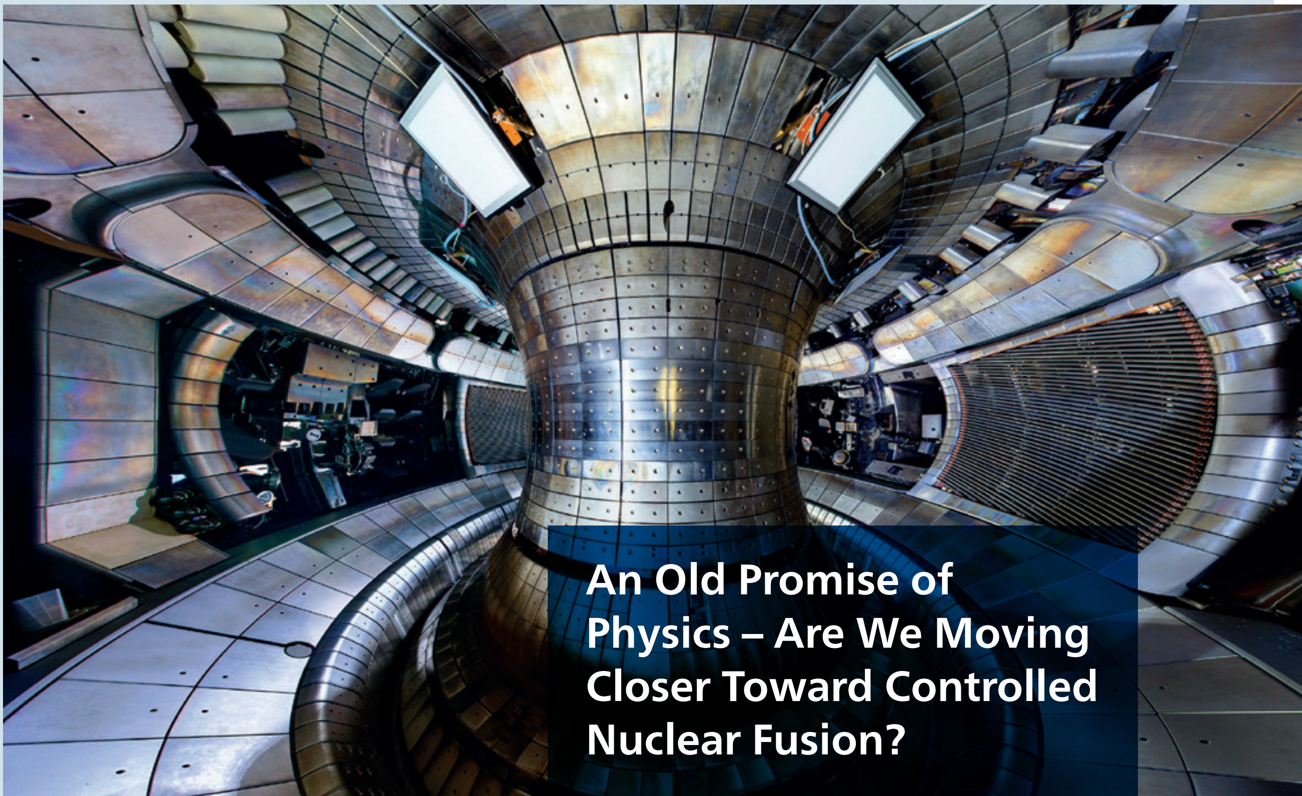
nucmag.com

atw

International Journal
for Nuclear Power

2020

11/12



An Old Promise of Physics – Are We Moving Closer Toward Controlled Nuclear Fusion?

Highlights of the World Nuclear Performance Report 2020

The EMPIrE Irradiation Test: Lower-Enriched Fuel for High-Performance Research Reactors

ISSN · 1431-5254
24.– €

Issue 11/12 2020

November/December

Contents

Cover:
ASDEX Upgrade during revision (Courtesy IPP/Bernhard Ludewig).

G = German
E/G = English/German

Feature

Major Trends in Energy Policy and Nuclear Power

An Old Promise of Physics – Are We Moving Closer Toward Controlled Nuclear Fusion?

Lars Jaeger

"Fridays for Future" demonstrations are invigorating the masses, the European Union launches a "European Green Deal" in which it commits to reduce net greenhouse gas emissions to zero by 2050, the new US president aims the same for the United States, China follows by announcing a carbon free economy by 2060, Germany decides on a multi-billion climate package, and at global climate summits government representatives and CEOs of multinational corporations and their PR strategists are trying to make a name for themselves as well-meaning climate protectors. It appears that the question of our future climate and energy production has finally reached the center of public attention and debate.

And it is precisely at this time that scientists, without a great deal of public attention, are making progress in an area that could solve the problems of global energy supply once and for all: the peaceful use of nuclear fusion. This is about nothing less than fulfilling the dream of unlimited, clean, and safe energy from the thermonuclear fusion of atomic nuclei, the very same that supplies our sun and the stars with seemingly endless amounts of energy.

The light of stars

Nuclear fusion research comes with a more than 80-year history[1]. Since the 1930s, physicists have known that under very high pressure and temperatures hydrogen nuclei fuse into helium nuclei. This is the very mechanism that enables the sun to generate its massive amounts of energy. In 1938, Carl Friedrich von Weizsäcker and Hans Bethe developed a first model for the nuclear reaction occurring inside stars. According to their model, the *fusion* of light atom nuclei, just like the *splitting* of very heavy nuclei, releases a significant amount of energy. The reason for this energy gain is that the fusion of the nuclei entails a loss of a small amount of mass. This mass deficit manifests itself directly in the (kinetic) energy of the particles produced. According to Einstein's famous formula $E=mc^2$ even with such low amounts of lost mass the released energy is enormous. In fact, about 10 times more energy is released in the fusion process of light nuclei than in the reverse fission process of heavy nuclei.

