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Fusion: A true challenge for an enormous reward

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Summary. — From nuclear physics we know that energy can be released not only from the fission of heavy nuclei but also from the fusion of light nuclei. Steady progress shows that fusion—one of the few possible options for the future—can be a clean and safe solution for mankind's long-term energy needs, with minimal environmental impact. A source of energy which would be inexhaustible, inherently safe and environmentally friendly, is this not a marvellous prospect? Nuclear fusion has been the energy source of our Sun and the stars in the universe for billions of years. This process requires temperatures of tens of millions of degrees, so extremely high and foreign to our daily experience as to seem out of reach. Nevertheless, these extremely high temperatures are routinely realised in several laboratories all over the world, and since the early 1990s, large amounts of energy have been released in a controlled way from fusion reactions. We are witnessing the birth of a new technology destined to meet the gigantic future energy needs of mankind with minimal impact on the environment.

1. – Fusion reactions in our Sun and on Earth

The dominant fusion reaction in our Sun converting hydrogen into helium is the p-p fusion chain, the other being the carbon-nitrogen-oxygen or CNO cycle. The CNO cycle is dominant in stars that are about 1.3 times heavier than our Sun, and only about 1.7% of the ^{4}He nuclei in the Sun are estimated to originate from the CNO cycle.

At first glance it seems easy to overcome the repulsion of the positively charged nuclei involved in those reactions. Why not simply provide the nuclei with sufficient energy in a particle accelerator and let them collide? Unfortunately, the probability for a fusion reaction is extremely small. Rather than fuse, the nuclei are scattered in all directions and only very few fusion reactions take place.

Our Sun offers a promising solution: its whole mass of gas is at a high temperature enabling a much larger number of fusion reactions to occur per unit of time. Gravity is responsible for confinement and heating of the fusing protons. An estimate of the temperature in the centre of the Sun can be found from the observation that the protons need to be sufficiently fast (*i.e.* have sufficient energy and thus be sufficiently hot) to overcome the compressional forces from gravitation. This means kinetic energy of a proton in the centre = potential energy from gravity, or

$$\frac{3}{2}kT_{\text{proton in centre}} = \frac{Gm_{\text{proton}}M_{\text{Sun}}}{R_{\text{Sun}}}, \tag{1}$$

$$T_{\text{proton in centre}} = \frac{2Gm_{\text{proton}}M_{\text{Sun}}}{3kR_{\text{Sun}}}, \tag{2}$$

with $k = 1.38 \times 10^{-23}$ J/K Boltzmann's constant, $G = 6.67 \times 10^{-11}\,\text{Nm}^2/\text{kg}^2$ the gravitational constant, $M_{\text{Sun}} = 1.989 \times 10^{30}$ kg and $R_{\text{Sun}} = 695\ 500\,\text{km} = 6.955\ 10^8$ m (more than 2 times the distance Earth-Moon...) we obtain

$$T_{\text{protons in centre}} = 1.56 \times 10^7\,\text{K} = 15.6\,\text{MK}. \tag{3}$$

Fusion of heavier nuclei in stars will occur at higher temperatures. From the formula above, it is immediately clear that a contraction of the star under its own gravity will further raise the central temperature. Fusion in heavy stars will continue to keep the star alive as long as the reactions are exothermic and thus are able to help the star defend itself against a full collapse under its own gravity. The mass defect curve (fig. 1) shows that energy can be gained from fusion reactions up to ^{62}Ni, which is the tightest bound nucleus [1]. Once the star tries to fuse heavier nuclei, gravity finally wins, and a collapse of the star follows. This ends in a spectacular supernova, leading to a neutron star or for the heaviest stars, the formation of a black hole.

Back to our Sun now, even at ~ 15 MK the p-p and CNO fusion reactions have still a much too low reaction rate to be useful on Earth. One of the underlying reasons is that to allow for the formation of a ^{4}He nucleus two protons have to be converted into two neutrons, involving a rather slow beta-plus decay reaction. Despite this fact, every seconds about 700 million tonnes of H are converted in our Sun into 695 million tonnes of ^{4}He; it thus means that every second about 5 million tonnes of the Sun's mass disappears in the form of light and radiation [2]!

On Earth we have to use nuclear fusion reactions that avoid the conversion from protons to neutrons. A number of fusion reactions [3] together with their cross-sections and energy released are listed in table I. Two points are immediately clear: i) the released

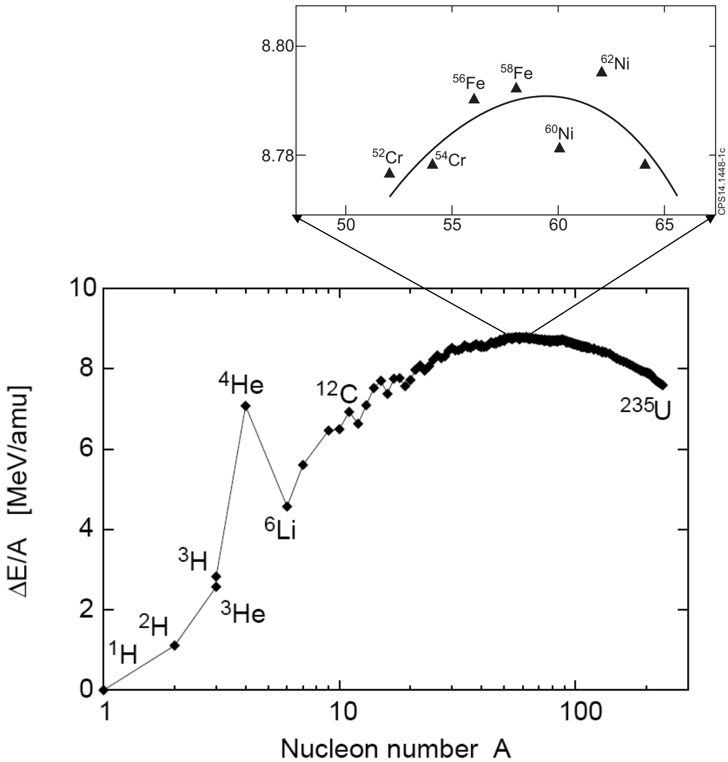

Fig. 1. – Binding energy ΔE per nucleon (in Mev/amu) *versus* nucleon number (logarithmic), for the most stable isotopes, including in addition the unstable tritium nucleus ($A = 3$), because of its importance for the discussions in this paper. Note the exceptionally large binding energy of the ^{4}He nucleus among the light nuclei. The insert shows the details of the maximum of the curve for the binding energy (adapted from ref. [1]). The tightest bound nucleus is that of ^{62}Ni.

energy is the largest in reactions where a ^{4}He nucleus is formed; and ii) reactions with the largest cross-sections are those involving isotopes of H. The first point becomes clear when looking at the curve of the binding energy of the nuclei (fig. 1): among the light nuclei ^{4}He has an exceptionally large binding energy. The second point learns that instead of protons we can use isotopes of hydrogen, which contain already the necessary amounts of neutrons, needed for the formation of ^{4}He. The fusion reaction which combines both properties and that has also the largest cross-section is the so-called D-T reaction:

$$\mathrm{D} + \mathrm{T} \rightarrow {}^{4}\mathrm{He}\ (3.5\,\mathrm{MeV}) + \mathrm{n}\ (14.1\,\mathrm{MeV}), \tag{4}$$

where D symbolizes deuterium (the stable isotope of hydrogen with a nucleus consisting of one proton and one neutron) and T is the symbol for tritium (the radioactive hydrogen isotope with a nucleus of 2 neutrons and 1 proton). In this fusion reaction, “only”

