MAGNETIC CONFINEMENT FUSION

11/19/2011

INTRODUCTION

The goal of the fusion research effort is to derive energy from the fusion of light atomic nuclei. Nuclear fusion is an important natural process. Many chemical elements originate from hydrogen through fusion in the process of nucleo-synthesis. Fusion is the energy source of the sun and stars. Under terrestrial conditions the two hydrogen isotopes, deuterium D and tritium T, fuse most readily. In the process, a helium nucleus is produced. It is accompanied by the release of a neutron and energy. Just one single gram of fusion fuel could generate 90,000 kW.hrs of energy in a power plant; equivalent to the combustion heat of 11 metric tonnes or 11,000,000 grams of coal.

The magnetic confinement approach exploits the interaction of charged particles with magnetic fields. Charged particles are deflected by a magnetic field and, if the field is strong enough, particles will orbit around the field lines, gradually progressing along it if they have some longitudinal velocity component. This feature forms the basis of magnetic confinement fusion, which has been under scientific and engineering investigation since the 1950s.

PLASMA AMPLIFICATION FACTOR Q

An important design parameter for a magnetic fusion reactor is its plasma amplification factor: Q, defined as the ratio of the thermonuclear power produced to the power input to generate and heat the plasma to thermonuclear fusion temperatures:

$$Q = \frac{P_{thermonuclear}}{P_{input}} \tag{1}$$

In a closed system, such as a toroidal device, large values of Q are possible. Once the energy in the ions released from the fusion reactions in the plasma exceeds the radiative and other losses, plasma ignition should occur. The use of neutral ion beams injection or microwave radiofrequency heating can thus be stopped, and the plasma burn becomes self-sustained, as long as the fusion fuel continues being supplied, and the plasma remains confined.

In an open system such as a mirror fusion reactor, because of the inevitable end losses, it is unlikely that ignition can be achieved. Such devices would have to be used as a driven power amplifier. With a low value of Q, energy would have to be supplied continuously and the fusion reaction would amplify the energy input to the plasma by the factor Q. In a single-cell plasma, Q may not exceed about 1.2. The magnetic fusion approach attempts at developing devices with a high value of Q. The enhancement of Q involves the reduction of end losses in open systems, particularly of high energy ions.

IGNITION CONDITION: LAWSON BREAKEVEN CRITERION

Like a wood fire, fusion fire does not burn on its own. Fusion requires particular ignition conditions to be met. In an ignited plasma, a substantial number of particles must collide with one another with sufficient frequency and intensity. The magnetic field must thus confine a number of particles whose thermal energy must not be transferred too fast to the plasma container. This imposes requirements on the density, temperature, and thermal insulation of the plasma. These are:

1. An absolute plasma temperature of at least:

$$T = 273 + {}^{o}C = 100 \times 10^{6}\ {}^{o}K.$$

2. An energy confinement time of:

$$\tau_{\varepsilon} \geq 2 \text{ seconds.}$$

This measure for the thermal insulation gives the time that elapses till the thermal energy pumped into the plasma by heating equipment such as neutral beams, transformer action, or microwaves is again lost to the outside.

3. A plasma density of about

$$n = 10^{14}\ [\text{particles/cm}^3]$$

This is 250,000 times less in density than the Earth's atmosphere. This extremely low density means that, despite its high temperature, a burning fusion plasma involves a power density scarcely larger than an ordinary light bulb.

4. Energy breakeven. The energy obtained from a plasma must exceed the energy input used to ignite it and the radiation losses from the plasma. This is expressed by the Lawson's breakeven criterion or the Lawson parameter as a product of the plasma density and energy confinement time:

$$n\tau_{\varepsilon} \geq 2.0 x 10^{14} [\frac{\text{particles.sec}}{\text{cm}^3}] \qquad (2)$$

LINEAR MIRROR FUSION CONCEPT

Charged particles spiraling around magnetic field lines tend to be repelled when they enter a region of increased magnetic field. In its simplest form, shown in Fig. 1, a magnetic mirror configuration is produced by a number of field coils wound around a straight open ended cylindrical tube. The coils are wound closer at the ends than in the middle, or a stronger magnetic field pinches the magnetic field lines closer near the ends. These regions at the ends where the magnetic fields are stronger constitute the mirrors.

The magnetic mirrors confine charged particles with large velocity components in the direction perpendicular to the axial field lines. Those particles with significant velocity components parallel to these field lines escape through the mirrors. Particles that are confined in the mirror would thus escape if, as a result of a collision, the direction of motion is changed so as to increase the velocity component parallel to the axial magnetic field lines. Thus, in a mirror device, the loss of particles is by motion along the field lines. The motion along the field lines is very rapid and no substantial gain is achieved by increasing the size of the plasma.

Two general ways exist to decrease the plasma losses from a simple mirror system:

1. **Increasing the mirror ratio**: Which is the ratio of the magnetic field strength in the mirror region to that in the region between the mirrors:

$$\text{Mirror ratio} = R_{\text{mirror}} = \frac{B_{\text{mirror}}}{B_{\text{linear}}} \qquad (3)$$

In this case, a larger velocity component parallel to the field lines is required for the particles to escape through the mirrors.

2. **Increasing the particle energy or temperature**: This decreases the probability of collisions between particles in which substantial changes could occur in the direction of motion. This means that mirror fusion reactors would have to be operated at higher plasma temperatures than other magnetic confinement concepts.

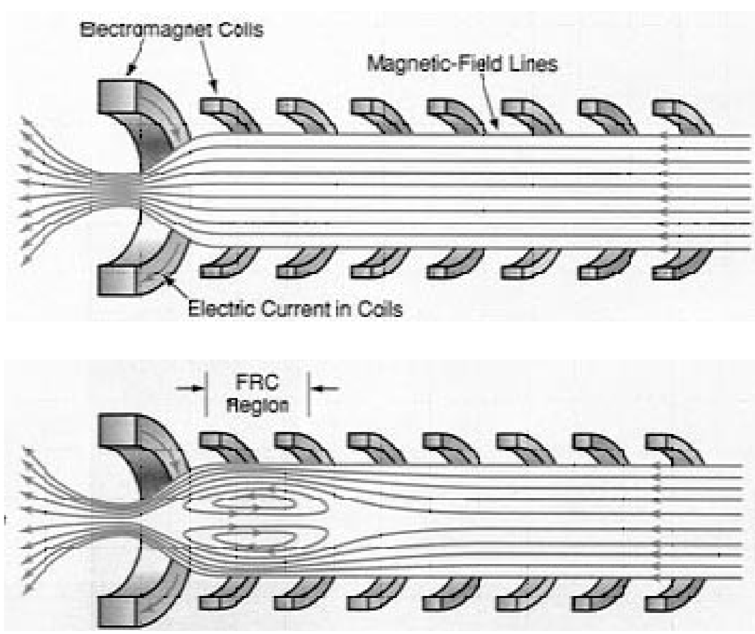


Figure 1. A basic configuration linear mirror (Top) and a mirror with a Field Reversed Configuration (FRC) end plug.

TANDEM MIRROR

Electrons in a plasma have a higher velocity than the ions, because of their smaller mass for the same energy or temperature. As a result, in a linear mirror, the electrons initially escape through the mirrors faster than the ions. This leads to an eventual partial charge separation. A positive potential or space charge is built up between the mirrors, designated as the ambipolar electric potential. As shown in Fig. 2, this holds the electrons, and tends to equalize the rates of escape of electrons and ions. The positive ambipolar potential formed between a pair of mirrors is an important feature of the tandem mirror fusion concept.

In the tandem mirror concept, the fusion plasma is contained in a relatively long cylindrical region where it is confined by a uniform axial magnetic field. Passing an electric current of the same strength through several coils surrounding the cylinder creates this field. This configuration is called a solenoid field. At each end of the solenoid region, is a mirror pair generated by other plasma configurations such as a baseball seam coil. Additional coils are added to provide continuity between the strong fields in the mirror pair end cells and the weaker solenoid field. Figure 3 shows the Tandem Mirror Experiment (TMX) device built at the Lawrence Livermore Laboratory.

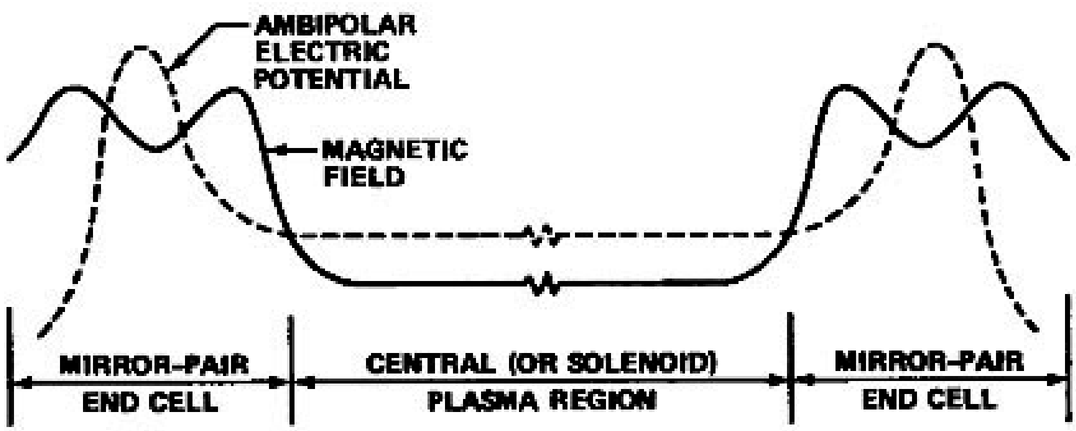


Figure 2. The Tandem Mirror fusion concept, showing the Ambipolar Electrical Potential. A mirror pair end cell is located at each end of a uniform central solenoid field.

A great deal of effort is spent on reducing the rate of loss of plasmas at the end plugs. Methods used included increasing the strength of the mirrors magnetic fields, the use of multiple mirrors, and various types of thermal barriers. The use of field reversed configuration as shown in Fig. 1 has been suggested to partially plugging the throat at the end of the mirror. The requirement for design and operation would thus entail constricting the throat just enough to prevent expulsion of the field reversed configuration plug, instead of attempting to reduce the plasma loss by applying a magnetic field strong enough to severely constrict the throat. Persistent and stable field reversal would be achieved by the superposition of a magnetic field that rotates at a frequency between the electron and ion gyro frequencies.

High temperature plasmas between the mirrors in the end cells are generated using high energy neutral beams injection. The less dense fusion plasma in the solenoid region would be heated by the particles escaping from the end cells.

