wall either continuously or in bursts. The effect on the wall surface is usually tolerable in present facilities but in future fusion power reactors the power load will be much higher and the duration of the plasma discharges much longer (current machines a few tens of seconds, future machines several tens of minutes if not continuous). The potential scale of the damage to the first wall challenges fusion research and technology, particularly for the development of the divertor. Even when most of the power of the plasma is exhausted in volumetric processes, some plasma facing components will have to withstand peak temperatures of more than 1000 degrees, despite being actively cooled!

The particle fluxes and heat fluxes onto solid surfaces lead to erosion and release surface material into the plasma where it acts as an impurity. Some of the released impurities can migrate to very remote locations inside the machine before they stick to a plasma facing component so forming a layer of an amorphous material. The studies of the processes responsible for erosion, migration and deposition of materials in fusion facilities constitute a significant fraction of the present fusion research program, see Fig. 14 and, for example, section 2.10.

The migrating particles can also make their way to the confined plasma volume, diluting the fusion fuel and cooling the plasma through increased radiation losses. Impurities can reduce the fusion gain to unacceptably low levels. Therefore, the choice of the first wall materials and control of the power fluxes set important boundary conditions for the performance of the future reactor.

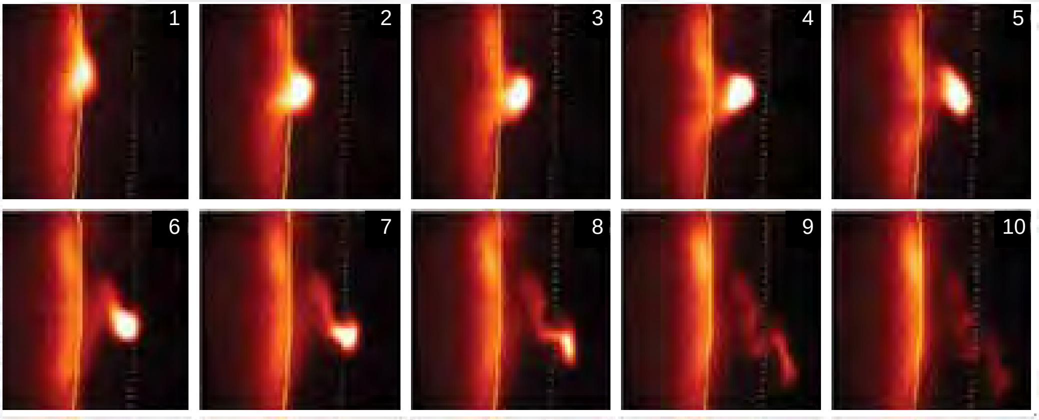


Figure 14: Blobs, or field-aligned coherent turbulent structures of the size of a centimetre, were discovered only recently. Blobs can travel beyond the SOL and increase the erosion of the first wall. This set of photographs shows experimental observations of a blob propagation with a time step of 8 microseconds. Image courtesy of Princeton Plasma Physics Laboratories.

Figure 15: As a part of the ITER R&D projects, this ITER divertor target mock-up was manufactured by Plansee GmbH. High melting temperature and high energy threshold for sputtering are attractive features of tungsten (the top part of the mock-up consists of W brush armouring). Tungsten, however, due to its high atomic number presents a burdensome plasma impurity. Carbon Fibre Composite tiles (CFC, applied in the bottom part of the mock-up) are popular due to their unique thermal resistance, however, in fusion plasmas they suffer from hydrogen absorption and chemical sputtering. Image courtesy of ITER.

The main mechanism for material erosion is sputtering by which atoms from solid walls are ejected due to bombardment by the energetic plasma ions. One may imagine this in a similar way as firing cannon balls on stone walls in order to slowly destroy the fortress. For some materials an energy threshold for sputtering exists and no particles are released when the surface is bombarded by particles that have less than the threshold energy. Another sputtering mechanism is through chemical reactions if the target material and the plasma form chemically active combinations, such as deuterium and carbon. This is called chemical sputtering. The yields of these sputtering processes are subject to intensive research as carbon has excellent thermal properties and is therefore an interesting candidate for target materials but is also chemically active in the presence of deuterium.

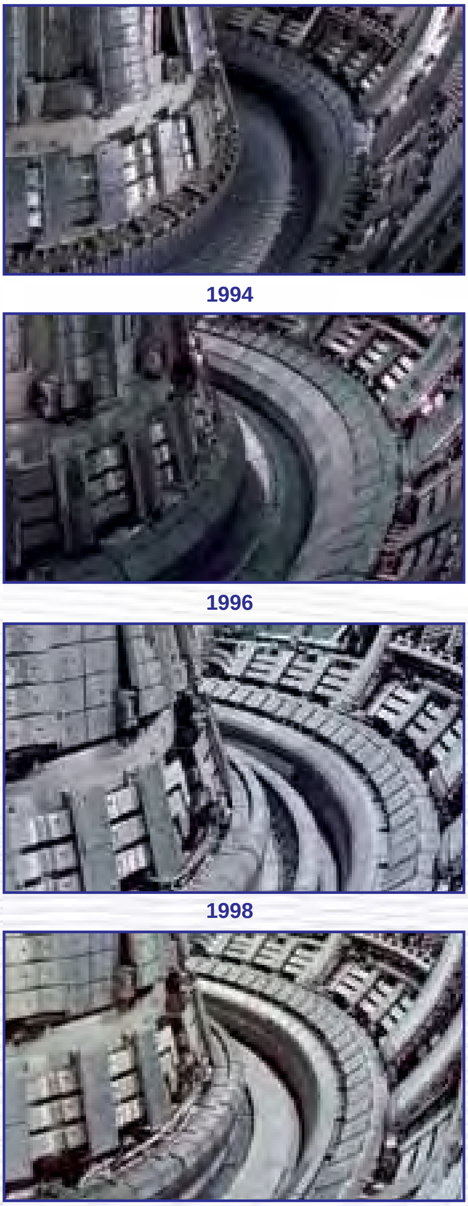
If the wall material reaches a certain temperature (i.e. a certain power flux, given the thermal properties of the first wall) melting and blistering of solid material may occur causing a very rapid erosion of the surface. Therefore, engineers and physicists have to design the reactor first wall and its cooling system so that the wall temperature is always safely below a critical temperature - see Fig. 15. To be successful, reliable predictions of the peak power fluxes that may arise are needed, particularly during plasma instabilities. This is a crucial task for researchers who, in parallel, continue their search for improved plasma operation scenarios that would further alleviate the peak power loads onto the first wall. A particular issue is again the appearance of ELMs that can deposit very high power levels in a very short time interval on plasma facing components, significantly decreasing their life expectancy. The control and suppression of these ELMs is another major field of research as they occur on a regular basis in the very preferable H-mode.

Plasma textbooks mention another potential source of local wall erosion - arcing - that may occur when the electric potential between a plasma and first wall materials exceeds a critical level. At present, this phenomenon is well under control in all standard fusion experiments.

Role of JET

JET acts as a bridge to ITER in many respects: It is currently the largest tokamak and, therefore, the closest facility to ITER in size; its shape and configuration is quite similar to ITER; and it is currently the only facility capable of operating with tritium, a fuel component of future fusion reactors. Many of the current JET experiments are devoted to the development of operating scenarios for ITER, including studies of the divertor physics as presented above. Due to its large size JET produces Edge Localised Modes (ELMs) of high amplitudes allowing appropriate scaling to ITER, and studies have clearly highlighted that certain types of ELMs must be avoided in ITER. In the recent past, JET has played a leading role in divertor design optimisation, which is documented in Fig. 16 as a series of historical photographs from inside the vessel.

In the near future, JET will assume the key responsibility as a test bed for the first wall materials that have been chosen under the current design for ITER. In particular, JET will assess the effect of the beryllium first wall on the divertor plasma operations. For details on this topic, see ITER-like Wall Project in section 2.11. Last but not least, JET exploits several diagnostic tools for plasma edge observations and contributes to their further development (see sections 2.5 and 2.9).


1994

1996

1998

2001

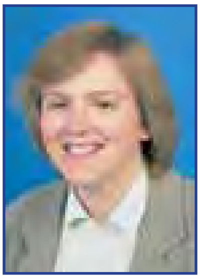
Figure 16: JET has been validating several designs of the divertor region

2005

Conclusion

Handling the fusion power and maintaining the required plasma purity (in particular, extracting the fusion exhaust) are essential achievements on our path towards harnessing fusion power. The role of the physics of the plasma edge is incontestable. Hand in hand with this complex discipline emerges another equally profound topic: physics of the plasma-wall interactions with its wide spread material research. Results from fusion laboratories obtained so far are encouraging. However they call for ongoing work and broadening of the research scope towards technological tasks. The accumulated knowledge will then be instrumental for the design of the plasma facing components (the first wall) in future fusion reactors, as well as for the optimisation of the reactor operation scenario.

"Computer modelling is a most valuable tool for achieving the physical understanding and control of fusion plasmas. The complexity of the problem is challenging, but tremendous progress has been gained in recent years. Close interaction between theoreticians, modellers and experimentalists is the key to success."



Paola Mantica,
Task Force Leader,
Force T (transport analysis)

Computer Modelling of Fusion Plasmas

2.8

In today's world, virtually anything can be simulated on computers, from flying an aeroplane to being a top football manager - or doing experiments in fusion plasma physics. These simulations, when done according to rigorous principles of mathematics and physics, are called "computer modelling" and form an important part of our science. Actually, though computer modelling is rarely seen on the main scenes of fusion research, it has a very distinguished role - the role of mediator between what is measured (data from experiments) and what is understood (by physics theories). In plasma physics, this task often proves to be rather difficult.

What is Modelling?

A quick look in a dictionary reveals that one meaning of “model” is, “a schematic description of a system, that accounts for its known or inferred properties and may be used for further study of its characteristics”. This is true in physics where the known properties can be written down in the language of mathematics (as functions, differential equations etc.). In any concrete situation we first aim to set out a complete “mathematical” description which we subsequently try to solve (i.e. we attempt to determine the unknown quantities from the known ones). However, in many cases this direct solution is not possible due to the complexity of the system. In these situations we have to have recourse to a simplified simulation, called a “model”. In the past, these models were often mechanical or electrical: for example, properties of crystal lattice were studied using many small spheres or bubbles, and resonant oscillations of big structures were sometimes modelled using an equivalent resonant electrical circuit.

Figure 1: This scale model of JET was originally used for design tests of new components. Made redundant by 3D computer design environments, half is now exhibited in the JET foyer and the other half has been donated to the British Science Museum.

Advantages and Drawbacks

At present, it is computers that provide us with the most powerful modelling tool. The “computer models” are nothing more than computer programs (also called “computer codes”) accompanied by numerical data to simulate a system - in our case, a plasma discharge in a fusion experiment, or a part of it. The computer models have strictly defined rules, offer any degree of precision needed (provided there is enough computer memory and time to compute) and can show results in a very convenient visual form. Notice that there is one more fundamental advantage of computer modelling: it allows for simple cloning of models (copying of programs and data) so that key tasks can be tackled by several research groups worldwide, all using a completely identical model.

What are the drawbacks of the computer modelling? Well, there aren’t many.

First of all, a good physicist must keep in mind that using mathematics is more fundamental than doing computer simulations. Today people tend to model every simple situation on computers just to avoid brain teasing with calculus, and forget that pure mathematical solutions can provide a much deeper and clearer understanding of the system.

Secondly, computer models can produce wrong results, for many different reasons. The most common reason is “bugs”, i.e. small errors in the computer codes. Today the programs are so complicated that “debugging” is a very tedious and unpopular procedure. With beginners, many errors stem from transcribing the physics equation into its software form, or “algorithm”. For example, it is not obvious how to write a correct algorithm solving a differential equation, as there are important distinctions between analytical mathematics and numerical (digital) computing. There are thick textbooks explaining how to transcribe correctly. Finally, sometimes the program is perfect but still the results are wrong - then it means that our model does not reflect all that happens in reality (in most cases it is just oversimplified).

The last major drawback is that a good model of a complex system may well be too demanding on our computer hardware, requesting far too much time to run and far too much memory to follow the system evolution. A state-of-the-art computer model is therefore usually a quite expensive tool for science. Of course, with the stunning progress in computer technology the accessibility of good models is much greater today than ever before. Nevertheless computers can never run a perfect model of nature, as it will always be just a subset of reality! Experiments and observations will always be required to provide the reference points on our way to understanding the world.

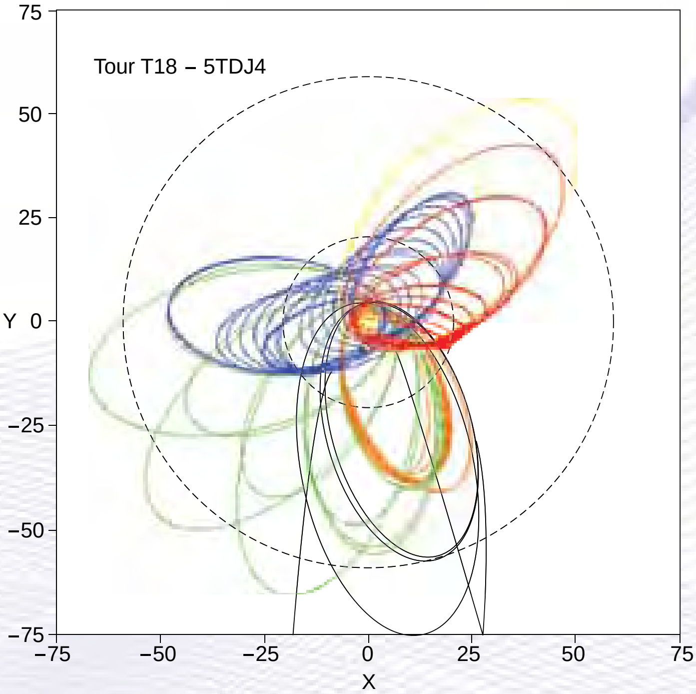


Figure 2: Although the law of gravity is simple, motion in combined gravitational fields is so complex that spacecraft navigation needs computer modelling and feedback control. This illustration shows the tour of the Cassini spacecraft around Saturn (courtesy Nasa/JPL-Caltech)

Background of Plasma Modelling

After these general remarks let us move into the realm of computer modelling of fusion plasmas. The first statement sounds quite promising: there is very reliable theoretical knowledge of fundamental physics acting in plasmas. Plasma can be modelled as a large set of free charged particles that move chaotically at very high velocities. All plasma particles are subject to electromagnetic interactions that were understood back in the 19th century (Maxwell's equations, Lorentz force). This understanding has been validated again and again ever since. In most cases the plasma models do not need any aspects of "modern physics" like space-time or quantum effects.

Unfortunately, this is about the only positive statement concerning the simplicity of plasma modelling. Real plasma is an extremely complex system of an unimaginable number of charged particles that follow the "basic rules" of electromagnetism. It is beyond the means of any model to follow the positions of billions of billions of these particles as they move rapidly in electric fields that are formed by the very same particles (the fields are "self-generated"). Due to this entanglement, plasmas are capable of building up many special phenomena, called "collective effects". These effects, even if very obvious in experiments, may still lack a clear and validated explanation in terms of theory and/or modelling. In plain words, some of the phenomena observed in plasma physics are not understood yet.

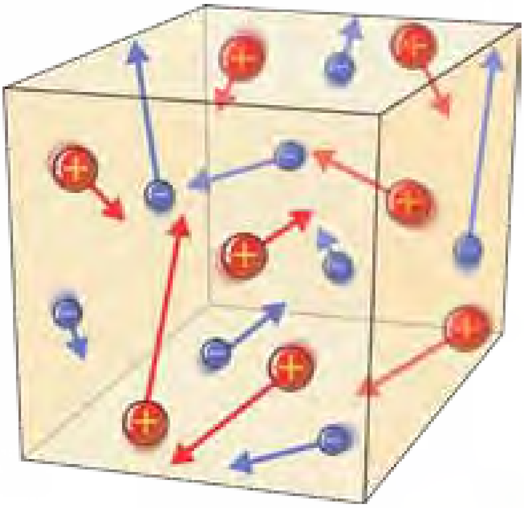


Figure 3: A snapshot of plasma's ions and electrons with arbitrary positions and velocities. Further evolution of the system is governed by laws of electromagnetism. Notice that in reality, the size of the particles is negligible compared to their mutual distances.

Besides, with respect to high velocities of plasma particles, there is hardly any realistic plasma volume to which one could apply a simpler model of the "infinite homogeneous plasma". When modelling real plasmas, steep gradients of basic parameters (temperature, density, electric and magnetic fields...) can never be omitted. External electric and magnetic fields, to which plasmas are extremely sensitive, must also be taken into account - in the case of our research, external magnetic fields play a fundamental role in shaping and containing the plasma. Last, but not least, models have to reflect that finite plasmas continuously exchange large amounts of energy and particles with the external world.

Successes of Plasma Modelling

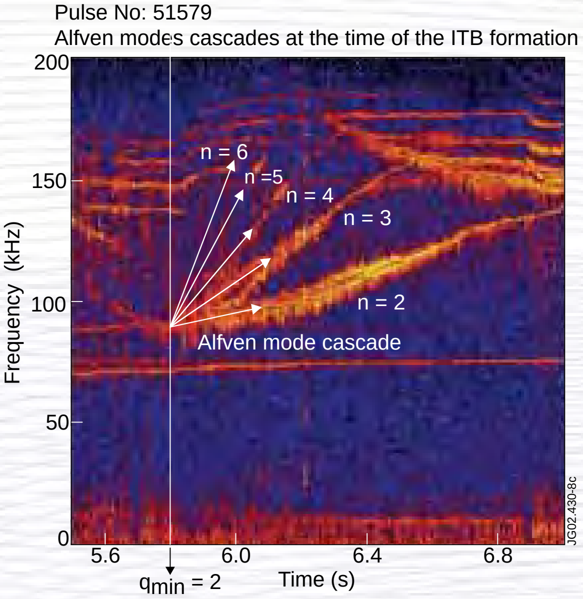


Figure 4: Experimental data showing cascades of Alfvén waves in the JET plasma after formation of the Internal Transport Barrier (frequency versus time; n denotes the number of Alfvén wave periods around the plasma loop)

Still, in plasma physics there are many cases when computer modelling is quite successful. For example, the incredibly rich “zoo” of plasma oscillations and waves of many different frequencies and speeds is well understood due to extensive theoretical and modelling works. As a result, electromagnetic waves can be used today to heat plasmas, and even to drive electric current in plasmas. In recent years, so-called Alfvén waves (oscillations of magnetic field lines) have been continuously studied with a steadily improving link between model prediction (i.e. computer simulation) and experimental measurements, see Fig.4.

Another example of a good match between theory, modelling and experiment is plasma radiation: as a result of this understanding, measurements of radiation properties allow us nowadays to derive fundamental plasma properties like temperature, density, purity, magnetic field intensity and direction, diffusion rates etc. Similarly, there aren’t any significant uncertainties concerning the relationship between the observed intensity of fusion neutrons and the plasma properties. In other words, the capability of tokamak plasmas to release fusion power is beyond any doubt, and the amount of released fusion power can be accurately predicted by theory and computer modelling.