It quickly became clear that nuclear fusion is the fundamental process at the bottom of a.) almost every form of energy on Earth, as well as b.) all material stuff in the universe besides hydrogen, as within the stars the process not only fuses hydrogen atoms to helium, but also produces larger atomic nuclei, carbon, oxygen and finally the heavy elements such as iron, gold, and manganese. When a star dies, it hurls in a supernova explosion in which the "hatched" heavy atomic nuclei spread out into the vastness of the universe. Several billions of years ago some of these heavy atomic nuclei eventually found their place in the vicinity of our forming planet.

However, fusion of nuclei requires enormous pressures (the product of temperature, i.e. kinetic particle energy, and particle density) so that positively charged nuclei can overcome their electrical repulsion and get close enough to each other to fuse. In stars like our sun these pressures are reached via the very high densities obtained by ultra-strong gravitational forces. Such forces and thus densities are not available on Earth. Terrestrial fusion would therefore have to employ far higher temperatures to make up for the lower density and thereby achieve similar pressure as in stars.

In 1934, Mark Oliphant, Paul Harteck and Ernest Rutherford achieved the fusion of two deuterium nuclei (an isotope of hydrogen with one extra neutron) by shooting one deuterium atom onto a metal foil containing other deuterium atoms. This way they measured what physicists call the "nuclear cross section" of the fusion reaction, a characteristic area that provides the probability that fusion might take place, i.e. how close the nuclei must get in order to react. This in turn allowed them to determine the energy necessary for the deuterium-deuterium (DD) fusion reaction to occur (under atmospheric pressure). Their result came in at around 100,000 electron volts (100 keV). This translates into a temperature of more than one billion Kelvin (the factor that translates the kinetic energy of atomic particles as measured by eV into the macroscopic variable of temperature as measures by the Kelvin scale is the inverse of the Boltzmann constant $1/k_B$, 11,604 K/eV, i.e. one eV corresponds to 11,604).

In the late 1940s, physicists first aimed at recreating the mechanism of nuclear fusion on Earth, however in an *uncontrolled* manner. Their goal was to create an even more terrible weapon than the atomic bomb (which is based on nuclear *fission*). On October 31, 1952, the US detonated their first "hydrogen bomb" releasing over ten megatons of TNT equivalent, an energy equivalent to 800 times the explosive power of the Hiroshima bomb. Less than a year later the Soviet Union detonated its first hydrogen bomb, and another eight years later, the Russians tested the "Tsar Bomb", at 50 megatons and 4000 times the power of the Hiroshima bomb the most powerful nuclear weapon ever ignited on Earth.

Left: Carl Friedrich von Weizsäcker 1993, Göttingen DPI (Source: Wikimedia); Right: Hans Bethe 1967 (Source: www.nobelprize.org)

Nuclear fusion – The forever future technology?

However, as early as in the early 1940s, even before its devastating military application, the American researcher (and later "father" of the hydrogen bomb) Edward Teller and the Italian Enrico Fermi (who was also the first to

1 Already in 1920, British astrophysicist Arthur Eddington suggested that stars draw their apparent endless energy from the fusion of hydrogen into helium. His theory was first published in 1926.

perform controlled nuclear fission) developed first ideas for power generation on the basis of *controlled* nuclear fusion. Shooting nuclei at others like Rutherford and his colleagues had done would surely not do it. Most nuclei will not hit another one, as the cross section of the fusion reaction is way too small. The concept Teller and Fermi developed remains the basis for nuclear fusion researchers today: In a kind of microwave a deuterium-tritium (DT) mix is heated to many million degrees so that ultimately the temperature is high enough for fusion to occur (tritium is another isotope of hydrogen with two neutrons added; the DT reaction has a larger cross section than the deuterium-deuterium (DD) reaction, i.e. it requires lower temperatures).

When heated to such high temperatures, the atoms lose their electrons, resulting in a fluid of nuclei and electrons called a "plasma". At temperatures of about 100 million degrees, around six times the temperature at the core of the sun, terrestrial fusion can release net energy. Although the kinetic energy of the two nuclei required to fuse is usually higher than the equivalent temperature of 100 million Kelvin (as we saw above, this values lies at around 100 keV, i.e. 1 billion Kelvin), due to the distribution of energies within the gas as given by the Maxwell-Boltzmann statistics a gas with less temperature still contains enough particles at high enough energies to fuse (reactions also proceed by quantum tunneling of the electric potential energy barrier, i.e. fusion inherently relies on quantum mechanics).

Important, however, are the conditions required for the reaction to become self-sustaining, i.e. the energy given off by the nuclear fusion reactions heats the surrounding fuel rapidly enough to maintain the temperature against losses to the environment. The ratio of the obtained fusion power and the input power required to maintain the reaction fusion scientists denote by the letter Q. When Q exceeds 1, fusion produces net energy. A plasma is "ignited" when the fusion reactions produce enough power to maintain the temperature without any external heating. An important variable for this to occur is the above-mentioned cross section of the reaction. For the fusion process in most reactors to exceed the losses of the energy to the environment a certain function of temperature, cross section and average particle velocity must be exceeded (in detail: the ratio of squared temperature and the product of cross section and average velocity of the particles, see Lawson criterion below). This condition provides a minimum temperature for the fusion reaction to hold up and become net positive energy producing. For the DT reaction this required temperature stands at around 150 million Kelvin (13.6 keV), for the DD reaction it is around 170 million Kelvin (15 keV).

In an uncontrolled nuclear fusion, the way to get to fusion conditions is using an atomic bomb. That is how an H-bomb works: An exploding atomic bomb creates the necessary pressure and temperature inside a gas for the nuclei to fuse. That happens so fast that the plasma does not need to be controlled in any way. In a controlled nuclear fusion, however, the high temperature plasma needs to be enclosed and controlled. This requires strong forces to keep the particles within the plasma as these are moving with those incredibly high velocities that are necessary to overcome the electrical repulsion of their positive charges. Thereby, the challenges are:

a. At such temperatures, the plasma possesses an enormous amount of thermodynamic pressure and thus, if not counteracted by another force, flies off which quickly stops the fusion.
b. Upon contact with the "outer world" (e.g. the container walls), the plasma immediately cools down which interrupts the fusion almost instantly.

