EPJ Web of Conferences **268**, 00011 (2022)
LNES 2021
https://doi.org/10.1051/epjconf/202226800011

Fusion: a true challenge for an enormous reward

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Summary. — A source of energy which would be inexhaustible, inherently safe and environmentally friendly, is this not a marvellous prospect? Nuclear fusion is a possible candidate for this role. It has been the energy source of our Sun and the stars in the universe for billions of years. The process requires temperatures of tens of millions of degrees, so extremely high and foreign to our daily experience that it seems out of reach. Nevertheless, these extremely high temperatures are routinely realised in several laboratories all over the world. Since the early 1990s, tens of MW of fusion power have been released from fusion reactions. Progress in the last years shows that fusion holds the promise to be a clean and safe solution for mankind's long-term energy needs. 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 is the p-p reaction, converting hydrogen into helium. Other fusion reactions occur in stars, *e.g.* the carbon-nitrogen-oxygen or CNO cycle. It is dominant in stars that are about 1.3 times heavier than our Sun. In our Sun only about 1% of the ^{4}He nuclei originate from the CNO cycle [1].

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

Our Sun offers a more promising solution: in this gaseous body, the particles that are confined in the core of the Sun undergo a much larger number of collisions and, hence, fusion reactions per unit of time. Gravity is responsible for the confinement and the heating of the fusing protons. An estimate of the temperature in the centre of the Sun can be found by remarking 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 $R_{\text{Sun}} = 695\,500\,\text{km} = 6.955{\times}10^8$ m (more than 2 times the distance Earth-Moon...) we obtain

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

From the formula above, it is immediately clear that a contraction of the star under its own gravity will further raise the central temperature, resulting in the production of heavier elements. Fusion in heavy stars will continue to keep the star alive as long as the reactions are exothermic and are thus 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 [2]. 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.

The p-p and CNO fusion reactions in our Sun have a far too low reaction rate to be useful on Earth. One of the underlying reasons is that from every four protons taking place in the reaction chain that leads to ^{4}He, two of them need to be converted into a neutron. In the p-p reaction, this occurs via the formation of a deuteron involving the slow beta-plus decay reaction:

$$\text{p} + \text{p} \rightarrow \text{D} + \text{e}^+ + \nu + 0.42\,\text{MeV}. \tag{4}$$

Once the neutron is created, a further set of reactions involving ^{3}He and the unstable nucleus ^{6}Be finally leads to the formation of ^{4}He. Despite this complex and slow chain

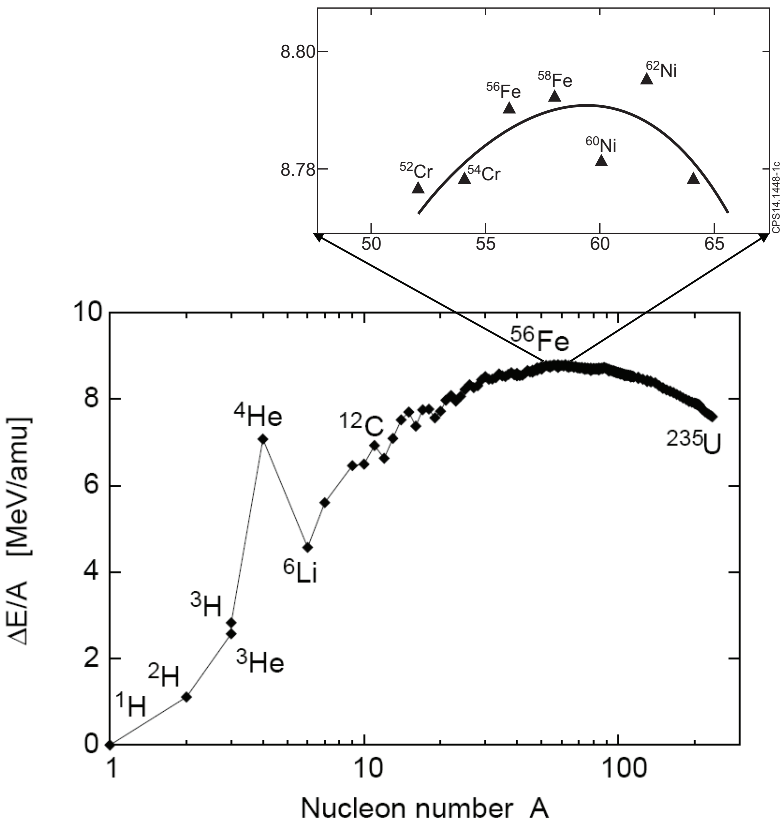


Fig. 1. – Binding energy per nucleon *vs.* atomic mass number showing the maximum in the curve reached for ^{62}Ni. Note the exceptionally large binding energy of the ^{4}He nucleus among the light nuclei. An approximate indication is given for the difference in binding energy per nucleon in fusion reactions of light nuclides with ^{4}He as one of the reaction products ($\sim 5\,\text{MeV/nucleon}$) and fission of ^{235}U ($\sim 0.9\,\text{MeV/nucleon}$). The exact numbers for the mass defects of selected nuclides with mass numbers up to 20 can be found in table II.

of reactions, every second 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 disappear and are totally transformed into energy.

On Earth we have to use nuclear fusion reactions that avoid the difficult conversion process from protons to neutrons. The evident solution is to use reaction products that already contain neutrons, needed for the formation of ^{4}He. Instead of protons as reaction products, we use the nuclei of the isotopes D and T or also of the rare isotope ^{3}He. Here 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). A number of fusion reactions [3] together with their cross-sections and energy released are listed in table I. Note that the

Table I. – *Fusion reactions.*

Reaction	σ at 10 keV (barn)	σ_{max} (barn)	Center-of-mass energy (keV) for σ_{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
$D + D \rightarrow {}^3He + n$	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

energy released is the largest in reactions that lead to the formation of a ^{4}He nucleus because of its exceptionally large binding energy (fig. 1). The fusion reaction with the largest cross section and resulting in the formation of ^{4}He is the so-called D-T reaction:

$$D + T \rightarrow {}^4He\ (3.5\,\text{MeV}) + n\ (14.1\,\text{MeV}). \tag{5}$$

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

The reaction products are an α-particle (^{4}He nucleus) and a neutron. Twenty percent of the reaction energy is carried by the α-particles and 80% by the much lighter neutron. This follows directly from the conservation of momentum. In magnetic confinement systems the neutron does not feel the presence of the magnetic field (because it is not charged) and escapes immediately from the reactor volume, while the charged α-particle remains confined by the magnetic field. The kinetic energy of these escaping fast neutrons will be converted into heat in an appropriate blanket surrounding the future fusion reactor and then into electricity using conventional technology (steam cycle). 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: about 15 g of a 50%/50% DT mix suffices to produce the electricity needed by one EU citizen for 80 years.