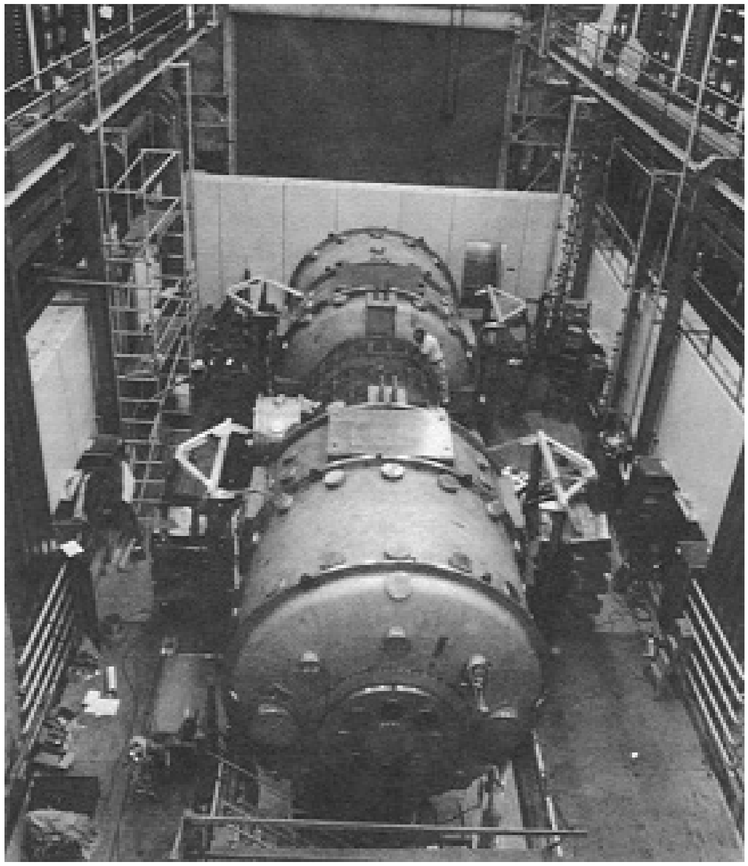


Figure 3. Tandem Mirror Experiment (TMX) device at the Lawrence Livermore National Laboratory (LLNL), USA.

The power generated in the solenoid region is proportional to the volume of the plasma. A typical value of the plasma amplification factor of Q = 5 can be expected, with a large enough volume. Since the end cells can serve as plugs of any plasma volume, the central cell can be made as large as desired without being affected by the size and design of the end cells.

Instead of using neutral beam injection heating, ion cyclotron radiofrequency heating can be used. The neutral beams would thus be smaller in size since they function would be do feed particles rather than feeding both particles and energy to the end plugs. Better control on plasma heating can be achieved this way, since the heating does not have to occur in the end plugs, but can also be done in the solenoid region.

TOKAMAK DESIGN

The Tokamak design was introduced by the Russian scientist Basov, and since then it has become the leading magnetic confinement concept. Tokamak in Russian stands for: Toroidal magnetic chamber. One early Tokamak was the T-15 design at the Khurchatov Institute in Moscow (Fig. 4).

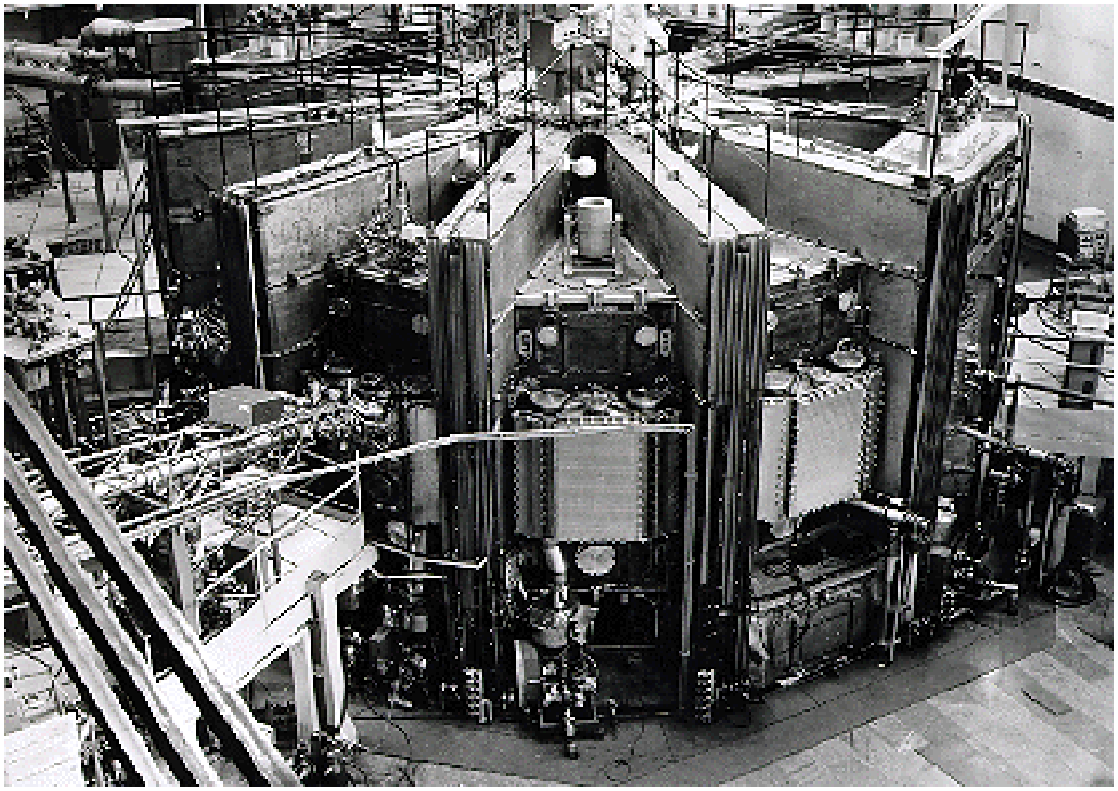


Figure 4. The T-15 Tokamak at the Khurchatov Institute, Moscow, showing its transformer coils.

To construct the magnetic field bottle in a Tokamak requires the generation of three superimposed magnetic fields:

1. The Toroidal Field, B_t:

First, a ring-shaped toroidal field is produced by the plane external magnets.

2. The poloidal Field, B_p:

Second, the poloidal field is generated from the plasma current I_p flowing in the plasma itself. The field lines of the combined field toroidal and poloidal fields are then helical. This is what produces a basket weave twisting of the field lines and formation of magnetic surfaces, which are necessary for confining the plasma (Fig. 5).

3. The vertical field B_v:

A third, vertical field fixes the position of the current in the plasma and prevent a drifting of the plasma due to the magnetic field gradient from the region of high magnetic field on the inside of the toroid to the region of lower magnetic field on its outside (Fig. 6).

The plasma current I_p is normally induced by a transformer coil. This is why a Tokamak does not operate in the steady state, but in a pulsed mode. In a transformer it is only for a limited time that an increasing current can be generated in the primary winding so that a current can be driven in the plasma. The transformer must then be discharged and the current started up afresh. In order to achieve steady state operation in a future Tokamak power plant, methods of generating current in a continuous mode, for instance by means of high-frequency microwaves must be adopted.

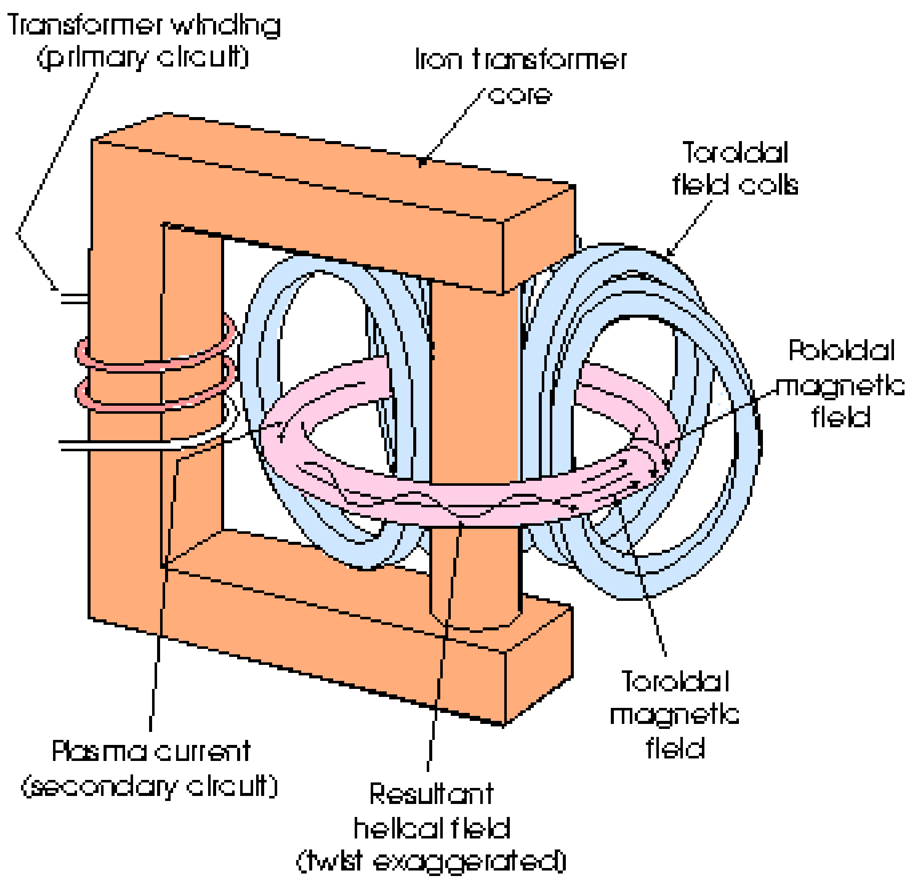


Figure 5. Tokamak concept showing the transformer core, toroidal field coils and toroidal magnetic field, poloidal magnetic field and the resultant helical field.

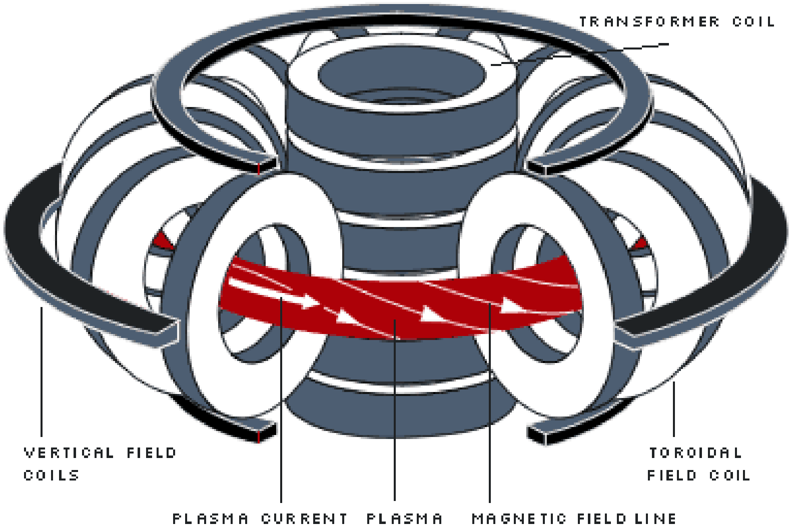


Figure 6. Overall Tokamak configuration showing an air core transformer coil and the vertical field coils.

STELLARATOR TOROIDAL DESIGN

Stellarators are three-dimensional toroidal plasma confinement devices that rely on a numerically determined plasma surface shape in order to achieve optimized plasma confinement, stability and steady state operation (Fig. 7).

In a stellarator the magnetic bottle is produced with a single coil system, without a longitudinal net-current in the plasma and hence without a transformer. This makes stellarators suitable for continuous operation, whereas Tokamaks without auxiliary facilities must be operated in the pulsed mode.