To address these challenges researchers and engineers have developed enormous magnetic fields to control the plasma. Such "magnetic confinement" of the plasma lies at the heart of most fusion energy projects.

It is difficult not to fall into ecstatic excitement in view of the practically unlimited possibilities of nuclear fusion. The energy thus released is safe, carbon-free and its required initial materials are abundantly available.

- The primary fuel – hydrogen isotopes – can be found in normal ocean water (albeit tritium is extremely rare on Earth and needs to be produced by irradiating lithium in a nuclear reactor).
- One kilogram of the deuterium-tritium (DT) mix is enough to supply an entire city with energy for a very long period. A functioning reactor would only need five kilograms of this hydrogen to produce the energy equivalent of 18,750 tons of coal, 56,000 barrels of oil or the amount of energy 755 hectares of solar collectors produce in one year.
- The only immediate by-product is helium.
- The risk of accidents with a fusion plant is limited: If something unexpected happens, the fusion reaction simply stops (note that in existing nuclear power plants based on fission the cooling of the reactor must be assured after shut down to safely handle the decay heat of the fuel).

Unfortunately, a 100 million degrees hot mixture of hydrogen nuclei has proven so difficult to control that a well-known joke among physicists is that nuclear fusion is the most promising technology of the future – and will remain so forever.

Between excitement and frustration – The development of magnetic confinement

In the 1950s physicists thought magnetic confinement would not be too difficult to achieve. Only over time did they learn about the complexity of the thermodynamic and magnetohydrodynamic properties of high temperature plasmas, their inner turbulences and instabilities that make them so extremely difficult to control. What became clear is that in order to contain the plasma and reach temperature and pressures sufficient to ignite the fusion reaction one had to build up ultra-strong homogenous magnetic fields. Top scientists all over the world have been working on the technological challenges this entails for decades, and so far no fusion reactor has ever been able to achieve a Q-value larger than one.

In the first designs of magnetic confinement for plasmas magnetic forces were designed to bring the fast-moving particles on more and more closely aligned paths so they can collide and fuse. Such magnetic fields can be created through a "solenoid", a simple coil wound into a tightly packed helix that generates a uniform magnetic field keeping the nuclei in line and preventing them from drifting away. However, eventually the particles will run out to the end of the coil and exit the magnetic field. The obvious solution was to bend the coil into a circle, resulting in a donut shape called a torus, in which the particles can circle endlessly. However, this comes with a new problem: The magnetic forces within the torus are now unevenly distributed with their lines being tighter together at the inside than on the outside of the torus. This leads to forces causing the plasma particles to drift away from the center line of the torus. A more complex arrangement of magnets was needed in order to balance these forces and keep the particles aligned. One design for that purpose was the "stellarator" invented by US scientist Lyman Spitzer of Princeton University, which twisted the entire torus at one end of the torus compared to the other end, thus forming a figure-eight layout. This design demonstrated some improved confinement properties compared to a simple torus, but also displayed a variety of effects that caused the plasma to be lost from the reactors at too high rates to reach fusion conditions.

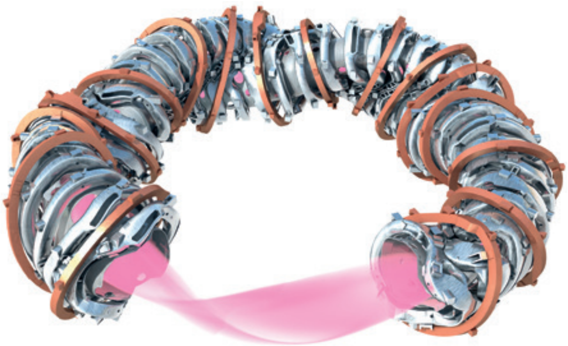


Fig. 1.
Computer graphics of plasma as well as the stellarator magnet coils and flat magnet coils of the fusion device Wendelstein 7-X. (Source: IPP)

Another early design was the "z-pinch" concept where a pulsed plasma is subjected to a strong electrical current flowing in its center. Based on the principle that parallel currents attract each other (through the Lorentz force), the plasma would transiently compress in the process (physicists speak of the "pinch effect") with the goal of reaching end stage conditions that create similar pressures as in a star, albeit only for a few nano-seconds (a nano-second being one billionth of a second). This design was envisioned to lead to a pulsed fusion concept without magnetic coils where a regular sequence of "mini-implosions" would lead to pulses of net energy being released. While this design showed some promise, it has so far failed to reach net energy capability, as various instabilities form during the compression process that prevent sufficient pressure build-up.

The various configurations of magnetic and electrical fields combined with the plasmas' self-induced pinching all left the plasma still too unstable. Already in 1949 David Bohm had, based on empirical observations, conjectured a relationship (scaling law) between the diffusion of the plasma and, amongst other things, the strength of the magnetic field. This relationship was supposed to by inverse linear, rather than inverse quadratic like classical physics would predict, so Bohm concluded. If the "Bohm diffusion" scaling held, there would be no hope one could ever build a fusion reactor based on magnetic confinement. The entire field of fusion research thus descended into a period of intense pessimism, what became known as "the doldrums" of nuclear fusion research.

However, in the late 1960s a concept originally conceptualized in the 1950s by Soviet physicists Igor Tamm and Andrei Sakharov started showing very promising results achieving a stable plasma equilibrium and promising deviations from the Bohm diffusion conjecture. In this construction, magnetic field lines wind and twist around the torus shaped confinement chamber in a helix like stripes on a candy cane. The asymmetry of the magnetic fields keeps the particles from drifting away: Each particle that finds itself at the outside edge of the torus follows the magnetic lines around the torus and ends up on the inside edge, where it will drift the other way towards the outside again. The more the magnetic field lines twist, i.e. the higher the frequency of the particles transiting from the outside to the inside and back, the more stable the plasma became.