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

$$D + D \rightarrow {}^3He\ (0.82\,\text{MeV}) + n\ (2.45\,\text{MeV}), \tag{6}$$

$$D + D \rightarrow T\ (1.01\,\text{MeV}) + H\ (3.02\,\text{MeV}), \tag{7}$$

$$D + {}^3He \rightarrow {}^4He\ (3.6\,\text{MeV}) + H\ (14.7\,\text{MeV}). \tag{8}$$

TABLE II. – *Atomic mass and binding energy per nucleon* [42], *stability and natural abundance for light nuclides. Note the remarkable absence of stable nuclides with mass number* 5 *and* 8.

Nucleus	Stable/unstable (half-life)	Natural abundance	Binding energy per nucleon (keV)	Atomic mass (u)
^{1}H	s	99.985%	n.a	1.0078250
n	u (12 min)	n.a.	n.a	1.0086649
^{2}H=D	s	0.015%	1112.283	2.0141018
^{3}H=T	u (12.32 yr)	n.a.	2827.265	3.0160493
^{3}He	s	0.000137%	2572.680	3.0160293
^{4}He	s	99.999863%	7073.915	4.0026033
^{6}Li	s	92.41%	5332.331	6.0151229
^{7}Li	s	7.59%	5606.439	7.0160034
^{9}Be	s	100%	6462.668	9.0121831
^{10}B	s	19.8%	6475.083	10.0129369
^{11}B	s	80.2%	6927.732	11.0093052
^{12}C	s	98.89%	7680.144	12.0000000
^{13}C	s	1.11%	7469.849	13.0033548
^{14}N	s	99.634%	7475.614	14.0030740
^{15}N	s	0.366%	7699.460	15.0001089
^{16}O	s	99.762%	7976.206	15.9949146
^{17}O	s	0.038%	7750.728	16.9991318
^{18}O	s	0.2%	7767.097	17.9991596
^{19}F	s	100%	7779.018	18.9984032
^{20}Ne	s	90.48%	8032.240	19.9924402
^{21}Ne	s	0.27%	7971.713	20.9938467
^{22}Ne	s	9.25%	8080.465	21.9913851

These are more difficult to realise 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 that are easier to absorb and shield. A reactor based on the D-^{3}He reaction would proceed with low neutron production (some neutrons would be produced in competing but much less occurring D-D and secondary D-T 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. For the interested reader, table II provides the masses and binding energies per nucleon for a selection of lighter nuclides, including those involved in reactions (5) to (8).

In order to undergo fusion reactions, the reacting particles have to approach each other to within short distances. 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

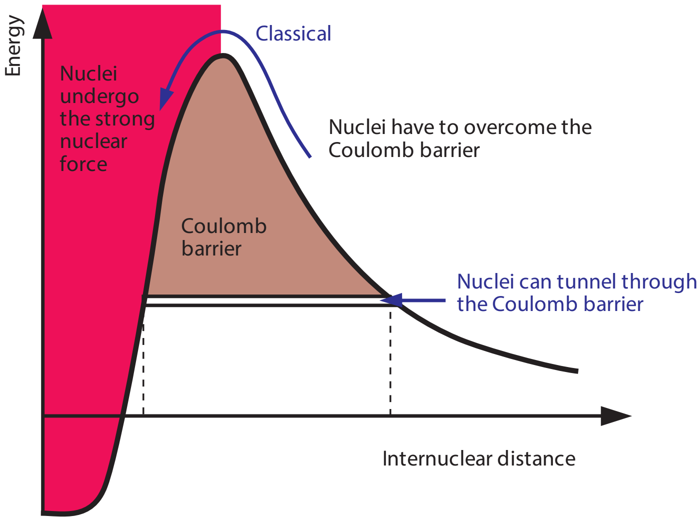


Fig. 2. – Atomic particles can overcome the Coulomb barrier (electrostatic repulsion) at much lower energies than the maximum by "tunnelling" through it. This increases the probability for fusion.

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

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

or

(10) $$V_C[\mathrm{MeV}] = 1.02\,\frac{Z_1 Z_2}{A_1^{1/3} + A_2^{1/3}}\,,$$

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

(11) $$R = 1.4\,A^{1/3} \times 10^{-15}\,\mathrm{m},$$

with A the mass number of the nucleus. For the reaction between deuterium and tritium we find 0.38 MeV. In the classical picture, nuclei should therefore at least acquire this energy before any fusion reaction can take place. The equivalent temperature of a Maxwellian plasma with this value as average energy 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

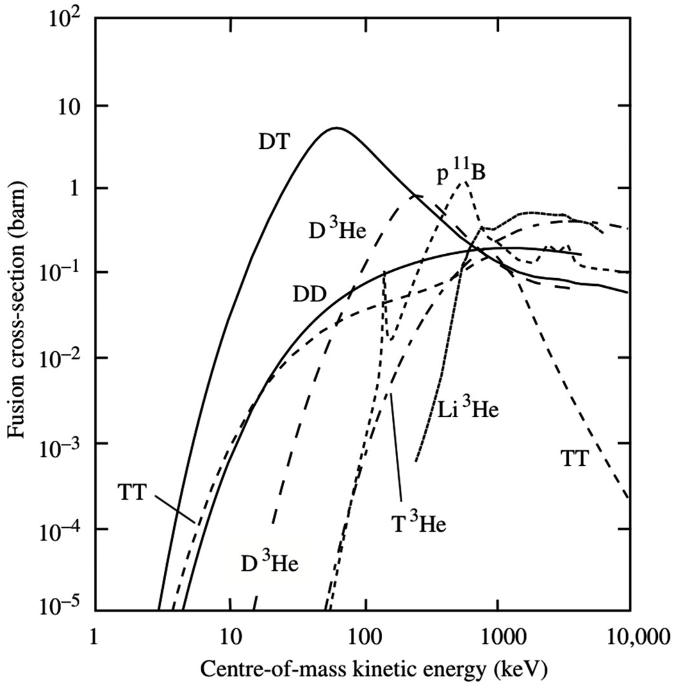


Fig. 3. – Cross-sections (in barn) as a function of the centre-of-mass energies of the reacting particles for various fusion reactions.