Major Challenge: Particle and Energy Transport

What is the main challenge then? It is the particle transport and the energy transport in high-temperature plasmas. By “transport” we actually mean the way in which particles (or some form of energy) travel from one location in our experiments to another location. Obviously transport is a key feature in understanding and controlling fusion plasmas: just imagine all the effort we take to prevent hot plasma particles touching any of containment structure! Similarly, if the transport were too low, fusion exhaust products would contaminate the plasma while new fuel could hardly get in. At the individual particle level, transport is due to mutual collisions and particle “drifts” caused by external forces. On the other hand, when plasma is studied as a continuum consisting of nearly infinite number of particles, transport can be described by “diffusion” and “convection”. A major challenge of present plasma science, and of plasma modelling in particular, is that experimentally measured diffusion and convection values substantially differ from what is predicted by simplified theories and models based on collisions and drifts of individual particles.

Turbulences and Non-linear Problems

Among experts there is a broad agreement, supported by data from dedicated experiments, that this discrepancy is caused by plasma turbulences. The turbulences can be imagined as eddies in which billions of plasma particles are involved. Real plasma is then a mix of many small and large turbulent regions, forming a very tumultuous environment altogether. Turbulences can modify the magnetic field around which they rotate; they can be stationary or can emerge and dissolve in time. Turbulences always enhance the transport as they effectively mix different regions. Indeed, when turbulences are suppressed, the plasma confinement improves, which has been verified in different kinds of experiments.

Figure 5: Turbulent flow of a fluid around an obstacle (courtesy www.wikipedia.org)

The principal problem of turbulences is that it is very difficult to predict their evolution. Even a tiny influence can substantially modify behaviour of a turbulent system. This feature also challenges, among others, the long-term weather forecasts, where it is said that the flutter of a butterfly's wings in one continent can cause a storm on another continent months later. In mathematics, so-called "non-linear" relationships reflect this behaviour, and they are generally more difficult to solve than "linear" relationships (the word "linear" indicates that the rate of change is proportional to the current state). Indeed, in non-linear systems, a slight change of an input parameter can lead to substantial modification of the solution (or even to multiple solutions). In computer modelling, the non-linear systems are extremely difficult to simulate because only few simplifications can be done reliably (remember "the butterfly effect"). No wonder that the theory studying these phenomena is known as "deterministic chaos".

Scaling Laws and Transport Barriers

Anyway, even in turbulent environments there are some basic features, some clear patterns of behaviour that can be understood and predicted, often using linear models. For example, the transport of energy and particles exhibit clear dependencies on engineering parameters of experimental machines (on their size, magnetic field etc.). In the case of tokamaks, the measured dependencies are collected today in a very large international database that is used to determine so-called scaling laws, which are instrumental in predicting performance of future facilities like ITER. These predictions are based on the similarity or similitude principle that is already widely applied, for example, in fluid mechanics (including the wind-tunnel techniques). In other words, our scaling laws extend the wide use of “engineering” scaling principles as well as dimensional analysis into the plasma physics domain.

Although the scaling laws are purely empirical (i.e. they are based on experience rather than on our basic understanding of physics) they have already proved to be quite robust. It is therefore expected that there is a dominant physical mechanism behind them which, even if it is due to the turbulent nature of plasmas, can eventually be modelled. Steady progress in the plasma modelling of transport has so far validated this strategy. Every time there is a better model available, we not only feel more confident about the performance of future facilities, but additionally we can claim progress in our understanding of plasma physics.

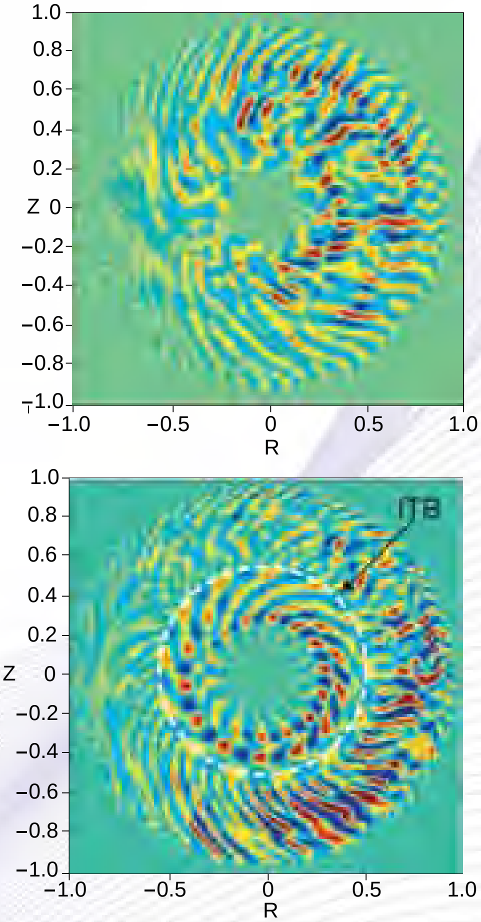


Figure 6: Lines of electric potential in a JET plasma turbulence simulation without (top) and with bottom) the Internal Transport Barrier (ITB).

Another important example of the “cutting edge” in computer modelling of plasmas is provided by studies of the so-called transport barriers. The External Transport Barrier, which is behind the H-mode of tokamak operation, was discovered experimentally in 1982, see section 3.9. Although there is a good qualitative picture of what is probably going on in the barrier, the available computer models do not totally predict the behaviour of the barrier. Similarly for the Internal Transport Barrier, which was first observed at JET in 1988, the models provide only a qualitative understanding (see Fig. 6).

Integrated Efforts

At present, some of the plasma models are quite successful in transport studies when constrained to specific conditions. Under other conditions (e.g. at lower temperatures) there are other models which can be applied. That is why many scientists try hard to put all the available plasma modelling tools together and form a singular compact package of models that would consist of many interlinked computer programs. The resulting package would, in principle, be able to simulate the whole tokamak experiment. This major project is very challenging, as different methods, approaches and even cultures have to be put together without introducing "bugs". In Europe, all the corresponding efforts have been evolving under the EFDA European Task Force "Integrated tokamak modelling".

Figure 7: Today, the analysis of JET plasmas relies on clusters of high performance PCs. The photo shows part of the JET Analysis Cluster which consists of 165 Athlon processors running under Linux (as at February 2007)

Future and Conclusion

However, in many regions (for example, at the plasma edge) reliable and quantitative models are not yet available. This does not necessarily mean the computer program is not there - sometimes the input data that the program requires is not yet available in sufficient quantity or accuracy, if indeed it is available at all. In reality, a high-quality computer modelling tool often calls for progress in the experimental work. Good computer scientists, like good theoreticians, often clearly specify regimes of plasma operation to be explored or plasma diagnostics which need to be enhanced.

In the complicated field of plasma transport, progress in modelling is being made on two fronts. On one side, modellers working within theoretic groups continually improve their codes based on basic physics principles. On the other side, modellers working within experimental groups keep enhancing their algorithms that evaluate basic plasma features such as diffusion and convection from the measured data (microwave, light and X-ray radiation, particle fluxes, intensity of magnetic fields etc.). The two fronts are continuously exchanging concepts and quantitative results with the aim to eventually merge their works on a single platform.

To conclude, it is clear that although plasma modelling cannot replace experiments, it can considerably accelerate our research and, at the same time, enhance our understanding of fusion plasmas.

> *"The last shutdown period was extremely busy. Indeed, it is a very stimulating experience to witness the period of ultimate 'put together' of so many items and it is a very exciting project management challenge."*
>
> *Alain Lioure,*
> *Former Head of Enhancements Department*

Enhancing JET's Capabilities

2.9

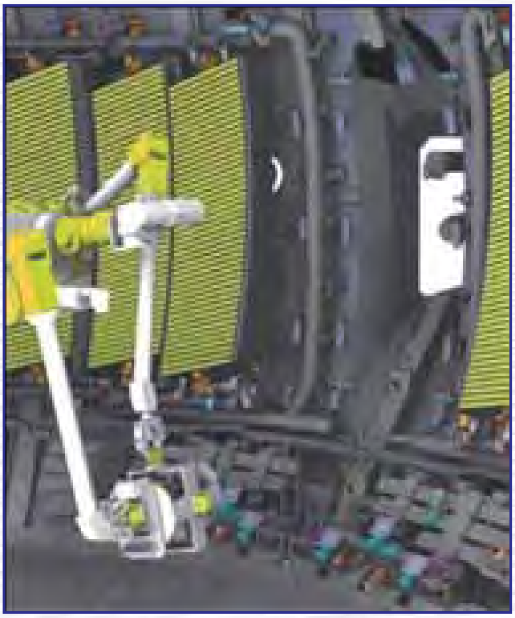


Figure 1: Remote Handling surveys the welded supports (simulation)

Due to its remarkable engineering flexibility, the Joint European Torus (JET) has been providing cutting-edge results in fusion research for two decades. Naturally, there is an outstanding concern: can we maintain this flexibility and yet significantly enhance JET's capabilities?

In every successful research centre, there is always a combination of at least three ingredients:

- a first-class scientific and technical team
- determination to carry out good experiments
- investment in new state-of-the-art equipment

Blending these three efficiently is not simple. In a machine of JET's complexity it is unthinkable to run experiments and install new equipments simultaneously. So experiments and enhancements compete for programme time. To keep JET up to date, shutdown periods cannot be avoided.

In 2004/2005 JET had one of its busiest shutdown periods ever, the main purpose of which was to further extend the plasma performance and diagnostic capabilities of JET so that we can undertake experimental campaigns that are completely focused on ITER-relevant studies.

This shutdown period was particularly challenging for our Remote Handling group, as most of the modifications inside the vessel (including welding) were carried out by the Remote Handling manipulator (robotic arm). In parallel to the in-vessel operations, new instruments were integrated into JET systems and thorough maintenance was undertaken. Additionally, all new components had to be rigorously tested according to the JET quality assessment rules.

A Few Examples of the New Installations

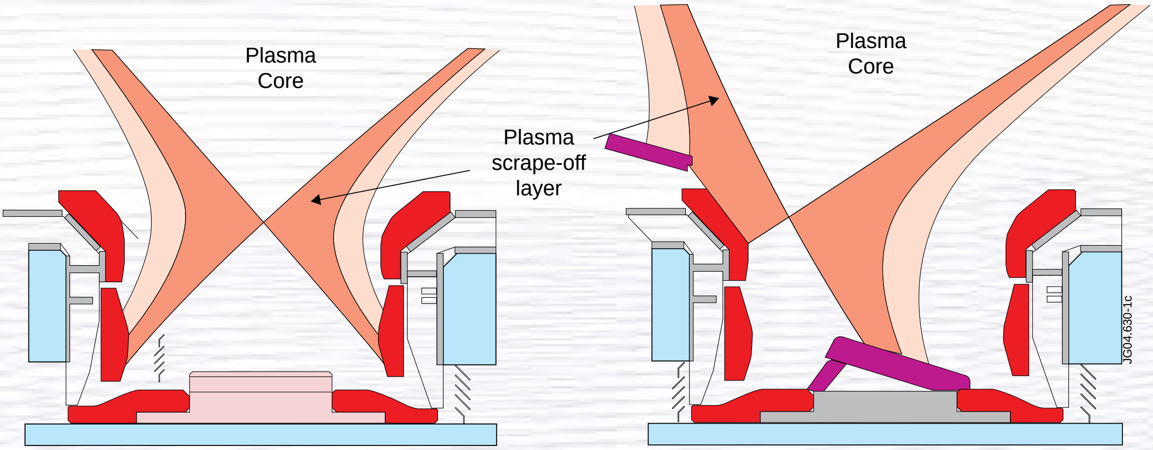


Figure 2: Schematics of the JET divertor - previous state (left) and new configuration (right)

During the shutdown, an upgraded divertor was installed at the bottom of the vacuum vessel, see Figs. 2 and 3. The divertor structure had to be designed with great care as it is exposed to the high power flux carried by the lost particles, see section 2.7.

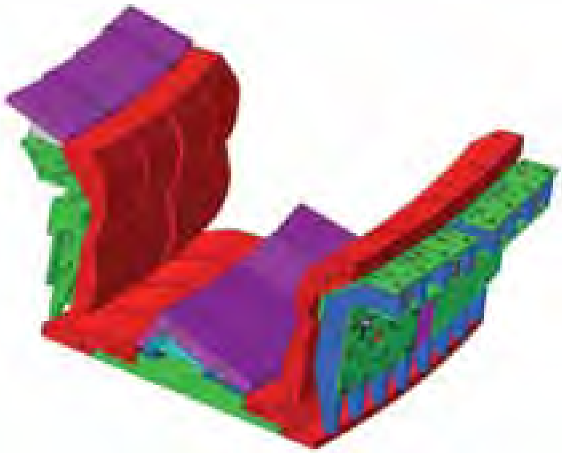


Figure 3: A section of the new divertor configuration in 3D (retained tiles in red, new tiles in violet) (simulation)

The enhancements also aimed to complement the ITER-relevant capabilities of JET in plasma diagnostics, i.e. in developing hi-tech equipment that allow us to reliably observe and precisely measure the processes in experimental plasmas, see section 2.5.

At JET, special attention has always been given to the measurement of neutrons. Neutrons carry vital information on the rate and location of fusion reactions in burning plasmas. With its ability to produce neutrons in both deuterium-deuterium (D-D) and deuterium-tritium (D-T) fusion reactions, JET provides a unique opportunity for development of neutron diagnostics and data analysis methods for future fusion reactors.

To further improve JET's neutron diagnostics, the Magnetic Proton Recoil Spectrometer (MPR) was upgraded and a new Time Of Flight for Optimised Rate (TOFOR) facility was installed during the current shutdown.

Figure 4: Upgraded Magnetic Proton Recoil detector at JET

Magnetic Proton Recoil spectrometer (see Fig.4) measures energies of protons released from a special target in head-on collisions with the tracked neutrons. The kinetic energy of protons is then almost precisely equal to the energy of incident neutrons. Protons have the advantage of being electrically charged, so that their energy can be precisely measured via their deflection in a well-defined magnetic field. Of course, to avoid interference, MPR needs heavy shielding against JET's powerful magnetic fields. Whereas the former MPR was limited to neutrons produced by D-T fusion (deuterium-tritium fusion that produces high energy neutrons), the upgraded version known as MPRu is also able to measure lower energy D-D fusion neutrons. Furthermore it has been rigorously calibrated for accurate absolute measurements of neutron energy and neutron flux.

A new neutron diagnostic known as TOFOR was installed in the JET roof laboratory, see Fig. 5 and Fig. 6. It is now used to measure energy spectra from D-D fusion neutrons only. Unlike MPR, the principle of TOFOR does not rely on rare head-on proton recoils so that the latter has higher count rate capability. In TOFOR, every proton recoil is registered in a small scintillation detector in the bottom of the device. Some of the recoiled neutrons are registered again in the top "umbrella-like" set of detectors. All pulses are seeded by a system of automated data analysis so that only the incidences of both bottom and top counts are followed up. The original energy of each neutron is then derived from the time that elapsed between the first count in the bottom detector and the second count in one of the top detectors.

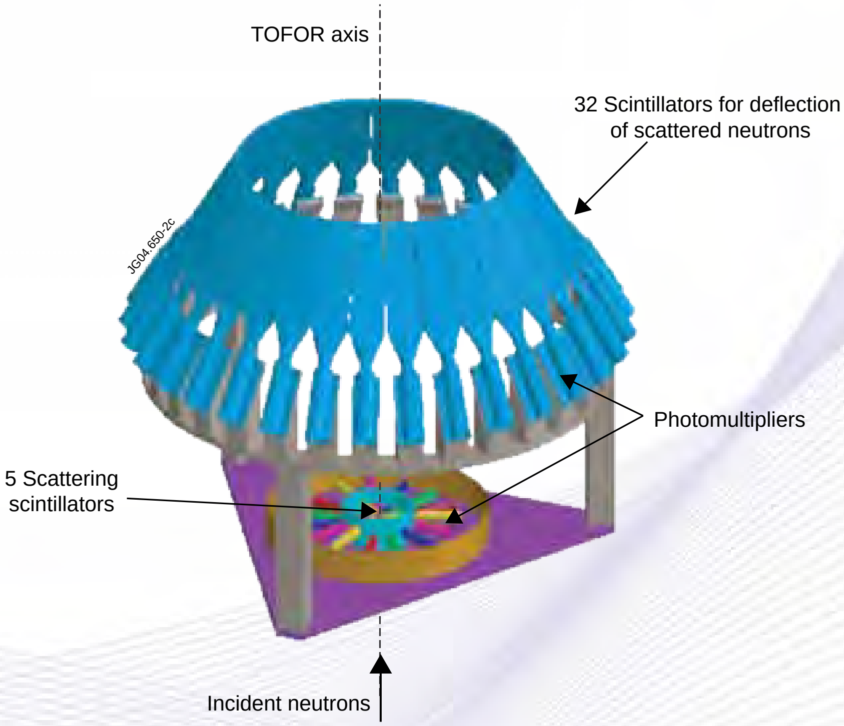


Figure 5: Schematic of TOFOR (simulation)

Figure 6: TOFOR assembly in the JET's roof laboratory (Photo by J Polverini and L Antalova)

For any reader keen on brainteasers here is a quick exercise: using the energy conservation law and simple geometry rules, show that time of flight between the bottom and the top units is not a function of the recoil angle, but purely a function of neutron energy and TOFOR size. Three hints:

- only a narrow beam of neutrons, coming along the TOFOR axis, can arrive at the bottom detector,
- the difference between proton and neutron mass can be ignored,
- and, most importantly, all the detection units are installed on an imaginary sphere.

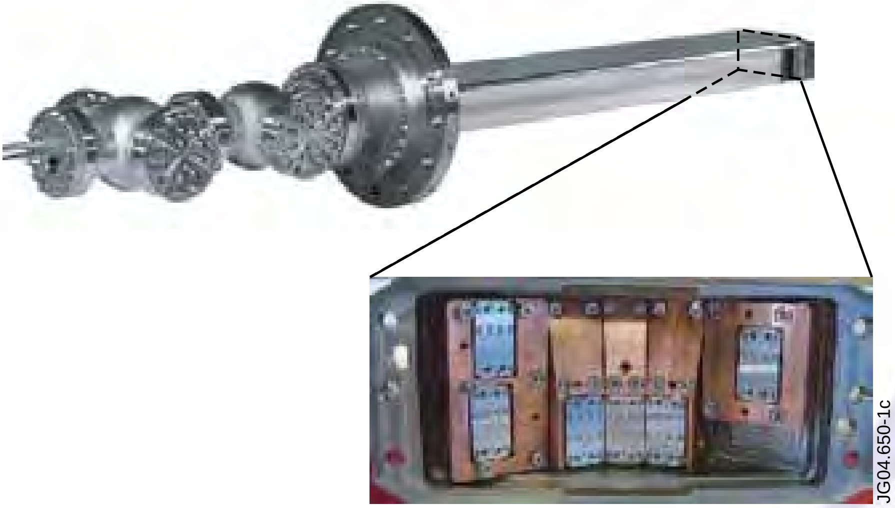


Figure 7: Bolometer camera and its head - six units can be distinguished, each with four separate bolometers

Another vital diagnostic tool for fusion plasmas is bolometry, which provides absolute measurements of total radiation losses of a plasma discharge, regardless the radiation wavelengths. A bolometer is just a tiny piece of metal with precisely defined thermal properties that heats up due to plasma radiation. The radiation comes through a narrow slit (pinhole) that defines a “viewing line” of each bolometer, see Fig 7. Plasma radiation losses along the viewing line are then derived from the increase in the bolometer temperature. With a sufficient number of viewing lines (i.e. with a set of suitably positioned bolometers) it is possible to find out the radiation emissivity pattern on plasma cross-section. The process of calculating cross-section patterns from viewing line projections is commonly known as (computer-aided) tomography or CAT.