Table I. – *Fusion reactions.*

Reaction	σ at 10 keV (barn)	$\sigma_{\max}$ (barn)	Center-of-mass energy (keV) for $\sigma_{\max}$	Energy released (MeV)
$D + T \rightarrow {}^4He + n$	2.72×10^{-2}	5.0	64	17.59
$D + D \rightarrow T + p$	2.81×10^{-4}	0.096	1250	4.04
$D + T \rightarrow {}^3He + n$	2.78×10^{-4}	0.11	1750	3.27
$T + T \rightarrow {}^4He + 2n$	7.90×10^{-4}	0.16	1000	11.33
$D + {}^3He \rightarrow {}^4He + p$	2.2×10^{-7}	0.9	250	18.35
$p + {}^6Li \rightarrow {}^4He + {}^3He$	6×10^{-10}	0.22	1500	4.02
$p + {}^{11}B \rightarrow 3{}^4He$	4.6×10^{-17}	1.2	550	8.68
$p + p \rightarrow D + e^+ + \nu$	3.6×10^{-26}	–	–	$1.44 + 0.27(\nu)$
$p + {}^{12}C \rightarrow {}^{13}N + \gamma$	1.9×10^{-26}	1.0×10^{-4}	400	1.94

a rearrangement of the nuclides is needed to form ^{4}He, which is clearly much more easy to realize: the cross-section σ for this reaction at *e.g.* 10 keV is about 10^{24} times larger than for the p-p reaction.

The reaction products are a α-particle (^{4}He nucleus) and a neutron. Twenty percent of the reaction energy is taken by the α-particles and 80% by the much lighter neutron. In magnetic confinement systems the neutron does not feel the presence of the magnetic field (because of its neutrality) and escapes immediately the reactor volume, while the charged α-particle is confined. The kinetic energy of these escaping fast neutrons will be converted into heat in a blanket and then into electricity using conventional technology (steam). About one million times more energy is released from a fusion reaction in comparison with a chemical one (MeV's instead of eV's for the latter). This is the reason why so little fuel can produce so much energy: when burnt in a fusion reactor, the deuterium contained in 1 liter of water (about 33 mg) will produce as much energy as burning 260 l of gasoline.

Other possible fusion reactions of interest between isotopes of hydrogen and helium are

$$D + D \rightarrow {}^3He\ (0.82\,\text{MeV}) + n\ (2.45\,\text{MeV}), \tag{5}$$

$$D + D \rightarrow T\ (1.01\,\text{MeV}) + H\ (3.02\,\text{MeV}), \tag{6}$$

$$D + {}^3He \rightarrow {}^4He\ (3.6\,\text{MeV}) + H\ (14.7\,\text{MeV}). \tag{7}$$

These are more difficult to achieve and have a lower power density than the D-T reaction [4,5] but show even more benign environmental features. The D-D reaction would eliminate the need for tritium and produce neutrons with lower energies and are therefore easier to absorb and shield. A reactor based on the D-^{3}He reaction would proceed with very low neutron production (some neutrons would be produced in competing but much less occurring D-D reactions) and lead to much less induced radioactivity in the reactor structures. However, the prospects for these "advanced" fuels are still too speculative and only the D-T reaction has immediate future prospects.

In order to undergo fusion reactions, the reacting particles have to approach each other to within very short distances. Due to their positive charge, however, they repel each other and resist such a close encounter. A first estimate of the energy necessary to realise fusion reactions can be obtained from the potential energy of one nucleus in the presence of the electric field of another one at a distance such that, in the classical representation, the nuclei just touch each other. The maximum of the Coulomb barrier between two nuclei with radius R_1 and R_2 and charges qZ_1 and qZ_2 can be found from (with $q = 1.602 \times 10^{-19}$ C, the elementary charge):

$$V_C[\mathrm{J}] = \frac{q^2 Z_1 Z_2}{4\pi\varepsilon_0(R_1 + R_2)}\,, \tag{8}$$

or

$$V_C[\mathrm{MeV}] = 1.44\frac{Z_1 Z_2}{1.4(A_1^{1/3} + A_2^{1/3})}\,, \tag{9}$$

where we made use of the formula for the radius R of the nuclei [6]:

$$R = 1.4A^{1/3} \times 10^{-15}\,\mathrm{m}. \tag{10}$$

For the reaction between deuterium and tritium we find 0.38 MeV. In the classical picture, nuclei should therefore dispose of at least this energy before any fusion reactions can take place. The corresponding equivalent temperature of the plasma amounts to more than 4 billion degrees.

A reduction of this huge temperature is made possible by the tunnel effect. Owing to the wave character of matter, nuclei have a finite probability to "tunnel" through the Coulomb barrier and thus can fuse at energies much lower than those given by the maximum of the barrier (fig. 2). As we shall see further, this reduction is substantial, and the optimum temperature for a magnetically confined D-T plasma is about 13 keV.

Cross-sections as a function of the energy in the centre-of-mass reference system of the reacting particles for the reactions eq. (4) to (7) above are shown in fig. 3. The largest cross-section is found for the D-T reaction (about 5 barn) at a center-of-mass energy of the colliding particles $\frac{1}{2}\mu(v_1 - v_2)^2$ of about 60 keV, with $\mu = \frac{1}{2}\frac{m_1 m_2}{m_1 + m_2}$. However in a gas one has to take into account that the velocities of the colliding particles are described by a Maxwell-Boltzmann distribution. Values for the reactivity $\langle\sigma v\rangle$ averaged over a Maxwell-Boltzmann distribution as a function of the temperature, for various reactions are shown in fig. 4. The maximum is now much broader but still around energies of about 60 keV for the D-T reaction. Thus one is inclined to conclude that the plasma has to be heated to temperatures of over 600 million degrees to obtain the maximum fusion rate. However, one has to remember that in a magnetic fusion devices like tokamak or stellarator (see sect. **2** below), the operating pressure $p = nkT$ is constant, and thus as

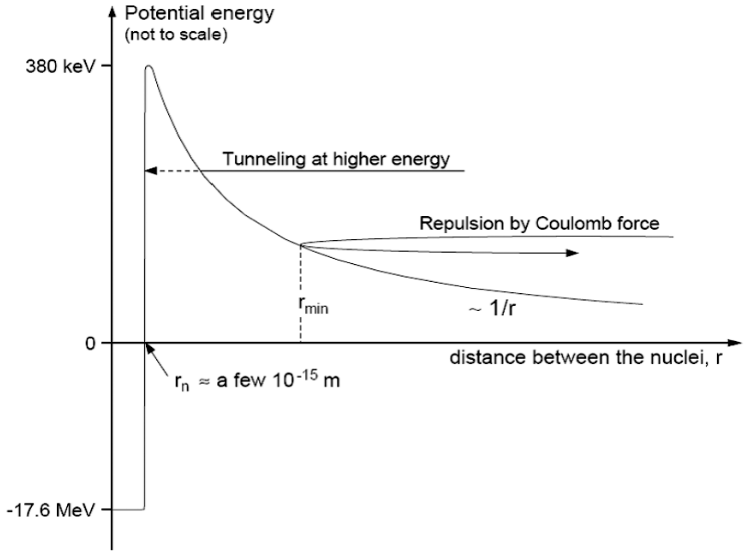

Fig. 2. – Atomic particles can overcome the Coulomb barrier (electrostatic repulsion) at much lower energies than the maximum by "tunnelling" through it. This increases the probability for fusion.