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 [3] as a function of the centre-of-mass energies of the reacting particles for the reactions (5) to (8) above are shown in fig. 3. The largest cross-section is found for the D-T reaction (about 5 barn) at the centre-of-mass energy of the colliding particles $1/2\ \mu\ (v_1 - v_2)^2$, where $\mu = 1/2(m_1 m_2/(m_1 + m_2))$ of about 60 keV. However in a gas one has to take into account that the velocities of the colliding particles are described by a Maxwell-Boltzmann distribution and values for the reactivity $\langle\sigma v\rangle$ averaged over this distribution as a function of the temperature are shown in fig. 4 for various fusion reactions. 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 device, tokamak or stellarator, the operating pressure $p = nkT$ is limited due to various instabilities and turbulence in the plasma (see, *e.g.*, [7]; for recent experimental progress towards the reduction of plasma turbulence, see [8, 9]). The fusion reaction rate $R = \frac{n^2}{4}\langle\sigma v\rangle$ can thus be written as $R = \frac{1}{4}\frac{\langle\sigma v\rangle}{T^2}$ and the maximum reactivity is determined by the maximum of this function [10] as shown in fig. 5. It is clear that for the D-T reaction the peak is located at about 13 keV. For the D-D or D-^{3}He reactions, the temperature is higher (or the power density is smaller) at

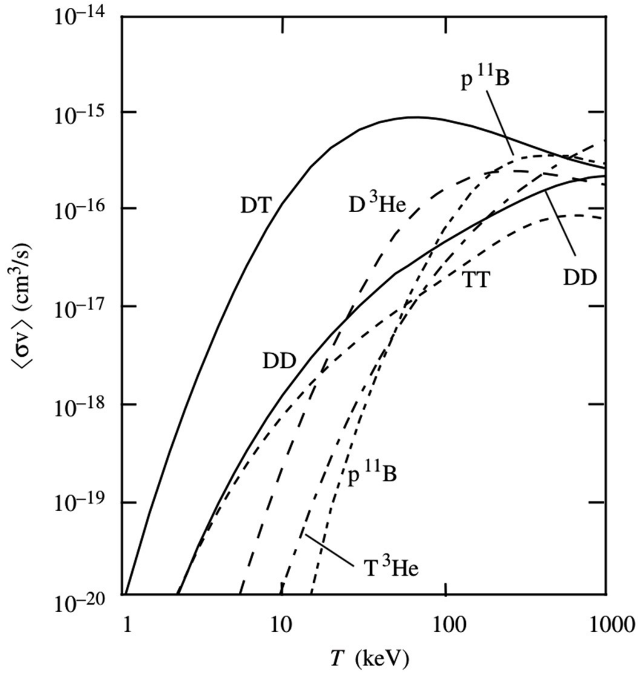


Fig. 4. – Reactivity averaged over a Maxwell-Boltzmann distribution as a function of temperature for the fusion reactions of fig. 3.

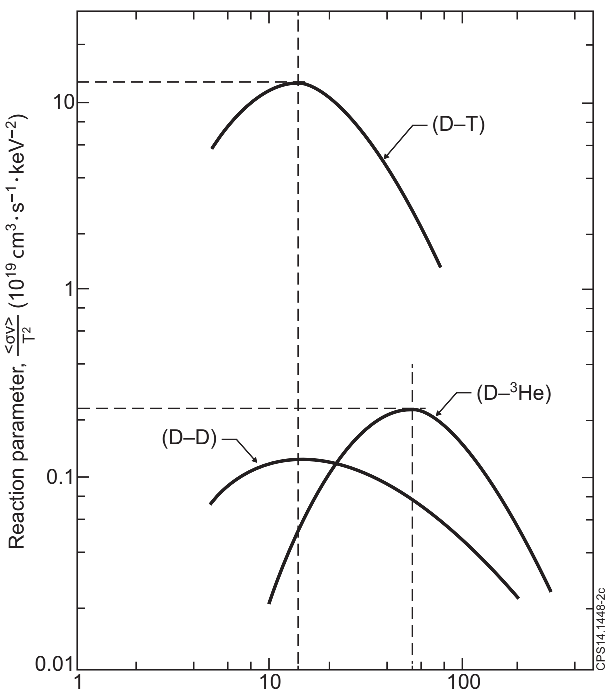


Fig. 5. – Maxwellian averaged values for $\frac{\langle \sigma v \rangle}{T^2}$ as a function of temperature for various fusion reactions.

the maximum of the $\langle \sigma v \rangle$ curve. For the D-T reaction we find that the reactivity is maximized at a temperature of about 150 million degrees (the temperature of a Maxwellian gas with an average energy of 1 eV corresponds to 11600 K), 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

Two radically different approaches have been followed towards the realisation of nuclear fusion on Earth: inertial and magnetic confinement. In the first 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 a few hundred 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 about 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 sphere.

The second approach is magnetic confinement. Since this has proven to be the most successful method to date, magnetic fusion research is under development in laboratories all over Europe and throughout the world. The rest of this article is focussed on magnetic confinement. For a recent overview of the status of inertial confinement, we refer to [11]. Recent inertial fusion results with the achievement of burning plasmas, are announced in [12, 13] and a nice summary of these results is presented in [14].

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 a hot plasma one can make use of magnetic fields, 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 can avoid these losses. A toroidal magnetic field, however, is not homogeneous. Its curvature destroys most of the nice confinement properties of a purely cylindrical configuration. 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