The elimination of the need for the toroidal plasma current I_p means the abandoning of the axial symmetry present in Tokamaks. As the helical twisting of the toroidal field lines is achieved solely with the external coils, the later have to be twisted accordingly. This results in the magnet coils and plasma having a complicated shape. This affords additional freedom in shaping the magnetic field and making it properties accessible to optimization.

For a fusion power plant stellarators could provide a technically simpler solution than what tokamaks might achieve. The absence of the transformer coils in the center provides room for the radiation shielding of the coils in a power reactor situation.

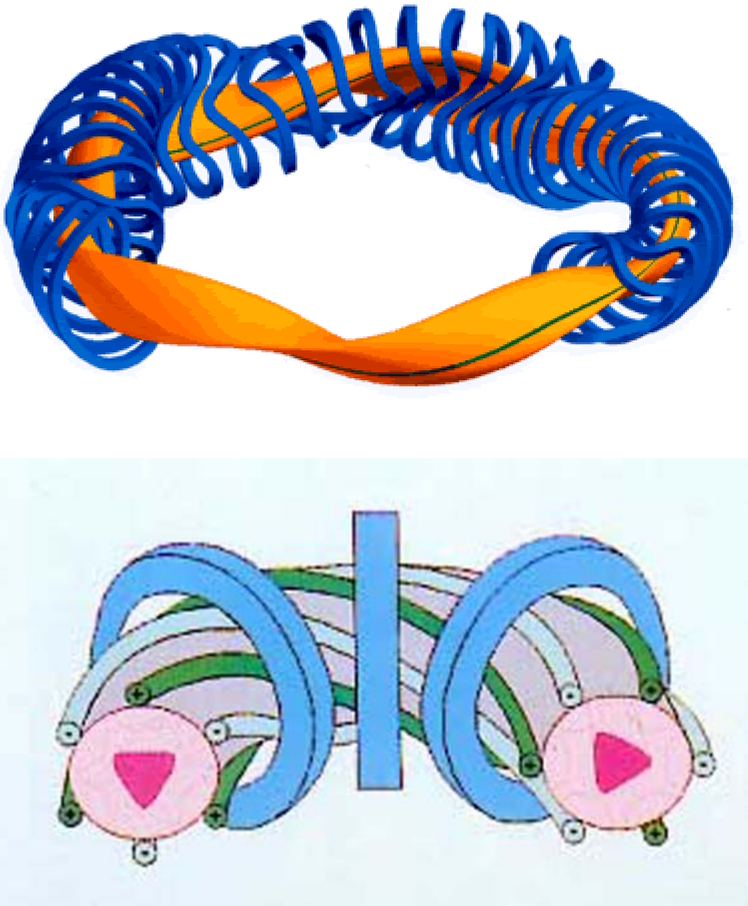


Figure 7. Two possible configurations for the Stellarator coils and magnetic field. In the lower configuration, toroidal coils and helical poloidal coils generate the resulting twisted toroidal magnetic field.

MAGNET COILS

The sophisticate shaped coils for the Stellarator devices are fashioned differently from the pancake coils for the Tokamak (Fig. 8). Instead of rigid copper rails one uses here more flexible copper strands embedded in winding forms. Mechanical strength is provided by fiber glass bands and synthetic resins.

The superconducting coils are made of a niobium-titanium and are capable of producing magnetic fields of about 6 Teslas in strength on the coils and about 3 Teslas on the magnetic field axis.

The superconducting material is embedded as thin strands in copper wires braided to form a cable. Cryogenic cooling with liquid helium to 4 ^{o}K is necessary for the superconducting coils. The liquid helium flows between the individual wires through the cable cavities. For this purpose the cable is enclosed by a helium-tight aluminum sheath. During the winding process the sheath material is soft and flexible and can be annealed afterwards. With fiber glass and synthetic resins reinforcement, the necessary mechanical strength overcoming the stresses generated by the powerful magnetic field is achieved.

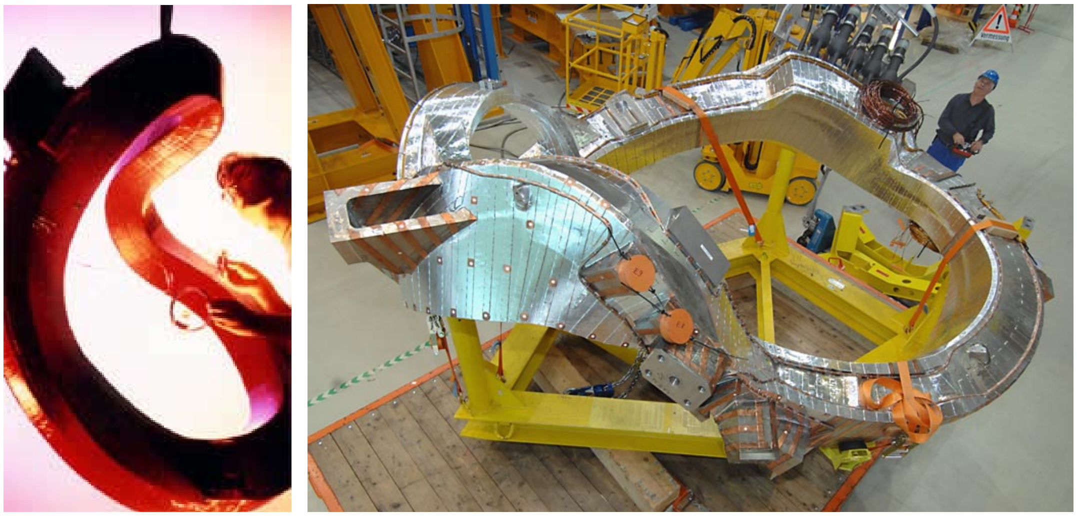


Figure 8. A single superconducting magnet coil for the 7-X Stellarator at Wendelstein, Germany.

PLASMA VESSEL

Although the plasma is confined by a magnetic field, it has to be produced in a vacuum vessel, which prevents both admission of air and escape of fuel. Small amounts of incoming air would immediately extinguish and quench an ignited plasma. The vessel has to be vacuum-tight and capable of being pumped down to an ultra high vacuum pressure of less than 10^{-8} millibar.

To withstand the high loads due to pressure and magnetic forces that can be caused by locally induced currents, high-grade steel that serves as vessel material. For instrumentation, heating and control facilities the vessel requires numerous apertures and ports (Fig. 9).

Figure 9. Inside of vacuum vessel of the Tore Supra Tokamak at Cadarache, France.

PLASMA BOUNDARY AND DIVERTORS

In contrast to a Tokamak, no additional magnet system is needed to divert the plasma boundary in a Stellarator (Fig. 10). The plasma boundary splits in keeping with the symmetry of the magnetic field into individual offshoots through which energy and particles move to limited areas of the vessel wall, just like the divertor plasma in a Tokamak. These areas of the wall are protected by special collector plates: typically ten of them along the plasma column. Here the incident particles, together with the undesirable impurities from the plasma, can be neutralized and pumped off. This greatly facilitates impurity and density control; the plasma power can be sparingly distributed on the collector plates by radiation.

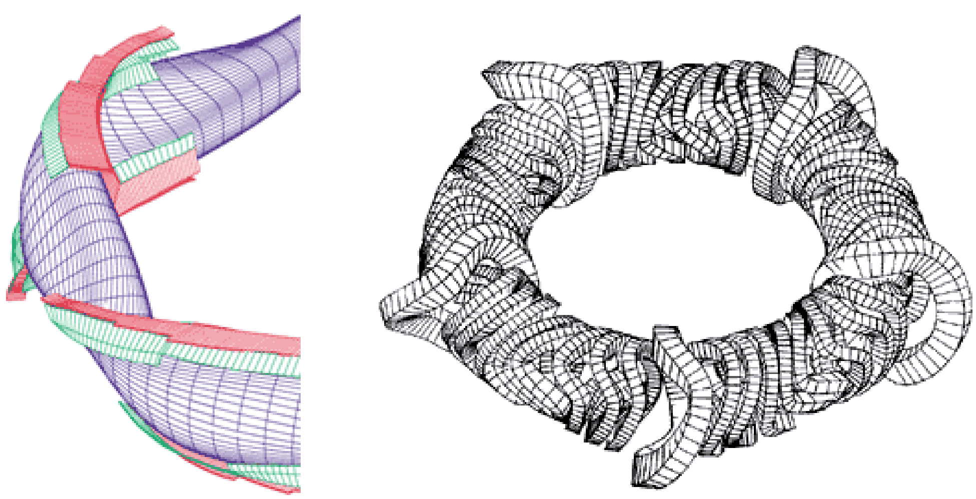


Figure 10. Divertor and coils of the 7-X Stellarator.

PLASMA REFUELLING

A plasma limited by a divertor keeps losing plasma particles, which are removed together with impurities by the divertor pumps. In a future fusion power plant the ash from the thermonuclear fusion process, helium, will also be removed in this way. There are various refueling methods: gas puffing from the edge of the vessel, neutral particle injection, and pellet injection. In the latter, the deuterium and tritium gas is cooled until it freezes and pellets a few millimeters in diameter can be formed. After being accelerated in a gas gun or a centrifuge, they are injected into the hot plasma at a rate reaching 20 pellets per second, where they again evaporate and the individual atoms are ionized.

PLASMA DISCHARGE

In a stellarator plasma discharge, first the modular magnetic field is switched on, its confinement properties already being present without the plasma. As in the Tokamak, hydrogen gas is admitted to the empty vessel just before the discharge. The plasma, however, is produced not by induction of a peripheral voltage and the ensuing plasma current, but by beaming in high-frequency electromagnetic waves or by neutral particles injection. The high frequency waves accelerate and heat the electrons in the hydrogen gas or in the evolving plasma, where they then completely ionize the gas through collisions.

As the slow and controlled current build-up occurring in the Tokamak is absent, the initial phase of the discharge is governed solely by the density build-up, so that the flat-top phase so crucial for plasma experiments is quickly reached. It is the heating time alone that determines the end of the discharge, thus making steady-state operation possible in principle.

PLASMA DIAGNOSTICS AND MEASUREMENTS

The extreme conditions in a fusion plasma call for special measuring methods for investigating it state in terms of temperature, density, energy content, currents in the plasma, impurities, etc. One generally tries to determine the properties of the plasma without perturbing it by investigating the effects exerted by the plasma on the outside. These are magnetic or electric fields, charged or neutral particles, and electromagnetic waves which the plasma emits in a wide spectral range from the radiofrequency to the x ray regions.

Besides these passive methods, active methods are also applied insofar as one can be sure that they do not change the state of the plasma. A particularly useful technique is to beam in laser light or microwaves, which can be influenced by the plasma and thus provide information on its properties. Particle beams are also used for diagnostics. To avoid systematic measuring errors various methods are applied to measure the same physical quantities. The diagnostic methods used in the tokamak and are basically similar.