In more detail, this construction consists of three arrays of magnets:

1. External coils around the ring of the torus producing a toroidal magnetic field, i.e. a field parallel to the inner circle of the torus.
2. A central solenoid magnet generating with strong energy pulses a perpendicular magnetic field and thus a toroidal current within the plasma. The movement of ions in the plasma then in turn creates a second poloidal (along the inner ring of the torus) magnetic field.
3. Poloidal coils around the circumference of the torus control the position and shape of the plasma.

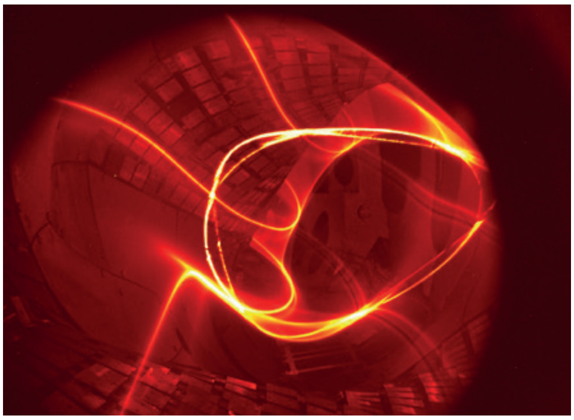


Fig. 2.
The magnetic field of Wendelstein 7-X (July 2015): The photo combines the traces of an electron beam on its multiple revolutions along a field line through the plasma vessel with the image points that it leaves on a fluorescent rod that is swiveled through the image plane. (Source: IPP, Matthias Otte)

Tamm and Sakharov called their design a "tokamak" which is a Russian acronym for "toroidal chamber with magnetic coils". The results they obtained were at least 10 times better than that of any other fusion machine before. The tokamak quickly would become the new standard in international fusion efforts in the coming years.

The research emphasis now turned to efficient ways to heat the plasma. Besides the conventional «Ohmic» heating by inducing a current through the plasma three techniques became state of the art (including combinations thereof):

1. Magnetic compression (also called adiabatic compression), a pinch-like technique in which a magnetic field compresses the plasma in order to raise its temperature.
2. Neutral beam injection, in which a particle accelerator shoots fuel atoms into the plasma, which collide with the particles in the plasma and thus heat it.
3. Radio-frequency heating: Like in a microwave high-frequency electromagnetic waves with the right frequency transfer their energy to the charged particles in the plasma.

In 1978 by combining the first two techniques the Princeton Large Torus (PLT) managed to reach temperatures of more than 60 million Kelvin. The global scientific community was more and more convinced that the road to a nuclear fusion reactor was now wide open. And the race was on: The Europeans created JET the „Joint European Torus", the Soviets continued to work on their tokamak, the Japanese created their JT-60, and the US continued to invest significant money and scientific effort into the Tokamak Fusion Test Reactor (TFTR). Even private investors put money into commercial tokamak projects, the first of them Bob Guccione, the founder of the Penthouse Magazine.

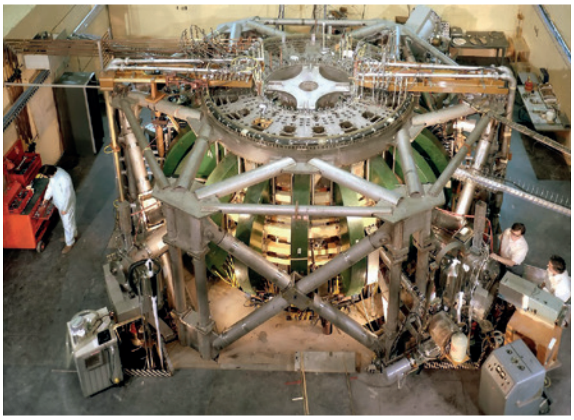


Fig. 3.
Princeton Large Torus. (Courtesy of Princeton Plasma Physics Laboratory)

But during the 1980s it became clear that plasmas at such high temperatures are even more difficult to control. New instabilities arose, and the plasma proved ever more difficult to be confined. The promising tokamak architecture ran into similar problems as early torus type concepts. Todd Evans, a physicist at General Atomics in San Diego, California, described the problem in illustrative terms: „Think of squeezing a balloon full of water. The harder you squeeze, the more the balloon bulges out through your fingers." The more the magnetic donut is squeezed, the more likely the pressurized plasma bursts. It became clear to physicists that much larger and more complex (and expensive) machines were needed to solve these problems. A second period of sobering and pessimism arose in nuclear fusion research.

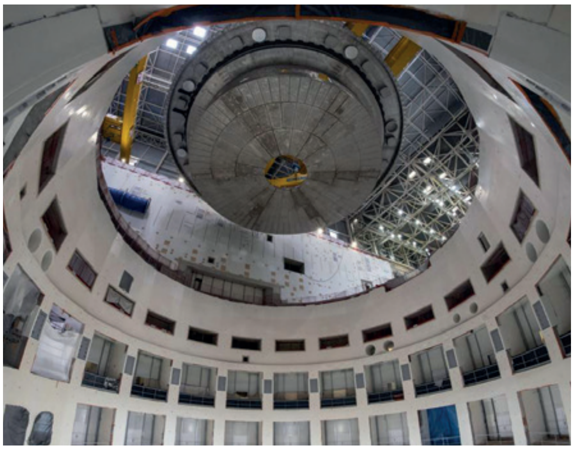


Fig. 4.
26 May 2020: First major component installed – Nearly five years after contractors to the European Domestic Agency poured the first concrete of the ITER bioshield, the first major component is installed at the bottom of the 30-metre-deep "machine well." (Source: ITER)

ITER – Great as well as expensive hopes

Researchers have in fact been able to confine fusion plasmas at high enough temperature for long enough to initiate fusion reactions. However, the confinement time reached was never long enough to allow for sufficient fusion energy to circulate in the confined region so that the plasma remains hot enough to maintain the appropriate level of fusion. Tokamaks have managed confinement times of about 30 milliseconds, but times of a second and more are likely to be needed. Essentially, the problem of achieving and maintaining fusion in a plasma involves three main variables:

1. The temperature (or velocity/energy of the particles in the plasma),
2. the density of the plasma (number of particles per volume),
3. and the inclusion time (how long the plasma is held together).