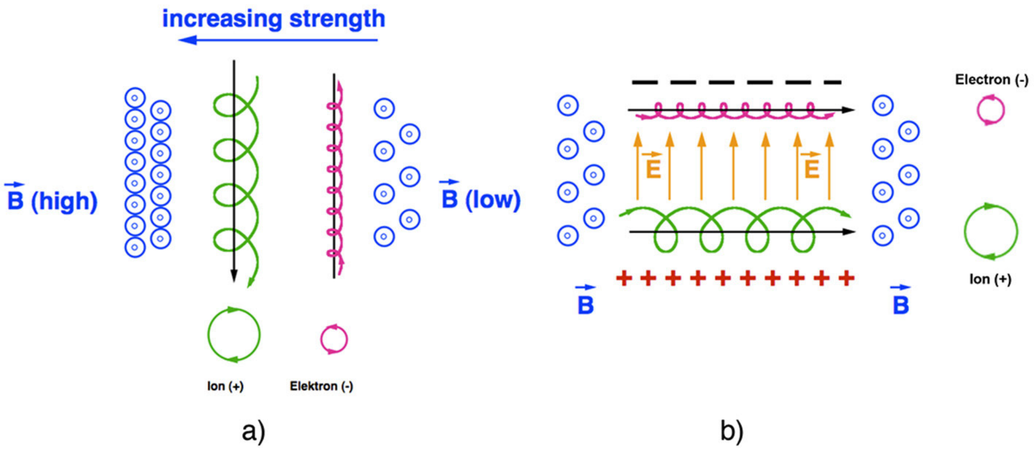


Fig. 6. – Illustration of the effect of the inhomogeneity of the toroidal magnetic field on plasma confinement. The effect can be easily explained in two steps considering the formula for the Larmor radius: $\rho = \frac{mv_\perp}{qB}$. For the first step see panel (a) on the left: formation of the electric 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 panel (b) on 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, respectively, decrease of the velocity of the particle. From the formula follows that with increasing velocity the Larmor radius increases and decreases with decreasing 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.

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 electrical current necessary for the stability of the plasma flows in the plasma ring, which serves as the (only) secondary winding of an enormous transformer. The induced current 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 (fig. 7). The magnetic structure thus generated consists of an infinite set of nested toroidal magnetic surfaces, each with a slightly different twist,

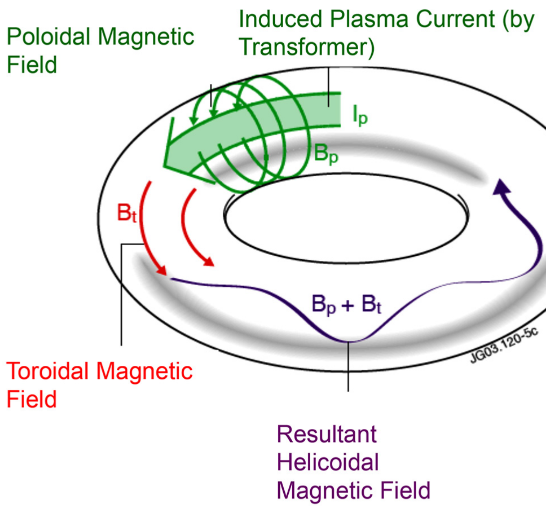


Fig. 7. – Principle of the tokamak: A large current induced in the plasma ring generates a poloidal magnetic field. The combination of this poloidal field with the main toroidal field results in a helical magnetic field, necessary for a stable confinement of the plasma in a toroidal configuration.

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 Lev Andreyevitch Artsimovich. The success of this configuration became at once clear at the Novosibirsk IAEA conference in 1968 when much higher temperatures were announced, obtained in a tokamak, compared to all other magnetic configurations under study at that time.

The tokamak is however a pulsed device, since the transformer needs a steadily increasing current in its primary winding to induce the plasma current. Continuous operation of a tokamak fusion reactor could be realised in theory using the bootstrap current [7] or non-inductive current drive by the heating systems. However this still will require considerable efforts before becoming a practically viable option [15].

A fusion device that operates without a plasma current and thus allows continuous operation, is the stellarator. Confinement in this device relies on currents *external* to the plasma to create the needed 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 complicate the construction. In addition such "classical" stellarator configurations lack good confinement properties. Modern stellarators have optimised confinement properties, and are equipped with a set of coils with a complex shape that is determined numerically to very high precision (fig. 9). Several devices of the stellarator type are in operation or in construction at this moment all over the world. The largest stellarator in the world that started operations in 2016 is Wendelstein 7-X, located in Greifswald, Germany (fig. 10) with successful experimental campaigns [16,17]

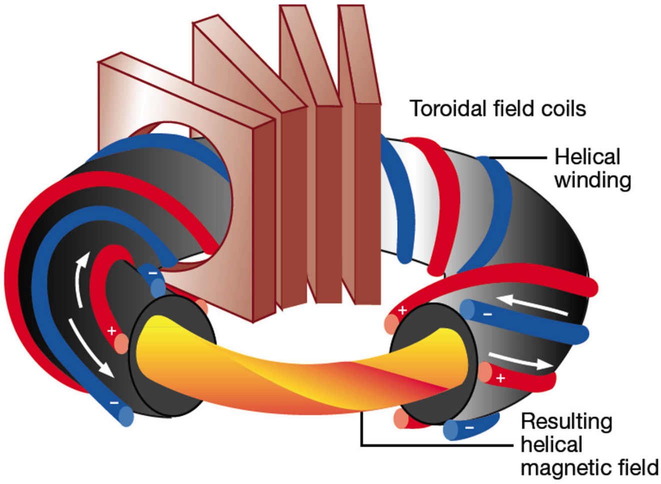


Fig. 8. – In a stellarator, helical coils external to the plasma ring create a supplementary magnetic field that, in combination with the main toroidal magnetic field, confines the plasma.

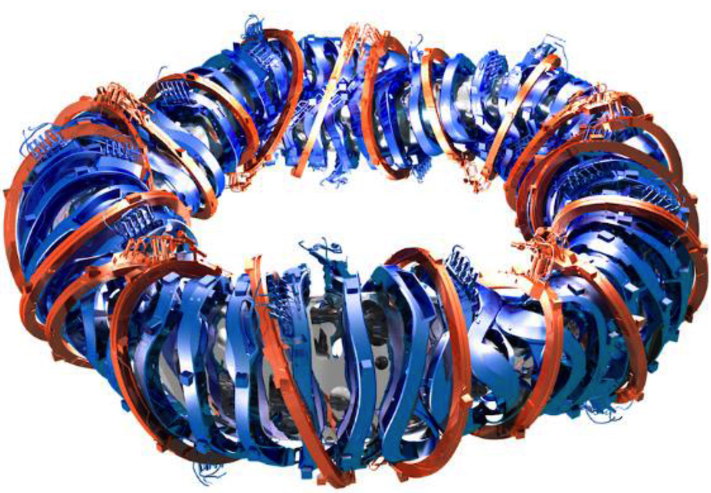


Fig. 9. – An illustration of the complex shapes of the coils of a modern stellarator, which combine the functions of the separate coil systems of fig. 8.

and further campaigns planned for the coming years. The device will be further upgraded in the coming years and in its final configuration will be able to run plasma pulses of 30 minutes. The largest stellarator-like device outside Europe is the LHD (Large Helical Device) of the National Institute for Fusion Science (NIFS, near Nagoya, Japan) that started operations in March 1998. Also this device has led to several rather important contributions [18].