PLASMA HEATING

Until ignition, the plasma in magnetic confinement has to be externally heated. Several methods are available for this purpose:

Current or Ohmic Heating

When an electric current I_p is passed through the electrically conductive plasma, it generates heat in the plasma through its resistivity R (Fig. 11). As this resistance decreases with increasing temperature, this method is only suitable for initial heating and is called Ohmic Heating. According to Ohm's law the heating energy is:

$$E = I_p^2 R \tag{4}$$

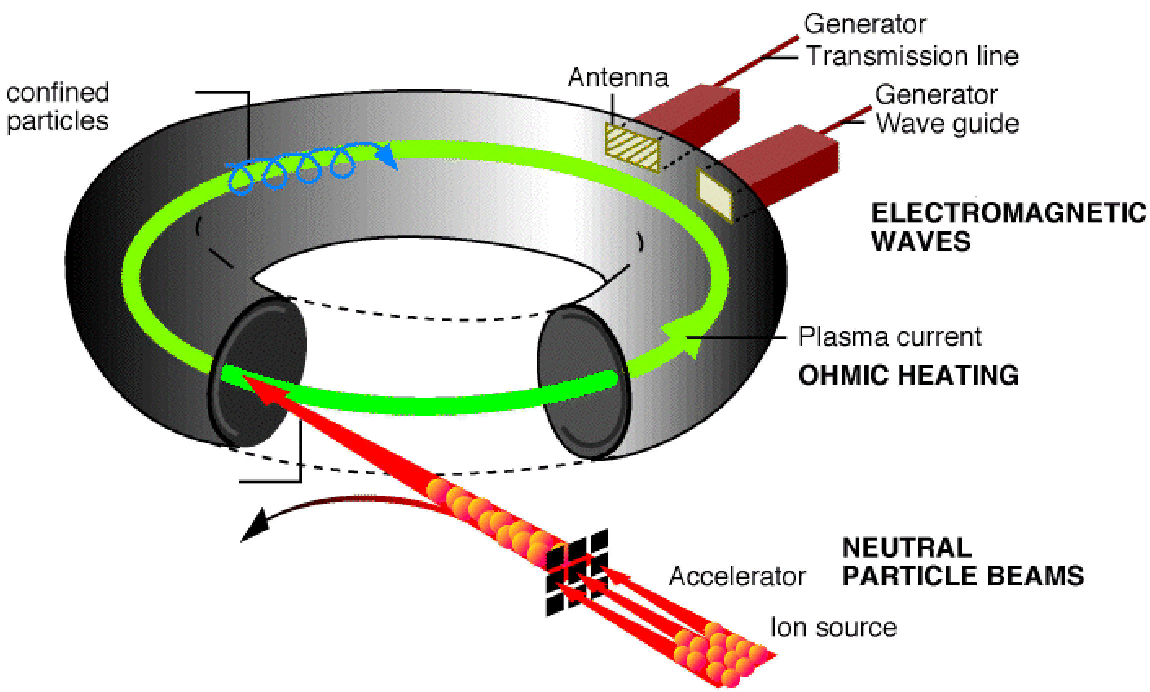


Figure 11. Plasma heating methods.

Microwave or high frequency heating

Electromagnetic waves of an appropriate resonant frequency are beamed into the plasma, the plasma particles absorb the energy from the field of the wave and transfer it to the other particles through collisions. The circular motions of the ions and electrons around the magnetic field lines are associated with suitable resonances. The orbital frequency of the ions is between 10 and 100 megahertz, that of the lighter electrons between 60 and 150 gigahertz (Fig. 12).

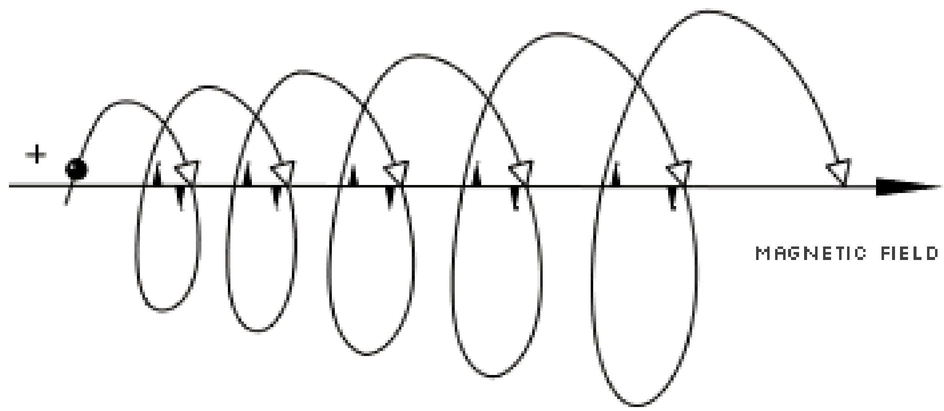


Figure 12. High frequency microwave plasma heating.

The Microwave heating antenna inside the Tore Supra device at the Cadarache, France research center is shown in Fig. 13.

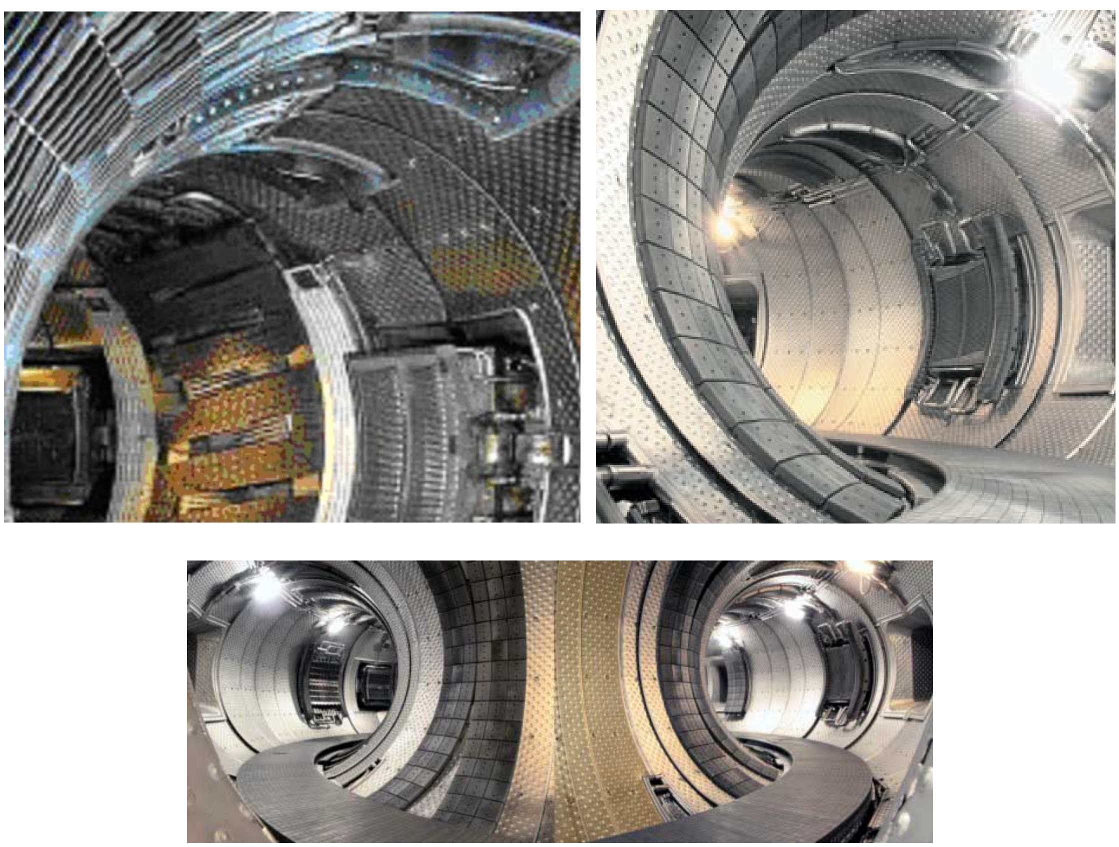


Figure 13. Tore Supra, Cadarache, France, microwave heating antenna, 2002.

Neutral particle heating

Particles with high kinetic energy that are injected into the plasma transfer their kinetic energy to the plasma particles through collisions and heat them. In a neutral particle injector first the ions are produced in an ion source and then accelerated by an electric field. To allow the fast ions to penetrate into the plasma without hindrance from the magnetic field, first they have to be neutralized. The neutralized particles are shot into the plasma and transfer their energy to the plasma particles through collisions (Fig. 14).

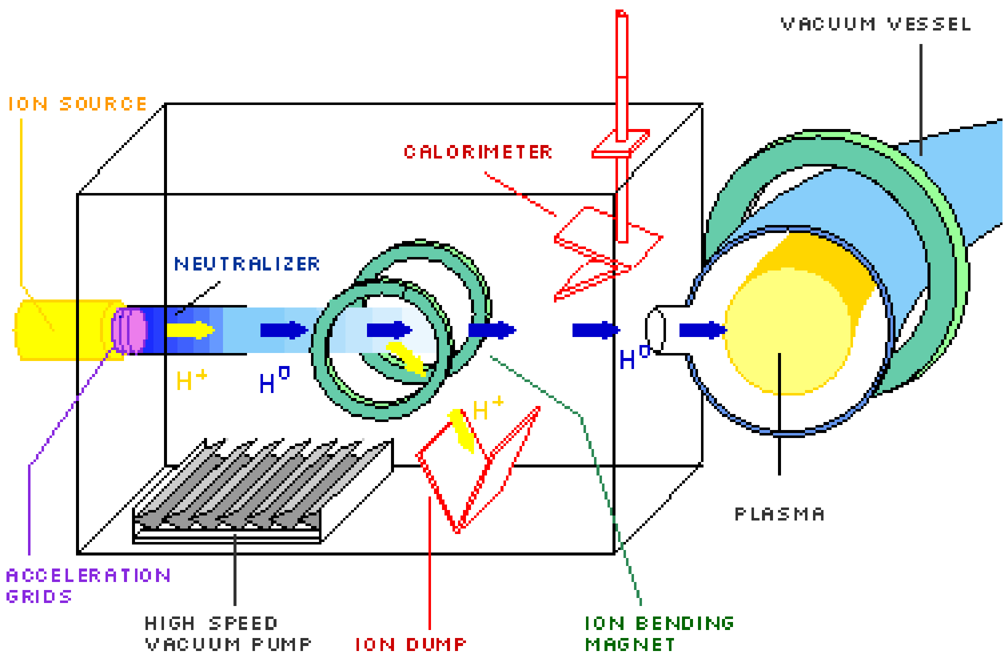


Figure 14. Neutral particle beam heating of a plasma.

WALL IMPURITIES AND DIVERTOR

Wall atoms sputtered from the wall of the plasma vessel by plasma particles can enter the plasma and contaminate it. Unlike light hydrogen atoms, however, the heavy atoms of the elements iron, nickel, chromium, oxygen, and the like, are not completely ionized even at the high fusion temperatures. The higher the atomic number Z of these impurities, the more electrons are still bound to the atom; the more strongly they radiate energy from the plasma as synchrotron radiation and reemit it as ultraviolet radiation or x radiation. In this way they cool the plasma, rarefy it, and thus reduce the fusion yield.

In order to protect the vessel from particles leaking from the plasma and, conversely, the plasma from impurities sputtered off the wall, a special magnetic field directs the plasma boundary layer to an specially equipped area of the vessel wall: the divertor plates (Fig. 15). It is thus possible to remove the disturbing impurities from the plasma. At the same time, the vessel wall is spared and good thermal insulation of the plasma is achieved (Fig. 16).