Fig. 5.
ITER arial May 2020. (Source: ITER, EJF Riche)

In 1955 John Lawson published a criterion that provides a minimum required value for the product of the plasma density and its confinement time in order to reach ignition and then maintain the temperature of the plasma for long enough against all losses such that fusion energy itself ultimately keeps the temperature up. Later an even more useful figure of a reactor's ability to ignite became the triple product of density, confinement time and plasma temperature. The minimum required value for the product of these three variables is today referred to as a more general form of the "Lawson criterion"[2]. According to a rule of thumb, for DT-fusion and for temperatures over 100 million Kelvin the product of particle density and inclusion time must be greater than 10^{14} seconds per cubic centimeter (10^{16} for the deuterium-deuterium reaction). Reaching such values should be achievable with larger devices and stronger magnetic fields, so the hope of the physicists. Existing tokamaks are simply not large enough to reach burning plasma conditions, they believe. As the costs estimates for such larger reactors kept mounting it became clear: International cooperation and funding was needed. This led to the creation of the project "International Thermonuclear Experimental Reactor" (ITER), a joint effort by equal participation of the Soviet Union (later Russia), the European Atomic Energy Community, the United States, and Japan, later joined by China, South Korea, Canada, and India. In 2005, it was decided that ITER would be built in the European Union in Southern

2 The original Lawson criterion, however, remained the density-confinement time product, which is what the nuclear research field typically refers to as the Lawson criterion. Many reactor kinetic equations can be normalized by the double product. However, people occasionally invoke the name Lawson criterion with the triple product, typically by referring to a more generalized form of the original Lawson criterion.

France, in the town of Cadarache, but only recently, in July 2020, more than 30 years after the initial talks about ITER, the assembly of the machines was launched. Fusion experiments with DT fuel are expected to start in 2035.

ITER is projected to be the first device that can generate and maintain a burning plasma, i.e. a plasma in which the fusion reaction is initiated and kept running. With DT fusion, ITER is expected to produce 500 MW of fusion power at a Q value of 10 – fifteen times the current world record of a Q value of 0.67 (at 16 MW) held by the JET tokamak in the UK, attained in 1997. For this ITER will have a central solenoid that will be the most powerful pulsed superconducting magnet ever constructed. However, ITER is not designed to create any electricity output. This would only happen in a successor reactor, already baptized DEMO (Demonstration Power Station) and being planned by EUROfusion, the EU's fusion organization, with a 2 to 4 gigawatts of thermal output, operational for electricity production at the earliest in the late 2040s.

The total projected costs of ITER stands at over 20 billion euros to date and will, according to some experts, go up to as high as 60 billion euros. It is already the most expensive experiment in the history of science. Despite all these tremendous costs and the long-time horizon their experiments entail, the nuclear fusion researchers at ITER do not yet know if "physics is not yet again going to bite them in their ass". The thermo-, fluid- and hydromagnetic dynamics and stability properties of a plasma at such temperature can still be subject to surprises at it has already been quite a few times in the past[3]. On top of this, the solution for two particular problems is not yet on the horizon:

1. The DT fusion reaction produces neutrons of very high energy (14.1 MeV). Since they are electrically neutral and thus not influenced by magnetic fields, these neutrons collide in large numbers and extremely high speeds with the material of the reactor's container, causing enormous damage to it over time. The container will therefore have to be replaced every one or two years, which would push the operating costs of a fusion reactor to unacceptable levels. In addition, the neutron bombardment in the container material creates radioactive nuclides, which generates radioactive waste and thus makes the disposal of the material yet more costly.
2. Tritium is extremely rare on Earth. One gram of the hydrogen isotope currently costs around 30,000 US dollars. Plus, tritium is beta-emitting radioactive with a half-life of 12.3 years. This requires special attention, as tritium is chemically equivalent to ordinary hydrogen found in water.

Material scientists are working hard on container materials that solve the first problem; however the path towards those remains long. For the second problem the physicists hope to be able to create enough tritium by neutron activation of lithium-6 for which the fast neutrons of the DT reaction themselves can be used (for this ITER will have a "breeder blanket" of lithium located adjacent to the vacuum vessel).

The call for an alternative to the D-T reaction, which does not have these problems, has been made by experts years ago. The next possible candidate for is D-He_3. Its neutron output is on order of 1 % of D-T. However, He_3 is not found terrestrially, but rather abundant on the moon, where mining would be very costly. The best candidate for an aneutronic fusion process that does not require tritium is perhaps the boron-proton reaction. It is "clean" as it produces three helium nuclei, which are charged particles that can be easily controlled by electro-magnetic fields and cause neither lifetime limitations on reactor materials nor any have any negative impact on the environment. Plus, boron (and protons) is readily available on our planet. Its problem: The reaction requires about 30 times higher plasma temperatures to ignite.

The range of paths is widening

Remember the Lawson criterion: For this to hold it does not matter whether the density of the plasma is low and its inclusion time high (as in the tokamak) or vice versa, the inclusion times being very short and the density very high. Any combination of these two values is also feasible as long as their product is about the same. One can thus attack the Lawson criterion from different directions, i.e. through different combination of the critical variables. The tokamak, although being most prominently supported, is thus not the only path on the road towards commercial fusion. In fact, some alternative approaches have in recent years generated considerable new excitement in the fusion community, as many plasma scientists now conjecture that in the middle between these two extremes, in the range of medium range inclusion times and medium range densities, could lie a very large playground, which has so far been largely left untouched by the tokamak approach. Is this maybe where the most promising opportunities for a controlled nuclear fusion reaction lie?