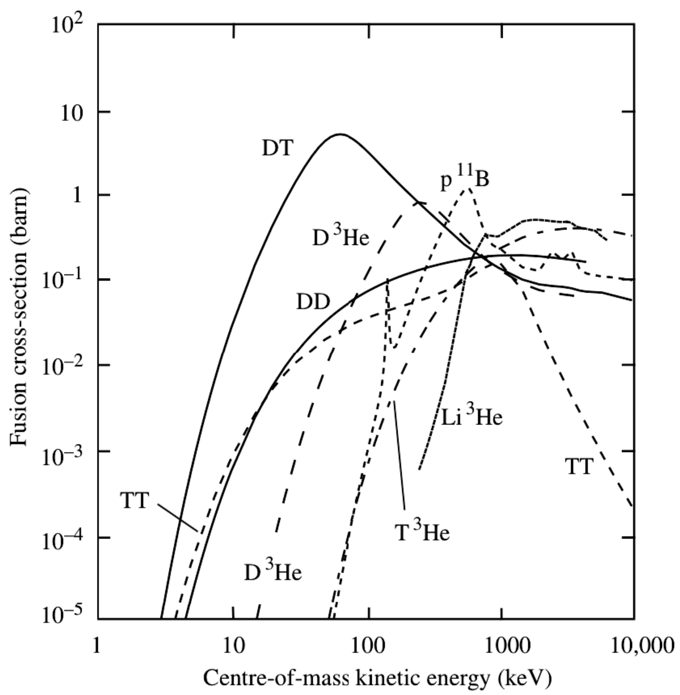

Fig. 3. – Cross-sections (in barn) as a function of the center-of-mass energies of the reacting particles for various fusion reactions.

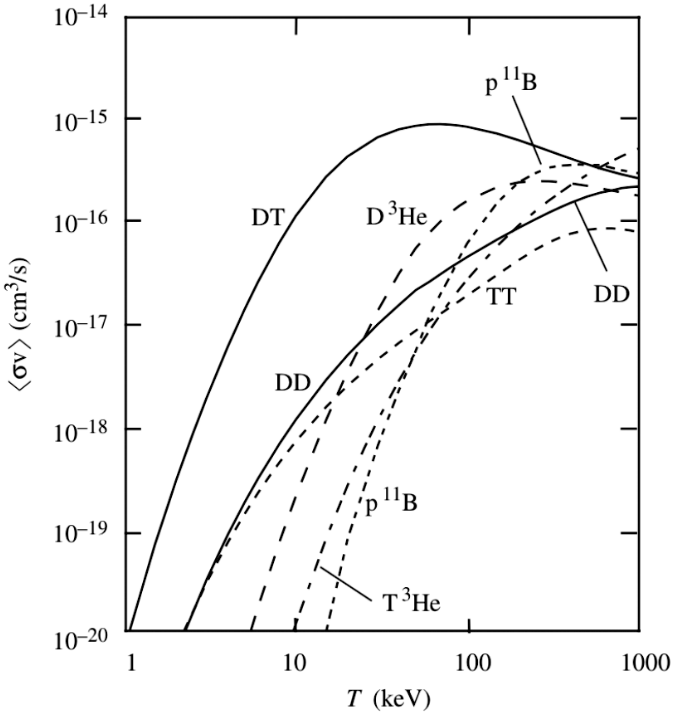

Fig. 4. – Reactivity averaged over a Maxwell-Boltzmann distribution as a function of temperature for the fusion reactions of fig. 3.

the temperature is increased, the density has to decrease, and consequently the number of fusion reactions also. The fusion reaction rate $R = \frac{n^2}{4}\langle\sigma v\rangle(T)$ is under those conditions proportional to $\frac{\langle\sigma v\rangle(T)}{T^2}$ and the operating temperature of a reactor will be determined by the maximum in this function [7]. This is shown in fig. 5. It is clear that for the D-T reaction the peak is located at about 13 keV. For the other reactions, D-D or D-^{3}He, the temperature is higher or the power density is smaller, depending on the pressure p that can be realised in a particular machine. For the D-T reaction we have thus to realize a temperature of about 150 million degrees, which is 10 times larger than in the Sun's core. In other words, the realisation of nuclear fusion on Earth requires the creation of a small but very hot Sun. Two questions then immediately arise: how does one realise such extreme temperatures and – equally important – how can one confine a gas at such high temperatures in a safe way?

2. – Plasma confinement

The hot plasma in the Sun's centre is confined by gravitation. This can evidently not be copied on Earth, and thus we have to look for totally different methods. Two approaches are currently being pursued: inertial and magnetic confinement. In the first

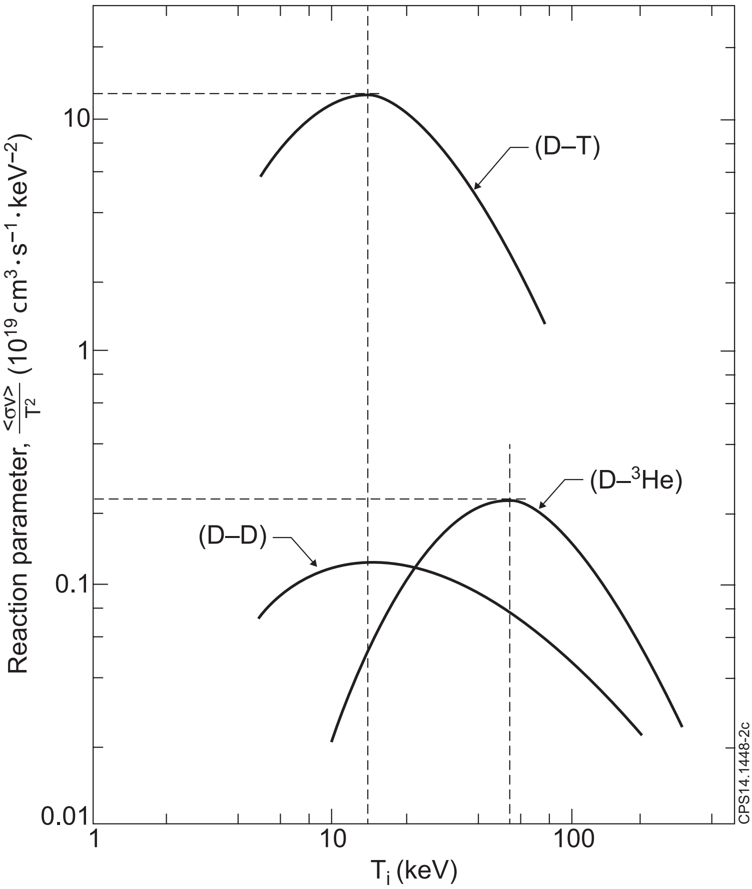

Fig. 5. – Maxwellian averaged values for $\frac{\langle \sigma v \rangle}{T^2}$ as a function of temperature for various fusion reactions (adapted from [7]).

approach, lasers or particle beams are used to rapidly compress the nuclear fuel in order to achieve the conditions required for fusion. To this end, a small sphere with a diameter of some hundreds μm is filled with equal amounts of deuterium and tritium. Powerful laser or particle beams irradiate the surface of this little sphere as uniformly as possible, for a billionth of a second. The outermost layers of the sphere vaporise nearly immediately, generating an inward-propagating spherical shock wave, which compresses the sphere's contents enormously. At the end of this short compression phase, a density of a thousand times that of water is reached at a temperature of some tens of millions of degrees centigrade. Under these conditions, the deuterium and tritium nuclei start to fuse. The energy released by these first fusion reactions further heats the rest of the strongly compressed fuel, allowing fusion reactions to spread throughout the whole sphere.