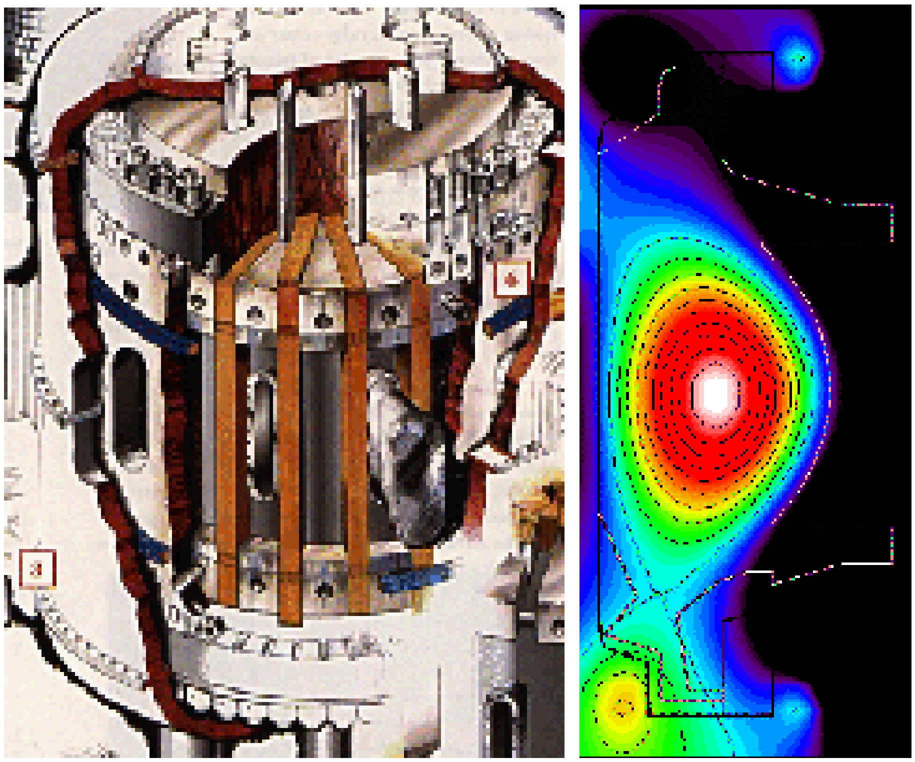
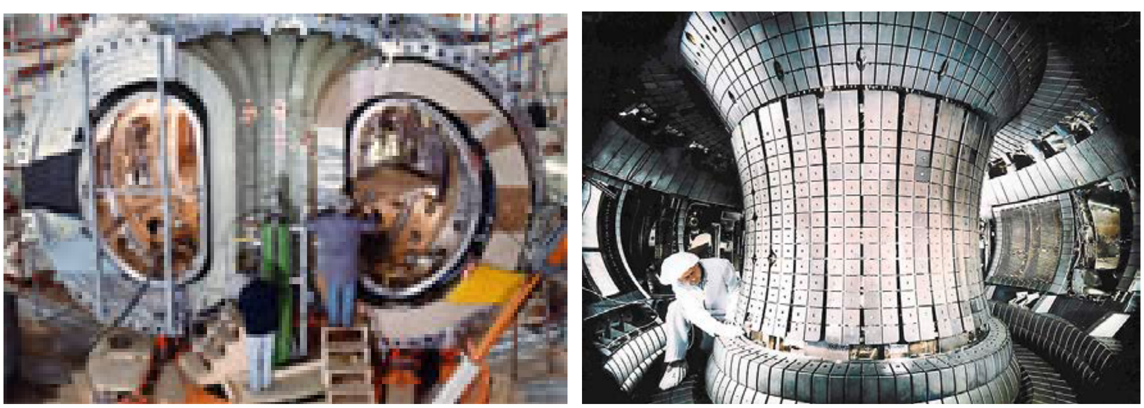


Figure 15. ALCATOR, MIT Tokamak plasma shape showing the divertor at the bottom left.



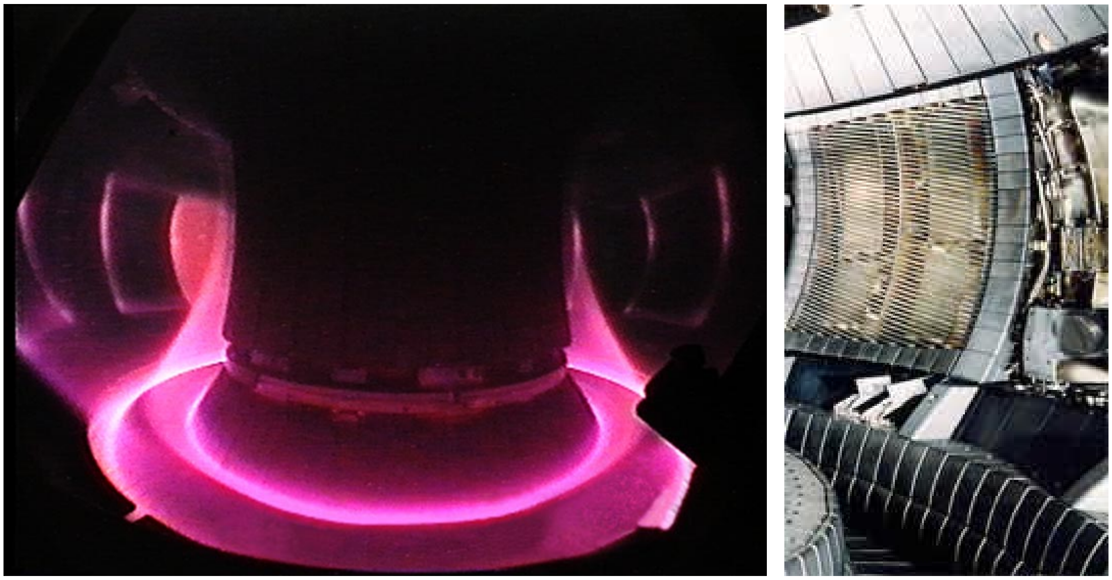


Figure 16. Asdex-U plasma and divertor plates inside reactor vessel at the Max-Planck Institut, Germany.

PLASMA INSTABILITIES

A process is said to be unstable when an initially slight perturbation induces a force that intensifies this perturbation. Such instabilities can hamper plasma confinement. They lead to undesirable deformation of the confinement geometry and - at worst a disruption of the plasma discharge.

The number of instabilities possible is very large. Identifying their causes and finding remedies was one of the main fields of fusion research.

MATERIALS CHOICES

The aim of materials research is to produce and further develop new materials for the special conditions in fusion devices. For particularly exposed areas of the plasma vessel, such as the divertor and the first wall, materials and coatings are needed which are heat resistant, thermally conductive, and resistant to physical and chemical erosion.

Of importance in a future power plant environment is the energy wall loading exerted by the high energy DT fusion neutrons. They penetrate the first wall and the blanket, where they deposit their kinetic energy. In the process they activate the materials and induce perturbations such as swelling, creep, solidification, and embrittlement. The objective of development work is materials with high resistance and low activation. Their composition should make activation as low and quickly decaying as possible, thus allowing simple re use or disposal.

MAGNET COILS DESIGN

Most fusion devices feature normally conducting magnet coils made of copper. For cooling purposes they are provided with bores to allow the passage of cooling water.

The windings are insulated with fiber glass bands and molded in synthetic resins, to connect them together and give the coil the necessary mechanical strength. The coil can thus withstand the strong forces exerted between the coils after the coil current is switched on.

A future fusion power plant will operate with superconducting coils. Unlike copper coils, superconducting coils, cryogenically cooled to low temperatures, use little energy after being switched on; and the coil current flows with almost no resistivity losses.

MAGNETIC FUSION EXPERIMENTS

TOTAMAK FUSION TEST REACTOR, TFTR

The Tokamak Fusion Test Reactor (TFTR) operated at the Princeton Plasma Physics Laboratory (PPPL) from 1982 to 1997. TFTR set a number of world records, including a plasma temperature of 510 million degrees centigrade, the highest ever produced in a laboratory, and well beyond the 100 million degrees required for commercial fusion. In addition to meeting its physics objectives, the TFTR achieved all of its hardware design goals, thus making substantial contributions in many areas of fusion technology development (Fig. 17).

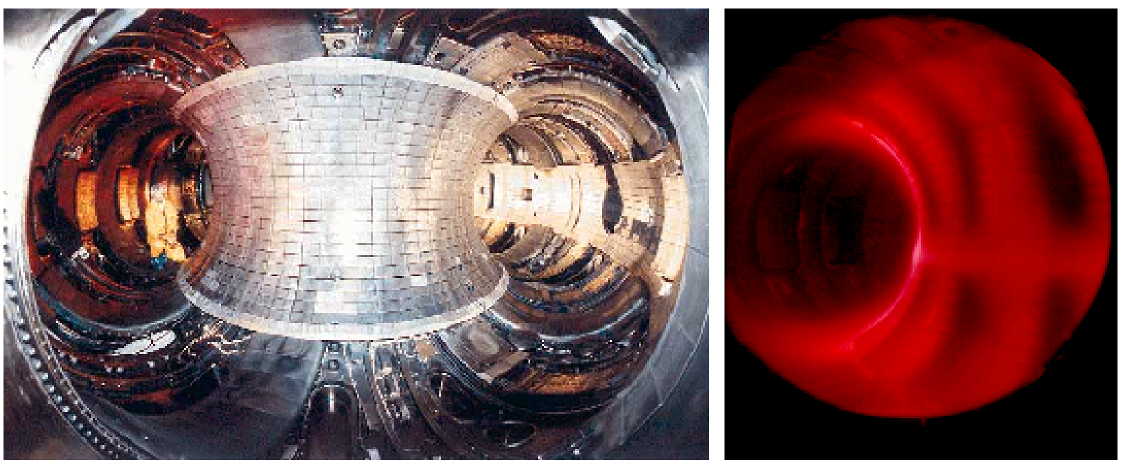


Figure 17. Plasma vessel of the Tokamak Fusion Test Reactor, TFTR, Princeton, USA, 1989.

In December, 1993, TFTR became the world's first magnetic fusion device to perform extensive experiments with plasmas composed of 50/50 deuterium/tritium, the fuel mix required for practical fusion power production. Consequently, in 1994, TFTR produced a world-record 10.7 million watts of controlled fusion power, enough to meet the needs of more than 3,000 homes. These experiments also emphasized studies of behavior of alpha particles produced in the deuterium-tritium reactions. The extent to which the alpha particles pass their energy to the plasma is critical to the eventual attainment of sustained fusion.

In 1995, TFTR scientists explored a new fundamental mode of plasma confinement; enhanced reversed shear. This new technique involves a magnetic-field configuration which substantially reduces plasma turbulence.

JOINT EUROPEAN TORUS, JET TOKAMAK

In the European Community's Joint European Torus (JET) Tokamak device, the product of temperature, density, and energy confinement time attained is only a factor of 5 short of the ignition criterion (Figs. 18, 19).