Public versus private financing

However, public funding for alternative approaches is quite limited, especially as ITER is taking up so much money. Governments' willingness to come up with more funding is … well … confined. Not surprisingly, in 2019 the US

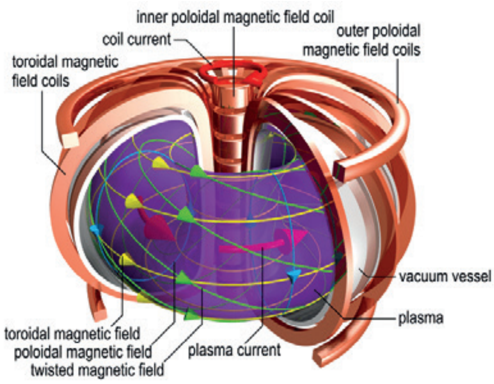


Fig. 6.
Schematic view of the tokamak magnetic confinement principle. The toroidal magnetic field coils establish a strong magnetic field (yellow lines) within the vessel that captures charged particles on magnetic field lines. The inner poloidal magnetic field coils are used to induce a current into the plasma. It produces a poloidal magnetic field (blue lines) in order to twist the magnetic field lines (green) to prevent particle outward drift. (Source: Max Planck Institute for Plasma Physics, Christian Brandt)

3 Until today theoretical physicists have not found a coherent solution for the general three-dimensional equilibrium equation in magneto-hydrodynamics (MHD) for an ideal three-dimensional plasma (these equations are combination of the Navier–Stokes equations of fluid dynamics and Maxwell's equations for electrodynamics). The processes and turbulences in the plasma are simply too complex. In addition, MHD is not universally applicable to many systems outside of tokamaks. For instance, the field reverse configurations (FRCs) discussed below are not describable by MHD models.

National Academies of Sciences stated in its *Final report of the committee on a Strategic Plan for U. S. Burning Plasma Research,* that the landscape of fusion research has changed substantially with the fusion research community now being much stronger building on significant progress and investments already made with better and better theoretical understanding of toroidal magnetic confinement and plasma control. All this has yielded "remarkable new technologies […] promise to reduce the size and cost of future facilities". Thus,

"a large DEMO device no longer appears to be the best long-term goal for the U.S. program. Instead, science and technology innovations and the growing interest and potential for private-sector ventures to advance fusion energy concepts and technologies suggest that smaller, more compact facilities would better attract industrial participation and shorten the time and lower the cost of the development path to commercial fusion energy".

Indeed, next to the government sponsored gigantic tokamak project a number of private companies have dedicated themselves to nuclear fusion research, and instead of walking along the one and only one true (and very expensive) path – large-scale plasma held together by gigantic superconducting magnets – these companies follow a variety of different ideas in order to possibly find one path towards the jackpot of a functioning fusion reactor. Although different in their approach all of them are looking for paths to fusion that employ much smaller and thus less expensive reactor technologies than ITER, aiming at generating electricity already in the next few years and thus also much faster than ITER with its time horizon of several decades. They are counting on possible mistakes and insurmountable obstacles in their ideas being found (and fixed) much faster than in a few decades time and before billions of dollars have been burned. The fact that they depend on risk capital that is hungry for returns could prove to be a decisive advantage. They simply cannot afford to turn to large, expensive, long-lasting, and untested projects. Rather, they must always decide step by step which next move to take and justify every step in front of their shareholders. In light of the nature of the described problems around thermonuclear fusion technology such a pragmatic approach might prove more appropriate.

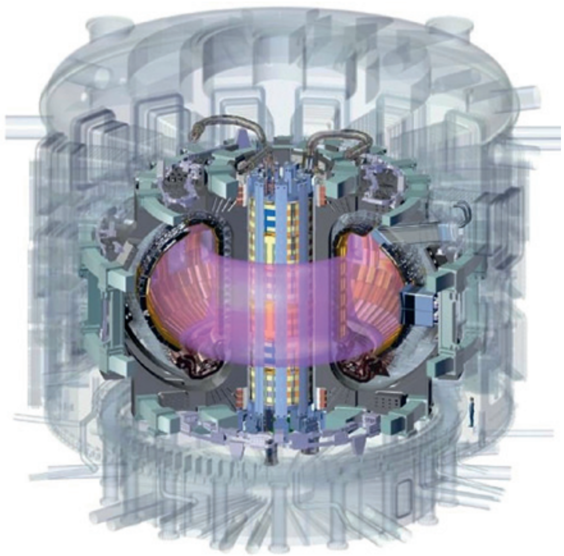


Fig. 7.
A tall electromagnet--the central solenoid--is at the heart of the ITER Tokamak. It both initiates plasma current and drives and shapes the plasma during operation. (Source: US ITER)

These private companies have in recent years made some considerable progress. A real public-private race for the best fusion technology solution has in fact developed. How fruitful such a race can be showed the example of the Human Genome Project some 20 years ago. The following provides a list of private initiatives that work on tokamak type designs:

- *Commonwealth Fusion Systems* (CFS) is a spin-off from MIT's (Massachusetts Institute of Technology) Plasma Science and Fusion Center, one of the pioneers of the US fusion research in the 1960s. The company is pursuing a more or less fairly conventional tokamak approach. However, they are trying to integrate some recent technological advances that will not be part of ITER, in particular new high-temperature superconducting material for a large scale electromagnet (barium copper oxide versus niobium-titanium in ITER) which will allow, so the scientists hopes, for magnetic fields in the range to 20 Tesla in overall smaller and more efficient design. CFS is pursuing a tokamak that would produce 50 MW to 100 MW of fusion power, i.e. one fifth of the foreseen ITER power, at a Q value of 3, less than one third of the foreseen ITER value. The company is funded by MIT itself as well as venture capital, including the Bill Gates – backed Breakthrough Energy Ventures, and Italian oil and gas producer Eni.
- *Tokamak Energy* based in the UK is employing a tokamak with a more spherical shape. It is also privately funded and raised about $86 million in an early 2020 funding round.