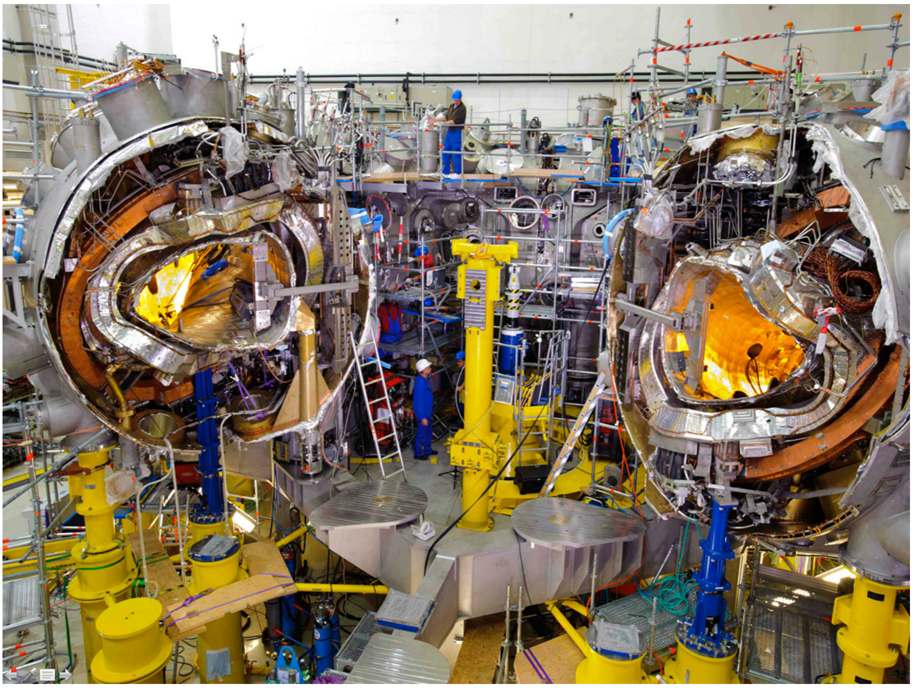


Fig. 10. – A picture of the stellarator Wendelstein 7-X, at the time of construction in November 2011.

3. – Plasma heating

The plasma current in a tokamak, needed to create the helical magnetic field providing stable confinement is a first source of heat. 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 heating methods 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. First ions are created in a plasma source and accelerated with voltages up to 150000 volts. The accelerated particles need to be neutralized because only neutral particles can penetrate the magnetic fields needed to confine the plasma. They pass through a cloud of neutral gas where they "steal" electrons from atoms in a charge-exchange reaction, and become energetic neutral particles. These in turn enter the hot tokamak plasma without impediment from the confining magnetic fields of the fusion device and, once in the hot plasma, are immediately ionised again, thus confined, and start to 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 to the plasma using this technique. Note that for higher acceleration voltages negative ions have to be used, as is now considered for ITER and DEMO (see sects. **8**·3 and **8**·4). The reason is that the neutralization of positive ions becomes very inefficient at higher voltages.

A second additional heating method sends electromagnetic waves into 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 emitted frequency is equal to a "natural" frequency of the particles that need to be heated. The cyclotron frequency with which the charged plasma particles gyrate around the magnetic field lines is an evident choice. Thus, two different heating systems exist: Ion Cyclotron Resonance Heating (ICRH) and Electron Cyclotron Resonance Heating (ECRH), depending on whether ions or electrons are heated. Ion cyclotron frequencies are in the MHz range (20 MHz and upwards), while electron cyclotron frequencies are in the range of 100–200 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 injected in the reaction chamber. 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. – 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 densities from auxiliary heating P_{heat} and α particles has to be at least equal to the power densities lost by radiation $P_{\text{radiation}}$ and transport, $P_{\text{transport}}$ (convection, conduction). This can be written as

$$P_{\text{heat}} + P_\alpha \geq P_{\text{transport}} + P_{\text{radiation}}. \tag{12}$$

To simplify the calculations, we consider in what follows a pure D-T plasma without impurities (*i.e.*, effective charge of the plasma $Z_{\text{eff}} = 1$). It thus implies also that we neglect the presence of He ash from the reaction. We assume only Bremsstrahlung losses for $P_{\text{radiation}}$ (given by the formula P_{Brems} (in $\mathrm{W/m^3}$) $= C_B T^{1/2} n^2$ if T is expressed in keV, and n in $\mathrm{m^{-3}}$ with $C_B = 5.35 \times 10^{-37}\,\mathrm{W\,m^3\,keV^{-1/2}}$ [7]) and we characterise all transport related energy losses, expressed by the term $P_{\text{transport}}$, making use of the confinement time τ_E, defined by the relation $\mathrm{d}W_p/\mathrm{d}t = W_p/\tau_E$, where W_p is the energy density in the plasma. From this definition it follows that the energy confinement time can also be defined as the characteristic time for the plasma to cool down, once all heat sources have been switched off. We also take into account that

$$P_{\text{heat}}Q = P_{\text{fusion}} = 5\,P_\alpha \tag{13}$$

and that the total plasma energy density is the sum of the ion and electron energy densities

$$W_p = \frac{3}{2}(n_e kT_e + n_i kT_i)\,, \tag{14}$$

with T_i and T_e in K, n_e and n_i in m^{-3}, and $k = 1.38\times10^{-23}$ J/K the Boltzmann constant.

In a neutral D-T plasma electron and ion densities are the same $n_e = n_i = n$; we also assume that the plasma is in thermal equilibrium, *i.e.* there is no difference between electron and ion temperatures $T_e = T_i = T$. Therefore

$$W_p = 3\,\text{nkT}. \tag{15}$$

Assuming a pure 50%D–50%T plasma leads also to $n_\text{T} = n_\text{D} = {}^1\!/\!{}_2 n_e = {}^1\!/\!{}_2 n$. The expression for the power density delivered to the plasma by the α particles, can thus be written as

$$P_\alpha = n_\text{D} n_\text{T} E_\alpha \langle\sigma v\rangle = \frac{1}{4} n^2 E_\alpha \langle\sigma v\rangle. \tag{16}$$

Expressing E_α and T_k in keV, (12) can be written as

$$\frac{1}{4} n^2 E_\alpha \langle\sigma v\rangle \left(\frac{Q+5}{Q}\right) \geq \frac{3nT_k}{\tau_E} + C_B^* Z_{\text{eff}} T_k^{1/2} n^2 \tag{17}$$

and finally

$$n\tau_E \geq \frac{3T_k}{\frac{\langle\sigma v\rangle E_\alpha (Q+5)}{4Q} - C_B^* Z_{\text{eff}} T_k^{1/2}}\,, \tag{18}$$

where $C_B^* = C_B/1.602\times10^{-16} = 3.34\times10^{-21}\,\text{W}\,\text{m}^3\,\text{keV}^{-1/2}$.