The second approach is by magnetic confinement. Since this has proven to be the most successful method to date, it is the branch of fusion research upon which the European

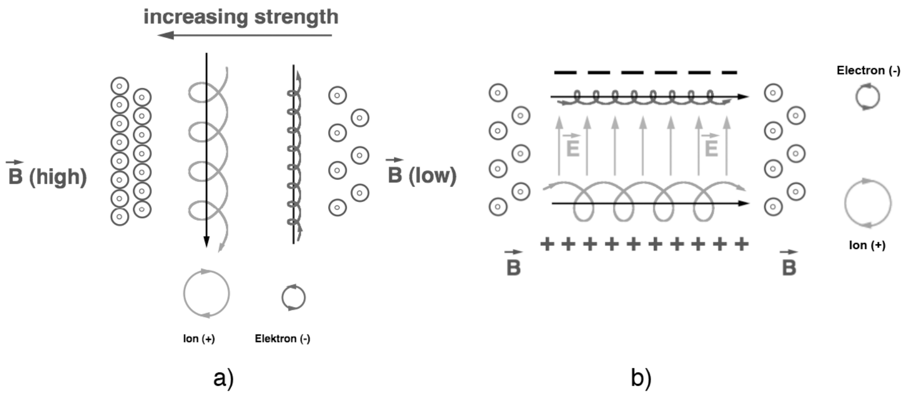

Fig. 6. – Illustration of the effect of the inhomogeneity of the toroidal magnetic field on plasma confinement. The effect can be easily explained in two steps considering the formula for the Larmor radius: $\rho = \frac{mv_\perp}{qB}$. For the first step see a) at the left: formation of the electric field due to the inhomogeneity of the toroidal field. The figure shows a cross-section of the plasma; the orbits of ions and electrons are no longer perfectly circular, but the particles spiral vertically up and down: indeed from the formula follows that ρ decreases as B increases and increases as B decreases. As ions and electrons rotate in opposite directions, they move vertically in opposite directions, creating an electric field in the plasma. Second step, see b) at the right: effect of the created electric field on the plasma particles. We consider a small section of the previous figure, such that B is to a good approximation homogeneous over the section, and thus the effect of E alone can be studied. As B is constant over this section, the only parameter influencing the movement of the particles is the velocity. Positive ions are accelerated towards the negative layer of charges and decelerated towards the positive layer of charges, leading to an increase resp. decrease of the velocity of the particle. From the formula follows that with increasing velocity the Larmor radius decreases and decreases with increasing velocity: thus the particle spirals vertically outwards. A similar reasoning for the electrons leads to exactly the same result. Both electrons and ions move thus horizontally outward: the plasma is unstable. To solve this problem, the formation of the electric field has thus to be avoided. Adding a poloidal component to the toroidal field is a way to do this.

Union has concentrated its efforts in many laboratories all over Europe and throughout the world.

At the high temperatures necessary for nuclear fusion, atoms break up into their constituents, electrons and nuclei, and the fuel becomes fully ionised, a plasma. To confine the hot plasma necessary for fusion in a material chamber, one can make use of the magnetic field, since charged particles will follow a helical path around the field lines owing to the Lorentz force. Possible movements perpendicular to the field are in this way highly restricted.

The most obvious way to realise this is a purely cylindrical configuration, which, however, suffers from plasma losses at both ends. Bending the magnetic field lines onto themselves, leading to a doughnut-shaped or toroidal magnetic field configuration avoids these losses. A toroidal magnetic field, however, is not homogeneous. Its curvature

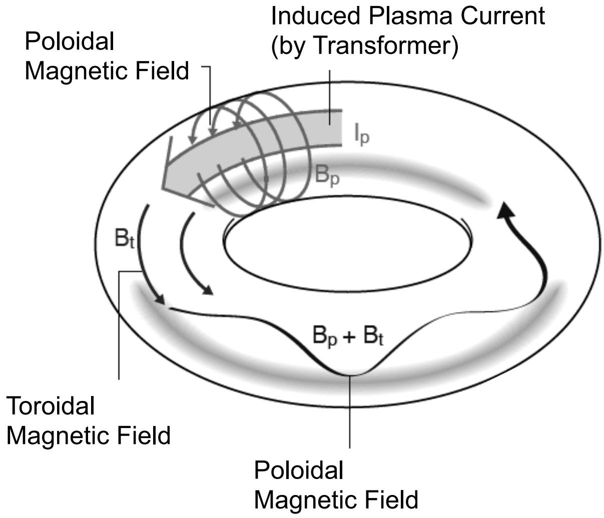

Fig. 7. – Principle of the tokamak: A large current induced in the plasma ring generates a poloidal magnetic field. The combination of this poloidal field with the main toroidal field results in a helical magnetic field, necessary for a stable confinement of the plasma in a toroidal configuration.

destroys most of the nice confinement properties of a purely cylindrical configuration. The magnetic field is largest near the axis of the torus, and decreases towards the outboard side. As a result, ions and electrons move in opposite vertical directions (fig. 6), giving rise to an electric field which, when combined with the toroidal magnetic field, expels all particles to the outside, irrespective of their charge. Without special measures, it is thus impossible to confine a toroidal plasma in a stable way. However, if the magnetic field can be given an extra twist, vertical drifts can be cancelled and a suitable trap can be made for fusion plasmas. This extra twist can be produced by means of electrical currents flowing inside or outside of the plasma ring. The *tokamak* concept relies on currents produced inside the plasma, whereas the *stellarator* concept relies on currents external to the plasma.

In a tokamak, a set of coils placed around the doughnut-shaped plasma chamber produces the main toroidal magnetic field. The conducting plasma ring itself serves as the sole secondary winding of an enormous transformer. A current pulse in the primary winding induces a large current in the secondary, *i.e.* in the plasma ring itself. This induced plasma current generates a poloidal magnetic field. The combination of this poloidal field with the main toroidal field results in a helical magnetic field (fig. 7). The magnetic structure thus generated consists of an infinite set of nested toroidal magnetic surfaces, each with a slightly different twist, reducing further the leakage of particles and heat from the plasma. On each of these surfaces, the plasma pressure is constant. Tokamak research started in the Kurchatov Institute in Moscow under the leadership of

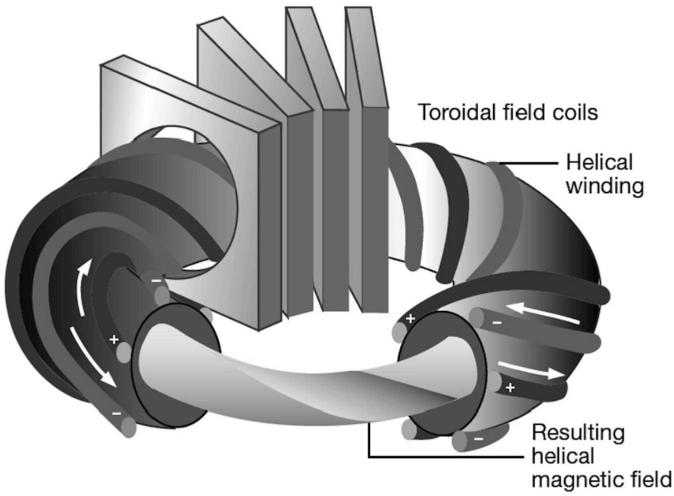

Fig. 8. – In a stellarator, helical coils external to the plasma ring create a supplementary magnetic field that, in combination with the main toroidal magnetic field, confines the plasma.

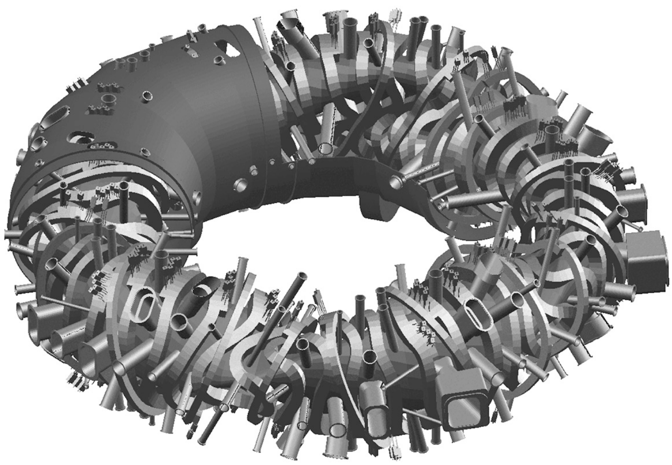

Fig. 9. – An illustration of the complex shapes of the coils of a modern stellarator, which combine the functions of the separate coil systems of fig. 8.