The alternatives

Other private companies have endeavored some highly interesting alternative paths towards a fusion reactor altogether:

- *(FRC):* FRC is an alternative magnetic confinement method which still involves a toroidal plasma, however without any magnetic coils running through the center of the toroid like in the tokamak and also no toroidal coils. It entails an external axial magnetic field wherein electric currents in the plasma create a poloidal magnetic field, which has an effective axial component that opposes, i.e. reverses, the externally applied field. This then self-confines the plasma torus which takes the shape of a smoke ring or, depending on the configuration, extends into a tubular shape. Plasma physicists refer to this as a "compact toroid". Its topology represents a minimum energy state and can be made very stable. The hope is that the less complex magnetic field topology with high magnetic efficiency (most of the field is produced by the plasma itself rather than the external magnets) will allow for the construction of dramatically simpler and less expensive fusion reactors.

  The main proponent of this method is a company called *TAE Technologies,* based in Irvine, California. Its publicly announced funding exceeds $750 million, and known backers include venture capital firms New Enterprise Associates and Venrock, the UK's Wellcome Trust, several sovereign funds, Alphabet (Google) and other high-tech investors. Rather than relying on DT fusion TAE seeks to ultimately fuse protons and boron. Though this requires temperatures of more than an order of magnitude higher than the temperatures necessary for the DT reaction it has the advantage of being "aneutronic", i.e. it does not produce the hard to control highly energetic neutrons. Furthermore, it does not require the rare to obtain tritium. TAE's prototype is a cylindrical colliding beam fusion reactor (CBFR) that first heats hydrogen gas to form two rings of plasma which are then merged together (see below for more details).

- *Sheared-flow stabilized Z-pinch:* This is a method extending the conventional z-pinch by trying to stabilize the plasma with a sheared flow, i.e. plasma flowing at different velocities at different radii. This way, the high-temperature, high-density reactive medium is targeted to be confined long enough for the fusion reactions to occur, while being "orders of magnitude cheaper" than fusion reactors requiring magnetic coils, so the claim of its supporters. This method is employed by the company *Zap Energy,* founded in 2017.
- *(Laser induced) Inertial confinement fusion* (ICF): While magnetic confinement tries to solve the Lawson criterion problem with long confinement times (several seconds) and comparably low plasma density (10^{14} ions per cm^3), the ICF approach takes the inverse path: ultra-high ion densities (10^{25} ions per cm^3, about 100 times the densest metal) and short confinement times or even no confinement all. The high density causes the fusion reactions to occur in around one nanosecond which is fast enough for it to navigate through the fusion material before this expands. In order to achieve such a high density (and thus temperature) ultra-strong and at the same time ultra-precise lasers are needed. These are then focused on the fusion fuel containing a mixture of frozen deuterium and tritium which typically takes the form of a pellet the size of a pinhead.

  The largest ICF experiment is the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL) in California with its Laser Inertial Fusion Energy (LIFE) program. However, different to its own predictions the NIF did not succeed in getting to more than 1/3 of the required conditions needed for ignition. LIFE was, therefore, stopped in 2014 and LLNL shifted its focus toward defense applications. However, with the power of lasers having rapidly increased in recent year on a Moore's-Law like path (especially with the development of Chirped Pulse Amplification (CPA) lasers; Physics Nobel Prize 2018) the ICF concept has more recently attracted attention again. The government financed company Sandia Laboratories, based in Albuquerque, New Mexico, has dedicated itself along this path.
- *Magnetized target fusion (MTF; or magneto-inertial fusion (MIF)):* MTF attempts to work in parameter regions between magnetic confinement and ICF aiming for plasma densities of 10^{19} ions per cm^3 and confinement times in the order of 1 µs. Like for magnetic confinement the fusion fuel is confined by magnetic fields while it is heated into a plasma. However, as in the inertial approach, the density required for fusion is then achieved by rapidly compressing the plasma. This approach suggests that the energy inputs to the plasma is comparably small such that a corresponding reactor would run more efficiently and thus be less expensive compared to trying to achieve long confinement times as in magnetic confinement or ultra-dense states as in the ICF approach.

  MTF is predominantly pursued by the Vancouver, British Columbia-based company *General Fusion.* General Fusion uses an array of pistons to create shock waves in a liquid metal to compress the plasma to fusion conditions. The company has raised $200 million in funding or commitments. The firm is supported amongst others by Amazon CEO Jeff Bezos, and other venture capital sources incl. Asian sovereign wealth funds, with the Canadian government having provided about $40 million.
- *Lockheed Martin Compact Fusion Reactor (CFR):* Lockheed Martin utilizes a different magnetic topology and set up claiming this would produce a much more effective magnetic field for plasma containment thus allowing an overall smaller (and thus less expensive) fusion reactor. However, it has yet to publicize any data on their progress. So far, no details on temperature or containment levels achieved have been published.
- *Muon-catalyzed fusion (μCF):* Muons are subatomic particles that have similar properties as electrons but are more than 200 times heavier. A muon can replace an electron in a hydrogen molecule, which due to its higher mass brings the nuclei in the molecule much closer together which increases the probability of nuclear fusion greatly, eventually to a point where sufficiently many fusion events might happen at much lower, possibly even room temperature. One therefore speaks of "cold fusion". However, the creation of the (naturally unstable) muons in sufficiently large numbers requires much more energy than would be produced by the targeted fusion. The company *Norrønt Fusion Energy AS* in Norway is currently working on laser produced muons for Muon-catalyzed fusion.

