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The dream of imitating our Sun: The hopes and prospects for unlimited energy

Abstract

This paper follows the historical development of the fusion research, with an ultimate goal to make a fusion power plant. Starting in the 1950`s, the different methods, setbacks and breakthroughs are explained. Fusion occurs in plasma, and initially the knowledge of hot plasma was limited. Several instabilities and other leakages of the plasma to the walls were early identified, leading to a greater task than first assumed.

Reasons why the tokamak machine are the preferred setup amongst many possible ways of confining the hot plasma are given. Results from the greatest tokamaks yet, JET, TFTR and JT-60U, are outlined and discussed. The next step towards a fusion power plant is ITER, a bigger and more powerful machine that are being built in France. The specifications and objectives of ITER are given, together with a discussion on the scientific meaning of the expected results. At the end, an overview of different power plant designs will show how the future of fusion depends on what results ITER gives.

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Contents

Introduction

The world we live in consumes much energy every year, and the energy consumption is expected to increase in the years to come, see Figure 1. The figure also shows that fossil fuels (coal, liquids and natural gas on the figure) are the most important sources of energy. The dependence on fossil fuel is a problem that will only grow larger, since they are non-renewable and emits CO_2 when burned. At some point the world will run out of fossil fuel to extract, the estimates vary a bit, but oil in 42 years, natural gas in 60 years and coal in 133 years are one of the less optimistic estimates (F. F. Chen, 2011, p. 54).

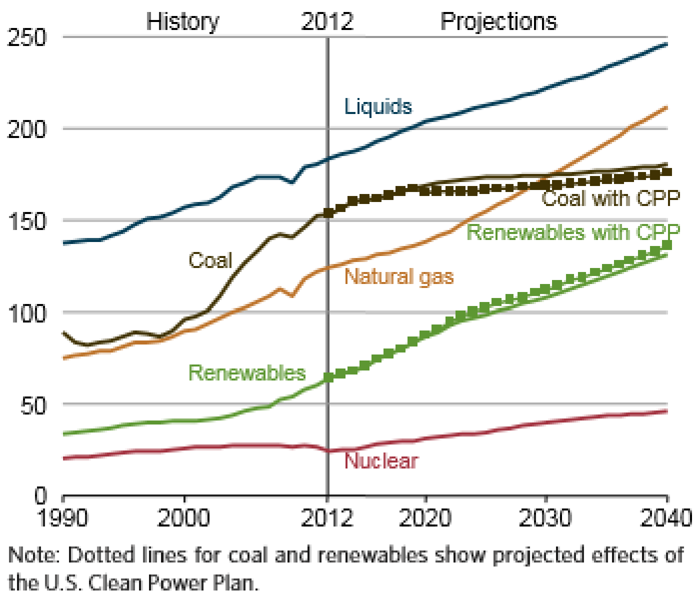

Figure 1 World energy consumption by energy source, with future expectations. Y-axis shows quadrillion Btu, a unit for energy (Conti et al., 2016, p. 9).

Since the fossil fuels are both a limited resource and contributes to the global warming, the world needs to find alternatives that can replace them as soon as possible. Renewable energy sources like solar cells and windmills are both inexhaustible and without the CO_2- emission, but they are often expensive and can only be used on specific locations. Nuclear fission is another possible source to use since we have available material on Earth for much longer than we do with fossil fuel. However; fission has the potential of meltdown with severe human and environmental damages, and it creates radioactive waste with very long half-life.

Fusion is an energy source that can provide energy with hardly any of the drawbacks listed for the sources above. It releases no CO_2 in the burning process, power plants can be built at almost any location, there is no risk of a meltdown or a similar damaging process and the fuel is practically inexhaustible. It is estimated that there are lithium available for about 30 million years, and deuterium in the ocean for about 30 billion years, so the two most important elements for fusion are abundant at Earth (F. F. Chen, 2011, p. 321). Additionally, the radioactive waste from fusion is only of low grade that has to be stored for about 100 years, and in some of the more complex fusion reactions hardly any waste is created.

The first scientific approaches towards fusion was however not to produce energy for the world. The fission bombs used at the end of the Second World War was extremely destructive, but the energy yield from fission showed an even greater explosion on impact. This, together with a beginning cold war between the USA and Soviet, made scientists in several countries pursue the idea of a hydrogen bomb. On November 1st 1952, the USA exploded their first hydrogen bomb, called "Mike", in the central Pacific. A fission device initiated the reaction, and there was no need to confine the explosion, so the setup was much easier than what a fusion reactor must achieve (The Columbia Encyclopedia, 2017). However, the bomb proved that great amounts of energy was possible to achieve from fusion at Earth, and several scientists turned towards pursuing controlled fusion after the bomb was finished.

The possible fusion reactions

In a future fusion reactor, we must make a choice of fuel. The fuel will be an isotope of Hydrogen, but several reactions are possible, with their own positive and negative sides. For the possible reactions, see Tabell 1.

${}_{1}^{2}H + {}_{1}^{2}H \rightarrow {}_{2}^{3}He + n + 3.2\ MeV$
${}_{1}^{2}H + {}_{1}^{2}H \rightarrow {}_{1}^{3}H + p + 4.4\ MeV$
${}_{1}^{2}H + {}_{1}^{3}H \rightarrow {}_{2}^{4}He + n + 17.6\ MeV$
${}_{3}^{6}Li + n \rightarrow {}_{2}^{4}He + {}_{1}^{3}H$
${}_{3}^{7}Li + n \rightarrow {}_{2}^{4}He + {}_{1}^{3}H + n$

Tabell 1 Possible fusion reactions and Tritium breeding (Berge, 1987, p. 5).

The first possibility is to use only deuterium, an isotope of hydrogen with one neutron. This has the great positive side of being almost inexhaustible at Earth, and leaves the least problematic waste for the environment. The problem with this solution is that it has a small energy output compared to the other reaction.

The second possibility is to use a mix of deuterium and tritium, an isotope of hydrogen with two neutrons. This reaction has much greater energy yield, more than four times as much as the one with only deuterium. Tritium is radioactive with a half-life of about 12.3 years, which makes it a rear isotope in nature. Because of this, a fusion reactor would need to breed tritium in order to maintain the reaction over a longer period. This can be done by making a neutron from the fusion reaction react with a Lithium isotope outside the fusion confinement. The first lithium reaction has large probability of occurring for slow neutrons, while the last is more probable with fast neutrons.

In a graph of reactivity (a measurement for probability for it to happen) of different fusion reactions to ion temperature we can see how different reactions occur, see Figure 2.