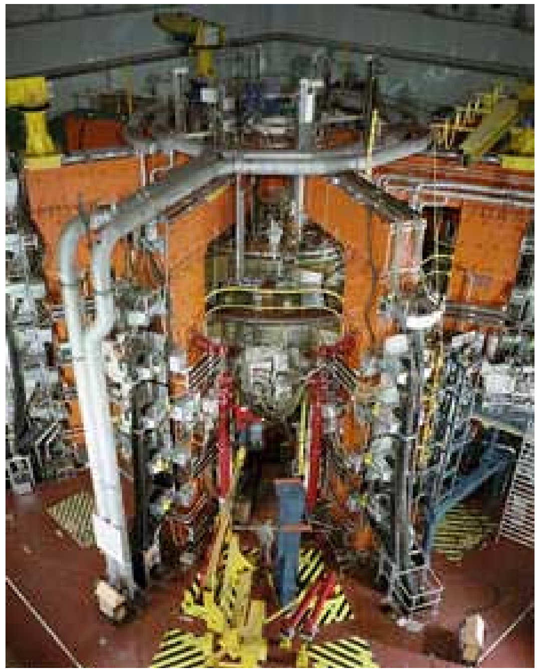


Figure 18. View of the Joint European Torus (JET) Tokamak.

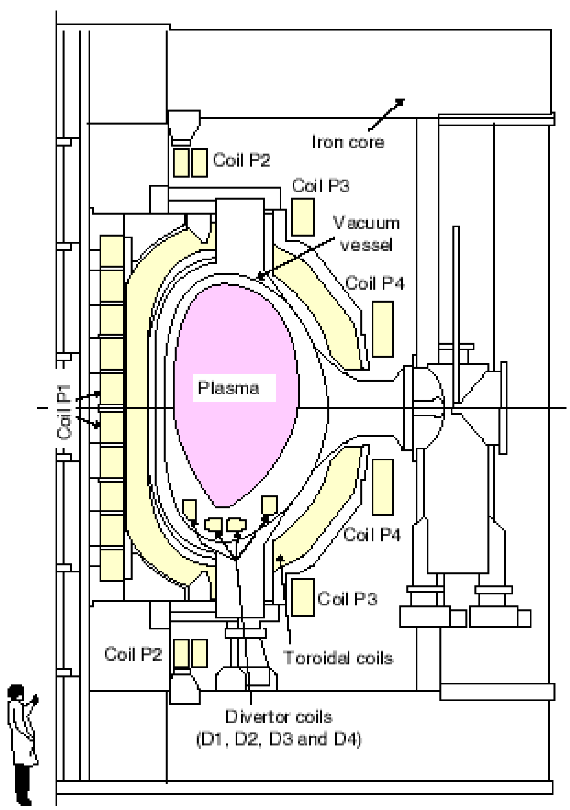


Figure 19. Cross section of the Joint European Torus Tokamak, JET.

In the early 1970's, following a series of successful small-scale experiments, discussions within the European fusion research program were taking place on a proposal to build a much larger experiment of the tokamak system. In 1973, agreement was reached to set up an international design team which started work in the UK later that year.

By the latter half of 1975, the design had been completed and accepted by the partners. Following lengthy discussions on the site of the project, the European Council of Ministers agreed in October 1977 that JET should be built at Culham, near Oxford in the UK. The JET Joint Undertaking was established in June 1978 to construct and operate the Joint European Torus.

The JET machine is a large tokamak device of approximately 15 meters in diameter and 12 meters high. At the heart of the machine there is a toroidal vacuum vessel of major radius 2.96 meters with a D-shaped cross-section 2.5 metres by 4.2 meters. 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.

A complex system of magnetic fields prevents the plasma from touching the walls of the vacuum vessel as such contact would quench the plasma and stop the reactions. The main component of the magnetic field, the so-called toroidal field, is provided by 32 D-shaped coils surrounding the vacuum vessel. This field combined with that produced by the current flowing in the plasma, the poloidal field, form the basic magnetic fields for the tokamak magnetic confinement system. The massive forces created when the toroidal coils are energized are resisted by a tightly-fitted mechanical shell.

Additional vertical coils positioned around the outside of the mechanical shell are used to shape and position the plasma.

During most operations of the machine a small quantity of hydrogen or deuterium gas is introduced into the vacuum chamber and it is heated by passing a very large current of up to seven million amperes for a pulse time of up to 30 seconds through the gas creating a high temperature plasma. The current is produced using a massive eight-limbed transformer. A set of coils around the centre limb of the transformer core forms the primary winding and the ring of plasma is the secondary. Currents up to 3 MA have been produced by a different method using radio frequency waves. This has the advantage of not being confined to pulsed operation as is the transformer action.

Plasma temperatures of 40-50 million degrees Celsius were routinely achieved by this heating method during the first phase of operation. Progressive amounts of additional heating have been provided in subsequent phases of JET operation by injecting beams of energetic hydrogen or deuterium atoms into the plasma (21MW) and by the use of high power radio frequency waves(20MW). Plasma temperatures in excess of 300 million degrees Celsius have been achieved.

The problem of impurities must be solved for a fusion reactor, and in particular for the International Thermonuclear Experimental Reactor (ITER) which is expected to succeed JET. The problem of impurities and the power exhaust has been fully recognized in the design of ITER for which a divertor has been incorporated for this purpose. The JET program is now studying divertor plasmas and in particular high power, deuterium-tritium plasmas. This required the installation of a pumped divertor inside the torus. The construction of the pumped divertor was a major undertaking for the project. Following successful experiments the design of the divertor is being progressively optimized by further modifications. In 1997 a new divertor structure has been installed during a further 10 month shutdown. It allows remote handling installation of various divertor "target" designs.

Essentially the divertor consists of four large coils in the bottom of the torus on which the carbon-tiled or beryllium target plates are assembled. Alongside the outer coil is a cryopump. Currents in the divertor coils modify the main tokamak magnetic field to create a null point of the poloidal magnetic field above the target plate. The bulk plasma is bounded by the last closed field line whilst the edge plasma, called the scrapeoff layer, flows along the outer field lines until intersecting with the divertor target plate.

The impurity atoms resulting from the plasma interaction with the divertor target plates are forced back towards the divertor and thereafter are "pumped" from the system by the cryopump.

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 center 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 stabilizing the position of the plasma inside the vessel.

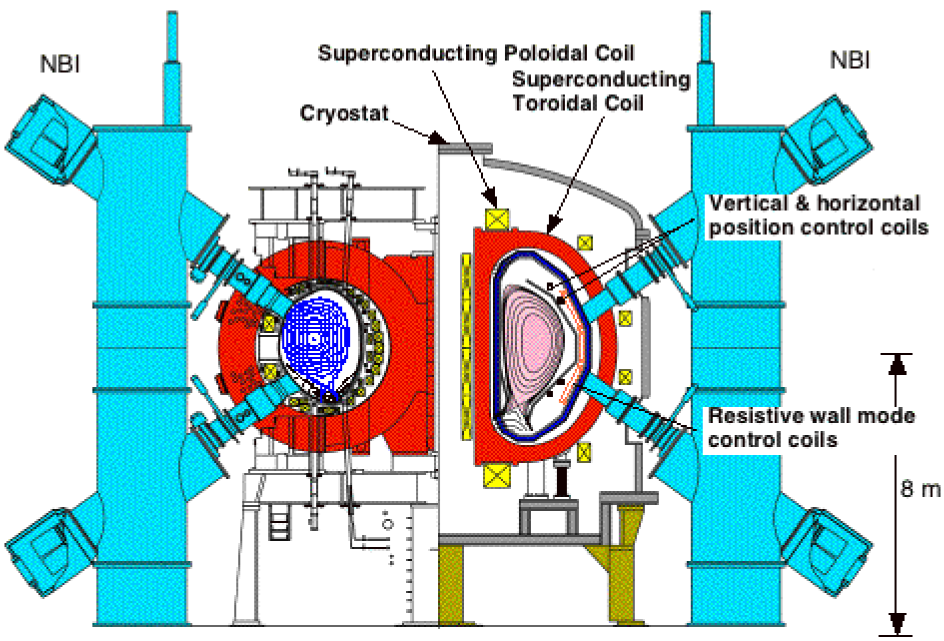


Figure 20. Cross-section of the JT-60 Tokamak.

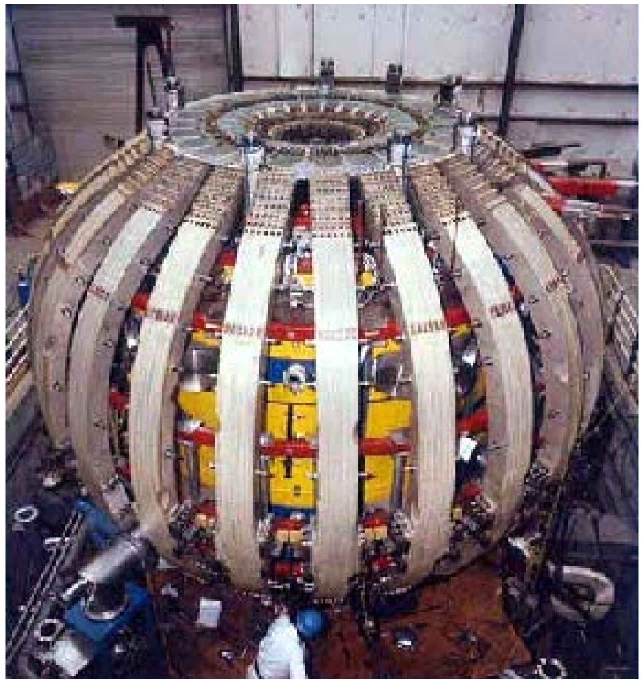


Figure 21. Doublet III-D Tokamak, General Atomics, San Diego, USA.

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 plasma is enclosed within the doughnut shaped vacuum vessel which has a major radius of 2.96 m and a D-shaped cross section of 4.2m by 2.5m. The amount of gas introduced into the vessel for an experimental pulse amounts to less than one tenth of a gram.

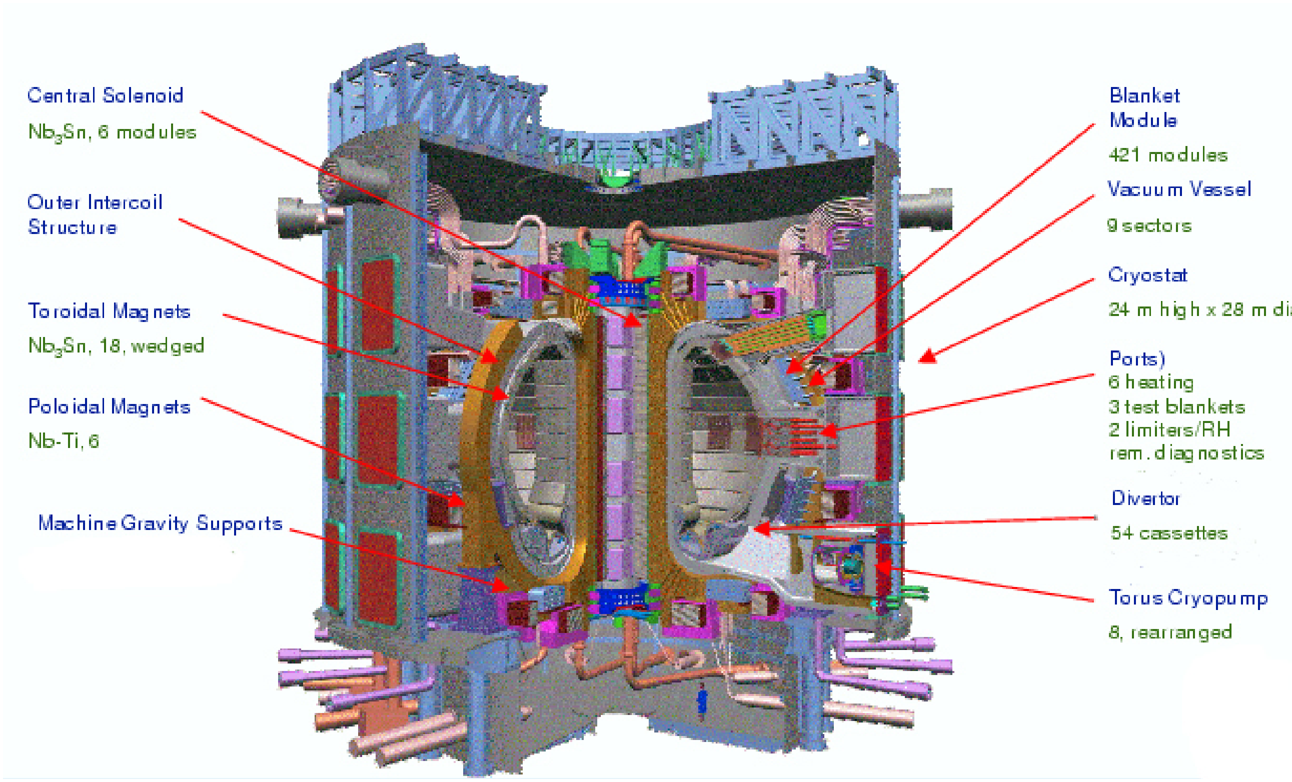
INTERNATIONAL THERMONUCLEAR EXPERIMENTAL TEST REACTOR, ITER.