During the 2004/2005 shutdown, several new sets of bolometers were installed that nowadays allow for precise mapping of both plasma emissivity and surface radiation. High spatial resolution is required in the divertor region in order to correctly localise large radiation losses caused by particle exhaust. That is why the array of viewing lines is denser in the divertor region (see Fig. 8) and why four other bolometric cameras dedicated purely to divertor observations were also refurbished within the diagnostics enhancements.

Active diagnostic methods are subject to considerable changes too. The LIDAR diagnostics (see section 2.5) was complemented by a new independent High Resolution Thomson Scattering system (HRTS) with better temporal and spatial resolution of steep changes in electron temperature and plasma density. This is significant for detailed characterisation of both edge and internal transport barriers.

Charge Exchange Recombination Spectroscopy (CXRS) was equipped with faster CCD cameras and two new spectrometers, see Fig. 9. This system has been used to study the behaviour of impurities along the plasma radius by analysing the characteristic light emission of impurities after collisions with neutral beams. With the new CCD cameras the system provides five to ten times better temporal resolution of these processes, and thanks to the two additional spectrometers it is possible to observe six different impurity elements simultaneously. Carbon, helium, neon, beryllium, nitrogen, oxygen, argon and/or beam emission can be analysed by CXRS at JET.

In addition, an independent CXRS system designed entirely for diagnostics of the colder edge region of plasma was refurbished. This “edge CXRS” can observe the plasma-beam interaction from the top and bottom.

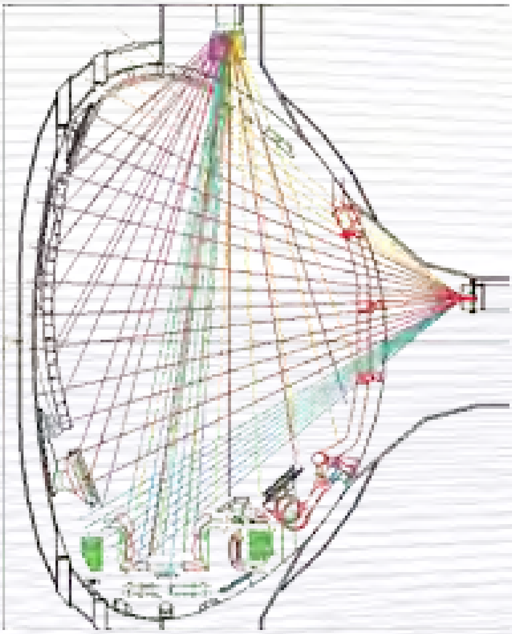


Figure 8: Viewing lines of bolometers after their enhancement

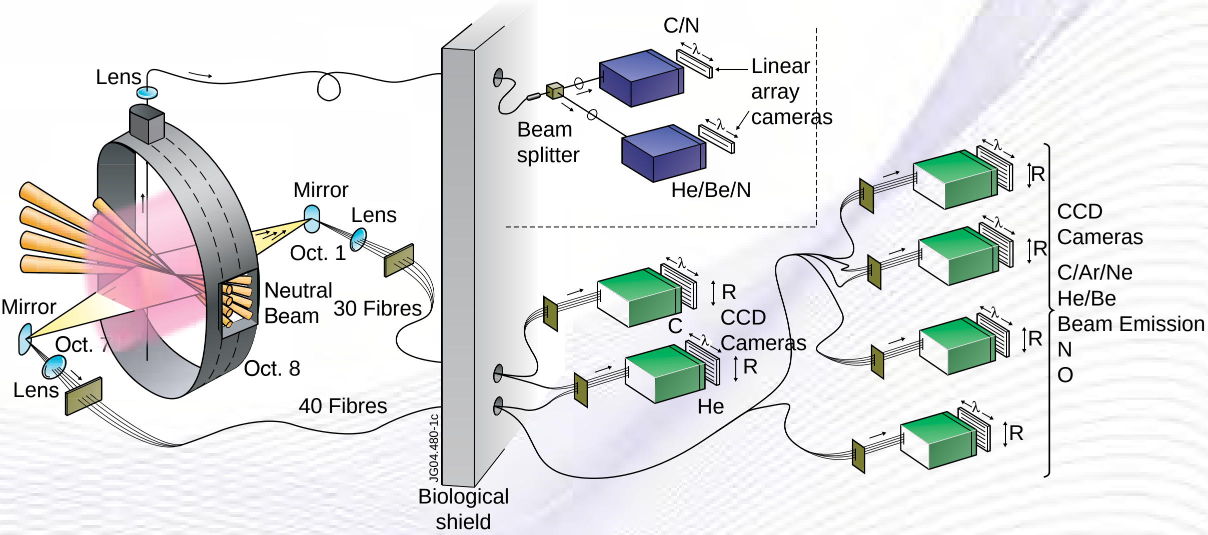


Figure 9: Scheme of the upgraded CXRS

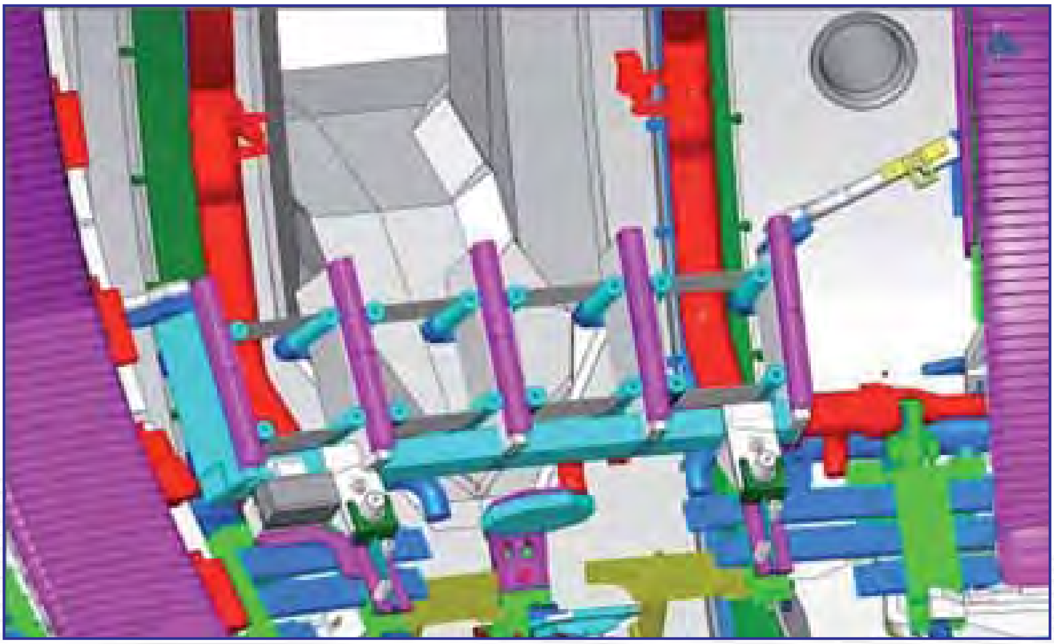
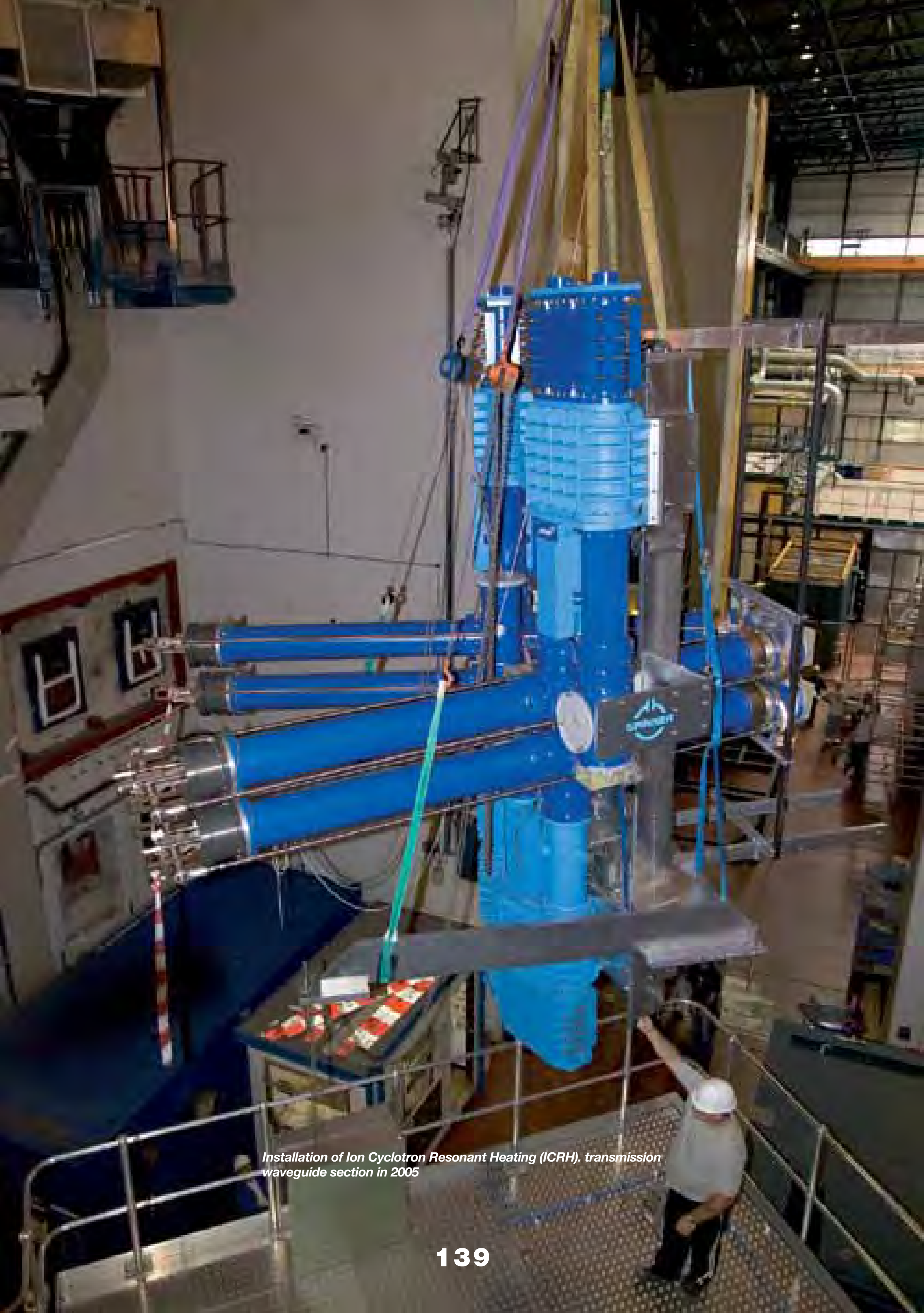


Figure 10: One set of the new TAE antenna structure (simulation)

A new unique diagnostic, known as Toroidal Alvén Eigenmodes (or TAE) antennas, was installed with potential to make a detailed measurements of magnetic field line oscillations, so called Alfvén waves, see Figs. 10 and 11. The diagnostic consists of two sets of four antennas. Some of the TAE antennas (four in maximum) can emit electromagnetic waves to actively modify the Alfvén waves, while the others passively observe the response of TAE. With this diagnostic, JET is well equipped to study and interpret interaction between Alfvén waves and alpha particles (i.e. helium nuclei that are born in fusion reactions). Their interaction is believed - from computer simulations - to play a significant role in confinement of the alpha particles and also in the overall stability of plasmas in future fusion reactors.



Installation of Ion Cyclotron Resonant Heating (ICRH). transmission waveguide section in 2005

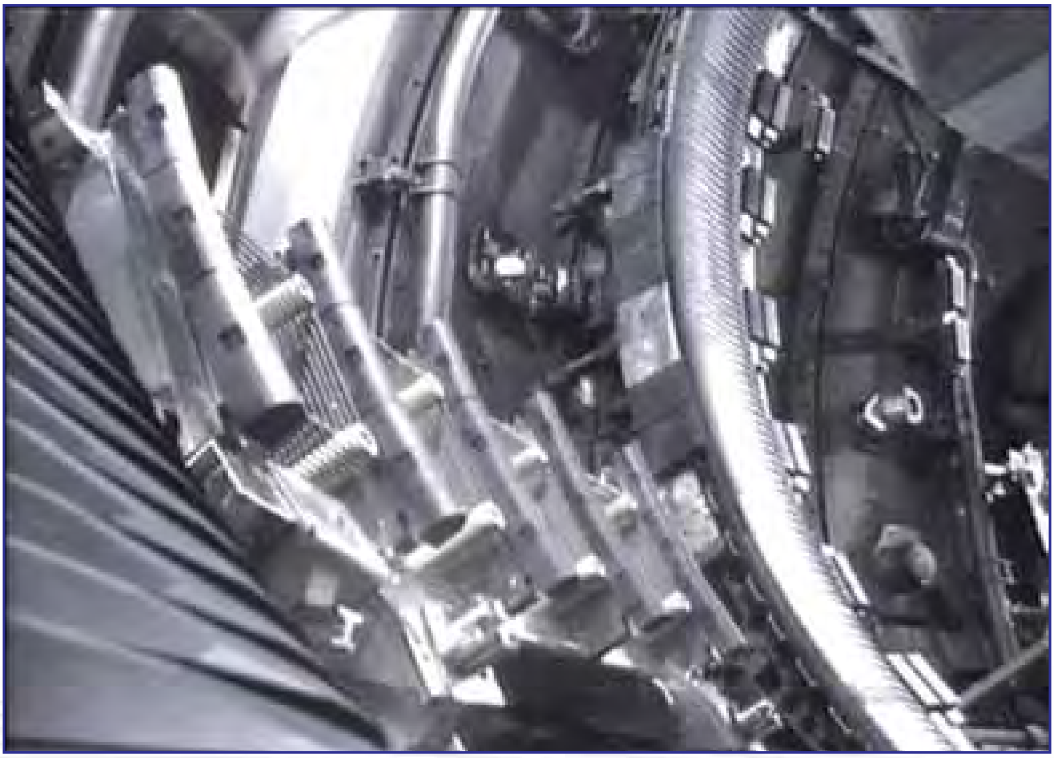


Figure 11: One set of the new TAE antennas installed in the JET vessel

Figure 12: View into the JET vessel by the new wide-angle infrared camera

Two new diagnostics systems are dedicated to the direct measurement of lost fast alpha particles. These particles, produced in fusion reactions, will provide the main heating power for plasmas in future fusion reactors - the power needed to sustain extreme temperatures of plasma. Therefore, studies of transport and confinement of fast alpha particles are of prime importance for our research.

Due to its size and capabilities, JET can confine fast alpha particles produced in two ways: either in actual D-T fusion, or by injection of helium beams into the plasma and consecutive acceleration of helium ions by suitable radio frequency power. The new diagnostics - Faraday cups and scintillation detectors - are capable of monitoring those alpha particles that are lost, measuring their fluxes, crude spatial distributions and velocity components; the former diagnostic tool in total (integral, average) particle fluxes, the latter by sampling individual particles.

Plasma-wall interaction is another important topic for our ITER focused research. At JET, several diagnostics were upgraded or newly provided in order to better understand and quantify the heat distribution on walls as well as erosion and deposition of wall materials. A new state-of-the-art wide-angle infrared camera was installed to overview the heat load on plasma-facing components and to estimate their temperature during experiments, see Fig. 12. Five new Quartz Micro-Balances (see section 2.5) and five Rotating Collectors were installed in the divertor region to register material deposition. Special coated or profiled "smart tiles" provide another precise tool to identify regions of erosion and deposition.

Figure 13: Maintenance work during 2004/2005 shutdown

In total, the recent JET enhancements included several tens of new or upgraded installations. Most of them are highly specialised one-off products. The actual extent of the works, challenges and physical principles involved cannot be covered in a single article. This is just an illustration of a busy shutdown period, with equipment being installed that is full of promise for increased performance in the subsequent JET campaigns.

"JET is the only tokamak in the world capable of operating in a tritium environment with ITER-relevant plasma facing components. This unique capability allows the assessment of several open ITER issues. The work is very challenging, attracting European physicists, engineers and technicians from many disciplines who are now collaboratively developing technologies for the future."

Christian Grisolia,
Leader of Fusion Technology Task Force

JET and Fusion Technology

2.10

Introduction

The basic task of magnetic fusion research - i.e. creating and confining sufficiently hot and dense plasmas for a reasonably long time - was to a large degree resolved in the 20th century. In particular, the "scientific feasibility of fusion" was demonstrated at JET and TFTR tokamaks in their experiments with deuterium and tritium fusion fuels, see section 3.11. In the early 21st century, the next step tokamak ITER and the accompanying research projects have to prove technological feasibility of fusion as a potential energy source.

With this mission objective, fusion research is literally entering a new era in which the key role will be played by technology research for future fusion reactors. Materials need to be selected, capable of withstanding extreme thermal and mechanical stresses in intense neutron radiation fields. Moreover, it is desirable that materials used in fusion reactors should have as low as possible activation from irradiation by fusion neutrons, and that any such induced activity decays in a reasonable time scale. Tritium breeding from lithium and the full fuel cycle have to be demonstrated and optimised. Plasma heating sources as well as superconductive coils need further development.

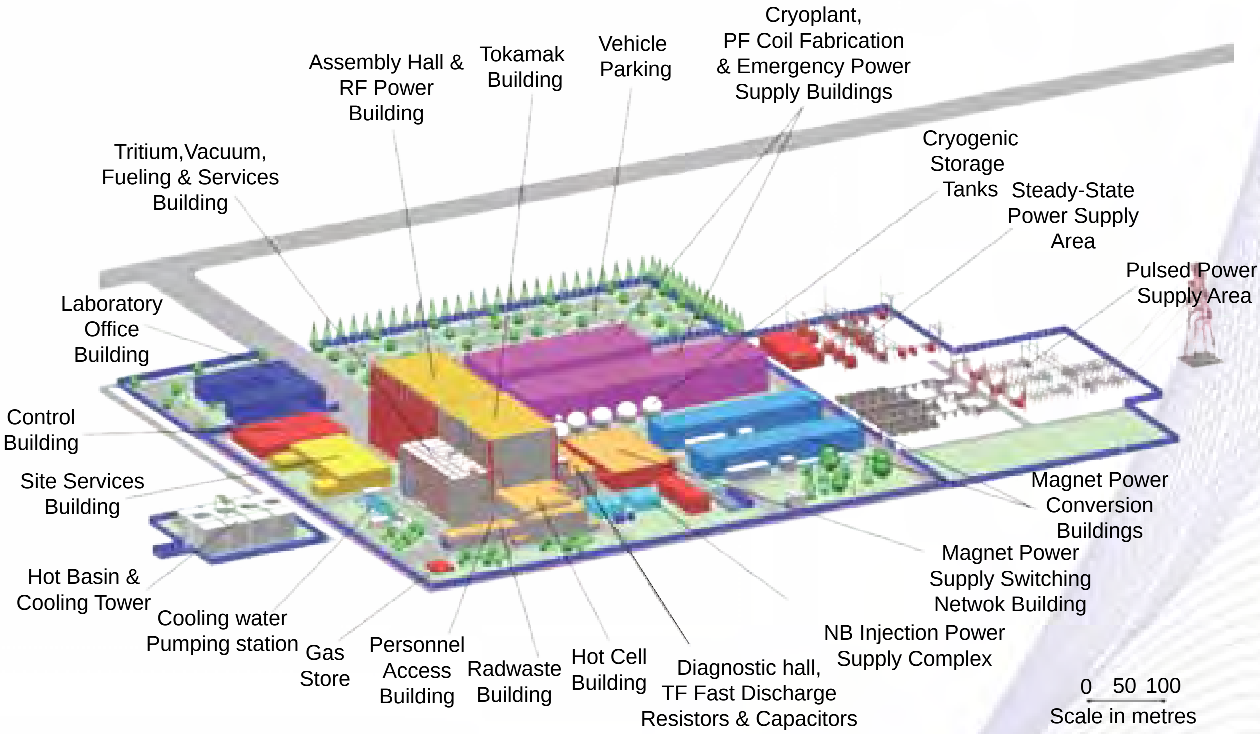


Figure 1: Generic view of the future ITER site (courtesy of ITER)

Undoubtedly fusion technology research will be no less complicated than the previous research into magnetic confinement. However the fact that technology research is now required gives a clear indication of the progress achieved in fusion and on the actual scale of available fusion power. With the unique role that JET has been playing in this progress it is an ideal place to pursue some of the necessary technology tasks. One important aspect of fusion technology that JET contributes to is in the realm of Remote Handling, see e.g. section 2.9. Other examples follow below.