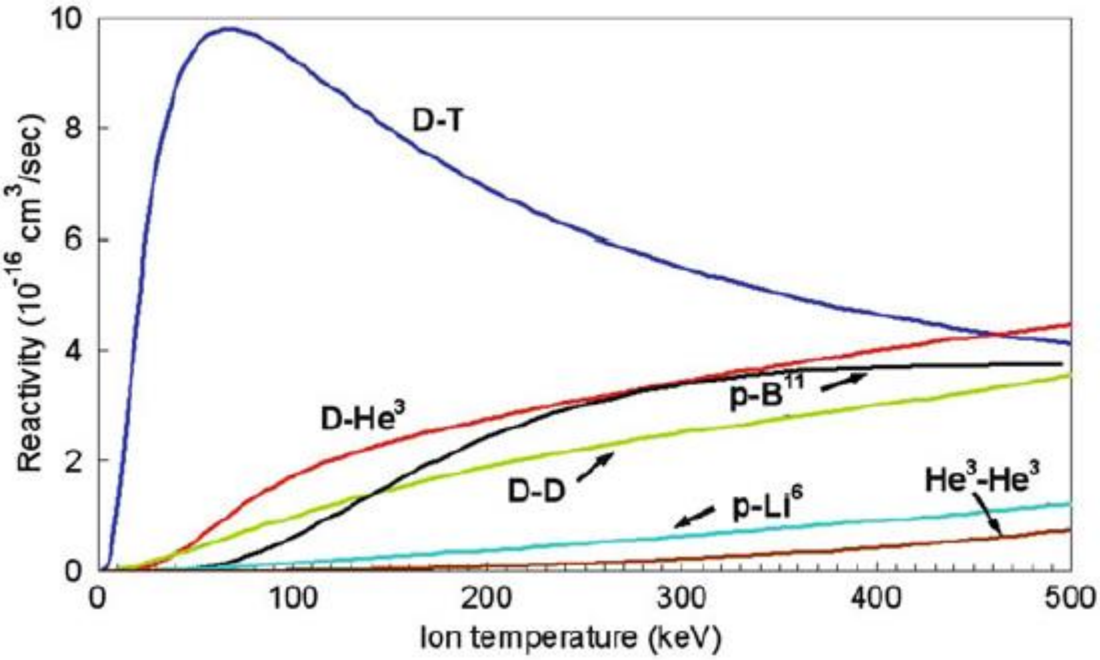

Figure 2 The reactivity of fusion reactions vs. ion temperature (Dean, 2013, p. 7).

The graph shows how the peak of the deuterium-tritium reaction gives much higher probability for the reaction to occur, compared with the deuterium-deuterium reaction and other possible reactions. It also illustrates that the temperature needed to reach the peak is much smaller for deuterium-tritium than any other. For these reasons, the reaction of choice for a future fusion power plant has been the deuterium-tritium.

Binding energy curve

When Albert Einstein formulated the famous equation $E = mc^2$, he showed a link between the energy, E, and the mass, m. For an element, the nucleons have released energy when they were bound by the strong force, and every element has different binding energy. As a general rule the binding energy per nucleon, the energy per nucleon needed to pull the nucleus apart, is increasing with nucleon number until $^{56}_{26}Fe$, before slowly decreasing, see Figure 3. This gives an idea of the energy that will be released in a fusion or fission reaction. The difference in binding energy per nucleon will be the energy released in a fusion reaction, and Figure 3 clearly shows how the energy output per nucleon for fusion will be much greater than that of fission.

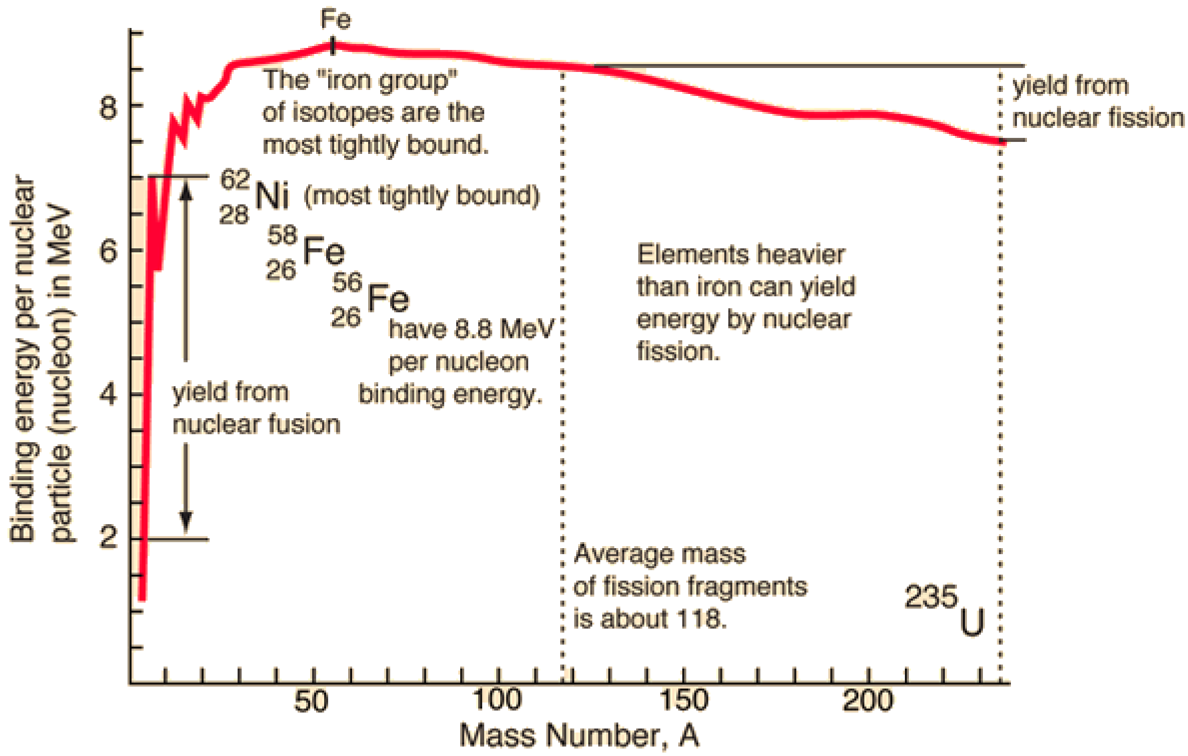

Figure 3 Binding energy per nucleon vs nucleon number (Nave, 2017).

The β-value

A useful parameter in fusion physics is the β-value. It combines the pressure from the magnetic field, $p_B = \frac{B^2}{2\mu_0}$, where μ_0 is the permeability of free space and B the magnetic field strength, with the plasma pressure, p

$$\beta = \frac{2\mu_0 p}{B^2} , \qquad (1)$$

where p is meant to be the maximum pressure and B usually measured outside the plasma. Since the plasma pressure divides the magnetic field pressure a value of β can approach 1, but if it gets higher the plasma would no longer be contained by the magnetic field and it would propel out to the sides.

The β-value measures how effectively the magnetic field is being used, and fusion power varies as β^2, so a high value is desirable in an economical viewpoint (R. F. Post, 1971, p. 1935).

The Q-value

If fusion should become a provider of electricity in the future, the energy we get out of the fusion reactor must be greater than the energy we put into it. This ratio is most often referred to as the Q-value, were it in its simplest state says that $Q = \frac{\text{Power produced in the reaction}}{\text{Heatingpower supplied to the reaction}}$ or $Q = \frac{\text{Energy out of the reaction}}{\text{Energy into the reaction}}$.

One milestone in fusion research is to achieve break even, defined as when fusion power equals heating power, or $Q = 1$. This is theoretically the point when a fusion device can be used in a power plant. However, much energy and costs are spent building, maintaining and disassembling the machine, so most fusion concepts requires at least $Q \geq 10$. If the plasma is able to self-heat so that the heating power can be shut off leading to $Q \to \infty$, we have what's called ignition.

The Lawson criteria and the triple product

Even though many scientists had great hopes for the new area of fusion power, John Lawson wanted to figure out what was needed to achieve the actual process in a fusion power plant at Earth. In an interview fifty years after his work, he claimed that:

“the main motivation for this work was that as an engineer he felt the responsibility to “pin down” the unrealistic expectations of his enthusiastic physics fellows….” (EUROfusion, 2005).