The right-hand side of the formula shows a minimum for about $T_k = 25\,\text{keV}$. Approximating $\langle\sigma v\rangle$ [in $\text{m}^{-3}\,\text{s}$] $= 1.1\times10^{-24}\;T_k^2$ (valid to within 15% in the interval $10\,\text{keV} < T_k < 25\,\text{keV}$) and setting $Z_{\text{eff}} = 1$ (pure D-T plasma) we find

$$\text{for breakeven } (Q=1)\text{: } n\tau_E \geq 2.5\times10^{19}\,\text{m}^{-3}\text{s} \tag{19}$$

and

$$\text{for ignition } (Q=\infty)\text{: } n\tau_E \geq 1.5\times10^{20}\,\text{m}^{-3}\text{s}. \tag{20}$$

An alternative formulation of the Lawson criterion is in the form of the so-called fusion triple product. Considering again only the temperature range where the minimum of eq. (18) occurs ($kT_e \sim$ 10–25 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. (18):

$$n\tau_E T_k \geq \frac{12QT_k^2}{(Q+5)\langle\sigma v\rangle E_\alpha}\,. \tag{21}$$

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

$$\text{for breakeven } (Q=1)\text{: } n\tau_E T_k \geq 5\times10^{20}\,\mathrm{m^{-3}s\,keV} \tag{22}$$

and

$$\text{for ignition } (Q=\infty)\text{: } n\tau_E T_k \geq 3\times10^{21}\,\mathrm{m^{-3}s\,keV}. \tag{23}$$

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 interesting paper by Rebhan and Van Oost [19].

6. – Outline of a fusion reactor power plant

The concept of a future fusion power device based on a tokamak is outlined in fig. 11. 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 D and T ions in the plasma and maintain the 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 confining magnetic field in the plasma chamber. These neutrons are not lost, but serve a dual purpose in the reactor. First, they produce tritium in a blanket surrounding the reactor containing lithium or lithium compounds, according to the following reactions:

$$^7\mathrm{Li} + \mathrm{n} \rightarrow {}^4\mathrm{He} + \mathrm{T} + \mathrm{n} - 2.47\,\mathrm{MeV}, \tag{24}$$

$$^6\mathrm{Li} + \mathrm{n} \rightarrow {}^4\mathrm{He}\ (2.05\,\mathrm{MeV}) + \mathrm{T}\ (2.73\,\mathrm{MeV}). \tag{25}$$

This is necessary to refuel the plasma with tritium, consumed in 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.

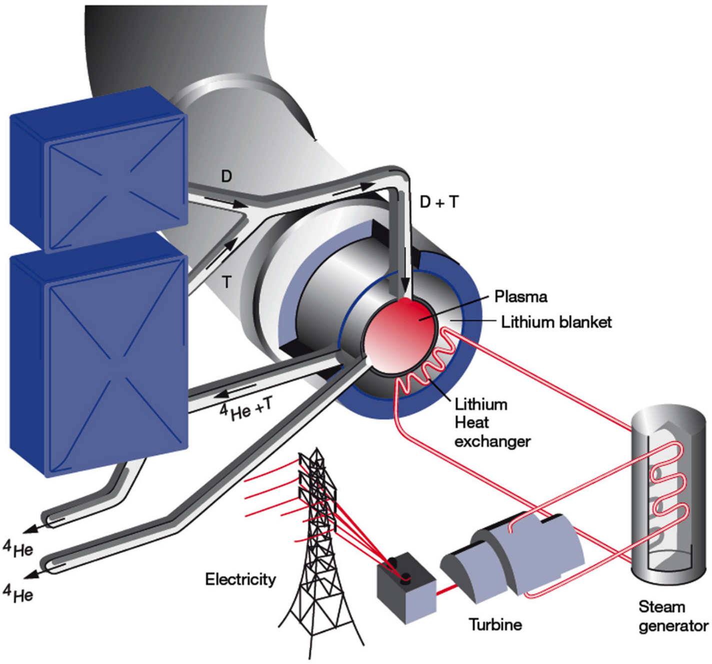
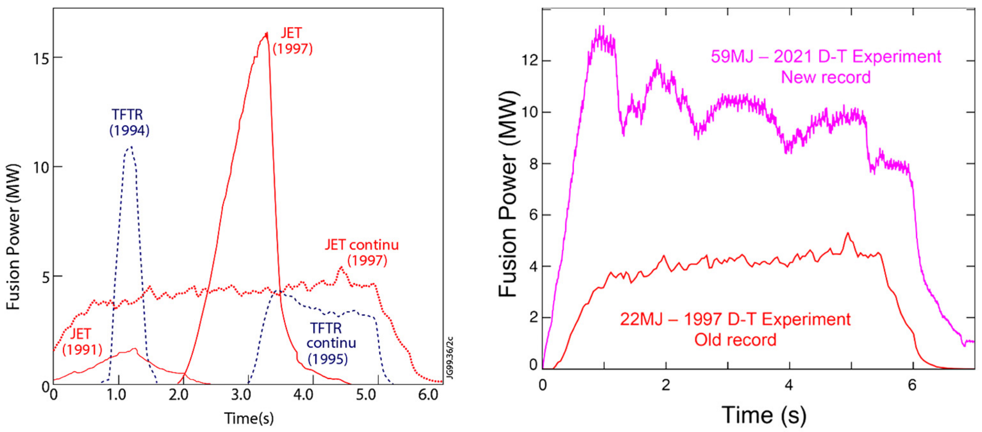


Fig. 11. – Many obstacles still have to be overcome before the first nuclear fusion power plant will be put into operation. Eventually, heat generated in fusion reactions will be used to generate steam to drive a turbine, with electrical power as final result.