Increased use of the JET facilities for Fusion Technology Research and Development in preparation for ITER was one of the key objectives assigned to the European Fusion Development Agreement (EFDA) in 1999. For this purpose, a dedicated Task Force on Fusion Technology was set up at JET in 2000, which has a close working relationship with the broader EFDA Technology Programme. Over the last five years, this Task Force has launched a large variety of activities involving several European laboratories. By presenting a few detailed examples of the topics under research at JET we hope to demonstrate that in hi-tech experiments, progress is achieved by careful, patient work rather than in big strides. At the cutting edge of the current technology, where new materials are tested under extraordinary conditions, improved performance has to be acquired gradually.

Plasma-facing Components and Tritium

Introduction

JET provides invaluable expertise for the whole fusion community due to its unique capability to operate with tritium, the heavy radioactive hydrogen isotope. To find how and where tritium can be trapped inside JET and to determine the characteristics of erosion and deposition of the plasma facing components, investigations are carried out based on the analysis of tiles or flakes removed during shutdowns or on direct deposition monitoring (using e.g. quartz microbalances or rotating collectors). The results of these activities are also used in the modelling of the impurity transport inside the JET torus.

In many current tokamaks - including JET - Carbon Fibre Composite (CFC) tiles act as the plasma facing material. The fusion fuel, i.e. hydrogen isotopes, are co-deposited together with carbon, beryllium and other elements present in-vessel on these tiles. The co-deposits can fragment off to form flakes, which in JET fall into sub-divertor zones close to the water cooled louvres adjacent to the inner divertor (left end of tile 4 in Figure 2). Flakes are collected via a remotely operated cyclone vacuum cleaner and analysed. They have an average diameter of 0.4 mm and are saturated with hydrogen isotopes. Optical spectroscopy reveals a layer structure coming from a sequential deposition process.

Atists impression to show the *fusion power plant*

Investigations of Plasma Exposed Surfaces

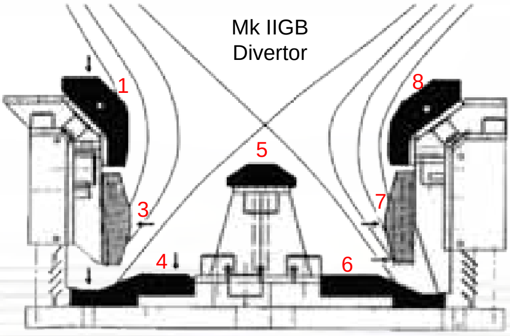


Figure 2: Cross-section of the JET divertor tile set used in 1997-2001

Plasma exposed surfaces are investigated to provide data for understanding and modelling the impurity transport in the plasma edge region (see section 2.7), and the material erosion and deposition processes inside the vessel.

The interaction of plasma with the CFC plasma facing tiles is the major source of free carbon in the plasma, while Beryllium Evaporators, used periodically mainly to reduce the amount of oxygen impurities in the plasma and improve plasma conditions, represent the primary source of beryllium in JET. Carbon and beryllium are transported towards the upper tiles of the inner divertor (tiles 1 and 3 in Fig. 2) where beryllium is stacked and carbon, after deposition, is re-eroded through chemical sputtering and transported towards the inner flat tiles (tile 4).

The divertor tiles exposed in JET in the 1998-2001 campaigns have been used to assess the amount of beryllium and carbon deposited at the plasma facing materials. Secondary Ion Mass Spectroscopy (SIMS) depth profiling has been made from a number of samples on inner divertor tiles 1, 3 and 4.

The deposit forms two layers on tiles 1 and 3. The outer layers (~2-6 µm thick on tile 1 and 10-16 µm on tile 3) contain mostly carbon together with deuterium and a smaller amount of beryllium. The films underneath the surface layer are very rich in beryllium (~2-14 µm on tile 1 & 12-21 µm on tile 3). The measurements allowed the estimation of the amount of beryllium on the tiles 1 and 3 and thus the calculation of the total amount of beryllium deposited at the inner divertor: 22 ± 9 g. Unlike tiles 1 and 3, very little beryllium was found in the ~85 µm thick film on tile 4 in the shadowed region, where almost only carbon, with very high deuterium content, and a well-marked interface to the carbon fibre composite substrate has been observed. Similar investigations have been carried out for the tiles of the outer divertor (6, 7 and 8) and, in general, the deposition patterns of fuel atoms, beryllium and carbon showed much less heavy deposition and fuel accumulation in the outer divertor than in the inner. This was not expected from classical modelling of erosion/deposition. The asymmetry in the JET deposition pattern could be explained by increased carbon erosion by the plasma in the main chamber and sputtering at the inner divertor surfaces.

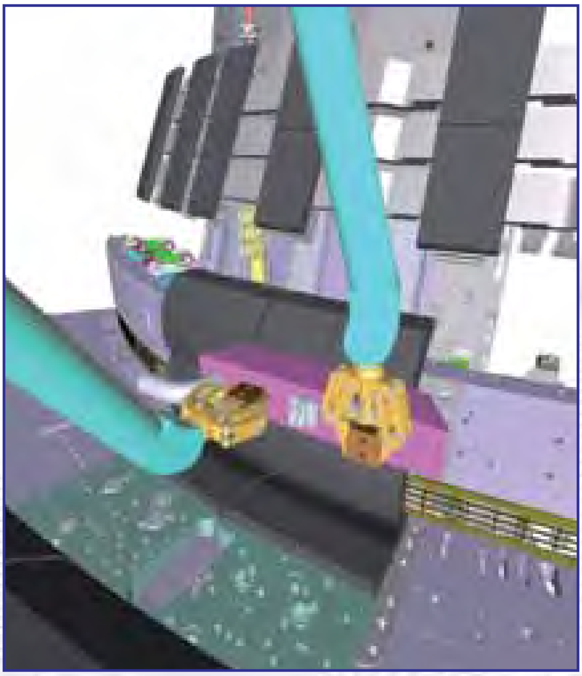


Figure 3: Computer simulation of the flash lamp cleaning inside JET

Cleaning of Plasma-Facing Components

To avoid excessive tritium retention during future ITER operation, in situ detritiation to be performed during operation-free periods would be useful. Detritiation processes based on lasers or flash lamps are being investigated at JET. After very promising results obtained on simulated layers in the laboratory, showing a possible cleaning rate of more than 3 m^2 per hour for a 50µm thick deposit, a flash lamp mounted on the JET Remote Handling arm has been used for in vessel tests, see figures 3 and 4. The technical feasibility of this technique in a tokamak environment has been demonstrated, and its efficiency is being assessed by Ion Beam Analysis, calorimetry and full combustion.

Laser cleaning of the plasma facing components via layer ablation is also very promising. Ablation (erosion) of 50 µm of deposited layer on CFC (Carbon Fibre Composite) was obtained in laboratory studies using a high frequency laser (output power 20 W, 2 J/cm^2, wavelength 1052 nm). A surface of 10x10 mm was automatically ablated at 0.2 m^2/hour, without damaging the graphite substrate. Extrapolation of these results predicts that a 100W laser would have a removal efficiency of 1m^2/h for a 50 µm co-deposited layer in air. Work is ongoing to develop and test a laser facility suitable for JET’s Remote Handling.

Figure 4: Flash lamp detritiation tests at JET.

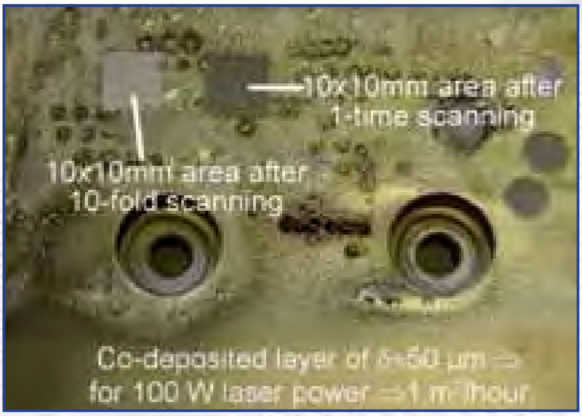


Figure 5: Laser ablation tests have been performed on a CFC plasma-facing component from the TEXTOR tokamak (Jülich, Germany). Both 1-time and 10-fold scanning fully removed the deposited layers without damaging the graphite substrate.

Management of Tritiated Materials

In fusion devices operating with tritium, different tritiated materials are produced. Two main strategies can be adopted for tritiated waste management: waiting for natural decay of the radio-nuclides or applying some detritiation process. The second strategy is being investigated by the Fusion Technology Task Force. Dedicated procedures for decreasing the tritium content inside the materials removed from the torus are being developed for stainless steel, carbon-based materials (graphite and carbon fibre composite), organic liquids (pump oils, liquid scintillation cocktails) and water, together with process and housekeeping wastes. In all these projects, the right balance between the production of secondary waste and the reduction of waste classification (according to the safety guides of IAEA - the International Atomic Energy Agency), has to be reached.

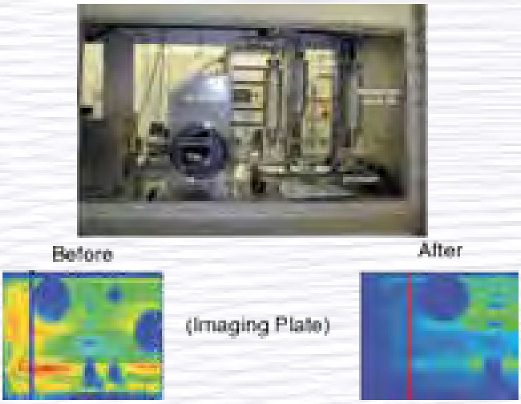


Figure 6: Autoradiography of the Carbon Fibre Composite (CFC) plates before and after detritiation by Radio Frequency heating

Oxidation has been used to transfer the tritium atoms from organic oil molecules to more stable and more easily treatable inorganic molecules. Thermal desorption in the range from 20 to 1100°C under a stream of helium containing 0.1% hydrogen has been used for carbon samples obtained from tritiated JET tiles.

Heating of full CFC divertor tiles via radio frequency has been performed. The amount of tritium before and after the procedure is being measured by calorimetry and full combustion. Autoradiography (a method of detecting and measuring the deposition, distribution and quantity of a radioisotope present on any material by registering its radiation on a photographic plate placed directly on the material) showed that after several heating cycles at the average temperature of only 490 °C, more than 99% of the tritium can be efficiently removed from a the surface of a tile, see Fig. 6. Full combustion measurements showed that 95% of tritium from the bulk was released.

Desorption tests have been also performed in a furnace under a stream of argon gas containing 5% of hydrogen. These experiments showed that the optimal detritiation temperatures are between 300 and 800°C and decontamination factors (i.e. initial activity / final activity) between 20 and 90 can be obtained.

For stainless steel the studies have been performed with the oxidation method on samples from the Belgian SCK-CEN laboratories and a French fast breeder fission reactor. Large samples (250 to 700 g) were used in order to determine the impact of the treatments on tritium trapped both at the surface and in the bulk. Using smear tests to evaluate the residual surface tritium contamination, a decontamination factor of about 210 was obtained. However, further developments with measurements of tritium content in the bulk material are needed to fully determine the efficiency of the process.

Other samples were treated in a furnace up to 1100°C in air, or in argon with 5% hydrogen. Heating the samples for 3 hours at 400°C led to a decontamination factor of about 5 in air and 8 in argon with hydrogen. The factor increased respectively to about 130 and 110 when heating at 1000°C for half an hour.

The system for water detritiation is based on tritium enrichment in a Liquid Phase Catalytic Exchange column of the contaminated water from the processing of the operational gases in JET’s Active Gas Handling Facility (Fig. 7), as introduced in section 2.3. This water is then dissociated in oxygen (discharged in the atmosphere) and a mixture of hydrogen isotopes in an electrolyser. Hydrogen (or protium, H), deuterium (D) and tritium (T) are then separated by Cryo-Distillation (method based on the different volatility that decreases from H2, through HD, HT, D2, DT to the molecule T2) and Gas Chromatography. The design of a fully integrated plant as well as the testing of all its key components has been carried out as part of research and development in preparation of the ITER plant and could be directly applied at JET.

Any active and/or toxic waste is either stocked on site, or safely disposed of. Even though the UK law is very strict concerning any such waste, JET imposes its own more demanding internal targets on safety. Both technical and scientific staff are well aware of our responsibility to keep the environmental impact of our research as low as possible.

Figure 7: Active Gas Handling Facility at JET

Vacuum Pumping and Gas Handling

Figure 8: New pumping cryopanels: schematic drawing with cryosorption panel before coating with activated charcoal and after coating.

Figure 9: Module of the Cryogenic Forevacuum System (JET Active Gas Handling System)

The design of the ITER high vacuum system is based on a number of supercritical helium cooled cryosorption pumps providing a high pumping speed and capacity, see section 2.3, as well as fast on-line regeneration. To pump helium, which cannot be condensed, and to help to pump hydrogen, the pumping cryopanels are coated with activated charcoal granules. Activated charcoal is a highly porous carbon with millions of tiny pores between the atoms, creating surface areas of several hundreds of square meters per every gram of charcoal, so that it has a unique adsorption capacity. After preliminary tests at FZK, Germany, a large scale test arrangement was built at JET in the Active Gas Handling System to assess in detail the carbon-tritium interaction and to derive performance parameters essential for the design of the ITER cryosorption pumps. This new pumping cryopanel, see Figs. 8-10, was first operated under the JET Trace Tritium Campaign in 2003, pumping gas from the JET torus and neutral beam injectors. It was observed that the pumping cryopanel worked according to the design specifications.

The JET vacuum pumps, including this new cryopanel system, pump all gases from the torus and other systems (e.g. Neutral Beam Injectors) into the Active Gas Handling System, where the different hydrogen species (H, D and T) are sorted out using isotope separation techniques, and deuterium and tritium are stored for future JET fuelling.

A new purification system called PERMCAT is also being installed in the Active Gas Handling System to remove impurity gases such as helium He, carbon dioxide CO_2, water H_2O, or methane CH_4 from the collected gases, see Fig. 11. Figure 12 shows a schematic of the system: Pumped gas flows into the PERMCAT where tritium is exchanged with protium (i.e. the common light hydrogen isotope H) through a palladium/silver membrane.

Figure 10: New pumping cryopanels installed

Figure 11: PERMCAT system developed at FZK, Germany

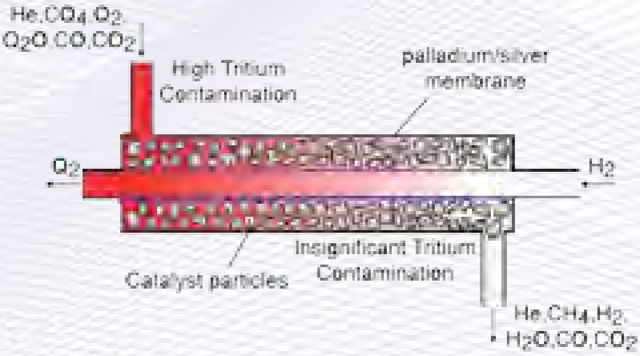


Figure 12: Schematic of the PERMCAT system (where Q represents all hydrogen isotopes, i.e. protium H, deuterium D and tritium T)

Diagnostics Studies - Optical Fibres

Optical fibres offer an attractive practical solution to transport light through the complicated geometry surrounding the fusion reactor. However they can suffer from serious radiation-induced optical absorption and radioluminescence. Special fabrication and glass hardening techniques must be used to deploy suitable radiation-resistant fibre in a tokamak machine like ITER that produces neutron and gamma radiation during plasma operations.

As JET is the closest machine to ITER, including radiation flux due to fusion reactions, studies have been undertaken to demonstrate the feasibility of using optical fibres in diagnostics systems during reactor operation, and in particular the possibility of using large diameter fibres, i.e. with a core diameter of 0.6 mm, acrylate coating and suitable hydrogen treatment to enhance radiation tolerance.

Special hardware was installed in the JET Torus Hall in order to test this fibre during Trace Tritium Experiments in 2003. As a result, a small but detectable loss in optical transmission due to radiation during plasma discharge was observed. The optical loss was measured to be 6% at maximum. When the radiation decreases the fibre recovers its transmission capabilities totally, suggesting that no permanent damage has taken place. The reserve of hydrogen implanted during the pre-treatment is probably sufficiently high to repair the damage.

Direct measurements carried out in luminescence mode revealed the presence of radioluminescence during the plasma pulse. Consequently, an increase of the optical transmission following the shape of the pulse is observed throughout the pulse. However, no correlation was found between the radiation conditions and the luminescence intensity. This probably results from the non-uniformity of the irradiation conditions.

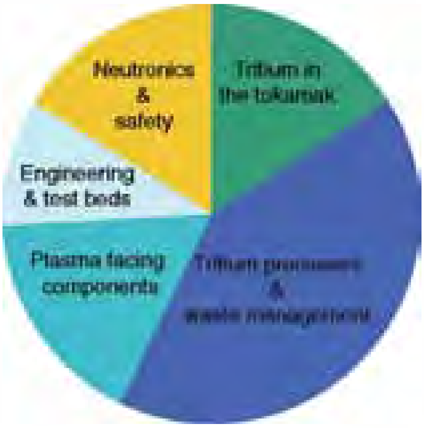


Figure 13: Overview of topics investigated in the JET Fusion Technology Task Force

Fusion Technology research and development at JET comprises five main topics, with substantial emphasis on tritium-related tasks (see pie chart, Fig.13). In addition to the investigations discussed above, parts of the JET Facilities are also used as test beds for studying prototypes for ITER, such as bypass switches for power supplies, or carbon-based tiles under high ion loads. Moreover, after more than 20 years of operation and experience with the use of tritium, beryllium and remote handling for maintenance, JET provides a unique source of information which helps ITER's design and licensing. Data is collected on component failure rates in various sub-systems (vacuum system, heating systems, power supply, active gas handling system) and on occupational radiation exposure (depending on worker categories and operation conditions). Despite the fact that the ITER design calls for a machine that is significantly larger than JET and different operational procedures are expected, the raw data and the analysis results obtained from its study are relevant and offer significant insights.