His idea was simple in theory; what was required from a fusion reactor to get a higher energy output than what was put in. In 1955, he found that it would rely on only three important conditions: the temperature of the plasma, T, the number density, n, and the energy confinement time, τ (Lawson initially called this the pulse length). These are basically the same as fusion power scientists use today as the triple product, $\hat{n}\tau_E\hat{T}$, where $\hat{n}$ and $\hat{T}$ are the peak ion density and temperature in the plasma and τ_E is the energy confinement time. Today the value are believed to be approximately $\hat{n}\tau_E\hat{T} \sim 5\times10^{21} m^{-3} skeV$ (John Wesson, 2011, p. 3).

The energy released is relying on particles colliding and fusing, so the number of particles in a certain region will be important when looking at how much energy comes out of the plasma fusing. The number density can easily be made great, but when the density increases, the plasma starts sending out bremsstrahlung. This can become so dominant that almost all the power in the plasma is radiated away, leaving the ideal number density to a surprisingly low value, about a million times less dense than air.

The speed of the nuclei has to be high, in order to overcome the electrostatic repulsion and get close enough for the strong force to work. The temperature, which depends on speed, has to be around 100-200 million K for optimal fusion, changing somewhat with different fusion materials. If it gets greater the bremsstrahlung increases due to faster moving electrons, and the time that two particles are close enough to fuse becomes too small.

When the first two criteria are fulfilled, fusion can occur. However, to get a high enough energy output for the fusion power to be economically viable, you need to allow the reaction to happen over a long enough time period, this is the third Lawson criteria. Lawson realized that the two requirements of density and confinement time is dependent upon each other. If the density is high, you need a short confinement time and vice versa. Therefor the representation is often shown as a temperature vs. density times confinement time graph.

Up to Geneva 1958

The reason why nuclear fission is much easier to achieve in a power plant compared to that of fusion, has to do with the repulsive force due to the two electrically charged particles that must be brought together for fusion to occur. The Coulomb force increases rapidly as the distance between the particles decreases, and because of this the temperature, and then also the speed, of the particles must be high. The Sun has so many particles that it can be cooler than classical physics predicts, and use the phenomena quantum tunneling to fuse the particles. On Earth, we cannot make such an abundance of particles, hence we must reach the desired temperatures without quantum tunneling. In 1920 Sir Arthur Eddington proposed that the source of energy in the Sun was fusing hydrogen to helium (Eddington, 1920), by that solving one of astrophysics unanswered questions of where the stars got their energy from.

During the 1930`s, small attempts to start up a fusion program were made, but it never came further than a torus with magnetic coils wrapped around it and heated with 150 W of power from a radio transmitter in the USA (Dean, 2013, p. 3). The scientists hoped to gain a hydrogen gas of one million degrees, but failed and abandoned the project.

In the 1940`s the scientists were working on plans for a hydrogen bomb, an easier setup than a power plant since it could be initiated by a fission device, and they did not need to confine the energy released in the reactions. After the war, several of the scientists started thinking about how to make the fusion happen in a controlled manner. In the UK, Sir George Thompson and Moses Blackman filed a secret patent application of a doughnut-shaped, current driven "pinch" device they designed at Imperial College. At the college a "pinch-machine" was also built and operated in a small scale in 1947 (Dean, 2013, p. 4). The US mainly worked with the bomb until 1951, and in the Soviet Oleg Lavrentiev wrote letters about fusion to the government in 1949, but also they did not launch any program until 1951.

In the spring of 1951 the president of Argentina, Juan Peròn, announced that they had successfully produced controlled liberation of atomic energy. This was not achieved through fission of uranium, but rather through hydrogen (Arnoux, 2011). Even though the findings turned out to be a hoax, the positive side of the announcement was that scientists in other parts of the world started working on ways to create fusion on Earth. Perhaps the most well-known outcome is Lyman Spitzer`s thoughts during a ski trip to Aspen. Ha had heard of the Argentinian breakthrough before he left, and wondered about how to confine a hot charged plasma in a magnetic field. The result became known as the stellarator, named after the Latin word for star (Greenwald, 2013a).

In the following years, researchers in several countries started up programs to investigate how to make a fusion reactor at Earth. Since the knowledge could be used both as an energy source and a bomb, all programs were classified and no results were shared across borders. This lead to many similar setups being invented without knowledge of the other. Communities reacted positively as to when and how one would reach the goal, expressed well by Homi Bhabha. He was the president of the first UN Conference on the Peaceful Uses of Atomic Energy, *Atoms for Peace*, in Geneva in 1955 and in his opening speech he said that:

> "*The historical period we are just entering in which atomic energy released by the fission process will supply some of the power requirements of the world may well be regarded one day as the primitive period of the atomic age. It is well known that atomic energy can be obtained by a fusion process as in the H-bomb and there is no basic scientific knowledge in our possession today to show that it is impossible for us to obtain this energy from the fusion process in a controlled manner. The technical problems are formidable but one should*

remember that it is not yet fifteen years since atomic energy was released in an atomic pile for the first time by Fermi. I venture to predict that a method will be found for liberating fusion energy in a controlled manner within the next two decades. When that happens the energy problems of the world will truly have been solved forever for the fuel will be as plentiful as the heavy hydrogen in the ocean." (Bhabha & Bohr, 1955, p. 283)

During the next few years however, the scientists realized that the quest was more formidable than first assumed. Initially there was no knowledge of the behavior of a hot plasma, but as the research progressed, the size of the task became clear. Short confinement time, instabilities and behavior not explained by the Magnetohydrodynamics, the leading physics theory on the behavior of the plasma, was difficulties that one had to overcome, and it became clear that the task was harder than initially assumed. Scientists in the different countries realized the advantages of, and need for, collaboration across borders. This lead to an agreement between the US, the UK and Soviet to remove the veil of secrecy that had surrounded the different fusion programs ever since the startup (Krivit, Lehr, & Kingery, 2011, p. 369).

Before this happened however, the British scientists revealed great news at a press conference on January 14th 1958. Sir John Cockcroft announced that ZETA, a toroidal pinch machine, had produced plasma with temperature 5 million degrees and held it for three thousands of a second (Herman, 1990, p. 50). After hard questioning from the journalists, he said that he was 90 % sure that there were thermonuclear reactions taking place. This indicated that ZETA had created the first controlled fusion reaction in the world. The British newspapers understood this as proof of fusion, and printed it as a great victory for the country. The Soviet had recently sent Sputnik into orbit, and the British needed a scientific breakthrough of their own. The day after the press conference *Daily Mail* had the headline:
"*THE MIGHTY ZETA… LIMITLESS FUEL FOR MILLIONS OF YEARS*" (Herman, 1990, p. 50).
While the headings in *Daily Herald*, *New Chronicle* and *Daily Thelegraph* were:
"*BRITAIN`S H-MEN MAKE A SUN*"
"*ZETA SPELLS H-POWER EVERLASTING*"
"*U.S. ADMITS THAT BRITAIN HAS THE LEAD*" (Herman, 1990, p. 50).

Unfortunately, the British did not have the equipment to measure temperature correctly. After a few months of experiments, they had to admit that the neutrons coming from the plasma came from byproducts of the plasma heating and not fusion reactions.