Lev Artsimovich. The success of this configuration became clear with the announcement at the Novosibirsk IAEA conference of 1968 that much higher temperatures could be obtained compared to what was reached in other magnetic configurations at that time. The tokamak is a pulsed device, since the transformer that induces the plasma current needs a steadily increasing current.

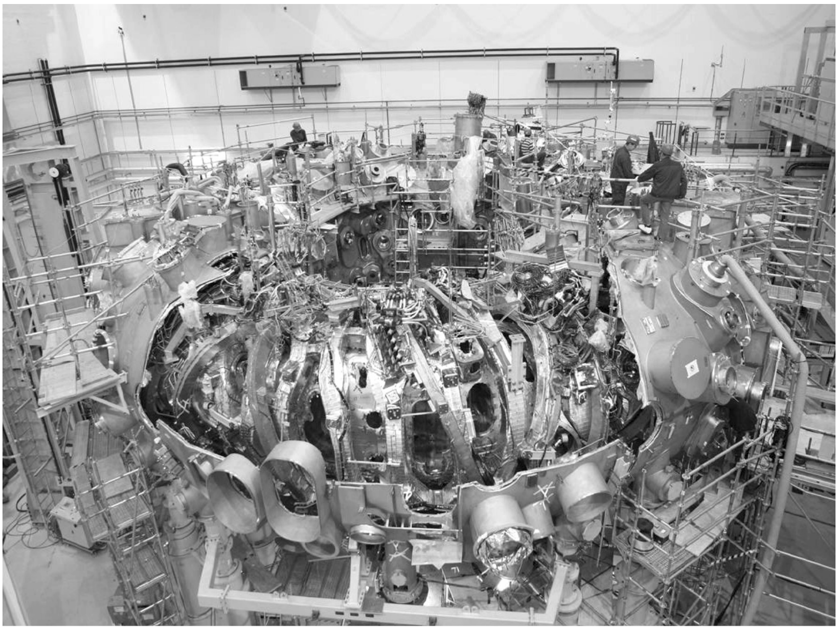

Fig. 10. – A picture of the stellarator Wendelstein 7-X, at the time of construction in November 2011, and now being commissioned in Greifswald, Germany.

Continuous operation of a fusion device can be obtained if the need for a (pulsed) plasma current could be avoided. The stellarator is such a solution, and it relies on currents external to the plasma for the helical magnetic configuration. In its basic configuration, extra helical coils around the toroidal plasma provide the necessary additional twist to the toroidal magnetic field generated by the main field coils (fig. 8). These helical windings around the plasma ring, however, complicate the construction of a stellarator, and also such stellarator configurations lacked good confinement properties. Modern stellarators have optimised confinement properties, and are equipped with a complex set of coils, that are determined numerically (fig. 9). Several devices of the stellarator type are in operation or in construction at this moment all over the world. The largest stellarator currently being built in Europe is Wendelstein 7-X, in Greifswald, Germany (fig. 10). Commissioning of this device is currently underway and first plasmas are planned for autumn 2015. A stellarator-like device of similar size, the LHD (Large Helical Device) of the National Institute for Fusion Science (NIFS, near Nagoya, Japan), started operation in March 1998.

3. – Plasma heating

The plasma current, which in the largest tokamaks can amount to several MA, serves a double purpose. It is necessary to obtain the correct magnetic configuration for the stable confinement of the hot plasma as explained above. In addition, the plasma current is used to heat the plasma. Since the heating results from the finite resistance of the plasma, just as in an electrical heating element, this is referred to as ohmic heating. The plasma resistance, however, decreases with increasing plasma temperature, and at some millions of degrees, the efficiency of ohmic heating becomes too low to be useful for further heating. In fact, at these temperatures the plasma becomes a better conductor than copper at room temperature. That is why auxiliary means have to be used to reach the temperatures required for fusion.

One additional heating method consists of injecting energetic particle beams of neutral hydrogen or deuterium into the plasma. This is possible because neutral particles can penetrate the magnetic fields needed to confine the plasma. To this end, ions are created in a plasma source, accelerated with voltages up to 150 000 volts and sent through a cloud of neutral gas. The accelerated ions "steal" electrons from atoms in this neutral gas cloud, and become energetic neutral particles which enter the hot tokamak plasma ring without impediment from the confining magnetic fields of the fusion device. Once in the hot plasma, they are almost immediately ionised again and deposit their energy via collisions to the rest of the plasma particles. Powers of up to several million watts per neutral injector can be delivered in this way.

A second heating method introduces electromagnetic waves into the plasma. The electromagnetic energy is delivered to the plasma by antennas or wave guides at the plasma edge. The principle underlying this method is similar to that of a microwave oven: the energy from the waves is most easily absorbed if the frequency used is equal to a "natural" frequency of the particles to be heated. The cyclotron frequency, with which the charged plasma particles gyrate around the magnetic field lines, is most often used in fusion plasmas. Thus, two different heating systems exist: Ion Cyclotron Resonance Heating (ICRH) and Electron Cyclotron Resonance Heating (ECRH), depending on whether ions or electrons are to be heated. Ion cyclotron frequencies are in the MHz range (20 MHz and upwards), while electron cyclotron frequencies are approximately a 1000 times higher (up to 200 GHz), due to the smaller mass of the electrons. Heating powers for high frequency systems range from 100 kW to several tens of MW.

4. – Characterizing the fusion reactivity of plasmas

The power amplification factor Q is defined as the ratio of the power produced by fusion reactions to the total heating power supplied externally. Two important milestones for the value of Q are customarily used in fusion research. The first, *breakeven*, is reached when the heating power is equal to the power produced from fusion reactions, corresponding to a Q value of one. The second, *ignition*, is reached when the additional heating systems can be switched off and the heat of the fusion reactions alone is sufficient to maintain the high temperatures needed for fusion. This corresponds to an infinite value for Q.

5. – Progress in recent years

The fantastic progress obtained in fusion research in the past three decades is clearly visible from the successively obtained values for the fusion product. Compared to the first fusion experiments, this value has increased by a factor of more than 10 000! The results obtained on JET (Joint European Torus, located at Culham Labs, close to Oxford, UK), the largest tokamak in the world, have contributed significantly to this progress, and to date, values very close to breakeven have been obtained in D-T experiments on this device. An important milestone was reached in 1991 with the first production of large amounts of energy from controlled fusion reactions, as tritium was used for the first time as fuel in a tokamak [8]. These experiments, obtained with a mixture of 90% D and 10% T, generated fusion powers in the megawatt range for nearly 2 seconds, with a maximum of about 1.7 MW, corresponding to a Q value of about 0.15.

Further successes were obtained early in 1994 in the American tokamak TFTR (Tokamak Fusion Test Reactor) at the Plasma Physics Laboratory of Princeton University. In plasmas consisting of a mixture of 50% deuterium and 50% tritium, multi-megawatt level fusion powers were generated for about one second, with a maximum of 6.3 MW [9]. Plasma temperatures in excess of 300 million degrees were reached in the plasma centre, 20 to 30 times hotter than in the centre of the Sun! In November 1994, fusion powers of more than 10 MW were generated, corresponding to Q values of about 0.27 [10].

Other record values were reached in 1996 on the Japanese Tokamak JT-60U of the Naka Fusion Research Establishment, located 150 km north of Tokyo, a division of the Japanese Atomic Energy Research Institute (JAERI). This machine demonstrated temperatures in excess of 520 million degrees [11], the highest temperature ever realised by man on Earth. Even more important, a record value for the fusion triple product was obtained in pure deuterium plasmas. If the same conditions had been realised in deuterium-tritium plasmas, it would, have resulted in a Q value of about 1.25, *i.e.* conditions better than breakeven [12].