> *"As the largest European fusion experiment, JET has played a key role in establishing the scientific and technical basis for ITER. Current and future JET programmes will be strongly focused on the preparation of ITER operation."*

Dr Jérôme Paméla,
EFDA Leader

JET's Programme in support of ITER

2.11

The decision to site ITER in France, next to the research centre at CEA Cadarache, was made on 28th June, 2005. This international project is the major experimental step between today's fusion research and tomorrow's electricity-producing fusion power plants. In the forthcoming years, ITER will be built by seven partners: European Union, India, Japan, Korea, People's Republic of China, Russian Federation and United States of America. Siting ITER in the European Union is very good news and an honour for the European fusion community. Europe, with its broad fusion programme which includes the largest fusion experiment to date - the Joint European Torus (JET) - is well-prepared for this commitment. Furthermore, France is a key participant in this programme, with the operation of the largest superconducting tokamak (Tore Supra), and with many experts from the Association Euratom-CEA, playing an influential role in JET and in fusion technology research. For historical notes on European collaboration and ITER see sections 3.8 and 3.10, respectively.

In this section we illustrate the capabilities of JET in the preparations for ITER's operation. In particular, three new projects are presented below that will further enhance the potential of JET's ITER-supporting role.

Figure 1: Fusion research centres in Europe (parties to EFDA), showing the JET and ITER sites.

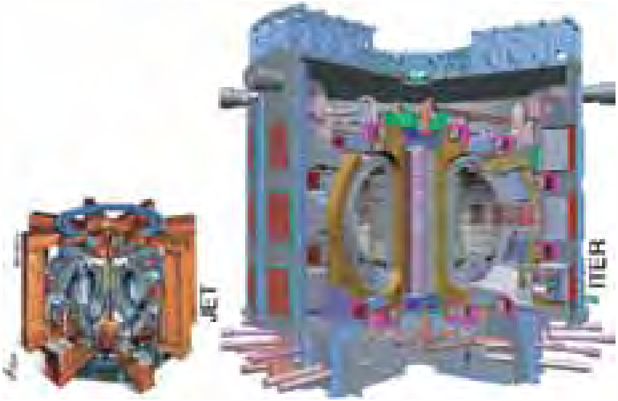


Figure 2: JET versus ITER

ITER is an acronym for the International Thermonuclear Experimental Reactor and means “the way” in Latin, hinting that it will lead on to future fusion power plants. The heart of ITER is a superconducting tokamak facility with striking design similarities to JET, but twice the linear dimensions (see figure above). Indeed, the ITER design is largely based on JET’s successful performance. ITER “just” needs to be twice as big in order to make plasma particles stay in the hot plasma four times longer, and needs to be superconductive to permit long plasma pulses (up to 30 minutes) with much lower energy consumption.

JET holds the current world record of released fusion power at 16 MW (16 million watts), a value comparable to the power needed for heating one thousand households in a cold winter. However, JET cannot produce more power than it consumes, and can produce fusion power for only a few seconds. ITER should produce about 500 MW of fusion power in the form of heat, five to ten times more than will be needed to power its plasmas, and will therefore require advanced material technology and plasma control in order to handle large fusion power fluxes.

The capabilities of JET can advance experience and understanding in many areas essential to ITER:

- due to its unique tritium handling capability, JET can actually study plasmas with a high rate of Deuterium-Tritium (D-T) fusion reactions (commonly known as “burning plasmas”)

- due to the size of JET, it is the best suited facility to study the confinement of the fusion products, the fast alpha particles (helium nuclei). The fast alpha particles have to be sufficiently confined in order to transfer their kinetic energy to other plasma particles (and thus maintain extreme plasma temperatures), but if they’re too confined, they hamper the fusion process by dissolving the D-T fuel and increasing plasma radiation losses. At JET, we can produce fast alphas either in D-T fusion, or by the acceleration in plasmas on special radiofrequency waves.

- JET provides key contributions to the material studies and plasma-wall interaction studies due to JET’s unique beryllium handling capability (beryllium being the design choice for the ITER first wall, i.e. the plasma facing material).

- JET extends experience of in-vessel remote handling techniques, based on its comprehensive Remote Handling facility.

Figure 3: JET during construction (1982)

Figure 4: Control Room of the JET Remote Handling .

Ongoing experimental studies on JET provide detailed groundwork for ITER operations. These include further optimisation of the “basic” operating scenario and development of “advanced” scenarios with a potential for increased fusion performance and steady state operation. An important part of this work is devoted to the development of extensive real-time control (section 2.6) and powerful heating systems (section 2.4), and to the development of new plasma diagnostics and heating schemes. JET plays a dominant role in the international tokamak database that is used for extrapolations to ITER, with data closest to the ITER working point. In addition, the JET experimental programme allows continuous benchmarking in order to develop an integrated set of modelling tools for the preparation and analysis of ITER experiments, see section 2.8.

In 2004/2005 JET underwent numerous enhancements; notably a new JET divertor configuration has been set up, able to accommodate plasmas of an ITER-like shape at high currents (3.5-4 MA), and new neutron and alpha diagnostics tools as well as numerous devices for studies of plasma-wall interactions have been installed (see section 2.9). A new high-power ITER-like Ion Cyclotron Resonant Heating antenna is to be installed in 2007 (section 2.4).

As a part of the “JET programme in support of ITER” proposed for 2005-2010, three major projects for upgrading JET were recently approved and launched. They are the “ITER-like wall”, the “Neutral Beam Enhancement” and the “High Frequency Pellet Injector”. Design work has started and calls for tenders are being made, with installation foreseen in 2009.

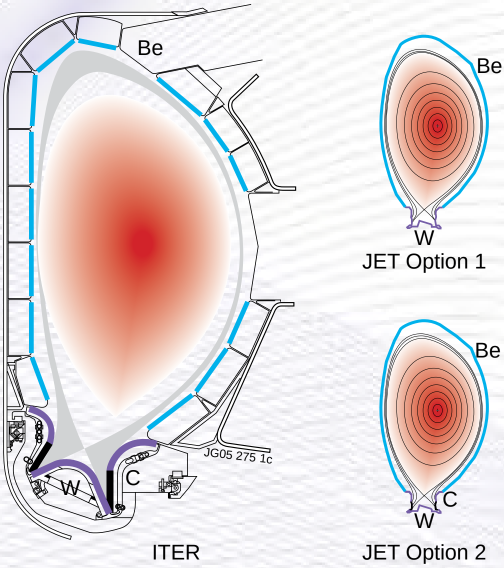


Figure 5 : ITER wall and two options of the JET’s ITER-like Wall Project (in scale)

ITER - like Wall Project

One of the main challenges for fusion reactors is the compatibility between a reactor-grade plasma and the materials facing the plasma (the "First Wall"). Most current tokamaks (including JET) use carbon composite (CFC) tiles for the First Wall, as does the Space Shuttle, which use it on the wings to withstand extreme heat fluxes. However, from JET's D-T experiments it is obvious that carbon composites are not suitable for the tritium operation due to tritium deposition in walls. Therefore the ITER design comprises a beryllium-clad First Wall in the main chamber, while use of carbon tiles is limited to the region where the edge plasma is deflected on to the wall ("divertor strike points", see section 2.7) and tungsten tiles are to be used elsewhere on the divertor (see areas marked Be, C and W in Fig. 5). Tungsten is very resistant to high temperatures (melting only at 3422 degrees Celsius) but it is a heavy element (proton number 74) that can pollute plasmas considerably: it gets highly ionised in extreme plasma temperatures which causes immense energy losses due to plasma radiation, and dilutes the D-T fuel. Beryllium is a light element with a proton number just 4. However it melts at just 1287 degree Celsius. The combination of beryllium and tungsten has never been tested in a tokamak, let alone in one with ITER-relevant geometry and plasma parameters like JET.

Figure 6: Two prototype beryllium tiles for the ITER-like wall project. Tile surfaces are segmented to relieve the stresses caused by thermal expansion and to reduce electromagnetic forces.

Figure 7: Part of the JET Neutral Beam assembly during a major maintenance period in 2001

During the one year installation period in 2009, extensive use of Remote Handling technology will be made in implementing the beryllium first wall and tungsten divertor. Following installation, the JET experimental programme will focus on optimising operating scenarios compatible with the ITER-like wall. The level of retained tritium and its dependence on plasma parameters will be determined. Plasma performance will be tested to show that the level of tungsten reaching the core is acceptably low. The lifetime of the wall will be studied with ITER-relevant power loading provided by increased heating due to Neutral Beam Enhancement Project. Also notice the synergy in the pan-European fusion research: while ASDEX Upgrade tokamak (Association Euratom-IPP Garching, Germany) is exploring the viability of an all-Tungsten first wall (tungsten is considered the long-term front runner as a material for fusion reactors), JET will be looking at more immediate ITER needs.

Neutral Beam Enhancement Project

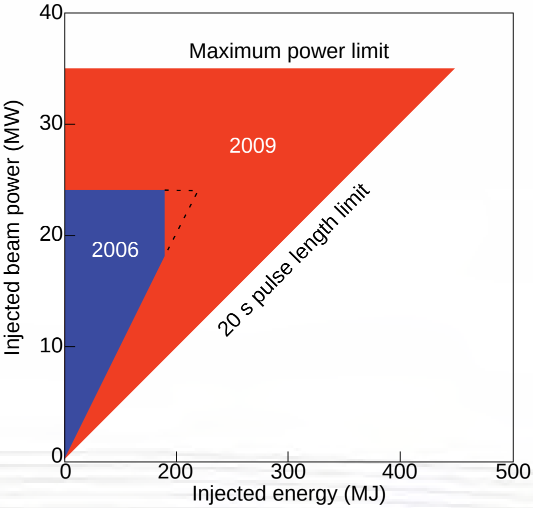


Figure 8: Expected power and pulse length of the JET's Neutral Beam Heating system after enhancement (in red) compared to its present performance (in blue).

Figure 9: Neutral Beam accelerator grid undergoing alignment checks

The performance of the Neutral Beam Heating system, that has been described in section 2.4, will be further extended. The Neutral Beam Enhancement Project will allow the power of neutral beams at JET to be increased up to 35 MW (from the current 25 MW) for up to 20 second pulses, or half this power for up to 40 seconds. Exciting advances in ITER scenarios will result from this enhancement: with the higher power, JET plasmas will be taken to higher pressures, where plasma control techniques will be studied in ITER-like conditions. Methods will be developed for mitigation against occurrences of large edge instabilities (the Edge Localised Modes, see section 2.7) and disruptions (i.e. sudden plasma terminations) - both of which could be potentially harmful to the new beryllium wall by causing it to melt locally. The long pulse (40 seconds) capability of the upgraded neutral beam system will be crucial to progress the Advanced Scenario, in which an additional current has to be driven in the plasma core.

The main increase in neutral beam power will come from converting the ion sources which generate the positive deuterium ions that are accelerated to form the neutral beams. With the conversion, the ion sources will produce larger fractions of molecular ions (D_2+ and D_3+) leading to an increase of neutral beam power due to better neutralisation efficiency for the molecular ions. In addition, all the 16 ion sources at JET (grouped as two beam columns of eight sources) will be modified to allow the maximum beam current to be raised from the present 60 Amperes to 65 Amperes. Furthermore, the accelerating voltage on eight sources will be increased from the current 80 kV (80 thousand Volts) to 125 kV. This voltage increase will only be made possible by the new power supplies, which will also improve the reliability of the Neutral Beam system. The Neutral Beam Enhancement Project is planned to be completed and brought into full operation in 2009.

High Frequency Pellet Injector Project

Another key component of the JET enhancement in support of ITER is a new High Frequency Pellet Injector, which will be capable of shooting into JET plasmas 50-60 deuterium ice pellets per second. This project has two main experimental objectives: deep plasma fuelling (i.e. getting more deuterium into the hot plasma core) and, more importantly, mitigation of the edge instabilities called ELMs (Edge Localised Modes, as mentioned above). It has been demonstrated in the ASDEX Upgrade tokamak in Garching, Germany, that the ELM frequency can be controlled by the pellet injection frequency, leading to a significant reduction of the energy ejected during each ELM.

The new injector will be designed on the basis of the injector recently integrated on Tore Supra at CEA Cadarache, France. It will be installed at JET close to the existing centrifuge pellet injector, which will be kept in place to allow maximum flexibility. In particular, simultaneous plasma fuelling by the centrifuge and ELM control by the new injector will be possible. For the ELM control, the new injector will produce small pellets at high frequency (pellet volume 1-2 mm^3, up to 60 pellets per second, with pellet velocity 50-200 metres per second), while for the deep plasma fuelling it will be able to produce large pellets at lower frequency (pellet volume 35-70 mm^3, up to 15 pellets per second, with pellet velocity 100-500 meters per second). The new High Frequency Pellet Injector will be capable of uninterrupted operation during the whole JET pulse.

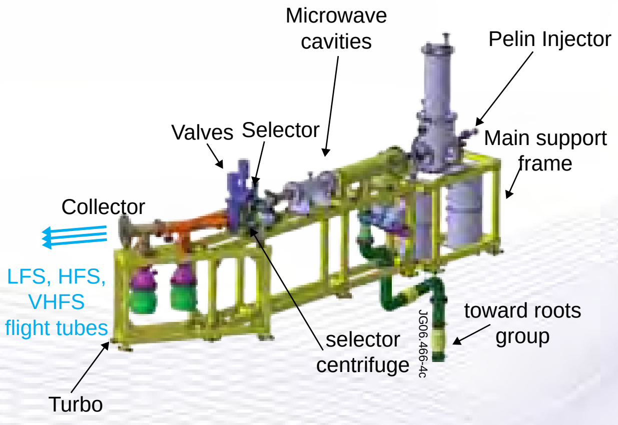


Figure 10: Design of the new pellet injector for JET.

Figure 11: Pellet Injector at Tore Supra

Diagnostics and Plasma Control

To arrive at the most effective scientific programme in support of ITER, the three large enhancement projects approved for JET will be accompanied by a significant upgrade of the present JET diagnostics and plasma control (see sections 2.5 and 2.6). The upgrades will include diagnostics for ITER scenario development and systems required to fully exploit the JET new projects. Final validation of diagnostics and control concepts for ITER could also be tested at JET before being installed on ITER. Indeed, many valuable proposals for diagnostics and plasma control have been submitted by experts from EFDA Associated laboratories.

It is a matter of great satisfaction to the many contributors to the JET workprogramme, and in particular to those who designed and built JET 25 years ago, to see that the JET device is still capable of delivering results of significant importance in the future. With its unique multinational character, JET also offers a working environment and organisational structure that could be used to train future ITER users from all over the world. From the engineering point of view, further JET operation would not pose any serious challenges: a recent technical assessment confirmed that only ~15% of the lifetime of the main hardware components (magnetic coils and vessel) has been used to date.

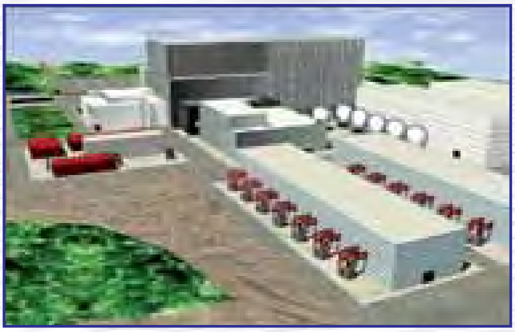


Figure 12: ITER Buildings in Cadarache in virtual reality
Courtesy and copyright CEA/EISS

Summary

With the decision on the ITER site, the worldwide fusion community is preparing the key large experiment on the path towards mastering fusion for energy production. ITER will be the second largest research project worldwide (after ISS – the International Space Station) so it is essential to conduct such experiments with worldwide international collaboration.

JET can play a key role in developing techniques and optimising operation “scenarios” for ITER. Due to its size, plasma current and magnetic field, JET offers access to the most ITER-relevant range of plasma parameters. The role of JET in enhancing our knowledge in fusion physics and technology has clear potential benefits to the ITER programme.

PART III:
HISTORICAL
MILESTONES

Discovery of $E = mc^2$

3.1

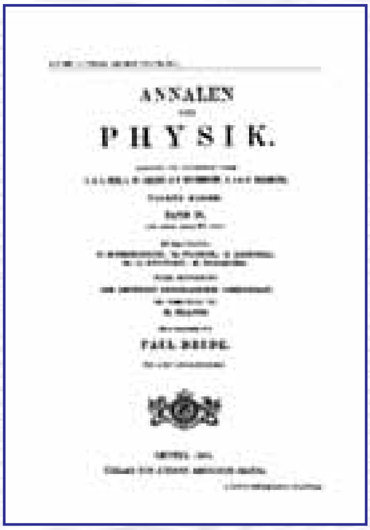
A. Einstein

Albert Einstein was only 26 when he published the brief, 3-page article that announced the equivalence between mass and energy, known today as $E=mc^2$. This article appeared as the last in the series of Einstein's four 1905 breakthrough papers. The 2005 World Year of Physics actually celebrated the 100th Anniversary of Einstein's "Annus Mirabilis".

From the paper "Does the Inertia of a Body Depend on its Energy Content?" by Albert Einstein, published (in German) in Annalen der Physik 18 (1905) page 639, article submitted on 27th September 1905:

> ***"If a body gives off the energy L in the form of radiation, its mass diminishes by L/V^2. The fact that the energy withdrawn from the body becomes energy of radiation evidently makes no difference, so that we are led to the more general conclusion that:***
>
> ***The mass of a body is a measure of its energy-content; if the energy changes by L, the mass changes in the same sense by $L/9 \times 10^{20}$, the energy being measured in ergs, and the mass in grammes.***
>
> ***It is not impossible that with bodies whose energy-content is variable to a high degree (e.g. with radium salts) the theory may be successfully put to the test.***
>
> ***If the theory corresponds to the facts, radiation conveys inertia between the emitting and absorbing bodies."***

Notice that in the original paper, Einstein uses V instead of c for the speed of light, and L instead of E for energy. Today's world famous formula is simply explained in words. Anyway, the message is fascinating: as the speed of light is constant, the energy inherent to a body is proportional to its mass, with a huge constant of proportionality (c^2 = 90 billion joules in each kilogram of mass). Remarkably, Einstein proposed an experiment to test his daring theory - and this is where good science can be instantly recognised. Credit must also to be given to the journal Annalen der Physik, for the courage to publish all the four revolutionary articles.



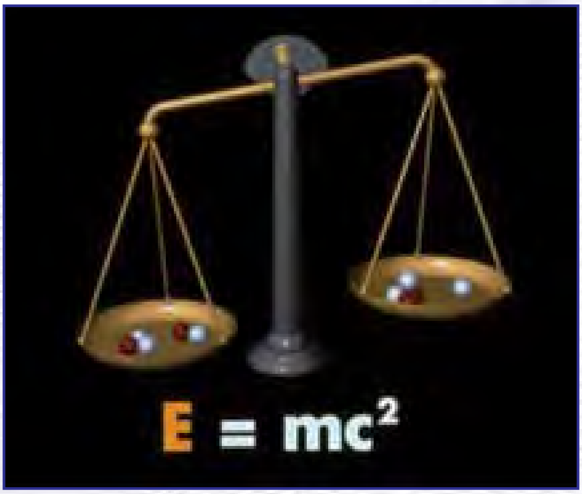
ANNALEN

PHYSIK.