The disclosure of the fusion programs was set to the second Geneva conference on the Peaceful Uses of Atomic Energy in 1958. The conference featured speeches from leading fusion scientists, and showed that the different programs had developed very similar setups for the task. There was also reports on all the instabilities and other problems the research had encountered, and the general optimism shown in the opening speech in 1955 had turned to a more carefully optimism with the understanding that reaching the goal of fusion would take both more time and effort than initially assumed. Edward Teller had the opening speech for the USAEC at the conference and said that:

" I believe that thermonuclear energy generation is possible. Whether it will be in precisely seventeen years, as our Chairman predicted three years ago, or at some other time is a matter that I think he will not argue with me and I shall not argue with him. However, I will say this: The problem is not quite easy… If we want to shoot for the jackpot, for energy production, I think that it can be done, but do not believe that in this century it will be a thing of practical importance… It is likely that we shall be dealing with an intricate machine which is inaccessible to human hands because of radiation and on which all control and maintenance

must proceed by remote control. The irradiation of materials by neutrons and gamma rays will cause the properties of these materials to change… These and other difficulties are likely to make the released energy so costly that an economic exploitation of controlled thermonuclear reactions may not turn out to be possible before the end of the 20th century… Can all this be done? I think we are at a stage similar to the stage at which flying was about one hundred years ago. There are some wise people now, as there were at that time, who have proved that it cannot be done. I should like to say that those people were perhaps better off because at least they saw the birds. All we can see are the sun and the stars…" (N. United, 1958, p. 32).

The delegate opening for Soviet, Lev Artsimovich, also showed belief in achieving the desired result, but that this would be in a much more distant future than what was believed in 1955:

> *"Three years have passed since this prophecy and now, before our eyes, there begins to emerge a rough outline of the scientific foundation on which the methods of solving the problem of controlled fusion reactions will probably rest. This foundation has been laid by the numerous experimental and theoretical results obtained in recent years in Great Britain, the USA, the USSR and other countries. For the first time these results will be discussed on an international scale, and this is probably the most important step which has been made towards the solution of this problem. The importance of this fact is greater than that of the separate investigations, which as yet have not brought us very much nearer to our ultimate goal. We do not wish to be pessimistic in appraising the future of our work, yet we must not underestimate the difficulties which will have to be overcome before we learn to master thermonuclear fusion. In the long run, the main difficulty lies in the fact that in such a light substance as rarefied plasma, any manifestation of instability develops at an enormous rate… A most important factor in ensuring success in these investigations is the continuation and further development of the international cooperation initiated by our conference. The solution of the problem of thermonuclear fusion will require a maximum concentration of intellectual effort and the mobilization of very appreciable material facilities and complex apparatus."* (United, 1958, p. 20).

The most positive of the opening speakers was Peter C. Thonemann for United Kingdom. He believed that the time span set by Bhabha was not far from correct, and that the collaboration across countries would give the desired answers within the next two decades. However, he does not say that the power plant should be ready by that time, only that we would know whether it is possible to do it or not:

> *"I think that the papers to be presented at this Conference, and the discussions which follow them, will show that it is still impossible to answer the question, 'Can electrical power be generated using the light elements as fuel by themselves?' I believe that this question will be answered in the next decade. If the answer is yes, a further ten years will be required to answer the next question, 'Is such a power source economically valuable?' "* (United, 1958, p. 38).

Magnetic confinement configurations

The high temperatures needed to get controlled fusion on Earth makes it difficult to confine the plasma in a container without cooling it as it touches the walls, or getting to many impurities into the plasma. One solution to this problem is to confine the plasma in a magnetic field (R. F. Post, 1971, pp. 79-80). The main idea is shown by following a single charged particle in the magnetic field. The particle will gyrate around the magnetic field lines, opposite charges in opposite directions of each other, see Figure 4.

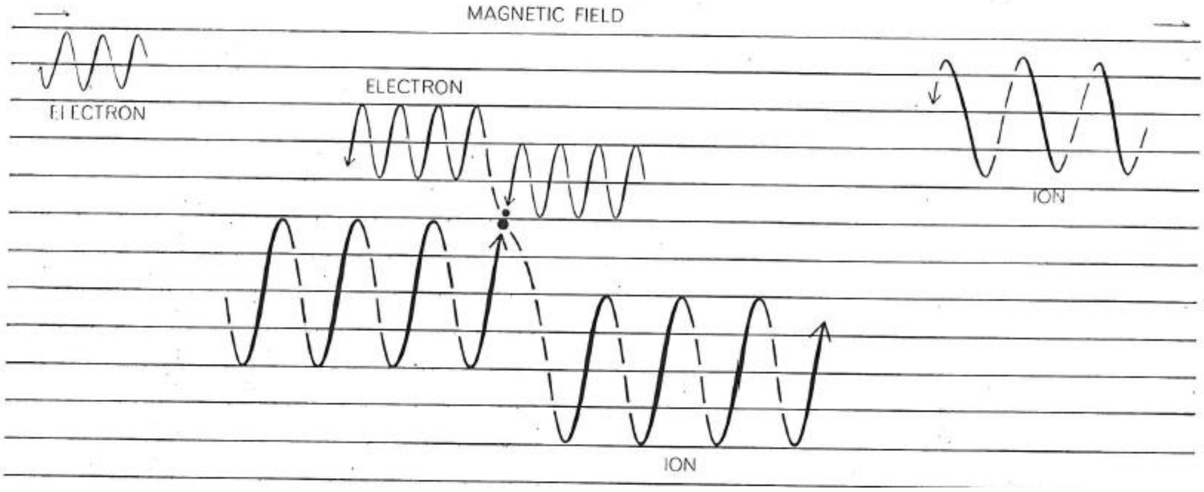

Figure 4 Electron and ion gyrating in a magnetic field. In center is a collision that changes the center of rotation of the particles (Chen, 1967, p. 79).

As long as the magnetic field is strong enough, the radius of gyration, or Larmor radius, will be small enough for the particle to be considered "stuck" to a field line. The Larmor radius depend on mass and thermal velocity, the hydrogen ions have a radius about 40 times larger than an electron of same energy. If the field line were infinitely long, the single particle could not move laterally across the field (Francis F Chen, 1967, p. 76).

In a plasma there are many particles, traveling in opposite direction of each other. These particles can collide with each other and move to the neighboring line. After several of these collisions, the particle can slowly move to the walls of the container where it transfers its energy before attaining fusion temperature. This diffusion is generally not considered a big problem for fusion because the high temperature makes the rate of collisions between ions and electrons low and the rate of escape of plasma through diffusion is inversely proportional to the magnetic field (Chen, 1967, p. 76).

Magnetohydrodynamics – MHD

As the knowledge of hot plasmas were limited, there was a need for a theory that described the motion of it. The initial idea was that the plasma would behave as an electrically conductive fluid in the electromagnetic field. The theory created, Magnetohydrodynamics, combines Maxwell`s equations of electromagnetism with the equations of fluid dynamics, to give a set of equations that has to be solved simultaneously (Schnack, 2009, p. 1). In the theory, the single identities of ions and electrons do not appear, the plasma is rather identified as a single fluid with density, velocity, pressure and several other properties of the entire plasma. If the model is simplified

$$\frac{d\rho}{dt} = -\rho \nabla \cdot \boldsymbol{v} \qquad \boldsymbol{j} = \nabla \times \boldsymbol{B}/\mu_0$$

$$\rho \frac{d\boldsymbol{v}}{dt} = \boldsymbol{j} \times \boldsymbol{B} - \nabla p \qquad \frac{\partial \boldsymbol{B}}{\partial t} = -\nabla \times \boldsymbol{E}$$

$$\frac{dp}{dt} = -\gamma p \nabla \cdot \boldsymbol{v} \qquad \boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} = 0$$

Figure 5 The equations of ideal MHD. Here ρ is mass density, v is velocity, B is the magnetic field, j is the electric current density, p is the plasma pressure, E is the electric field, γ is the ratio of specific heats (usually 5/3) and t is time (John Wesson, 2011, p. 77).

further, by making the plasma a perfect conductor with no viscosity or thermal conductivity, it is called the ideal MHD.