The most impressive results in fusion research up to now were obtained in the JET, in October and November 1997. Experiments in 50% D-50% T plasmas resulted in over 16 MW of fusion power during about 1 second, with Q values in excess of 0.7 [13]. These are the highest fusion powers and Q values ever reached, thereby effectively resulting in the first demonstration of breakeven in reactor grade D-T fusion plasmas. A quasi steady-state generation of fusion power has also been demonstrated: over 4 MW of fusion power were produced for time intervals of more than 5 seconds [14], a duration only limited by the actual technical constraints of JET.

A summary of the different high performance D-T pulses obtained on JET and TFTR, as discussed above, is presented in fig. 11.

The success of the D-T experiments on JET and TFTR proves the scientific feasibility of controlled nuclear fusion. In addition, those experiments also allowed to get a first glimpse of the effects on the plasma of fast alpha particles.

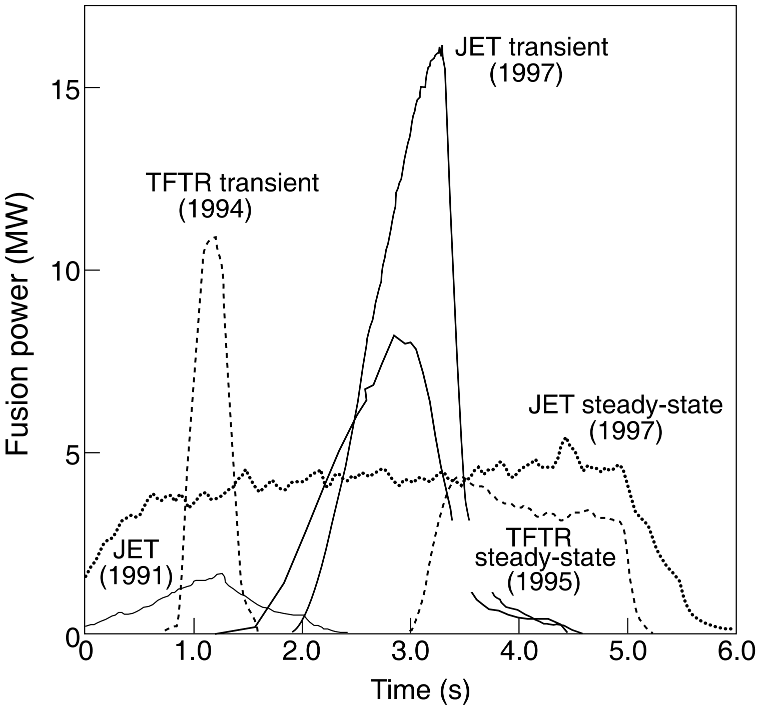

Fig. 11. – Time traces of the fusion power released in different high performance deuterium-tritium fusion experiments in TFTR and JET (adapted from [14]).

6. – Conditions for a fusion reactor: Lawson criterion

The Lawson criterion determines conditions for an operating reactor. In its simplest form it can be defined as follows: the sum of the power from auxiliary heating P_{heat} and α particles has to be at least equal to the losses from radiation $P_{\mathrm{radiation}}$ and transport, $P_{\mathrm{transport}}$ (convection, conduction). This can be written as

$$P_{\mathrm{heat}} + P_{\alpha} \geq P_{\mathrm{transport}} + P_{\mathrm{radiation}}. \tag{11}$$

To simplify the calculations, we consider in what follows a pure D-T plasma without impurities (*i.e.* effective charge of the plasma $Z_{\mathrm{eff}} = 1$); this implies also that we neglect the presence of He ash from the reaction. We assume only Bremsstrahlung radiation for the radiation losses (given in $\mathrm{W/m^3}$ by the formula $P_{\mathrm{Brems}} = C_{\mathrm{B}} Z_{\mathrm{eff}} T^{1/2} n^2$ if T is expressed in keV, and n in $\mathrm{m^{-3}}$ with $C_{\mathrm{B}} = 5.35 \times 10^{-37}$ [15]) and we characterize all transport related losses by the confinement time: W_p/τ_E, where W_p is the energy contained in the plasma. Taking into account that

$$P_{\mathrm{heat}} Q = P_{\mathrm{fusion}} = 5 P_{\alpha}. \tag{12}$$

The plasma energy is the sum of the energies in ions and electrons:

$$W_p = \frac{3}{2}(n_e kT_e + n_i kT_i). \tag{13}$$

From quasi-neutrality of the pure D-T plasma follows that electron and ion densities are the same $n_e = n_i = n$; we also assume that the plasma is in thermal equilibrium thus there is no difference between electron and ion temperatures $T_e = T_i = T$. Therefore

$$W_p = 3nkT \tag{14}$$

with $k = 1.38 \times 10^{-23}$ J/K the Boltzmann constant.

Assuming a pure 50% D-50% T plasma leads also to $n_T = n_D = 1/2n_e = 1/2n$. The expression for the heating by α particles, can thus be written as

$$P_\alpha = \frac{1}{4} n_D n_T E_\alpha \langle \sigma v \rangle = \frac{1}{4} n^2 E_\alpha \langle \sigma v \rangle. \tag{15}$$

Expressing E_α and T_k in keV, we thus arrive at

$$\frac{1}{4} n^2 E_\alpha \langle \sigma v \rangle \left(\frac{Q+5}{Q} \right) \geq \frac{3nT_k}{\tau_E} + C_\mathrm{B}^* Z_\mathrm{eff} T_k^{1/2} n^2. \tag{16}$$

And finally at

$$n\tau_E \geq \frac{3T_k}{\dfrac{\langle \sigma v \rangle E_\alpha (Q+5)}{4Q} - C_\mathrm{B}^* Z_\mathrm{eff} T_k^{1/2}}, \tag{17}$$

where $C_\mathrm{B}^* = C_\mathrm{B}/1.602 \times 10^{-16} = 3.34 \times 10^{-21}$.

The right hand side formula shows a minimum for about $T_k = 25\,\mathrm{keV}$. Approximating $\langle \sigma v \rangle$ (in $\mathrm{m^{-3}s}$) $= 1.1 \times 10^{-24}\, T_k^2$ (valid to within 15% in the interval $10\,\mathrm{keV} < T_k < 25\,\mathrm{keV}$) and setting $Z_\mathrm{eff} = 1$ (pure D-T plasma):

$$\text{For breakeven } (Q = 1)\text{: } n\tau_E \geq 2.5 \times 10^{19}\,\mathrm{m^{-3}s} \tag{18}$$

and

$$\text{For ignition } (Q = \infty)\text{: } n\tau_E \geq 1.5 \times 10^{20}\,\mathrm{m^{-3}s}. \tag{19}$$

An alternative formulation of the Lawson criterion is the in the form of the so-called fusion triple product. Considering again only the temperature range where the minimum of eq. (17) occurs ($kT_e \sim 10$–$25\,\mathrm{keV}$), we can neglect to a first approximation the corrections for the Bremsstrahlung losses. Thus we find, with the same conventions for the various physical quantities as in eq. (17)

$$n\tau_E T_k \geq \frac{12QT_k^2}{(Q+5)\langle\sigma v\rangle E_\alpha}\,. \tag{20}$$

The minimum for the right hand side is obtained at the maximum for $\langle\sigma v\rangle/T_k^2$, *i.e.* as shown above, at about $T_k = 13\,\mathrm{keV}$. We thus find

$$\text{For breakeven } (Q=1)\text{: } n\tau_E T_k \geq 5\times 10^{20}\,\mathrm{m}^{-3}\mathrm{s\,keV} \tag{21}$$

and

$$\text{For ignition } (Q=\infty)\text{: } n\tau_E T_k \geq 3\times 10^{21}\,\mathrm{m}^{-3}\mathrm{s\,keV}. \tag{22}$$

These simplified expressions should give a good idea of the physics behind the famous Lawson criterion. For a more detailed treatment, taking into account radiation, impurities etc. we refer to the very interesting paper by Rebhan and Van Oost [16].