PAUL DRUDE.

The discovery opened vast new horizons for physics, although it took quite a few years before physicists fully recognised the consequences. As a striking example, Arthur Eddington - a forefront supporter of Einstein's theories - realised in 1920 that the mass difference between four hydrogen atoms and one helium atom would provide enough energy to power our Sun, thus solving one of the major physics puzzles of that time (see section 3.2).

Einstein's most intriguing masterpiece, his General Theory of Relativity that explained equivalence between weight and mass (inertia), was published in 1915. In 1921, Einstein was awarded the Nobel Prize for his 1905 explanation of photoelectric effect - but gave his Nobel Lecture a year later on a different subject, on his Theory of Relativity. The genius of Einstein was not just in his ability to derive formulas - some of the relativity equations were known even before Einstein - but mainly in his capability to correctly interpret the meaning of the results.



When fuels are burned, rest mass is always lost but the loss is generally barely discernible. However, in a fusion reaction the difference in mass between the fuel (deuterium and tritium, left side of scales in the image) and the products (helium and neutron, right side of scales) is clearly evident as it is almost 3%. Given the huge c^2 *multiplier, very little fuel is therefore needed to produce a lot of energy. The unique efficiency of fusion power is one of the key motivations for our research at JET.*

Discovery of the Energy Source in Stars

3.2

A.S. Eddington

From “The Internal Constitution of the Stars”, Presidential Address of Professor A.S. Eddington to Section A of the British Association at Cardiff, on 24th August 1920, published in The Observatory Vol. XLIII No. 557, October 1920:

“A star is drawing on some vast reservoir of energy by means unknown to us. This reservoir can scarcely be other than the sub-atomic energy which, it is known, exists abundantly in all matter; we sometimes dream that man will one day learn how to release it and use it for his service.”

“F.W.Aston’s experiments seem to leave no room for doubt that all the elements are constituted out of hydrogen atoms bound together with negative electrons. The nucleus of the helium atom, for example, consists of 4 hydrogen atoms bound with 2 electrons. But Aston has further shown conclusively that the mass of the helium atom is less than the sum of the masses of the 4 hydrogen atoms which enter into it - and in this, at any rate, the chemists agree with him. (...) Now mass cannot be annihilated, and the deficit can only represent the mass of the electrical energy set free in the transmutation. We can therefore at once calculate the quantity of energy liberated when helium is made out of hydrogen. If 5 per cent of a star’s mass consists initially of hydrogen atoms, which are gradually being combined to form more complex elements, the total heat liberated will more than suffice for our demands, and we need look no further for the source of a star’s energy.”

“If, indeed, the sub-atomic energy in the stars is being freely used to maintain their great furnaces, it seems to bring a little nearer to fulfilment our dream of controlling this latent power for the well-being of the human race – or for its suicide.”

Sir Arthur Stanley Eddington (photo) was born in Kendal, England in 1882 and died in Cambridge, England in 1944. For most of his career he worked in the Cambridge Observatory. He was knighted in 1930 and received the Order of Merit in 1938.

In his landmark lecture from 1920, Arthur S. Eddington for the first time ever realised that fusion powers our Sun as well as all other stars, thus solving a major mystery of contemporary

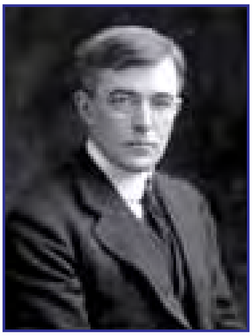
In his landmark lecture from 1920, Arthur S. Eddington for the first time ever realised that fusion powers our Sun as well as all other stars, thus solving a major mystery of contemporary science. He could do so only thanks to his exceptionally prompt support to the Einstein's Theory of relativity, including the relationship between energy and mass $E=mc^2$. The above excerpt from Eddington's lecture shows his bold and ingenious application of the formula on the brand new results of precise measurements of atomic weights made by Francis William Aston (Nobel Prize in Chemistry, 1922) in the Cambridge Cavendish laboratory - a birthplace of many other important results, including the discovery of D-D fusion, see section 3.4.

Notice that the knowledge of subatomic structure was very poor in 1920 so the lecture had to have a very vague frameset. Actually, helium atoms do not consist of "4 hydrogen atoms bound by 2 electrons", but of a light cloud of two electrons and a 100.000 times smaller nucleus in its centre with two protons and two neutrons bound by the so called strong force. For this reason, we would not say today that the energy released in fusion is "electrical". No wonder that it took a long time to evaluate how fusion reactions exactly work in the Sun. First calculations were published in 1929 by Robert E. Atkinson and Fritz G. Houtermans - five years before fusion reactions were actually observed in a laboratory. However, a reliable theory, complete with the results of several cycles of fusion reactions, was published only in 1939 by Hans Bethe (Nobel prize in Physics, 1968).

This is a picture of the surface of the Sun in the helium spectral line showing a huge eruption. The image was taken by the ESA/ NASA satellite SOHO (SOlar and Heliospheric Observatory) and its EIT diagnostic (Extreme ultraviolet Imaging Telescope). The wavelength of the observed He line was 30.4 nm, corresponding to ultraviolet (invisible) light, i.e. the image is not in true colour.
Courtesy of SOHO/EIT consortium. SOHO is a project of international cooperation between ESA and NASA.

Origin of the Word "Plasma"

3.3



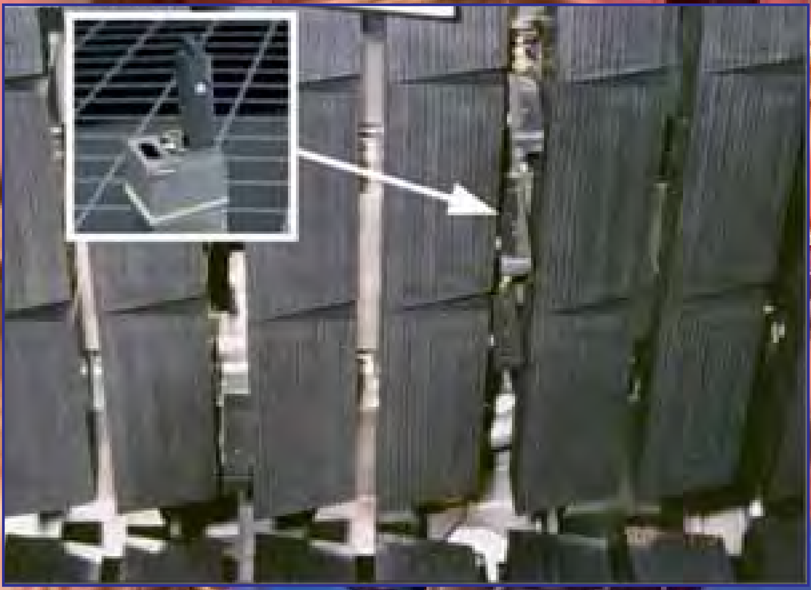
I. Langmuir

In a letter to Nature Vol 233 (1971) page 219, Harold M. Mott-Smith recollects how Irving Langmuir started using the word "plasma" in about 1927:

"We noticed the similarity of the discharge structures. (...) Langmuir pointed out the importance and probable wide bearing of this fact. We struggled to find a name for it. For all members of the team realized that the credit for a discovery goes not to the man who makes it, but to the man who names it. Witness the name of our continent. We tossed around names like 'uniform discharge', 'homogeneous discharge', 'equilibrium discharge'; and for the dark or light regions surrounding electrodes, names like 'auras', haloes', and so forth. But one day Langmuir came in triumphantly and said he had it. He pointed out that the 'equilibrium' part of the discharge acted as a sort of sub-stratum carrying particles of special kinds, like high-velocity electrons from thermionic filaments, molecules and ions of gas impurities. This reminds him of the way blood plasma carries around red and white corpuscles and germs. So he proposed to call our 'uniform discharge' a 'plasma'. Of course we all agreed.

But then we were in for it. For a long time we were pestered by requests from medical journals for reprints of our articles."

U.S. scientist Irving Langmuir (1881-1957) won the Nobel Prize in Chemistry in 1932 for discoveries and investigations in surface chemistry. Amongst other things, his research into molecular adsorption provided insight into the physics of vacuum pumping. Without this knowledge, nobody would be able to build today's tokamak vessels that provide vacuum conditions needed for fusion. Irving Langmuir also invented, and used, a very simple but effective diagnostic to measure electron temperatures and densities of low temperature plasmas, which today we call the "Langmuir probe". Langmuir probe consist of an electrode (in a contact with the plasma) whose electric potential is varied and the resulting collection currents are measured. At JET there are tens of Langmuir probes installed in the carbon tiles (i.e. in the plasma-facing wall), used to characterise JET plasmas at their very edge; within the recent JET enhancements (see section 2.9), 45 new Langmuir probes were installed. Indeed, the importance of "plasma-wall interactions" studies has escallated as we contemplate future fusion reactors like ITER. And this is just one of the reasons why today's plasma science plays an inspirational role for further research into surface chemistry. Perhaps this is the best recompense to Irving Langmuir for his merit in giving plasma its name.

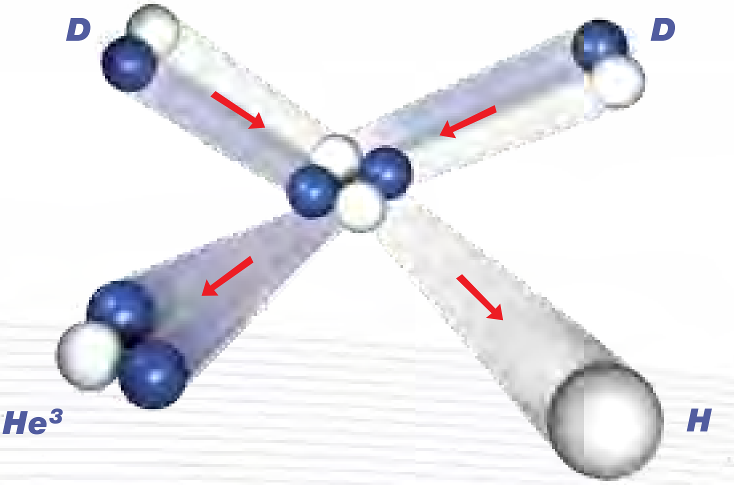


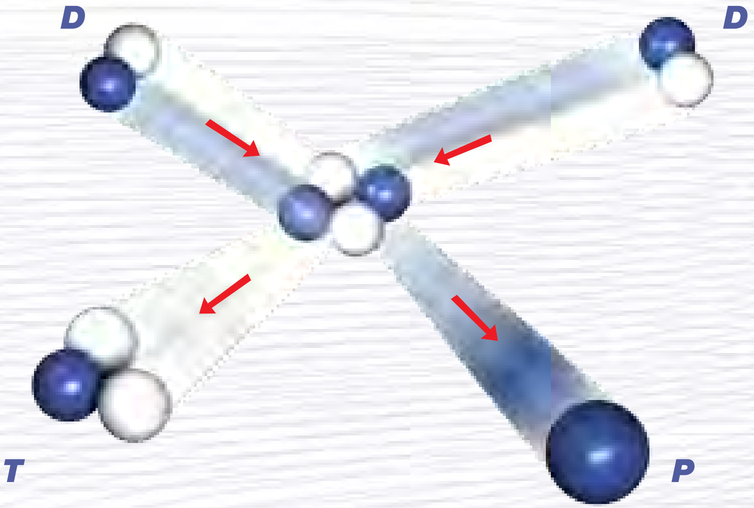
Langmuir probes in an early divertor tile structure of JET

Discovery of D-D fusion

3.4

E.Rutherford





M.L.E. Oliphant, P. Harteck and Lord Rutherford in "Transmutation effects Observed with Heavy Hydrogen", published in Proceedings of the Royal Society, A, vol. 144 (1934), p. 692 (Note: in the original article, authors use the term "diplogen" for deuterium (heavy hydrogen), and "diplons" for deuterium nuclei):

"The most interesting and important reaction which we have observed is that of heavy hydrogen on heavy hydrogen itself. Experiment has shown that diplogen is not appreciably affected by bombardment with alpha-particles from polonium, and we have been unable to detect any specific action of protons on diplogen for energies up to 300,000 e-volts. We were therefore surprised to find that on bombarding heavy hydrogen with diplons an enormous effect was produced. (...) Subsequent observation at much lower bombarding potentials showed that we were dealing in reality with a very large emission of protons."

"The simplest reaction which we can assume is

$${}_1D^2 + {}_1D^2 \text{--->} {}_2He^4 \text{--->} {}_1H^1 + {}_1H^3$$

(...) If we neglect the energy of the bombarding particle (...) the mass of this helium atom must be 4.0272, and it therefore possesses an excess energy over the normal helium atom, of mass 4.0022."

"It seems clear that the production of the isotope of hydrogen of mass 3 in these reactions is established beyond doubt. (...)The possible existence of this isotope has been discussed by several writers and although a careful search has been made no evidence of its presence has been found. It seems probable, however, that it could be formed by the process we have considered in sufficient quantity to be detected ultimately by spectroscopic or positive-ray methods. "

"It was (also) at once evident that there was present a very intense radiation capable of producing an undiminished effect on the counter through 20 cm of lead. As a check on this a search was made for recoil nuclei with the linear counter, and it was found that neutrons are emitted in numbers comparable with the number of protons."

"In order to account for the production of neutrons of the observed energy and number we have been led to assume the transformation

$${}_1D^2 + {}_1D^2 \text{--->} {}_2He^4 \text{--->} {}_2He^3 + {}_0n^1$$

in which the unstable ${}_2He^4$ ***nucleus first formed breaks up into a helium isotope of mass 3 and a neutron"***

"No evidence of the existence of an ${}_2He^3$ ***isotope has been obtained by ordinary methods, although the possibility of its existence has been suggested at various times. It is not unlikely that while the new isotope may prove to be unstable over long periods it may yet have a sufficiently long life to be detected by counting methods and in the expansion chamber."***

The article on the discovery of fusion reactions gives us a fascinating insight into an intense period of early research into nuclear physics. The experimental work was undertaken in the Cavendish laboratory by Marcus L.E. Oliphant (1901-2000), Paul Harteck (1902-1985) and world famous Ernest Rutherford (1871-1937). Lord Rutherford had already won the 1908 Nobel Prize in Chemistry for the discovery of alpha and beta radioactivity, but the best was yet to come - in 1911 he published his discovery of atomic nucleus and in 1919 he accomplished the first nuclear transmutation.

In the article on D-D fusion, published in 1934, a few details deserve special attention:

- The authors recognised neutrons, although the discovery of the neutron was announced only two years before, by James Chadwick (Nobel Prize in physics in 1935). It must have helped that James Chadwick worked in the same laboratory!

- The two possible D-D fusion reactions were correctly identified, and a third option was discussed - a gamma decay of the interim $_2He^4$ nucleus (current preferred notation is ^4_2He) . The article stated that “it was impossible to decide whether a gamma ray of high energy is present”. Today we know that the fusion reaction is instantaneous, and that the interim nucleus is not properly formed. Therefore, the gamma decay option hasn’t enough time to occur and so it is extremely rare.

- There was a real master-stroke: products of both D-D reactions were named even though neither tritium nor helium 3 were known at that time. Consequently, this very article is often considered to mark the discovery (although indirectly) of tritium $_1H^3$.

Cockroft-Walton 100keV accelerator in the Cavendish laboratory
Image courtesy of Cavendish laboratory

The 60 inch (16 MeV) cyclotron in Berkeley with which L Alvarez studied Tritium and Helium 3
Image courtesy of Lawrence Berkeley National Laboratory

Even in today's physics there are many fascinating discoveries, but most of them require major collective efforts and complex facilities. This image shows construction of the Sudbury Neutrino Observatory that in 2001 solved the mystery of missing solar neutrinos. Thanks to this observatory we at last see products of fusion reactions in the Sun, so that fusion is confirmed as a power source of stars. However, some solar neutrinos change their properties on their way from the Sun to the Earth - this discovery gives a big push to modern particle theories.
Photo courtesy of Lawrence Berkeley National Laboratory

- The observations also supported the previous indirect discovery of helium 3 ($_2He^3$) made by M. Oliphant, B.B.Kinsey and Lord Rutherford in their studies of the lithium disintegration by proton in 1932. This reaction had first been observed by J.D. Cockcroft and E.T.S. Walton as the first nuclear reaction ever - only a few months before, and again in the same laboratory! (Nobel prize in 1955).

- However, it was only in 1939 in the US Berkeley National Laboratory that Luis W. Alvarez (Nobel prize in 1968) and Robert Cornog succeeded in directly observing tritium and helium 3 isotopes ("Helium and Hydrogen of Mass 3", Phys. Rev. 56 (1939), page 613). In their measurements, a cyclotron accelerator was first used as a mass spectrometer and tritium was indeed produced by D-D fusion.

- The authors speculated that helium 3 could be quite an unstable element. It is also known that Lord Rutherford thought tritium would be stable and tried to separate it from water. Therefore it came as a surprise that L.W. Alvarez and R. Cornog found helium 3 to be a stable isotope, while tritium was unstable! Although helium 3 is a stable isotope, it is very rare on Earth: There is only one helium 3 atom in one million helium 4 atoms (helium 4 being a product of natural "alpha" radioactivity). Tritium is a beta-source with a half-life of 12.3 years.

All the incredible developments of the 1930s seem very remote today, when D-D fusion reactions are well understood and can be observed in most fusion experiments. At JET, the D-D fusion neutrons provide a valuable tool to measure plasma properties, and therefore neutron diagnostics at JET are being enhanced with new instruments, see sections 2.5 and 2.9.

Lawson Criteria

3.5

J.D. Lawson explaining his criteria at a meeting in Dublin in 1957

J.D. Lawson in “Some Criteria for a Useful Thermonuclear Reactor”, A.E.R.E. report GP/R 1807, December 1955, declassified April 9th 1957:

“In a terrestrial reactor of controllable size (...) it does not seem possible to contain neutrons, but it is not inconceivable that the charged particles could be kept in by suitable electric and magnetic fields. (...) The minimum temperature at which such a system could operate may be found by equating that portion of the reaction energy carried by the charged particles to the radiation loss. This temperature is 3x10^8 degrees for the D-D reaction and 5x10^7 degrees for the T-D reaction.”