The equations for ideal MHD are listed in Figure 5. The first equation is mass conservation, showing that matter is neither created nor destroyed. The second one (from the top) is the equation of motion for an element in a fluid, corresponding to Newton's second law in mechanics. The third equation is the adiabatic energy equation where the right side represents heating/cooling due to adiabatic compression/expansion. The fourth equation is Ampere`s law giving the link between current and magnetic field. The fifth equation is Faraday`s law of induction, showing how a varying magnetic field will set up an electric field that can drive a current. Finally the sixth equation is an ideal version of Ohm`s law for fluids where the resistivity is neglected.

Even though there are several big assumptions made in the MHD, it turns out that the equations are describing the macroscopic behavior of the plasma well. Most plasma researchers agree that a fusion reactor must be both in MHD equilibrium and be MHD stable in order to function as desired (Freidberg, 2014, p. 1).

Drifts

If there are non-uniformities in the magnetic and/or the electric field, a charged particle will move. We refer to these motions as drifts. To model the behavior, we use Lorentz force law

$$m\dot{\boldsymbol{v}} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) \tag{2}$$

Here $\dot{\boldsymbol{v}}$ is the time derivative of the velocity (the acceleration), q is the charge, $\boldsymbol{E}$ is the electric field, $\boldsymbol{v}$ is the velocity and $\boldsymbol{B}$ is the magnetic field. A bold letter indicates a vector. The $\times$ symbol is the vector product. This equation shows us how the motion is superimposed from the forces due to the electric field and the magnetic field. If we first look at a case where the electric and magnetic field are uniform and perpendicular we can divide the velocity into gyromotion, $\boldsymbol{v}_\Omega$, describing the particles rotational movement,, and a drift, $\boldsymbol{v}_{E\times B}$, describing the translational motion of the particle

$$\boldsymbol{v} = \boldsymbol{v}_\Omega + \boldsymbol{v}_{E\times B} \tag{3}$$

Using this it is possible to decompose the equation of motion into two equations

$$m\dot{\boldsymbol{v}}_\Omega = q\boldsymbol{v}_\Omega \times \boldsymbol{B} \tag{4}$$

This equation gives the gyromotion of the particle, and

$$0 = q(\boldsymbol{E} + \boldsymbol{v}_{E\times B} \times \boldsymbol{B}) \tag{5}$$

This equation gives the $\boldsymbol{E} \times \boldsymbol{B}$ drift. Solving it for the drift velocity gives

$$\boldsymbol{v}_{E\times B} = \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2} \ , \tag{6}$$

This drift is independent of the charge of the particle, so even if it produces a net drift, there will be no charge separation coming from the drift.

If we rather consider a situation where the magnetic field line is curved, and write the velocity as composed of one making gyromotion and one describing curvature drift, $\boldsymbol{v}_c$, we get

$$\boldsymbol{v} = \boldsymbol{v}_{\Omega} + \boldsymbol{v}_c \tag{7}$$

and can separate the equation of motion into an equation describing the gyromotion and one for the curvature drift. The curvature drift equation becomes

$$0 = \frac{-mv_{\parallel}^2}{R}\boldsymbol{n}_c + q\boldsymbol{v}_c \times \boldsymbol{B} \tag{8}$$

where $v_{\parallel}$ is the speed parallel to the magnetic field. Here it is used that the centrifugal force, $\boldsymbol{F}_c$, for a particle moving along a curved arc with radius R and unit vector in the direction of the radius of the curvature $\boldsymbol{n}_c$ is

$$\boldsymbol{F}_c = \frac{-mv_{\parallel}^2}{R}\boldsymbol{n}_c \tag{9}$$

Solving equation 8 for $\boldsymbol{v}_c$ gives

$$\boldsymbol{v}_c = -\frac{mv_{\parallel}^2}{qR}\frac{\mathbf{B} \times \mathbf{n_c}}{B^2} \tag{10}$$

The equation shows how the drift velocity will be of opposite direction for electrons and ions so the particles are separated depending on their charge.

If we rather had a non-uniform magnetic field strength, the changing field would produce a force

$$\boldsymbol{F} = -\frac{1}{2}\frac{mv_{\perp}^2}{B}\boldsymbol{\nabla}\mathrm{B} \tag{11}$$

where $v_{\perp}$ is the speed perpendicular to the magnetic field and ∇ is the gradient. If we again separate the velocity into

$$\boldsymbol{v} = \boldsymbol{v}_{\Omega} + \boldsymbol{v}_{\nabla B} \tag{12}$$

it is possible to separate into a gyromotion equation and a ∇B drift.

$$0 = \frac{-\frac{1}{2}mv_{\perp}^2}{B}\boldsymbol{\nabla}\mathrm{B} + q(\boldsymbol{v}_{\nabla B} \times \boldsymbol{B}) \tag{13}$$

Solving this for $\boldsymbol{v}_{\nabla B}$ the same way as the $\boldsymbol{v}_c$ gives

$$\boldsymbol{v}_{\nabla B} = \frac{mv_{\perp}^2}{2q}\frac{\boldsymbol{B} \times \boldsymbol{\nabla}\mathrm{B}}{B^3} \tag{14}$$

This equation also shows us that electrons and ions will drift in opposite direction of each other creating a charge separation in the plasma.

Single Mirror

The simplest way to confine the plasma in a magnetic field would be to have infinitely long field lines and have particles travel along them. However, given the high speed of the particles to make the fusion happen, we would need a fusion vessel of hundreds of kilometers to satisfy the Lawson criteria (R.F. Post, 1973, p. 32). This is not possible to obtain practically on Earth, which is why a fusion reactor must have a way to confine the plasma without letting the particles travel in a straight line.

One solution to this problem was in 1952 and 1954 proposed independently by Richard F. Post (R.F. Post, 1959) at the Lawrence Livermore National Laboratory, and Gersh Budker (Romanovskii, 1968, p. 46) at the Kurchatov Institute. The setup is simple, following Fowler and Post (Fowler & Post, 1966, p. 22): set up a magnetic field, and make the field strength stronger at the ends, making it look like a bottle with a bottleneck at each end. When a charged particle gyrates towards a bottleneck, the strengthened magnetic field will slow it down and eventually reflect it back into the bottle. Therefore, the two ends act as a mirror for charged particles, see Figure 6. The field could be strengthened at each end by a coil that would squeeze the field lines together.