ITER means: The way, in Latin. ITER is the experimental step between today's studies of plasma physics and tomorrow's electricity-producing fusion power plants. It is based around a hydrogen plasma torus operating at over 100 million °C, and will produce 500 MW of fusion power.

It is an international project involving The People's Republic of China, the European Union (represented by Euratom), Japan, the Republic of Korea, the Russian Federation, and the United States of America, under the auspices of the IAEA.

The first plasma operation is expected in 2015. ITER is a multinational collaboration between all the countries involved in fusion research worldwide. It operates by consensus among the participants. The collaboration involves primarily scientists, who establish the requirements of the experiment and eventually will measure its success, and engineers, who find ways to produce these required conditions safely, reliably and as cheaply as possible, and who in its operation will also gain design information for future fusion power plants.

The niobium titanium superconductor envisaged for the International Thermonuclear Experimental Reactor (ITER) test reactor is to generate a magnetic field of 13 teslas on the coil and 5.7 teslas on the magnetic field axis. The superconducting strands are embedded in copper wires and enclosed in a blanket of high-grade steel. Inside the blanket liquid helium circulates and cools the coils to 4.5 ^oK, close to absolute zero (Fig. 20).



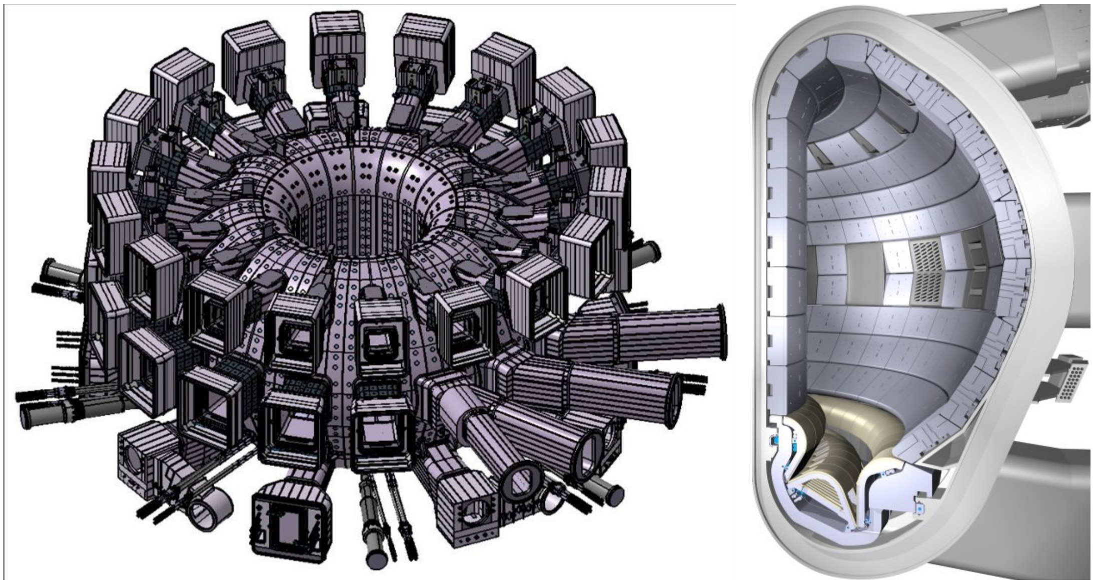


Figure 22. Cross section of the International Thermonuclear Experimental Reactor (ITER).

Figure 23. ITER facility at Cadarache, France. ITER Organization.

THE DEMO REACTOR

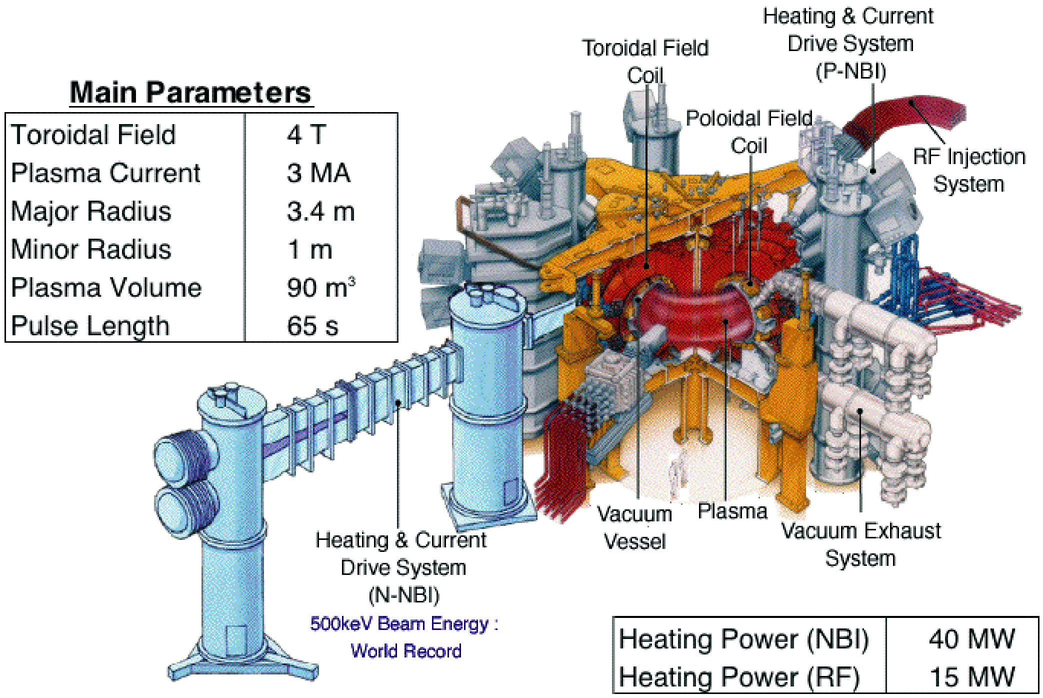


Figure 24. Jaeri JT-60 Tokamak.

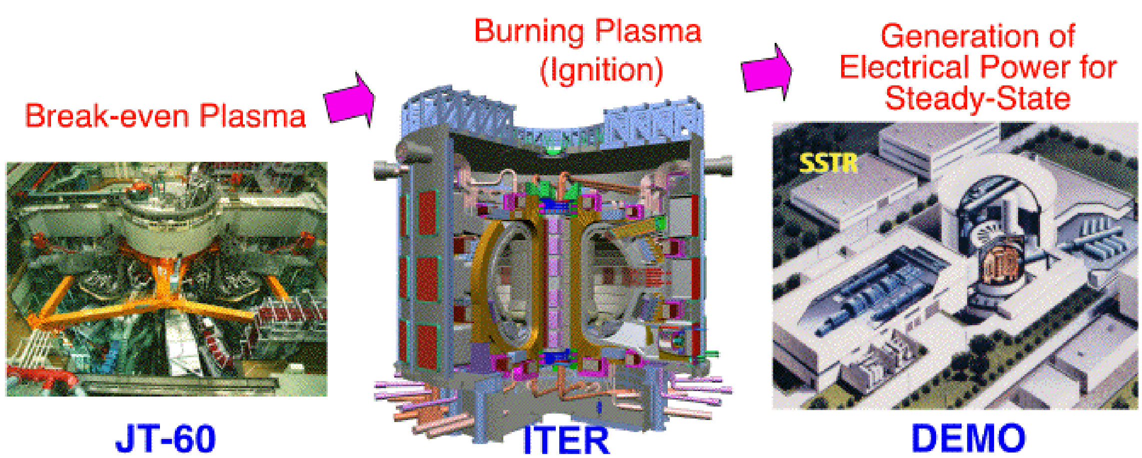


Figure 25. Steps toward controlled fusion.

ITER is planned to operate at a nominal fusion power of 500 MW_t. If DEMO (the next device after ITER, and the first to generate electricity) is to be a device of approximately similar physical size (and hence cost), its fusion power level has to be increased by about a factor of 4, so that the electrical power potentially delivered to the network will be in the range of 500 MW_e, typical of one of today's power stations (albeit rather a small one). The general level of heat fluxes through the walls will be about 4 times higher than in ITER, and plasma performance needs to be improved to gain this 4-fold increase. Calculations show that this performance could be achieved with an ~15% increase in ITER linear dimensions, and an ~30% increase in the plasma density above the nominal expected to be confined by the basic magnetic fields on ITER (this capability can be checked on ITER). It then remains for enough to be learnt on the ITER blanket test beds to allow the DEMO blanket to be designed to withstand 4 times the ITER steady heat loads on those components.

If these systems work successfully on DEMO, DEMO itself can be used as a prototype commercial reactor creating a fast track to fusion. This would accelerate the availability of fusion as an energy option by about 20 years. A further step would no doubt subsequently be made for the first-of-a-series commercial-sized fusion power reactor (PROTO), doubling the electrical power by increasing linear machine dimensions by less than 10%, without assuming any improvement in physical behaviour.

FUSION POWER PLANT LAYOUT AND FUNCTION

The hot DT plasma in a torus shaped plasma chamber is kept away from the first wall by magnetic fields. Till ignition a start up heating system supplies the plasma for a few seconds with a power of 50 to 100 megawatts. The fast helium nuclei resulting from the ensuing fusion reactions are trapped in the magnetic field as charged particles and transfer their energy to the plasma through particle collisions. Ultimately, external heating can be almost totally switched off and the plasma maintains the fusion temperatures through self-heating.

The divertor removes the helium ash emerging from the plasma in order not to extinguish the fusion fire. The electrically neutral neutrons can leave the magnetic field without hindrance. They impinge on the blanket surrounding the plasma vessel, where they breed the tritium fuel from lithium. This fuel is collected and reinjected into the plasma together with deuterium. A 1000 MWe fusion power plant will need about 20 grams of tritium and 13 grams of deuterium per hour.