7. – Progress in recent years

The progress obtained in fusion research in the past three decades is clearly visible from values obtained 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 the largest tokamak in the world, JET (Joint European Torus, located at the laboratories of the Culham Centre for Fusion Energy (CCFE), close to Oxford, UK), have contributed significantly to this progress, An important milestone was reached in 1991 with the first production of MWs of fusion power from controlled fusion reactions, as tritium was used for the first time as fuel in a tokamak [20]. 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 [21]. 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 [22].



(a) (b)

Fig. 12. – (a) Time traces of the fusion power released in different high performance deuterium-tritium fusion experiments in TFTR and JET in the 1990s. (b) Time traces of the D-T experiments with record fusion energy production in JET in December 2021.

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 [23], 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 [24].

The most impressive results in fusion research up to now were obtained in the JET. Experiments in 50%D–50%T plasmas resulted both in maximum fusion power and record fusion energy production values in JET. Over 16 MW of fusion power for about 1 second, with Q values in excess of 0.65 [25, 26] were reached in 1997. These are the highest fusion powers and Q values ever reached in D-T reactions, thereby effectively resulting in the first demonstration of breakeven in reactor grade D-T fusion plasmas. In December 2021, a world record amount of 59 MJ fusion energy has been produced in pulses of 5 seconds, a duration limited mainly by the use of copper magnetic field coils. This is an improvement by a factor of about 3 of the D-T results obtained in 1997. A summary of the different high performance D-T pulses obtained on JET and TFTR, is presented in figs. 12(a) and (b).

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 of fast fusion born alpha particles on the stability and the confinement of the plasma.

8. – Future prospects: JET, JT-60SA, ITER and DEMO

8˙1. *JET as a testbed for ITER.* – JET is currently focused on providing experimental evidence to questions raised by the ITER team. ITER, short for International Thermonuclear Experimental Reactor, is the next step device in fusion research and currently under construction in Cadarache, France, as a combined effort between Europe, Japan, the Russian Federation, South Korea, India, China and the United States (see sect. **8**˙3). Because of its worldwide unique capabilities (able to operate with both beryllium as wall material and tritium) and its large size, JET is ideally placed to do so. JET's "Programme in Support of ITER" has been elaborated along three main axes: i) experimentation with an ITER-like wall (combination of W and Be as a first wall), ii) development of plasma configurations and parameters towards the most ITER-relevant conditions achievable today and iii) integrated experimentation in deuterium-tritium. The JET auxiliary heating systems are upgraded with currently 45 MW of installed heating power, allowing access to ITER-relevant operational conditions. 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 anded advanced scenarios for ITER, which require full or partial current profile control, thereby making use of new dedicated diagnostics. Results from recent operations with the ITER like wall in JET are summarized in [27].

8˙2. *JT-60SA.* – In February 2007, EURATOM and Japan signed the so-called Broader Approach agreement. It 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 at developing 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 centre for advanced materials development and a supercomputing centre [28].

Parameters for JT-60SA are summarized in table III. JT-60SA is a fusion experiment designed to support the operation of ITER and to investigate how best to optimise 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. **7** 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 the coming months. More information on this interesting tokamak can be found in [29].

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

	T-10	DIII-D	JT-60SA	JET	ITER
Country/ 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)	1.18(hor)	1.25(hor)	2.0(hor)
		1.74(vert)	2.30(vert)	2.1(vert)	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	

8˙3. *ITER*. – The results summarized in sect. **7** provide crucial information for the design of a next large tokamak, ITER, aimed at demonstrating the technical feasibility for large-scale energy production. ITER will thus for the first time in history allow mankind to produce hundreds of MW of fusion power 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 III. 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.

8˙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, a large gap

TABLE IV. – *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
Low n-fluence, low dpa Low material damage	High n-fluence, high dpa Significant material damage

remains between ITER and DEMO. The main differences between ITER and DEMO are summarized in table IV.

DEMO is currently based on the tokamak configuration, as this is the most advanced fusion concept to date. In parallel, reactor studies are also being developed for Helical Devices (see, *e.g.*, [30-33]). 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 by the then European Fusion Development Agreement (EFDA) [34]. 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 V 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 IV 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

TABLE V. – *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 operation mode	DEMO 1 pulsed	DEMO 2 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

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 (a prototype facility, LIPAc [35], exists already in Japan and preparations for a fusion materials research facility in Europe are underway [36]), a facility to develop, *e.g.*, Neutral Beam Heating systems (if these are viable at all for DEMO) with acceleration energies between 1 and 2 MeV, based on negative ion sources (in contrast to the positive ion sources used currently, as mentioned before) etc. This research is done in the PRIMA facility in Padova, Italy, for the development of the ITER NBI systems [37]. But more efforts in various other fields will have to follow, and this will unavoidably take time.

The European Fusion Development Agreement (EFDA) released in November 2012 a roadmap for the realization of fusion electricity to the grid by 2050; the EUROfusion consortium recently published an updated document [38]. 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). For more technical details on the challenges in the design of a fusion reactor, we refer to the paper by Romanelli "Fusion energy: technological challenges", in this volume.

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

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, as it is in essence a "gas burner" and thus can be halted in a very short time by cutting the supply of fusion fuel. There is thus 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). As explained above, 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. Studies are underway to also extract it from seawater [39, 40]. If at a later stage the D-D reaction could be used (requiring, however, even much higher plasma temperatures), 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 helium, which is chemically inert and non-radioactive. With nuclear fusion there is thus no release of gases which contribute to the greenhouse effect, acid rain or the depletion of the ozone layer. Moreover, helium is the only gas still liquid at temperatures down to absolute zero, thus offering the only possibility for cooling low-temperature superconductors (as, *e.g.*, in modern MRI devices). It is thus not a "waste product" but in fact is essential for all applications involving ultra-low temperatures. This is especially important since helium is rather scarce on Earth.

The high-energy neutrons will 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 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 evidently be up to the young researchers to tackle these interesting problems. If successful, this will be an important contribution to the benefit of all people on Earth. A true challenge for an immense reward!

Further reading

A recent overview of the status of fusion research (magnetic and inertial) can be found in the "Insight Section" (66 pages) of the May 2016 volume of *Nature Physics* (`http://www.nature.com/nphys/insight/nuclear-fusion/index.html`) [41].