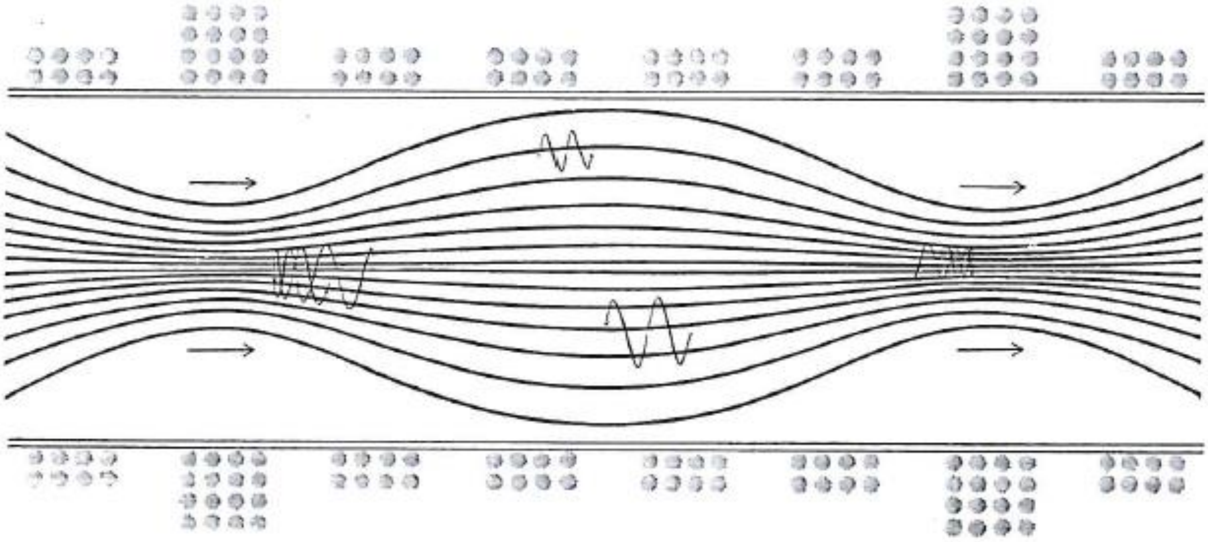

Figure 6 The magnetic mirror setup with magnetic field lines shown (Fowler & Post, 1966, p. 25).

To explain how the mirror works as a container for the plasma, we follow the reasoning of Stacey (Stacey, 2010, pp. 37-39), see Figure 7 for definitions of the variables.

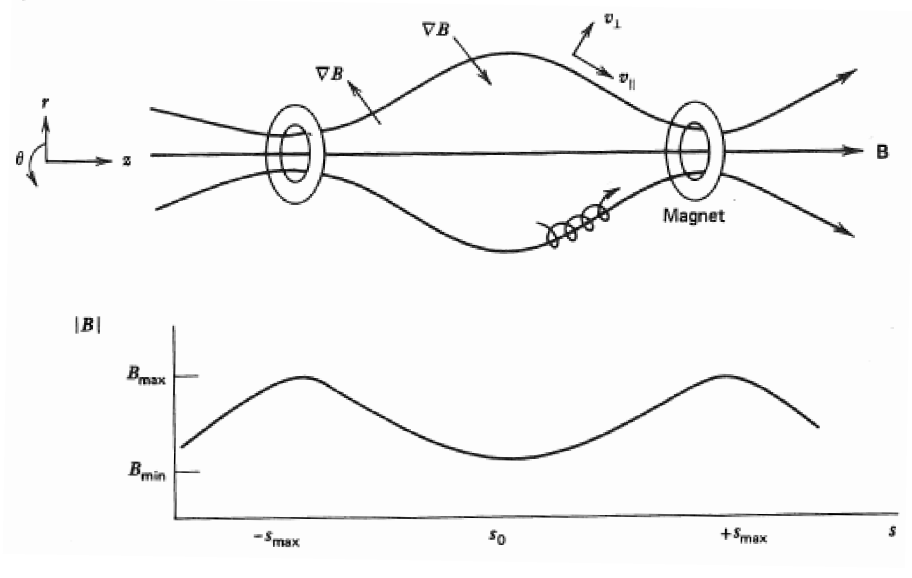

Figure 7 Simple mirror configurations (Stacey, 2010, p. 38).

In the single mirror, the kinetic energy, KE, must be conserved since the stationary magnetic field does no work on a charged particle

$$\frac{1}{2}m[v_{\parallel}^2(s)+v_{\perp}^2(s)]=KE=constant \tag{15}$$

here s is the distance along the z-axis, with s_0 midway between the coils and $\pm s_{\max}$ at the coils where the magnetic field is at its maximum.

There must also be conservation of the angular momentum so that

$$p_\theta = mr_L v_\perp = \frac{mv_\perp^2(s)}{B(s)} = constant \tag{16}$$

or more commonly written as

$$\mu \equiv \frac{\frac{1}{2}mv_\perp^2(s)}{B(s)} = constant \tag{17}$$

If we combine these two we obtain an equation for the kinetic energy of a particle traveling parallel to the magnetic field

$$\frac{1}{2}mv_{\parallel}^2(s)=KE-\mu B(s) \tag{18}$$

This shows us that a particle of $B(s)=\frac{KE}{\mu}$ where $B_{min} \leq B(s) \leq B_{max}$ will be trapped since $v_{\parallel}$ vanishes.

The two constants in the equation, KE and μ, can be evaluated at $s=s_0$:

$$KE=\frac{1}{2}mv_{\parallel}^2(s_0)+\frac{1}{2}mv_\perp^2(s_0) \tag{19}$$

$$\mu=\frac{\frac{1}{2}mv_\perp^2(s_0)}{B_{\min}} \tag{20}$$

putting this into equation 18 gives

$$\frac{1}{2}mv_{\parallel}^2(s)=(\frac{1}{2}mv_{\parallel}^2(s_0)+\frac{1}{2}mv_\perp^2(s_0))-\frac{1}{2}mv_\perp^2(s_0)\frac{B(s)}{B_{\min}} \ . \tag{21}$$

We can now use that the boundary between trapped and untrapped particles can be found by evaluating the above equation for $v_{\parallel}(s_{max})=0$

$$0=(\frac{1}{2}mv_{\parallel}^2(s_0)+\frac{1}{2}mv_\perp^2(s_0))-\frac{1}{2}mv_\perp^2(s_0)\frac{B_{\max}}{B_{\min}} \tag{22}$$

rearranging and solving for $v_\perp(s_0)$ gives the equation

$$v_\perp(s_0) = \pm\left(\frac{B_{\max}}{B_{\min}} - 1\right)^{(-\frac{1}{2})} v_\parallel(s_0) \tag{23}$$

Knowing that the $v_\perp$ is a two-dimensional velocity component that lies in the plane perpendicular to the magnetic field, the equation is defining a cone. The cone shows which particles are lost from the mirror-system, and which are trapped inside, see Figure 8.

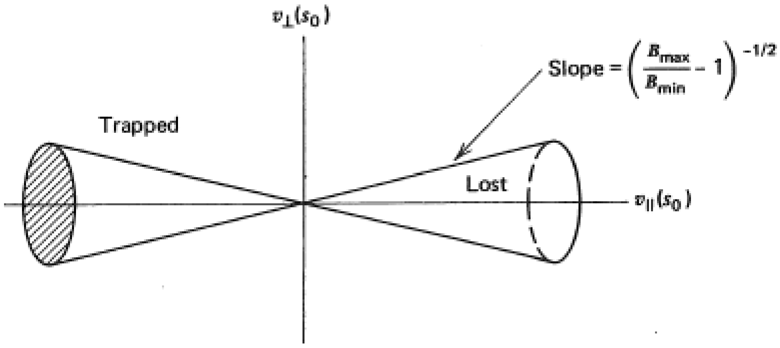

Figure 8 Loss cone for a single mirror (Stacey, 2010, p. 39).

The particles inside the cone will immediately be lost from the system, while the rest are trapped until they are scattered into the cone and then gets lost. This shows that in a single mirror-system the confinement will not be perfect and particles will leak out. The result is that such a system must get particles reinjected in some form to keep a steady fusion reactor running.