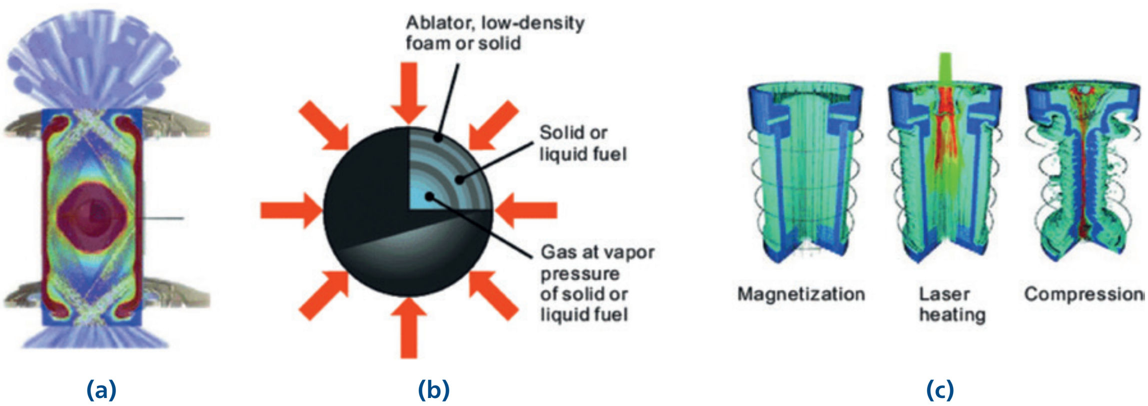


Fig. 8.
Inertial confinement fusion (ICF) concepts: (a) laser indirect drive (LID); (b) laser direct drive (LDD); and (c) magnetized liner inertial fusion (MagLIF).
(Source: Laser-direct-drive program: Promise, challenge, and path forward - Scientific Figure on ResearchGate)

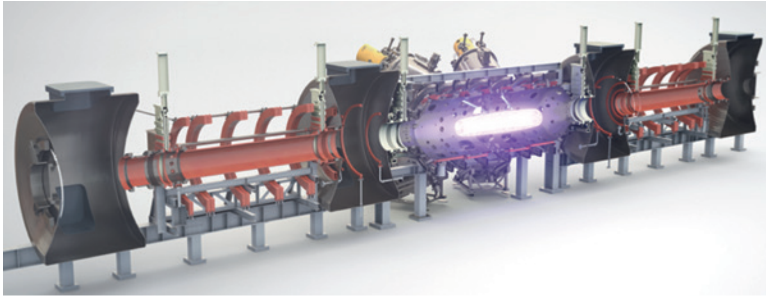


Fig. 9.
The fusion device for field-reversed configuration. (Courtesy of TAE Technologies)

A deeper look into one alternative path

While almost all efforts focus on making the DT reaction work and become commercially viable, the "neutron problem" of the DT reaction demands, as we saw, a look into alternative fuel sources. While achieving a confined enough plasma at 100 million Kelvin is already a tough challenge, achieving such at three billion Kelvin as required for the best candidate, the boron-proton reaction, seems insurmountable. Unless one finds a new, more effective approach to reach stable confinement. Such would need to prove more favorable at higher temperatures than at lower temperatures. That is what TAE Technologies is trying to achieve.

For this purpose, TAE created a reactor that appears to be some strange combination of a particle accelerator and an ordinary plasma. The ultra-high temperature in the plasma is achieved by accelerating beams of fuel particles and have them collide with plasma particles, something particle physicists have done for decades. The typical magnetically contained plasma donuts are thereby replaced by a long-stretched plasma tube taking the shape of a hollow cigar. To improve its stability, this tube would be made to spin around itself such that the gyroscopic effect makes it a lot more stable. This is the essence of the advanced FRC approach pursued by TAE. In theory, this approach can be scaled up to much higher temperatures than those in a tokamak. TAE has found evidence that the FRC induced stability and quiescence in the plasma actually increases with higher temperature! It is the very hypothesis that this beneficial scaling property will rest in place all the way to 3 billion degrees that TAE's approach is based upon.

In detail, TAE's mix of a particle accelerator and plasma confinement works as follows:

- It sends off short ultra-strong bursts of electric power from two sides which generate corresponding magnetic fields that create plasmas in each of the separate ends of the machine.
- A second strong electric pulse then accelerates the two plasmas to a million km/h and makes them crash into each other in the middle of the machine.
- This creates a larger tube-like plasma structure that, heated further with intense beam accelerators, shall eventually become hot, dense, and contained for long enough to cause the fusion reaction.

The company has just started to build its next generation device called "Copernicus" targeting temperatures of more than 100 million Kelvin and thus establishing deuterium-tritium fusion conditions and the viability of achieving net energy from DT fusion. If this proves to be viable the firm will build a successor device to prove the commercial viability of a fusion energy reactor designed to operate with the proton-boron reaction, the ultimate holy grail of fusion research.

Outlook

The science of plasma underlying nuclear fusion research and our understanding how plasmas behave under the required extreme circumstances have advanced a great deal in recent years, much of that out of the public eye. Thus, there is some optimism that the technology is well on its way to commercial use, despite that the engineering obstacles remain high. However, besides the immense technological challenges, the ultimate deciding factors for the application of fusion energy will be social and economic. Fusion power plants will be built when investors and public utility commissions view them as worthwhile investments. It is worth noting that the likely time frame of such commercial viability roughly coincides with the period when many operating fission plants in industrialized countries are reaching the end of their license periods, as well as with the objective to reach net-zero carbon emissions around 2050 or 2060. Under such circumstances, the advantages of fusion power could well be economically and socially compelling.

Commercially available fusion technology, if one day it were actually available to mankind, would represent a social, technological and economic paradigm shift. Were we really able to produce energy like the sun does and thus have access to the most efficient, safest and most environmentally friendly form of energy nature provides, we would certainly experience not only another major technological advance, but rather a leap forward in civilization itself, comparable only to the invention of the steam engine that provided the energy that lifted humanity into the modern age 250 years ago.

Author
Dr. Lars Jaeger
lars.jaeger@larsjaeger.ch
Dorfstrasse 1
6340 Baar, Switzerland