7. – Future prospects: JET as a testbed for ITER, JT-60SA, ITER and DEMO

7·1. *JET as a testbed for ITER.* – The mission of JET is focusing more and more on becoming a testbed for ITER. The JET tokamak has recently completed a major enhancement programme as part of its mission to support efficient ITER operation. This enhancement programme intends to address the main operational risks identified by ITER with particular emphasis on the unique capabilities of JET: machine size and capability to use both beryllium and tritium. JET's "Programme in Support of ITER" has been elaborated along three main axes: i) experimentation with an ITER-like wall; ii) development of plasma configurations and parameters towards the most ITER-relevant conditions achievable today and iii) integrated experimentation in deuterium-tritium. A full replacement of the first wall material has been undertaken (beryllium in the main wall and tungsten in the divertor). These include answers to plasma surface interaction questions, tritium retention, operational experience in steady and transient conditions with ITER wall materials under relevant geometry and relevant plasma conditions. In addition, the JET auxiliary heating is upgraded to $\sim 45\,\mathrm{MW}$, allowing access to ITER-relevant disruption and edge localised modes energy loss densities. This will provide access to conditions of melt layer formation both on the beryllium first wall and the tungsten divertor and, help to make further progress in hybrid and advanced scenarios for ITER, which require full or partial current profile control, thereby making use of new dedicated diagnostics. Results from two years of operations have provided important information for ITER [17]. In the coming years a new D-T campaign is planned on JET.

TABLE II. – *Main parameters of important tokamaks.*

	T-10	DIII-D	JT-60SA	JET	ITER
Land/Organisation	Russian Federation	USA	Japan	GB/ EURATOM	International
Plasma shape	circular	elliptical(D)	elliptical(D)	elliptical(D)	elliptical(D)
Minor radius (m)	0.3	0.67(hor) 1.74(vert)	1.18(hor) 2.30(vert)	1.25(hor) 2.1(vert)	2.0 (hor) 3.7(vert)
Major radius (m)	1.5	1.67	2.96	2.96	6.2
Toroidal magnetic field (T)	2.5	2.2	2.25	3.5	5.3
Plasma Current (MA)	0.7	3.0	5.5	5.0	15 (17)
Pulse length (s)	4	10	100	60	300-500
Injection of Neutral particle beams (MW)	–	20	34	30	73 (130) in total
Injection of electromagnetic waves (MW)	1.5	8	7	38	

7˙2. *JT-60SA*. – In February 2007, EURATOM and Japan signed the Broader Approach agreement. This aims to complement the ITER Project and to accelerate the realisation of fusion energy by carrying out R&D and developing some advanced technologies for future demonstration fusion power reactors (DEMO). Within the Broader Approach, three main projects are being implemented: i) the construction in Japan of the large superconducting tokamak JT-60SA aimed to develop operational scenarios relevant for ITER (International Thermonuclear Experimental Reactor) and DEMO; ii) the construction of facilities to test components to be adopted in the research machine IFMIF (International Fusion Material Irradiation Facility) aimed to study the material damage caused by high energy neutron flux generated in fusion reactions, the construction of a prototype of the liquid lithium IFMIF target; iii) the creation of the International Fusion Energy Research Centre (IFERC) including a center for advanced materials development and a supercomputing centre.

Parameters for JT-60SA are summarized in table II. JT-60SA is a fusion experiment designed to support the operation of ITER and to investigate how best to optimise

TABLE III. – *Main differences between ITER and DEMO.*

ITER	DEMO
Experimental device	Close to commercial plant
400s pulses Long interpulse time	Long pulses, high duty cycle or steady state
Many diagnostics	Minimum set of diagnostics only needed for operations
Many H&CD systems	Reduced set of H&CD systems
No T breeding required	Self sufficient T breeding
316 SS structural material	Reduced activation structural material
Modest n-fluence, low dpa Low material damage	High n-fluence, high dpa Significant material damage

the operation of fusion power plants that are built after ITER. It is a joint international research and development project involving Japan and Europe, and is to be built in Naka, Japan using infrastructure of the existing JT-60 Upgrade experiment, for which we cited several important experimental results in sect. **5** above. SA stands for "super, advanced", since the experiment will have superconducting coils and study advanced modes of plasma operation. According to the current planning, first plasmas on JT-60SA are foreseen in 2019. More information on this interesting future tokamak can be found in [18].

7˙3. *ITER*. – The results summarized in sect. **5** provide crucial information for the design of a next large tokamak, aimed at demonstrating the technical feasibility for large scale energy production. This next step is ITER, short for International Thermonuclear Experimental Reactor, currently under construction in Cadarache, France as a combined effort between Europe, Japan, the Russian Federation, South Korea, India, China and the United States. This device will thus for the first time in history allow mankind to produce huge quantities of energy from nuclear-fusion reactions at temperatures over 100 million degrees. ITER is expected to generate fusion powers of the order of 500 MW in pulses of 300-500 seconds. Specifications for ITER (and a few other major tokamaks) are summarised in table II. After ITER, the construction of a demonstration reactor, currently termed DEMO, is foreseen, which should show not only the technical, but also the economical feasibility of fusion.

7˙4. *DEMO*. – Before DEMO can become a practical demonstration of electricity generation on a power-plant scale that satisfies various socio-economic goals, major challenges must be resolved. Although ITER will bring significant advances, there remains a large gap between ITER and DEMO. Main differences between ITER and DEMO are summarized in table III.

DEMO is currently based on the tokamak, as this is the most advanced fusion concept to date. Reactor studies are also being developed for Helical Devices (see, *e.g.*, [19-22]).

Table IV. – *Main parameters of the early DEMO 1 and more advanced DEMO 2 model currently under investigation by the PPP&T Department of EFDA. Shown are the thermal output power* (P_{th})*, the net electrical power to the grid* (P_{net})*, the recirculating power* (P_{rec})*, the auxiliary heating power* (P_{aux})*, major radius* (R_0) *and minor radius* (a) *of the device, plasma current* (I_{p}) *and toroidal magnetic field on axis* (B_{t})*.*

Device	DEMO 1	DEMO 2
Operation mode	Pulsed	Steady state
P_{th} (MW)	2200	2700
P_{net} (MW)	500	500
P_{rec} (MW)	594	600
P_{aux} (MW)	50	350
R_0 (m)	9.0	8.15
a (m)	2.25	3.0
I_{p} (MA)	14.1	19.8
B_{t} (T) on axis	6.8	5.0

However, a decision on a next step stellarator/helical device can only take place when the main results of the current large helical devices in operation or construction have been obtained.

To lead a coordinated effort in the EU towards DEMO, the Power Plant Physics and Technology Department (PPP&T) has been established in 2011 [23]. The aims of the DEMO studies in Europe are: i) to quantify key physics and technology prerequisites for DEMO; ii) to identify the most urgent technical issues that need to be solved in physics and technology and iii) to plan and implement supporting physics and technology R&D.

Two DEMO design options are currently being investigated by PPP&T. (See table IV for main characteristics):

i) DEMO Model 1: A "conservative baseline design" that could be delivered in the short to medium term, based on the expected performance of ITER with reasonable improvements in science and technology *i.e.* a large, modest power density, long-pulse inductively supported plasma in a conventional plasma scenario.

ii) DEMO Model 2: an "optimistic design" based upon more advanced assumptions which are at the upper limit of what may be achieved, leading to a steady state plasma scenario where a large fraction of the plasma current is induced non-inductively, *i.e.* without making use of the transformer. This is currently a rather speculative option.