Since the magnetic field in a mirror has both curvature and gradient, equations 10 and 14 tell us there will be drifts present in the system

$$\boldsymbol{v}_c = -\frac{mv_\parallel^2}{qR_c}\frac{\boldsymbol{B}\times\boldsymbol{n}_c}{B^2} = \frac{mv_\parallel^2}{qR_c B}\boldsymbol{n}_\theta \tag{24}$$

with R_c the radius from the center of the mirror and $\boldsymbol{n}_\theta$ a unit vector in θ direction. Also

$$\boldsymbol{v}_{\nabla B} = \frac{\frac{1}{2}mv_\perp^2}{q}\frac{\boldsymbol{B}\times\nabla\boldsymbol{B}}{B^3} = \frac{\frac{1}{2}mv_\perp^2}{q}\frac{|\nabla B|}{B^2}\boldsymbol{n}_\theta \tag{25}$$

Since both of these drifts are in the θ direction they will only give a rotation about the axis of symmetry, but there will be no net radial motion of the plasma due to the drifts.

A problem soon arose when the setup was tested experimentally. The plasma was leaking out to the walls of the container within milliseconds. This was expected by the MHD, since the plasma behaves much more as a fluid than single particles. Since the magnetic field strength weakens with distance away from the axis in the bottle, the particles are subjected to a weaker magnetic force when on the outer side of a turn than the inner one. This means that the orbit is less sharply curved in the outer parts of the circuit. If the plasma is in equilibrium the different charges will cancel each other, but if it is momentarily displaced off-center the drift of the particles leads to particles gathering at the edges of the displaced region, see Figure 9.

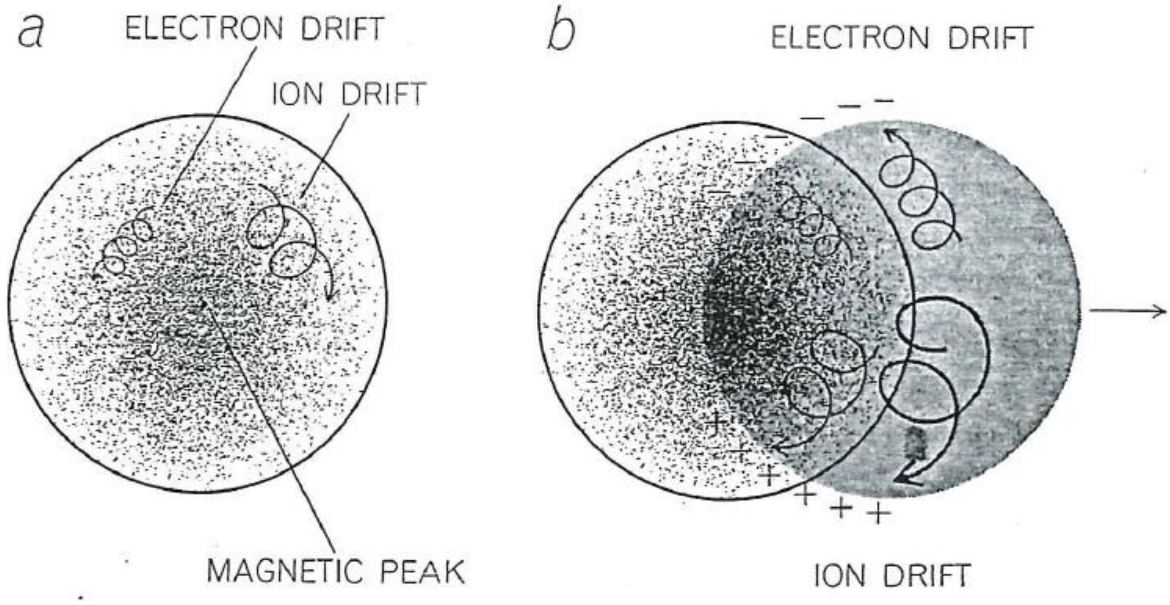

Figure 9 a) Without an off-center displacement the charges drifting cancel.
b) With an off-center displacement the charges builds up at the edge of the displaced regions (Fowler & Post, 1966, p. 25).

Since the different charge makes the electrons and the ions drift in opposite directions, one edge will become positive and the other negative. The electric field created will increase the effect of the off-center displacement and propel the plasma out to the walls. This is known as an interchange instability, or flute instability, since the ripples made in the plasma follows the field lines and therefore looks like the flutes of a Greek column.

Magnetic well

Since the MHD predicts this instability to occur, the general optimism for fusion power was still high, even though the plasma was leaking quickly out of the confinement in the first attempts of fusion. The everyday analogue to the flute instability is a ball on the top of a hill (Fowler & Post, 1966, pp. 22-23). If the ball is given a small displacement from the top, it will roll down the hill. Analogue, the plasma will fall off the magnetic “hill”, the declining field strength, if it experiences a small displacement from center. A way to avoid the problem with the ball is to put it in a well, so that the field lines increases in all directions away from the ball. This was also the idea to suppress the flute instabilities. If one could make a setup for the mirror machine so that the magnetic field lines increased in all directions away from the plasma, then the force due to the electric field made by the charges would be suppressed by the increase in magnetic field strength in that direction. This type of a magnetic well would then stop any flute instability in the start and prevent it from propelling the plasma to the walls.

The magnetic configurations for such wells were suggested in 1958 by H. Grad and M. Levine (Richard F Post, 1973, p. 32), but the first experimental evidence of how it works did not come until 1961 when M. S. Ioffe and his colleagues demonstrated how the magnetic well stabilized the flute instability (Fowler & Post, 1966, p. 23).

A simple setup for the magnetic well would be to include four current-carrying rods around the coils that compresses the field lines to make the mirror. The current is made to flow in the opposite direction for adjacent rods, making the fields from the rods cancel at the center so only the field created by the coils are present. Near the rods however, the field from the rod and the coils add up, making a stronger field and hence creating the magnetic well at the center, See Figure 10.