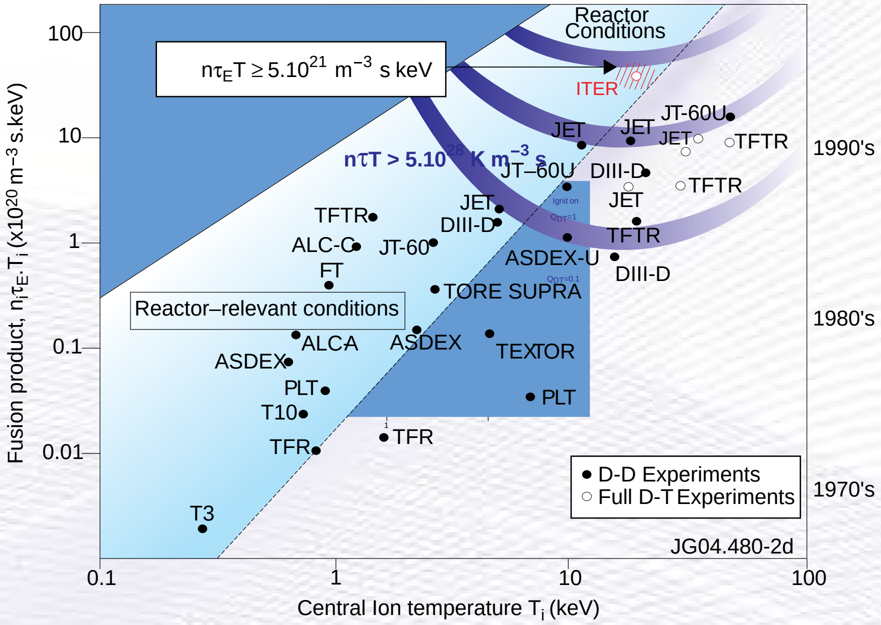
“We now define an important parameter R, as the ratio of the energy released in the hot gas to the energy supplied. (...) R is a function of T and nt. (...) It is seen that for a useful reactor T must exceed 10^8 degrees and nt must exceed 10^{16}. These conditions are very severe. Conditions for a T-D-Li^6 reactor (...) are easier though still severe. The corresponding values of temperature and nt are T=3x10^7 degrees, nt=10^{14}. To conclude we emphasise that these conditions, though necessary are far from sufficient.”

Fifty years ago, the young Harwell engineer John D. Lawson - who had joined the then secret British fusion research - spontaneously wrote a short and rather basic report “Some Criteria for a Useful Thermonuclear Reactor”. In this report, two criteria were introduced that have to be met in order to achieve a power-generating fusion reactor: minimum temperature and minimum product of density and time.

In the original article, Lawson considered very short discharges with ideal plasma confinement. However, today’s magnetic fusion research investigates sustained discharges with limited plasma confinement. Therefore, while Lawson introduced t for pulse length, nowadays we use “energy confinement time” τ (tau) instead, which is equal to plasma energy divided by plasma power losses (with plasma in energetic equilibrium). Similarly, Lawson describes fusion gain using the parameter R which relates input and output energies, while nowadays the “fusion gain” factor Q gives the ratio of fusion power to the external power needed to sustain the energetic equilibrium. Also notice that densities n were in particles per cubic centimeter (rather than cubic metre). Nevertheless, the physics behind the two criteria remains perfectly valid, with the numerical values of the nt (or $n\tau$) limit varying according to the definition being used.

Interestingly, in August 1956 (while the Lawson report was still secret) the role of the $n\tau$ product was mentioned in the introductory and concluding parts of a talk by Russian fusion physicist L.A. Artsimovich at the International Astronomical Union Symposium in Stockholm. In his talk, τ is defined as a “time of life of fast particles in the system” which is similar to our current definition. Shortly afterwards, fusion research was declassified in the UK and a slightly amended article by Lawson was submitted for publication in November 1956, and published in January 1957 in Proceedings of Physical Society B, vol. 70(6).

Notice that the $n\tau$ limit is a function of plasma temperature. For D-T reactions, the $n\tau$ limit has a minimum around 300 million degrees - however, in magnetic confinement facilities it is easier to achieve higher $n\tau$ at lower temperatures. The optimal trade-off appears around 100-200 million degrees, where (to a very good approximation) the $n\tau$ limit decreases with increasing temperature T. Thus, in this rather narrow temperature interval the triple product $n\tau T$ sets a constant limit. This limit is today commonly known as the “fusion product”, and for fusion ignition (Q -> infinity) with an ITER-like plasma profile it has the value of



This graphic shows the fusion triple product achieved on different magnetic fusion facilities. Notice that the unit on the temperature scale, one kiloelectronvolt (keV) is equivalent to 11.6 millions of degrees, and that at very high temperatures the difference between Kelvins (K) and degrees Celsius (°C) is negligible. The graph shows clearly that new facilities performed better than previous ones. The present large machines, from the point of view of the fusion product, have now achieved their engineering limits so that only the next step facility, ITER, can bring about decisive progress.

Lecture of I.V. Kurchatov at Harwell

3.6

Front page of the bi-lingual report based on Kurchatov's lecture at Harwell

From the address of I.V. Kurchatov: "On the possibility of producing thermonuclear reactions in a gas discharge" at Harwell on 25th April 1956 (printed as a bi-lingual report in Moscow, 1956):

"Among the more important problems of modern engineering science the utilization of energy of thermonuclear reactions is a problem of foremost significance. Physicists over the whole world are attracted by this extraordinarily interesting and very difficult task of controlling thermonuclear reactions."

"In 1952 soon after experiments with pulsed discharges were started it was found that at sufficiently high currents the discharge in deuterium becomes a source of neutrons. (...) At the early stages of investigation it was quite natural to assume that the neutrons resulted from thermonuclear reactions in the plasma heated to a high temperature. This was exactly what was expected from the beginning and the fact that the effect was detected under conditions which completely corresponded to the a priori theoretical predictions seemed to speak in favour of this viewpoint. The behaviour of the neutron radiation (its dependence on pressure and current) observed in the first experiments qualitatively concorded with the assumption that the phenomenon was due to thermonuclear mechanism. However, very soon serious doubt concerning the correctness of this assumption began to appear."

"On appraising the various approaches to the problem of obtaining intense thermonuclear reactions we do not deem it possible to completely exclude further attempts to attain this goal by using pulsed discharges. However, other possibilities must also be carefully considered. Especially interesting are those in which the idea of stationary processes may be used."

In 1950s, in the period when thermonuclear fusion only began to be perceived as a potential source of safe energy, the world was divided into two rival social systems. Because of the newly developed nuclear weapons, their military industries worked under extremely secret conditions, and any nuclear research was by default believed to have important military consequences.

In this situation, scientists on both sides slowly realised that in the case of magnetically confined thermonuclear fusion there wasn't actually any potential for military exploitation. Although this message seemed suspicious to any non-expert politician, scientists pushed it hard, knowing the strength of a free and broad international science collaboration.

In 1956, a Soviet delegation lead by Nikita S. Khrushchev (First Secretary of the Soviet Communist Party), Nikolai A. Bulganin (Prime Minister of the USSR) and Academician Igor V. Kurchatov (leading Soviet atomic research physicist) visited the United Kingdom in an attempt to appease the cold war. On April 25, I.V. Kurchatov read a lecture at Harwell. The Harwell site, located just a few miles from our Culham Science Centre, was then the leading research centre of the UK's Atomic Energy Research Establishment (AERE).

The lecture of Academician Kurchatov is remembered as a complete surprise with respect to its openness and deep insight into the problems of controlled thermonuclear fusion. Notice that it has even mentioned the extreme challenge of understanding the origin of measured neutrons - the very issue that would seriously hamper the fusion research at Harwell in 1957.

Partly under the influence of the lecture, in early 1957 the UK decided to declassify thermonuclear research, and so did the USA. The US even organised a major exhibition on their fusion research within the second UN Conference on the Peaceful Uses of Atomic Energy in Geneva in 1958. Since this conference, where fusion research had its first plenary session, there have been no veils of secrecy over our research efforts. This openness enhances our scientific horizons and enforces our trust in the potential benefits of the project.

Igor V. Kurchatov (in the middle, with beard) during his visit at AERE Harwell, 25th April 1956. On his right is Nikita S. Khrushchev, to his left is Nikolai A. Bulganin. Opposite is Sir John D. Cockcroft, director of AERE Harwell (Nobel Prize winner in Physics, 1951)

Breakthrough for Tokamaks

3.7

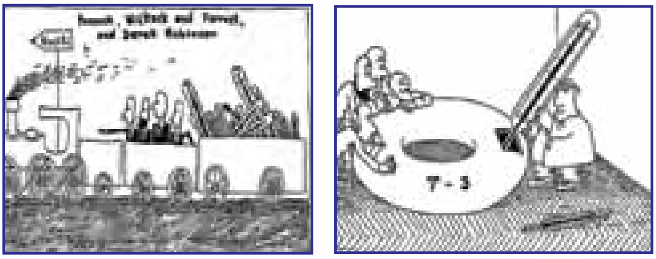
N.J. Peacock, D.C. Robinson, M.J. Forrest, P.D. Wilcock and V.V. Sannikov in “Measurement of the Electron Temperature by Thomson Scattering in Tokamak T3”, Nature Vol. 224, November 1, 1969:

> ***“Measurements have been made of the electron temperature and density of the plasma in the toroidal discharge apparatus Tokamak T3 at the Kurchatov Institute, using Thomson scattering by the plasma electrons of 6943 Å light from a Q-spoiled ruby laser. Important features of recent measurements on Tokamak T3 have been the high total energy of the plasma, the long confinement time and the evidence for thermonuclear reactions in the confined plasma column. In the T3 torus (which has a major diameter of 2 m and a minor diameter of 0.4 m) the electron energy has previously been obtained only for a short (20 ms) current pulse using the diamagnetic technique. In the Thomson scattering experiment on T3 the discharge period is 70 ms, with a flat topped current pulse. (...) Temperatures of up to about 1 keV have been measured.”***

In the 1950s, physicists believed that mastering thermonuclear fusion would be straightforward, and there were even a few premature claims of the controlled release of major fusion power. Following significant developments in plasma diagnostics, a quite pessimistic period followed in the 1960s. It was demonstrated that man-made plasmas could not confine heat energy as well as was theoretically predicted. Consequently, achieved temperatures were quite low in comparison with the requirements for thermonuclear fusion. Besides, due to the bitter experience of blunders in the 1950s, scientists were sceptical of any extraordinary claims.

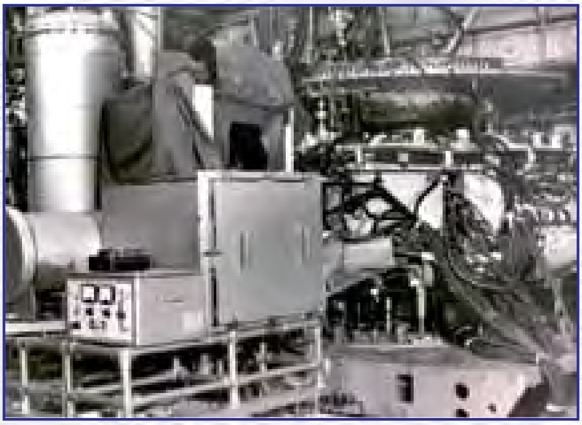
This was still the case at the 1968 conference in Novos birsk, where scientists from the Moscow Institute of Nuclear Physics announced that their tokamak T-3 facility could produce plasmas with temperatures above 1 keV (more than 10 million degrees). Although the Russian team was highly respected, the result seemed too good to be true and doubts were cast on the reliability of the method used to evaluate plasma temperature.

Indeed, temperatures on T-3 had been measured indirectly by using the plasma’s magnetic properties. British scientists at Culham had just mastered a more trustworthy, direct approach to measuring very high temperatures based on the then novel method of laser light scattering on plasma electrons (Thomson scattering, see section 2.5). The obvious need to validate the T-3 performance was of such importance that it transcended political difficulties. The Soviets invited the British team to Moscow, and the Brits accepted the invitation. In the winter of 1968/1969, an apparatus of several tons was dispatched to Moscow and four Culham experts were sent on mission there.



The two drawings are from the talk "Evolution of the Tokamak" given in 1988 by B.B. Kadomtsev at Culham.

The mission was a resounding success. Surprisingly high temperatures of the T-3 plasmas were confirmed, blowing a fresh wind through fusion research worldwide. In particular this was a major breakthrough for the tokamak concept which had, until then, only been developed in the U.S.S.R. (tokamak is the Russian acronym for "toroidal chamber with magnetic coils"). Following Nature's publication of the above article in November 1969, the U.S. scientists in Princeton immediately decided to convert their toroidal experiment to a tokamak (giving birth to the ST device) and the French designed the TFR tokamak. Given their imminent success, projects for large tokamaks including JET emerged in the 1970s.



A British spectrometer (left) coupled to the Soviet tokamak T-3 (right). To exploit the Thomson scattering phenomenon for plasma temperature measurements, a powerful laser and sensitive spectrometer are required. The laser fires light through the tokamak's plasma, while the spectrometer measures the wavelengths of light that plasma scatters from the laser's path. Changes in wavelength are then directly linked to the temperature of plasma electrons.

Growth of European Fusion Collaboration

3.8

Prof. D. Palumbo, former Director of the Euratom Fusion Programme in the EC, in “The Growth of European Fusion Research”, talk presented at the symposium at Culham Laboratory on 8th December 1987, published in Plasma Physics and Controlled Fusion, Vol. 30, No 14 (1988) p.2069:

“Let me go back to 1958 when EURATOM was constituted having fusion as a modest element of the initial research programme. In September of the same year at the Geneva Conference important activities and progress in fusion (mainly in the USA, USSR and UK) were reported. (...) The first contract was signed in 1959 with the French CEA (Laboratories in Fontenay aux Roses and Saclay), after with Italy (Frascati), with Germany (Garching and Julich) etc. In the sixties, the main activities were the development of the not previously existing ‘plasma physics’ and the tentative exploration of a variety of confinement schemes together with some effort on heating methods. The role of Brussels was to promote the exchange of information, the training and exchange of staff (and some instruments) and to avoid unnecessary duplication of effort.”

“The turning point for several reasons occurred at the end of the sixties. From the scientific point of view, in August 1968 at the Novosibirsk Conference the emergence of the Tokamak became evident. (...) We realised that in order to keep pace with the progress in tokamak a vigorous programme was necessary so that (...) we submitted for the agreement of the Council of Ministers a new five year Fusion Programme of expansion. We proposed to focus the activity on toroidal configurations, and in particular on tokamaks. A special fund was foreseen in order to give higher rate support to the laboratories for building new machines. This was later called ‘the priority support’. The necessity of starting a joint project for a very large tokamak, afterwards called JET, to be built as a common enterprise was also mentioned. We were successful and we got from the Council of Ministers the requested money and even a little more.”

After the second world war, the first main players in fusion research were the USA and USSR, with a brief but key contribution from the United Kingdom in the 1950s. However, due to the constant efforts of people like Prof. Palumbo, the emerging European fusion community could take advantage of international developments, including the success of the tokamak configuration and the continuous growth of the European Union. Consequently, since the 1970s, Europe has become increasingly influential in our research field, together with another rising power, Japan. Today, the European Union plays a leading role in fusion research both in terms of resources and results. This can be demonstrated on national levels (see e.g. section 3.9) and in the collaboration at JET, currently the world's only magnetic fusion facility with Tritium capability, which holds the world record in actual fusion power production (16 MW, see section 3.11)

JET design team, with Dr Paul-Henri Rebut in front of the model

The idea of a Joint European fusion experiment was born in 1971. From the very beginning, the Joint European Torus (JET) Design Team (photo) was enthusiastically managed by a young French expert, Dr Paul-Henri Rebut. A quite ambitious target was set - the plasma volume of the proposed JET machine was planned to skip the current state by two orders of magnitude! JET's foundation stone was laid at Culham Science Centre on 18th May 1979 by Commissioner Dr Guido Brunner after a difficult three year wait for the JET siting decision to be made from several European candidate sites. JET was then completed on time and on budget. The first JET plasma was attained on 25th June 1983, and in the very same year JET achieved a world record 1 MA (1 million amperes) electrical current in the plasma. The Official Opening Ceremony took place on 9th April 1984, with participation of Her Majesty Queen Elizabeth II, M. Francois Mitterand (President of the French Republic) and M. Gaston Thorn (President of the European Commission). Since these days JET has been providing a working example of a fully international fusion research centre (see the JET chronology concluding this booklet).

In this new century, countries like China, South Korea and India are joining in the fusion endeavour with priceless "new blood", including superconductive research projects and growing numbers of trained manpower. With such a positive background, the European fusion community is looking forward to construction of ITER, where our present expertise will be shared on a truly global scale (see section 3.10).

The map shows countries (marked in yellow) which are parties to the European Fusion Development Agreement (EFDA) through the Euratom Associated Laboratories, represented in most cases by national fusion research centres and shown with red points. Bulgaria, Slovakia and Lithuania joined EFDA in 2007.
(Note: information about JET as well as national fusion programmes can be found in national languages on the JET webpage http://www.jet.efda.org/, by clicking on the corresponding flags).

JET construction works in 1980

Discovery of the H-mode

3.9

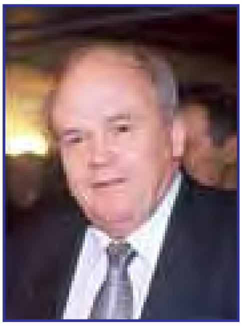
F. Wagner et al.: "Regime of Improved Confinement and High Beta in Neutral-Beam-Heated Divertor Discharges of the ASDEX Tokamak", Physical Review Letters Vol. 49 (1982) p.1408:

> ***"At t=1.18 s, the density suddenly increases without modifications from the external controls. The gas valve closes, but nevertheless the density continues to rise and exceeds the value obtained during the plateau of the Ohmic phase. From bolometric measurements and from the intensity of OVI and FeXVI radiation (O and Fe are intrinsic impurities), it can be excluded that the density rise is caused by an enhanced impurity influx. All three signals, normalised with respect to the plasma density, decrease at the transition into the H regime.***
>
> ***The increase in density is caused by a sudden improvement in particle confinement."***

The high confinement mode of tokamak operation, or simply "H-mode", was unexpectedly discovered in the ASDEX Tokamak at Max Planck Institute for Plasma Physics, Garching, Germany, on 4th February 1982, during intense plasma heating experiments in the new "divertor" configuration (see section 2.7). The phenomenon was then confirmed by many other magnetic fusion experiments, including JET in 1986. A transport barrier that builds up at the very edge of the plasma is responsible for the H-mode phenomenon. The barrier is due to suppression of plasma turbulences at the edge, but the detailed mechanism causing the suppression is still unclear and challenges many plasma physicists specialised in plasma theory and computer modelling, see section 2.8.

The H-mode is characterised by an improvement of plasma confinement by a factor of about two, which enhances our prospects of mastering fusion power at an industrial scale. Nowadays the H-mode is considered to be a "standard scenario" for most magnetic fusion experiments. Indeed the future ITER device, which has been designed to release significant fusion power, is assumed to operate in the H-mode.

This picture shows the ASDEX tokamak where the H-mode was observed for the first time. The insert picture shows a plasma in ASDEX. At present, the Max Planck Institute for Plasma Physics in Garching operates a larger tokamak, ASDEX Upgrade, and is building a major superconductive stellarator Wendelstein 7-X in its new branch in Greifswald. The Max Planck Institute for Plasma Physics is an EFDA Associate and its experts are also significantly involved with JET work, both on-site and remotely.
Photo courtesy of Max Planck Institute for Plasma Physics.



E.P Velikhov

The ITER Initiative

3.10

From the Joint Soviet-United States Statement at the Summit Meeting (Reagan - Gorbachev) in Geneva, November 21, 1985:

"The two leaders emphasized the potential importance of the work aimed at utilizing controlled thermonuclear fusion for peaceful purposes and, in this connection, advocated the widest practicable development of international cooperation in obtaining this source of energy, which is essentially inexhaustible, for the benefit for all mankind."

The short paragraph from the joint statement can be considered as marking the birth of ITER, the International Thermonuclear Experimental Reactor project. Potential joint research into fusion energy played an ice-breaking role at the first Summit of President Reagan and General Secretary Gorbachev, after several years of difficulties between the two super-powers. The same common standpoint on fusion was also declared two months earlier, in September 1985, during the meeting of Gorbachev with the French President Mitterand. Following the two summits, in December 1985 the importance of fusion development found general acceptance in the United Nations General Assembly and since then, other countries decided to participate.