From table III there follows immediately a minimum set of research topics that need to be (much) further developed: heating systems capable of heating the large plasmas foreseen for DEMO, diagnostic systems that can sustain the heavy neutron loading, tritium generating modules (so-called tritium blankets) to foresee tritium self-sufficiency, and new materials that will be compatible with the high heat and neutron loads. This implies also that new laboratories will have to be built to be able to explore possibilities and further develop existing systems. Among others, a material research facility to study the behaviour of various candidate materials under a flux of 14.1 MeV neutrons (preparations for such a facility, IFMIF, are already underway in Japan and Europe [24]), a facility to develop, *e.g.*, Neutral Beam Heating systems (if these are viable at all for DEMO, another research topic) with acceleration energies between 1 and 2 MeV, based on negative ion sources (in contrast to the positive ion sources used currently) etc. A first step in this direction is the PRIMA (Padova Research on Injector Megavolt Accelerated) facility being built in Padova, Italy, for the development of the ITER NBI systems [25]. But more efforts in various other fields will have to follow, and this will unavoidably take time.

The European Fusion Development Agreement (EFDA) has released in November 2012 a roadmap for the realization of fusion electricity to the grid by 2050 [26]. This roadmap covers three periods: i) the upcoming European Research Framework Programme, Horizon 2020, ii) the years 2021-2030 and iii) the period 2031-2050. ITER is the key facility of the roadmap as it is expected to achieve most of the important milestones on the path to fusion power. The second period is focused on maximizing ITER exploitation and on preparing the construction of DEMO. Building and operating DEMO is the subject of the last roadmap phase (time horizon about 2050).

8. – Will fusion be a safe, clean and inexhaustible energy source?

The concept of a future fusion power device based on a tokamak is outlined in fig. 12. Due to the high reactivity of the D-T fusion reaction, deuterium and tritium will most likely be selected as fuel for the first generation of fusion power stations. The electrically charged α-particles from fusion reactions are confined by the magnetic field. These high-energy helium nuclei collide with the background plasma particles, *i.e.* with the combustibles D and T and maintain the plasma temperature rendering additional heating systems quasi unnecessary as soon as ignition is reached.

In contrast to the α-particles, the neutrons generated by the D-T reaction have no electrical charge and escape immediately from the plasma chamber. These neutrons are not lost, but serve a dual purpose in the reactor. First, they produce tritium in the blanket surrounding the reactor containing lithium or lithium compounds, according to the reactions given in table V. This is necessary to refuel the plasma with tritium that is consumed in the fusion reactions. Second, the energy of the neutrons deposited in the blanket is converted into heat, which is in turn is transported to the exterior by the cooling system and used to generate steam and drive classical turbines for the production of electricity.

TABLE V. – *Tritium production from lithium.*

${}^{7}\mathrm{Li} + \mathrm{n} \rightarrow {}^{4}\mathrm{He} + \mathrm{T} + \mathrm{n} - 2.47\,\mathrm{MeV}$
${}^{6}\mathrm{Li} + \mathrm{n} \rightarrow {}^{4}\mathrm{He}\ (2.05\,\mathrm{MeV}) + \mathrm{T}\ (2.73\,\mathrm{MeV})$

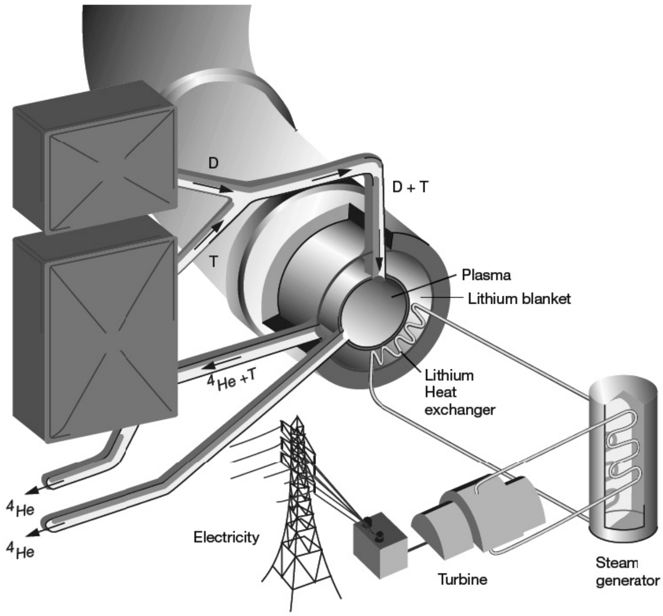

Fig. 12. – Many obstacles still have to be overcome before the first nuclear fusion power plant will be put into operation. Eventually, heat generated in fusion reactions will be used to generate steam to drive a turbine, with electrical power as final result.

The main advantage of fusion is the absence of any long-lived radioactive waste and its inherent safety. The quantity of fuel in the reaction chamber at any moment is only a few grams, in contrast to the presence of several tons of fuel in the core of a fission reactor. Furthermore, the fusion process is not susceptible to an uncontrolled release of energy, since numerous conditions have to be fulfilled before fusion reactions can take place. A small perturbation of these conditions, *e.g.* a slight change in the topology of the magnetic fields, can already lead to the immediate extinction of the hot plasma. There is no risk of a runaway reaction, and Chernobyl-like accidents are absolutely excluded.

As previously mentioned, the fuels for the most accessible fusion reactions are deuterium and tritium. Deuterium can be extracted in large quantities from ordinary water found in rivers and oceans, rendering each country less dependent on fuel supply from other parts of the planet. Moreover, a minimal amount of fuel is necessary to cover the lifetime electricity needs of a European citizen: about 10 g of D and 15 g of T (and about twice this amount for a citizen of the United States). Tritium will be produced in-situ from the irradiation of Li with the neutrons from the fusion reaction. Thus the real combustibles are in fact D and Li, both of which are non-radioactive. World reserves of Li are sufficient for many thousand years of operation of D-T fusion power plants. If at a later stage the D-D reaction could be used, we could have at our disposal a virtually unlimited energy source, as reserves of D are sufficient for several million years of energy production. In both cases, the reaction product is the harmless gas helium, which is chemically inert and non-radioactive. With nuclear fusion there is thus no release of gases that contribute to the greenhouse effect, acid rain or the depletion of the ozone layer. Moreover, since helium is the only gas with which temperatures down to absolute zero can be reached, it is not a waste product, but in fact a very useful industrial product, especially since helium is rather scarce on Earth.

The high-energy neutrons from the D-T reaction facilitate the extraction of energy from the fusion device, as they escape the plasma unhindered by the confining fields. At the same time, however, they activate the metallic reactor structure and hence make it radioactive. Low activation materials have to be selected to minimise this effect. In this way, the total radioactive inventory of a fusion reactor could be made one million times smaller than that of existing fission reactors. The activation problem could be drastically reduced in a distant future by the use of other fusion reactions, which liberate fewer neutrons. The radioactivity induced by the D-^{3}He reaction for example, would be about 50 times lower.

The various steps that remain to be taken by thermonuclear fusion research indicate that some decades will still be needed to realise a practically useable energy source. The increasing scale of investigation and technological support of magnetic confinement fusion research has dictated a collaborative European effort under the auspices of the European Commission. Analogous enlargements of existing cooperative efforts on a worldwide level are beneficial for maintaining the present rate of advancement towards fusion as an economically viable source of energy. The most recent results support the attractiveness of the fusion concept for energy production. A sustained effort—in laboratories worldwide—brings the vision of an energy supply by thermonuclear fusion ever closer to realisation. We all know that fusion is a challenging undertaking and that patience will be needed, but it is more than worth the effort given the difficulties we are facing in the future with our current energy supply and its suspected influence on climate. It will be evidently up to you, young researchers, to tackle these interesting and very important problems. If successful, this will be your very important contribution to the benefit of all people on Earth. A true challenge for an immense reward!

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