REFERENCES

[1] Agostini M., Altenmüller K., Appel S. *et al.*, *Nature*, **587** (2020) 577.
[2] Fewell M., *Am. J. Phys.*, **63** (1995) 653.
[3] NACRE (Nuclear Astrophysics Compilation of Reaction Rates) `http://pntpm.ulb.ac.be/nacre.htm`; Angulo C. *et al.*, *Nucl. Phys. A*, **656** (1999) 3.
[4] Raeder J. *et al.*, in *Controlled Nuclear Fusion: Fundamentals of Its Utilization for Energy Supply* (John Wiley & Sons, New York) 1986, Chapt. 1, ISBN-13: 978-047110312.
[5] Rebhan E., in *Heisser als das Sonnenfeuer* (Piper Verlag, München and Zürich) 1992, Chapt. 5, ISBN-13: 978-3492031097.
[6] Atzeni S. and Meyer-ter-Vehn J., in *The Physics of Inertial Fusion: Beam Plasma Interaction, Hydrodynamics, Hot Dense Matter* (Oxford University Press, Oxford), 2004, Chapt. 1, ISBN-13: 978-0198562641.
[7] Wesson J., *Tokamaks*, fourth edition (Oxford University Press, Oxford) 2011, Chapts. 5 and 7, ISBN 978-199592234.
[8] Mazzi S., Garcia J., Zarzoso D., Kazakov Ye. O., Ongena J. *et al.*, *Nat. Phys.*, **18** (2022) 776.
[9] Nespoli F., Masuzaki S., Tanaka N., Shoji M., Gilson E. P. *et al.*, *Nat. Phys.*, **18** (2022) 350.
[10] Emmert G. A., El-Guebaly L., Kulcinski G. L. *et al.*, *Nucl. Fusion*, **29** (1989) 1427.
[11] Betti R. and Hurricane O. A., *Nat. Phys.*, **12** (2016) 435.
[12] Zylstra A. B., Hurricane O. A., Callahan D. A. *et al.*, *Nature*, **601** (2022) 542.
[13] Kritcher A. L., Young C. V., Robey H. F. *et al.*, *Nat. Phys.*, **18** (2022) 251.
[14] Atzeni S., Batani D., Danson C. N. *et al.*, *Europhys. News*, **53** (2022) 18.
[15] Giruzzi G., Artaud G. F., Baruzzo M. *et al.*, *Nucl. Fusion*, **55** (2015) 073002; Garcia J., Giruzzi G., Artaud G. F. *et al.*, *Nucl. Fusion*, **48** (2008) 075007.
[16] Wolf R., Alonso A., Äkäslompolo S. *et al.*, *Phys. Plasmas*, **26** (2019) 082504.
[17] Beidler C. D., Smith H. M., Alonso A. *et al.*, *Nature*, **596** (2021) 221.
[18] Osakabe M., Takahashi H., Yamada H. *et al.*, *Nucl. Fusion*, **62** (2022) 042019.
[19] Rebhan E. and Van Oost G., in *Proceedings of the Sixth Carolus Magnus Euro-Summer School On Plasma And Fusion Energy Physics, Brussels, Belgium*, Fusion Sci. Technol., **45** (2004) 15.
[20] The JET team, *Nucl. Fusion*, **32** (1992) 187.
[21] Strachan J., Adler H., Alling P. *et al.*, *Phys. Rev. Lett.*, **72** (1994) 3526; Hawryluk R. J., Adler H., Alling P. *et al.*, *Phys. Rev. Lett.*, **72** (1994) 3530.
[22] McGuire K. M., Adler H., Alling P. *et al.*, *Phys. Plasmas*, **2** (1995) 2176.
[23] Ishida S., Neyatani Y, Kamada Y. *et al.*, in *Proceedings of the 16th IAEA Conference on Fusion Energy, Montreal*, Vol. **1** (IAEA, Vienna) 1997, p. 315.
[24] Fujita T., Kamada Y., Ishida S. *et al.*, *Nucl. Fusion*, **39** (1999) 1637.
[25] Keilhacker M., Gibson P., Gormezano C. *et al.*, *Nucl. Fusion*, **39** (1999) 209.
[26] Jacquinot J. and the JET Team, *Plasma Phys. Control. Fusion*, **41** (1999) A13.
[27] Mailloux J., Abid N., Abraham K. *et al.*, *Nucl. Fusion*, **62** (2022) 042026.

[28] Tsunematsu T., *Fusion Eng. Des.*, **84** (2009) 122.
[29] Barabaschi P., Kamada Y. and Ishida S., in *Proceedings of the 25th IAEA Conference on Fusion Energy, St-Petersburg, Russian Federation, 2014*, paper OV/3 (IAEA, Vienna) 2015.
[30] Beidler C. D. Harmeyer E., Hernegger F. *et al.*, "Stellarator Fusion Reactors – An Overview", in *Proceedings of the 12th International Toki Conference on Plasma Physics and Controlled Nuclear Fusion (ITC-12), Toki-city, Japan* (2001) Paper XI-3.
[31] Wobig H., Andreeva T. *et al.*, in *Proceedings of the 36th EPS Plasma Physics Conference Sofia, Bulgaria* (2009) Paper P4.192.
[32] Sagara A., Mitarai O., Imagawa S. *et al.*, *Fusion Eng. Des.*, **81** (2006) 2703.
[33] Sagara A., Imagawa S., Mitarai O. *et al.*, *Nucl. Fusion*, **45** (2005) 258.
[34] Federici G., Biel W., Gilbert M. R. *et al.*, in *Proceedings of the 25th Symposium on Fusion Engineering (SOFE), 10–14 June 2013, San Francisco, USA* (2013) paper WO1-1.
[35] Kondo K., Akagi T., Arranz F. *et al.*, *Fus. Eng. Des.*, **153** (2020) 111503.
[36] Królas W., Ibarra A., Arbeiter F. *et al.*, *Nucl. Fusion*, **61** (2021) 125002.
[37] Sonato P., Antoni V., Bigi M. *et al.*, in *Proceedings of the 3rd International Symposium on Negative Ions, Beams and Sources (NIBS), Jyväskylä, Finland*, *AIP Conf. Proc.*, **1515** (2013) 549.
[38] Donne A. J. H., *Philos. Trans. R. Soc. A*, **377** (2019) 20170432.
[39] Hoshino T., *Desalination*, **359** (2015) 59.
[40] Swain B., *Sep. Purif. Technol.*, **172** (2017) 388.
[41] Ongena J., Koch R., Wolf R. and Zohm H., *Nat. Phys.*, **16** (2016) 398.
[42] Wang M., Huang W. J., Kondev F. G. *et al.*, *Chin. Phys. C*, **41** (2017) 030003.