The blanket also absorbs the energy of the neutrons where they are decelerated in the blanket material, thus heating it. This thermal energy is then converted to electric energy by means of coolants, heat exchangers, and turbogenerators.

The blanket is enclosed in a shield that screens the magnets, heating facilities, and the other surroundings from radiation and neutrons. The entire power plant core is finally enclosed in an external biological shield.

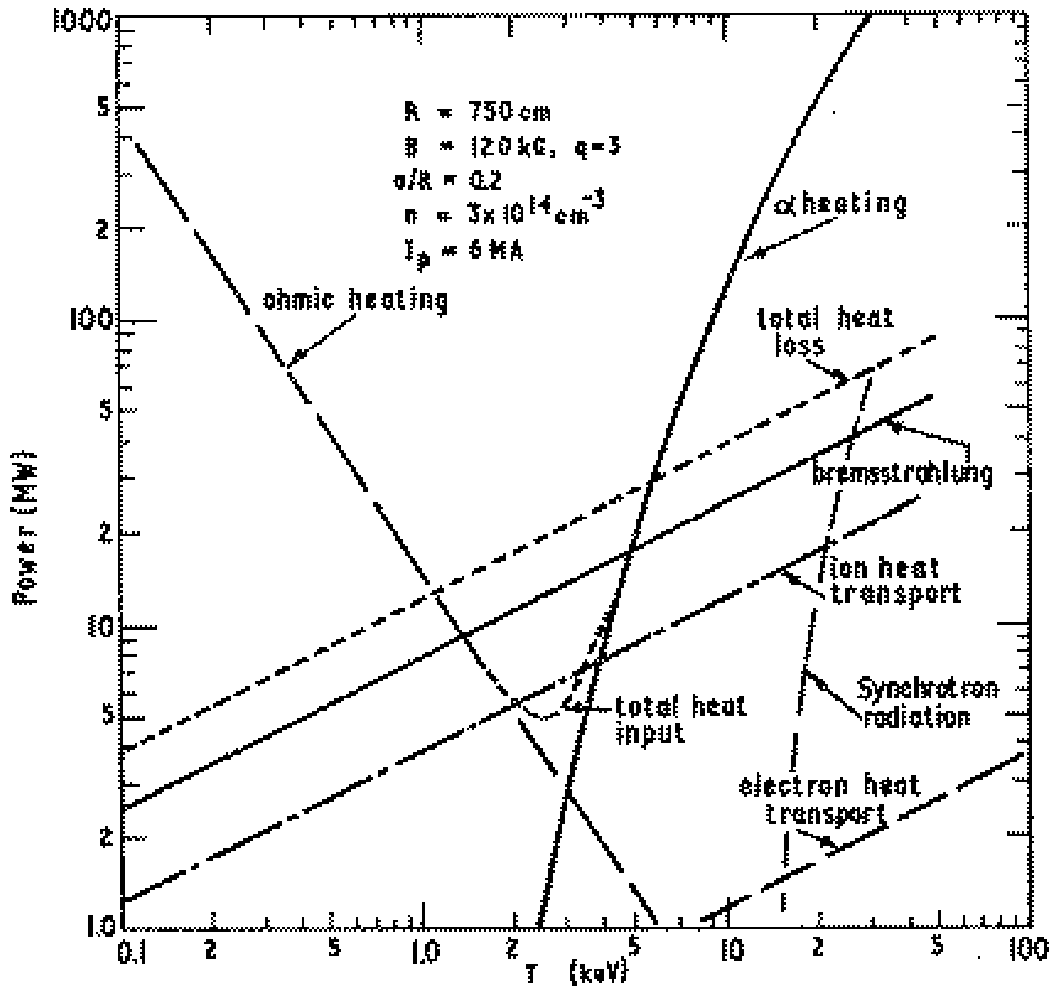


Figure 26. Energy balances in a typical Tokamak.

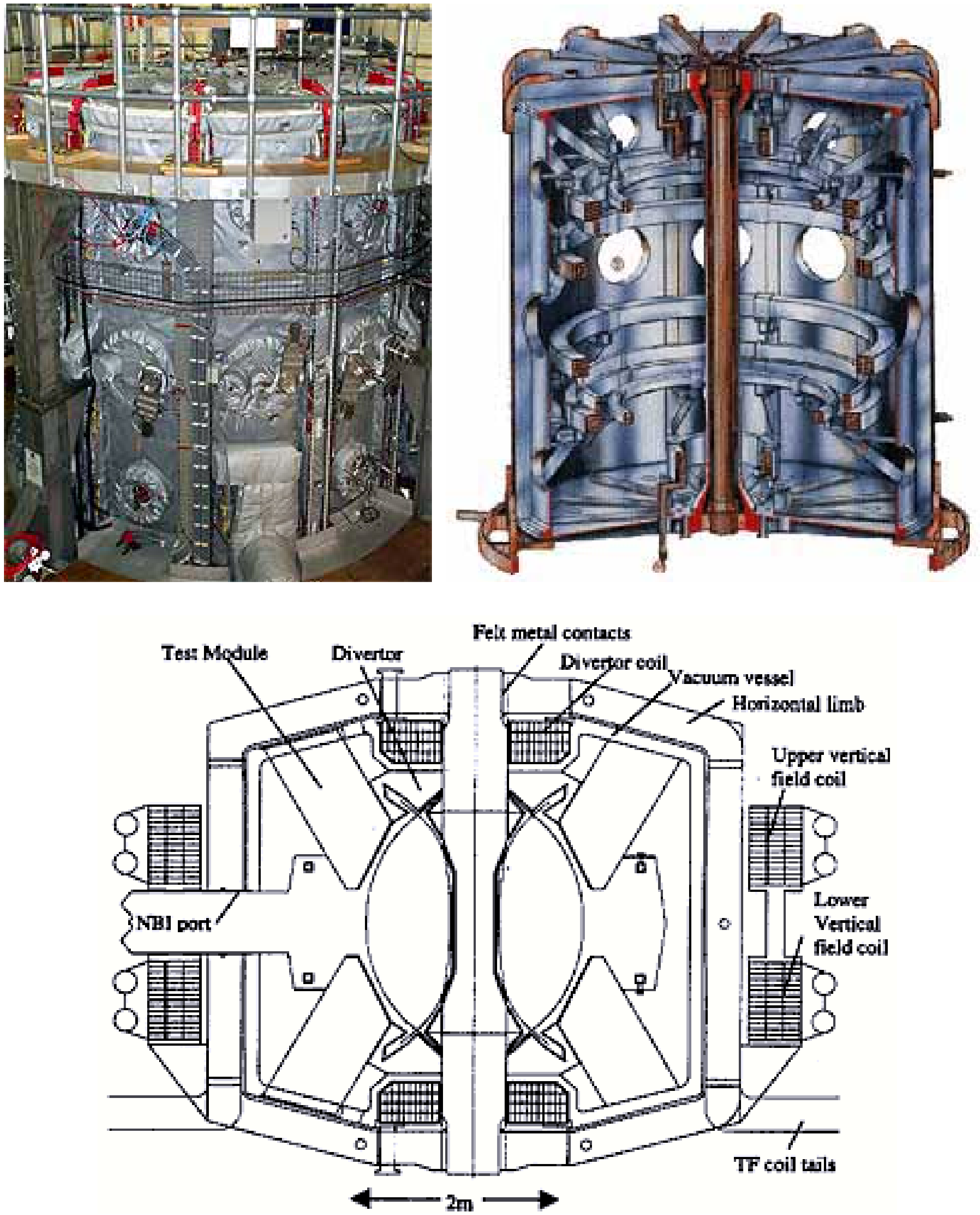


Figure 27. The MAST Tokamak.

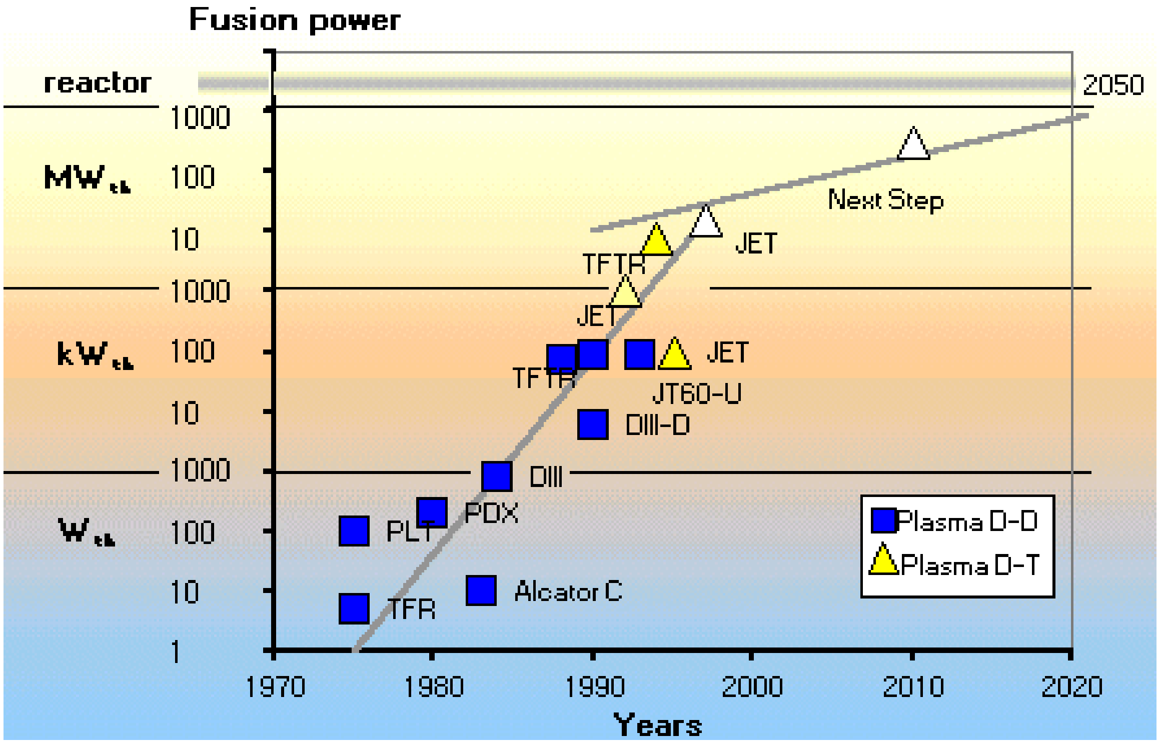


Figure 28. The path towards fusion power production.

CONCLUSIONS

Fusion research and development has continually thrown up new challenges to test the ingenuity and skills of at least two generations of scientists and engineers. There are many challenges still to be faced, and there may be some which are unseen from today's perspective.

The next step in magnetic confinement fusion or ITER is essential to realizing the key technologies of a viable energy source and has to be operated successfully first. Only then will it be possible to check with confidence the accuracy of the prediction of Lev Artsimovitch, grandfather of the Tokamak concept, who said in 1972: "Fusion will be there when society needs it".

REFERENCES

1. W. J. Emrich, Jr., "Field-Reversed Magnetic Mirrors for Confinement of Plasmas," NASA Tech Briefs, March 2001.
2. S. Glasstone, "Fusion Energy," U. S. Department of Energy, Technical Information Center, 1980.