Behind the initiative to promote fusion on an international scale was Academician Evgeny P. Velikhov, the then Deputy Director of the Kurchatov Institute in Moscow and a close advisor to Gorbachev.

Note that the acronym of ITER also means "The Way" in Latin.

Ronald Reagan and Mikhail S Gorbachev in Geneva,1985

Representatives of Russian Federation, Japan, European Union and United States of America signing the ITER EDA agreement under the auspices of the International Atomic Energy Agency (IAEA) in Washington on 21st July 1992. From left to right (seated): Professor Viktor Mikhailov, Minister of the Russian Federation for Atomic Energy, Minister Hiroshi Hirabayshi, Deputy Chief of Mission in the Embassy of Japan, Ambassador Andreas van Agt, Head of the Delegation of the Commission of the European Communities to the U.S.A, U.S. Secretary of Energy James D. Watkins. From left to right (standing) Akihiro Aoki, First Secretary, Embassy of Japan, Helen Donaghue, European Union, Washington Office, Michael Roberts, U.S. Department of Energy, Anatoliy A. Shurygin, First Secretary, Embassy of the Russian Federation. Image courtesy of ITER.

The success of the initiative led to the signing of the ITER agreement between the United States, the Soviet Union, the European Community and Japan in 1987, which first allowed for limited "Conceptual Design Activities" (CDA). Successful completion of the CDA phase, together with major changes on the political scene, enabled the ITER collaboration to progress to a new level of detailed "Engineering Design Activities" (EDA). The key ITER EDA agreement was signed by the four parties on July 21, 1992. Based on this agreement, about 170 scientists and engineers worked on ITER in three joint design teams based in Naka (Japan), San Diego (USA) and Garching (Germany). In 1998, a detailed Final Design Report was published by IAEA. In parallel, seven large R&D projects were launched, aimed at validating key aspects of the ITER Design . Following the withdrawal of the USA from the project, and some scepticism concerning the project exaggerated ambitions, a less ambitious goal was set for ITER, with a view to reducing costs. The new design was completed in July 2001 and subsequently developed in "Coordinated Technical Activities" (CTA) phase. In 2004, China and South Korea entered into the global collaboration on ITER, and USA rejoined the project, giving it a very high national priority.

ITER collaboration was then encompassed in the "Interim Transitional Arrangements" (ITA). On 28 June 2005 the six parties participating in the ITER project decided to build this project in Cadarache in Southern France. In December, India joined ITER parties, so that over half of the world's population is now represented in this global endeavour.

On 21 November 2006 ministers of the seven ITER parties met in Paris, at a ceremony hosted by the President of the French Republic and the President of the European Commission, and signed an agreement establishing the new international organisation to implement the ITER project.

The ITER design is remarkably similar to that of JET, but double in linear dimensions (to increase plasma confinement) and fully superconductive (to allow for long pulses). Indeed, the ITER design is to a large degree based on the results of European endeavour in fusion and of joint research at JET in particular.

The signatories of the ITER Agreement in November 2006, together with French President Jacques Chirac. From left to right: Vladimir Travin (Deputy head of the Federal Atomic Energy Agency Rosatom, Russian Federation), Takeshi Iwaya (Vice-Minister for Foreign Affairs, Japan), Xu Guanhua (Minister of Science and Technology, People's Republic of China), José Manuel Barroso (President of the European Commission), Jacques Chirac (President of the French Republic), Woo Sik Kim (Vice Prime-Minister, Ministry of Science and Technology, Korea), Anil Kakodhar (Secretary to the Government of India, Department of Atomic Energy), Raymond Orbach (Under Secretary for Science, U.S. Department of Energy), and Janez Potocnik (European Commissioner for Science and Research).
Image courtesy of ITER.

JET Demonstrates Alpha Particle Heating

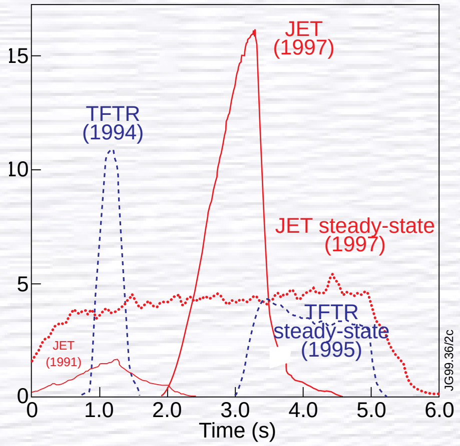
3.11

From “Observation of Alpha Heating in JET DT Plasmas” by P.R. Thomas et al, published in Physical Review Letters Vol 80, No 25 (1998) p. 5548:

“The Joint European Torus (JET) tokamak was designed with sufficient plasma current that alpha particles, at their birth energy of 3.5 MeV, have orbital excursions away from their mean magnetic flux surfaces which are at most 10% of the plasma minor radius.”

“The TFTR team was the first to observe alpha heating in a Magnetic Confinement Fusion plasma. The alpha power was 3% of the total heating power absorbed by the plasma, so the electron heating due to alphas was only twice the error arising from pulse to pulse variation. With a fusion power gain 3-4 times that of TFTR, JET was in a better position to observe alpha heating.”

“Alpha particle heating has been unambiguously observed in JET DT plasmas. A scan of DT mixture was used successfully to separate the effects of alpha heating and potential isotopic dependence of energy confinement. A change in central electron temperature of 1.3 +/- 0.23 keV is ascribed to 1.3 MW of alpha heating. (...) With a plasma energy confinement time of 1.2 s, the alpha heating produced an increase of plasma energy content of more than 1 in 9 MJ. Alpha heating was observed, in this study, to be as effective as hydrogen minority ICRH. This is a strong indication that there are no unpleasant surprises with respect to alpha heating and that there are no anomalous effects on trapping or slowing down. Furthermore, it is higly encouraging that the peaked alpha heating profile shows up in the heating rate and the energy confinement time.”



Evolution of fusion power released in DT record plasma discharges

In a magnetic confinement fusion reactor the plasma self-heating is provided by “alpha particles” i.e. helium nuclei - charged fusion products that carry one fifth of the released energy. JET unambiguously observed alpha particle heating in the deuterium-tritium experiments of September 1997. So far, only two tokamaks have been capable of handling Tritium, and thus experimenting with Deuterium-Tritium (D-T) fusion - by far the most efficient nuclear fusion process: the U.S. TFTR (now decommissioned) and the E.U. JET. In 1991, JET was the first tokamak ever to run plasma discharges with Tritium (on November 9th, discharge #26147), when D-T fusion was confirmed by observing 14.1 MeV neutrons. In 1994, TFTR ran with the optimal 50% D, 50% T fuel mixture and was the first to trace plasma heating from fusion alpha particles. In 1997, JET set the current world record of released fusion power - on October 31st, discharge #42976, 16.1 million Watts (to compare, a family house central heating needs a few thousands Watts of power) - and energy, on November 5th, discharge #42982, 21.7 million Joules (enough to hoist one hundred tons by twenty-two metres).

This is the recollection of some of the D-T plasma discharges from the December 1997 issue of the periodical “JET News”, predecessor of the current EFDA JET Bulletin. Notice that the power amplification factor Q in the following quote is the ratio of fusion power produced to the net external power for plasma heating.

“The first successful high power tritium beam injection into the plasma took place on the evening of 20 September. Following some further high-voltage conditioning with tritium the record-breaking JET DT discharge (#42676) was obtained on the evening of 22 September producing 12.9 MW of fusion power. (...) Also a world record fusion energy (21 MJ) has been produced in a 3 second duration pulse. (...) The afternoon following the press conference (31st October 1997) brought our best high power results so far. Shot number 42976 reached a fusion power of 16.1 MW and Q rose to 0.65.”

This picture from the JET control room was taken on 22nd September 1997 following the record-breaking JET D-T discharge. The JET Diagnostics Coordinator’s screen attracted considerable interest!

An accessible overview of technology and physics involved in the DT experiments can be found in J. Wesson’s book “The Science of JET”, that can be downloaded for free from the JET website http://www.jet.efda.org. For detailed scientific information, we can recommend (besides the above Physical Review Letter) for example the following 1998 preprints of the following articles on the JET record fusion performances: “JET Deuterium-Tritium Results and their Implications” JET-P(98)70, “Deuterium-Tritium Operation in Magnetic Confinement Experiments: Results and Underlying Physics” JET-P(98)65 and “Overview of ITER Physics Deuterium-Tritium Experiments in JET” JET-P(98)31. Notice that the JET preprints and reports can be found on the Institute of Physics website http://www.iop.org/Jet/

In the next-step facility ITER, which will be also capable of the D-T operation, alpha-particle self-heating is expected to provide more than a half of the heating power required in order to maintain the extreme plasma temperature, with the target power amplification factor Q = 10. Although from the current knowledge it seems difficult for ITER to reach ignition (i.e. fully self-sustained thermal balance, Q -> infinity, see also section 1.4), it is not precluded in its design.

Interview with JD Lawson

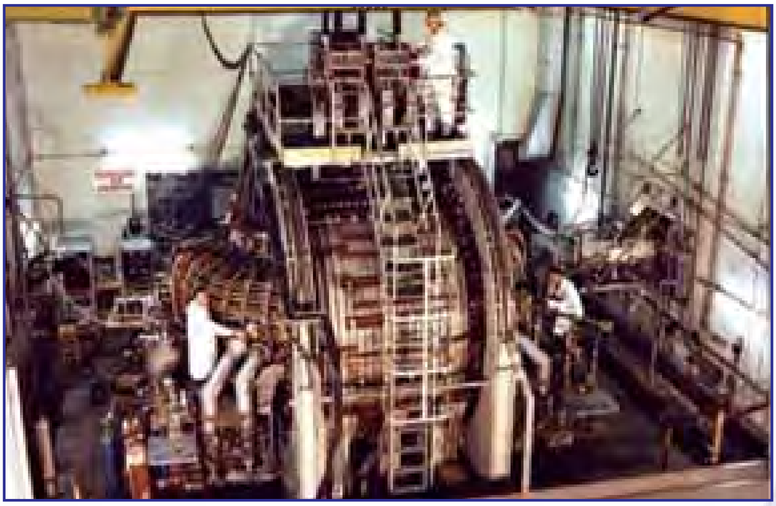
John D. Lawson (photo, born on 4 April 1923) originally trained as an engineer. Through a series of coincidences he became involved in fusion research from its early days, and made important contributions that continue to influence the design of proposed fusion reactors.

“I started during the Second World War,” he recalls. “I was one of the lucky people who were just about to take Higher Certificate and try for a scholarship for university; in 1941 the government suddenly realised that they needed a lot more scientists, so everybody who was doing science was given a free one or two year university course. Although encouraged to study Classics at school, I had wanted to read physics at university, but they wouldn’t take me because I hadn’t done chemistry in grammar school, so I took mechanical sciences, which is an engineering degree. For that reason I was somewhat different from most people who had taken a conventional physics degree. And as an engineer my method of thinking is slightly different.”

His first scientific job was during the war. He was based at TRE (Telecommunications Research Establishment) Malvern where he worked on microwaves and microwave aerials. In 1951 Lawson moved to AERE Harwell General Physics Division. With the outbreak of the Korean War in 1950 researchers who had worked on defence projects were encouraged to return to defence work. Lawson, because of his experience with microwaves, was assigned to lead a section designing a klystron, a vacuum tube for producing high power at very short wavelengths, or microwaves, within a group led by Peter Thonemann. Thonemann, having completed a Masters degree at Sydney University, came to the Clarendon Laboratory Oxford in October 1946 to carry out research into controlled fusion for his PhD. By 1952 Thonemann was working at Harwell, where he took charge of the development of the ZETA fusion experiment, which was first operated on 12 August 1952.

It was through sharing an office with Thonemann that Lawson heard about fusion for the first time. The emphasis at Harwell at that time was on mechanisms for producing fusion. Lawson (the engineer) insisted that it was important to check that more energy was produced than consumed in a complete system - hence the criterion, which, according to him, was “very simple to deduce”. This now plays an important role in assessing the efficacy of fusion reactor design.

“Being an engineer I wondered what different parameter ranges there could be for a practical device. People were describing all sorts of things such as colliding beams which have come back in a different form in inertial confinement fusion now, but what I did was to put some parameters on a sheet of paper and then worked out a whole lot of actual numbers that would make sense in that they lay within a practical range.”



The ZETA experiment at Harwell

At the suggestion of the Harwell Director John Cockcroft, Lawson was chosen to present a paper on fusion power in Dublin in September 1957 at the British Association for the Advancement of Science Meeting. The paper created great excitement and was widely reported in the media. “ZETA and other experiments were classified because of the fact that they could be neutron sources to produce fissile material,” he notes, “but my criterion was not, so it was allowed to be talked about.”

But in spite of the stir his worked caused, Lawson says, “I never was really in fusion. I spent most of my working life working on particle accelerators. My main original achievement here was to show that the parameters suggested for a strong focusing machine were not realistic, although it’s still a very strong and powerful principle. Sharing an office with Peter Thonemann I saw what the fusion problem was. I produced the criterion, produced the report, and then I got involved with lots of other discussions and wrote the other report, a survey of different methods. And that was it. Then I was back to accelerators.”

“I wrote one or two other papers surveying the other ideas that had been suggested and showing that most of them wouldn’t work. I also knew that I wouldn’t see fusion power in my own lifetime, although most people were talking about it coming in 20 years or so. They still are. My work was always negative and was tending to be showing things that wouldn’t work, or surveying an area to see whether it might possibly be feasible.”

After Lawson transferred to the Rutherford Laboratory in 1961 to continue his work on accelerators he did have one more foray into fusion research with a two year sabbatical at Culham in 1975-76 working on a design study of a conceptual fusion power reactor based on the reversed field pinch principle with Hugh Bodin and Roger Hancox.

He retired in 1987. During his long, productive and ultimately satisfying career he published numerous papers and reports. He also wrote The Physics of Charged-Particle Beams, now in its second edition and still considered to be a classic textbook on particle accelerators.

“I’ve been lucky - very lucky - in always being in the right place at the right time,” he says. “Finishing my education just when they wanted scientists during the war got me straight into a very elite group that had already been recruited from universities and so at the age of twenty I was able to get started without needing a PhD. I was later awarded a Cambridge Doctorate of Science in engineering based on my published papers. I was able to do interesting work and had the chance to visit very interesting places, including Russia and China, at a time when they were generally inaccessible to western travellers. All in all, I’ve had a good career.”

JET Chronology

1971	Council of the European Community decided in favour of a robust fusion programme and provided the necessary legal framework
1973	Design work began for the JET machine
1977	Machine construction work began
	25th October, Culham site selected for JET project
1978	1st June, framework established the "JET Joint Undertaking" legal entity
1979	Site work began
	18th May, JET foundation stone laid in Culham, UK
1983	JET construction completed on time and on budget
	25th June, the JET first plasma (19 kA)
	October, the world's first 1 MA plasma current. 3 MA by year end
1984	9th April, official opening by Her Majesty Queen Elizabeth II
	First Vertical Displacement Event (disruption)
1985	Technical objectives met: plasma current (4.8 MA) and toroidal field (3.4 T)
	5 MW of ICRF coupled to the plasma
	3 MA X-point operation demonstrated
	Radiation induced collapse in density limit disruptions observed
1986	8 MW of ICRF coupled to the plasma - electron temperature 10 keV
	10 MW of NBI injected into the plasma – ion temperature 12 keV
	X-point operation gives H-mode confinement
	World first observation of 'monster' sawteeth, stabilised by fast ions
	Single pellet injection – peak density 2.5x10^{20} m^{-3}

1987	7 MA plasma current achieved
	q=2 disruption limit verified
	LIDAR system installed
1988	NBI power increased to 21 MW – ion temperature 20 keV
	Total heating power of 35 MW achieved
	World first production of Internal Transport Barrier (ITB) with Pellet Enhanced Performance (PEP) discharges
	Confinement time of 1 s achieved in Ohmically heated plasmas
	First JET Hot-ion H-mode
1989	Beryllium components and evaporation used in JET
1990	ICRH coupled power enhanced to 22 MW
	Prototype LH launcher introduced – current drive up to 1 MA
1991	9th November, World first controlled release of Deuterium-Tritium fusion power when the Preliminary Tritium Experiment (PTE) achieved 1.7 MW peak fusion power and 2 MJ fusion energy
	Ion Cyclotron Current Drive demonstrated, leading to sawtooth stabilisation
	L-mode plasma maintained for 1 minute
	Confinement time of 1.8 s in OH plasma
	Steady state H modes for 18 seconds
1992	Full cycle AC operation
	TF ripple experiments
1993	Installation of Mark I pumped divertor
	7 MW LHCD system introduced
1994	Plasma detachment in divertor
	Saddle coils used for TAE experiments
	Steady state ELMy H-modes
1995	Installation of Mark II divertor
	“Wind tunnel” energy confinement experiments
1996	Optimised shear plasmas developed with internal transport barriers produce record Deuterium-Deuterium fusion power
	Ion temperature exceeds 30 keV


1986


1991


1994


1997

1997 World record Deuterium–Tritium campaign (DTE1) achieved 16.1 MW fusion power, 22 MJ energy release

First clear evidence of alpha-particle heating of the plasma

Steady fusion power of 4MW maintained for 4 seconds

Ion temperature of 40 keV achieved

1998 First fully remote exchange of divertors - gas-box divertor installed

Pellet centrifuge used

1999 Toroidal field increased to 4.0 T

Confinement increases with triangularity

Inside-launch Pellet Injector installed and enhanced fuelling demonstrated

First observation of large SOL flows

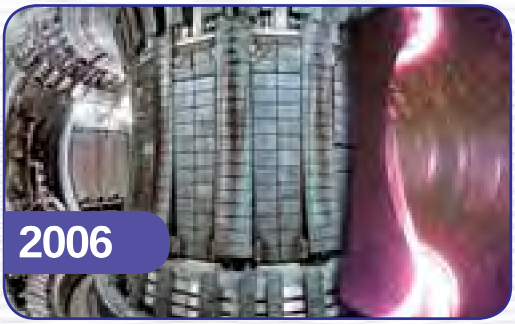
MSE measurement of q-profile

European Fusion Development Agreement (EFDA) established, with respons bility for the future collective use of JET

JET's "Joint Undertaking" ended.

2000 1st January, JET Facilities now operated under contract by UKAEA. Further use of JET, and JET's scientific programme now carried out under the EFDA

31st May first experiment under the new EFDA framework



2001	First alpha simulation experiment
2002	ITER normalised confinement, density and shape achieved
	Material migration studies using Quartz Micro-Balance
	Divertor discharge lasts record 50 s
2003	Real-time feedback control of pressure and current profiles simultaneously
	Hybrid regime established and extended towards ITER conditions
	ELMs moderated with impurity seeding
	Trace Tritium Experiment campaign
2005	New divertor and twenty-five new or considerably upgraded diagnostics were implemented during the 2004/2005 shutdown
	ITER-like ICRH antenna under construction
2006	JET operates with ITER-like plasma shapes
	Experiments with high heating power > 30 MW
2007	High plasma current and field ripple experiments
	Installation of the ITER-like ICRH antenna

To be continued…

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