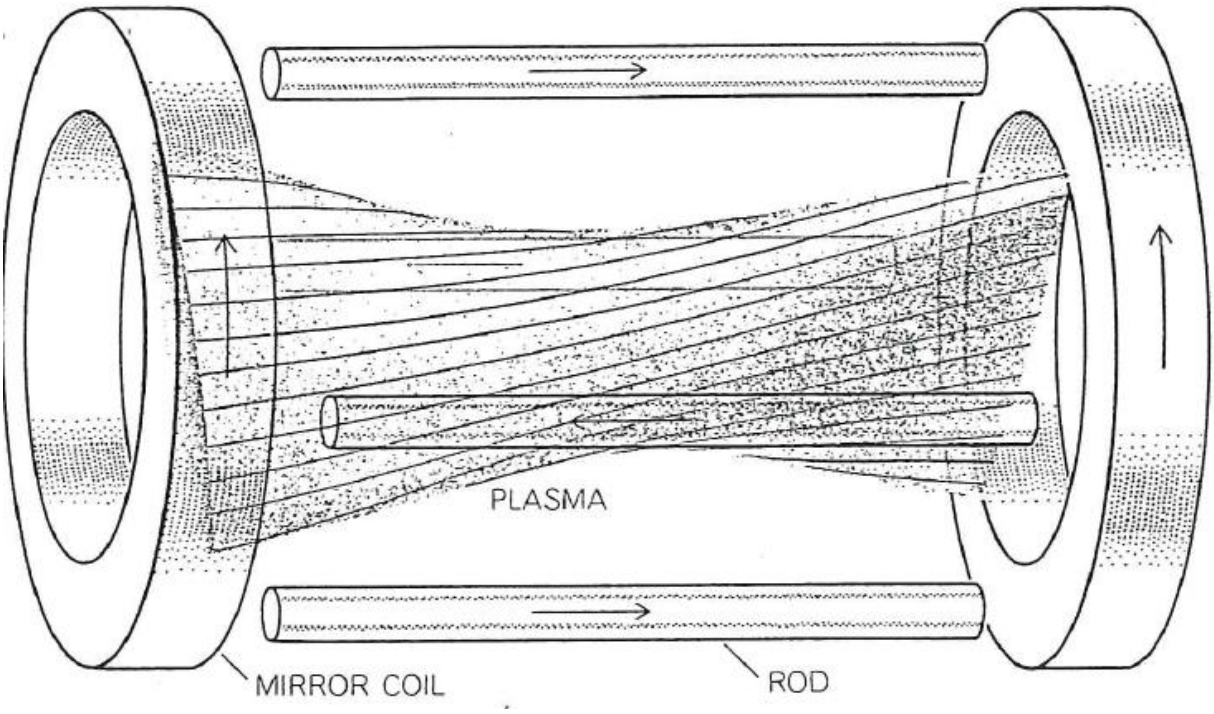

Figure 10 Simple setup of a magnetic well. The resultant field (color) is twisted and increases in all directions from the center. The arrows shows the direction of the current (Fowler & Post, 1966, p. 26).

The result of the well was astonishing. Walton A. Perkins and William L. Barr ran a series of experiments to determine the decrease in rate of escaping particles before and after they turned the current on in the rods. The result showed that the escape of particles to the walls were reduced by a factor of hundreds of thousands after the rods turned on, See Figure 11.

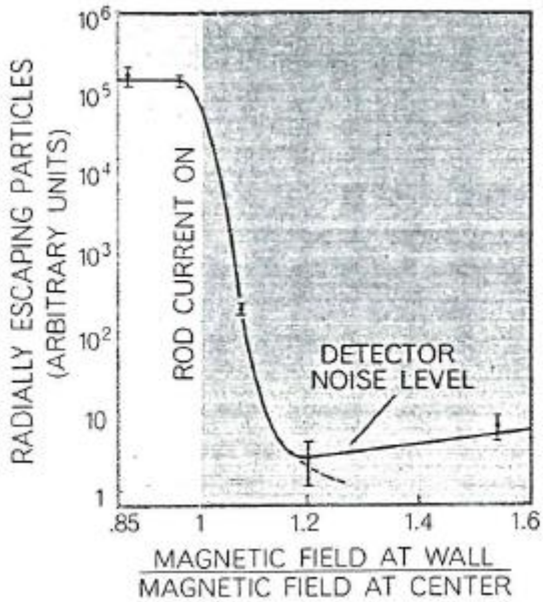

Figure 11 Graph showing the escaping particles before and after the rods making the magnetic well were turned on (Fowler & Post, 1966, p. 26).

Toroidal

There was also a different approach to the problem of containing the plasma for a long enough time without making the field lines many kilometers. Rather than compressing the magnetic field lines at the ends to make the mirror setup, the field lines are bent on closed loops making a doughnut-shape. This is known as a toroidal installation, in its simplest form no more than the doughnut-shaped field lines. These were quickly found to be as instable as the magnetic mirror without a magnetic well, with much the same reason for it. In the doughnut the magnetic field lines are decreasing from the center of it, making the same interchange instability present here. The interchange instability got its name since the plasma changed place with the vacuum due to the decreasing field strength, and this is also what happens in the toroidal system. To prevent the plasma to drift towards the walls, the toroidal systems makes a twist on the magnetic field lines that are greater near the walls than the center. This prevents the plasma from interchanging place with the vacuum, since the sheared magnetic field prevents the flute perturbation from following the field lines from one surface to the next (Chen, 1967, p. 78). The different toroidal setups make this shear in different ways, the stellarator by a geometric setup or external coils and the tokamak by an internally induced current.

The Stellarator

Lyman Spitzer first suggested the stellarator in 1951, in a paper to the U.S Atomic Energy Commission, AEC, in Washington. Spitzer, working at the Princeton University, chose the name "Project Matterhorn" when he got funding to further research (Stix, 1998, p. 3). Spitzer was a hobby climber, and felt the task he started at resembled climbing a great mountain. In the design, Spitzer thought of a plane through the stellarator tube and perpendicular to the magnetic field (Spitzer, 1958, pp. 181-182), see Figure 12.

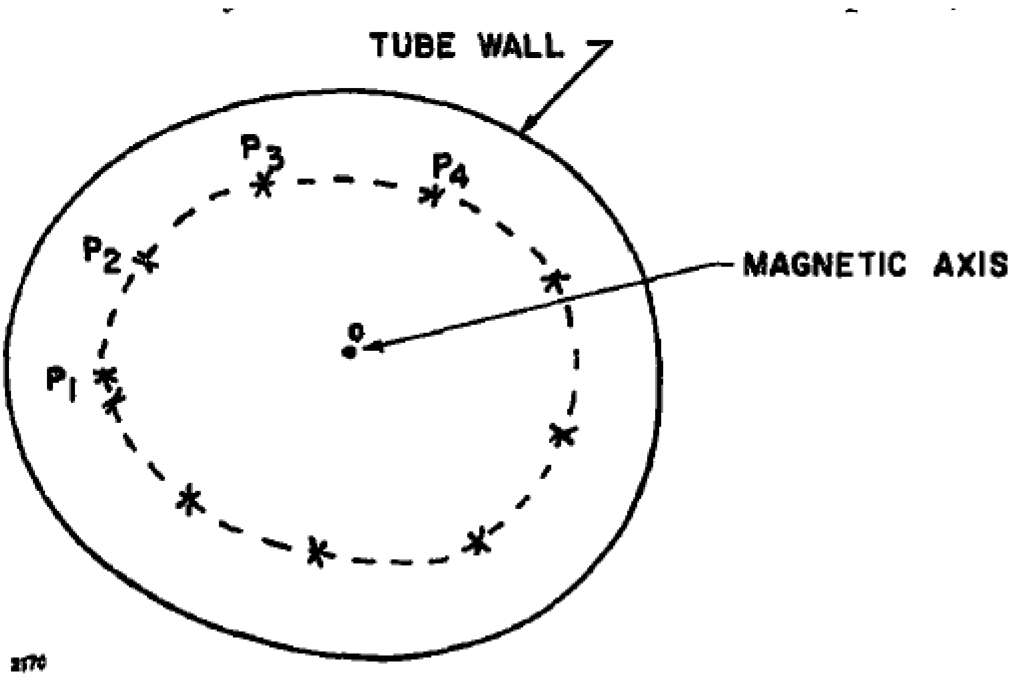

Figure 12 Cross section of stellarator tube. The points represents successive intersections of a single magnetic field line (Spitzer, 1958, p. 182).

If the magnetic field is non-zero at all points, then at point P_1 there must be a field line we could follow. After one complete circuit, it once again intersects the plane in P_2. If P_1 coincides with P_2 then it corresponds to the field lines in an ideal torus. Such a mapping is called a transform. Given the geometric setup of the stellarator, there is only one field line that closes onto itself immediately, called the magnetic axis. It is also shown that the points do not move far from a single closed curve, as P_1, P_2, P_3 and P_4 shows. Therefore, a single field line would after many circuits make a magnetic surface, or at least close to one.

The actual design of the stellarator must be made so that the rotational transformation occurs, and Spitzer`s initial geometrical construction was a figure-eight stellarator, see Figure 13.

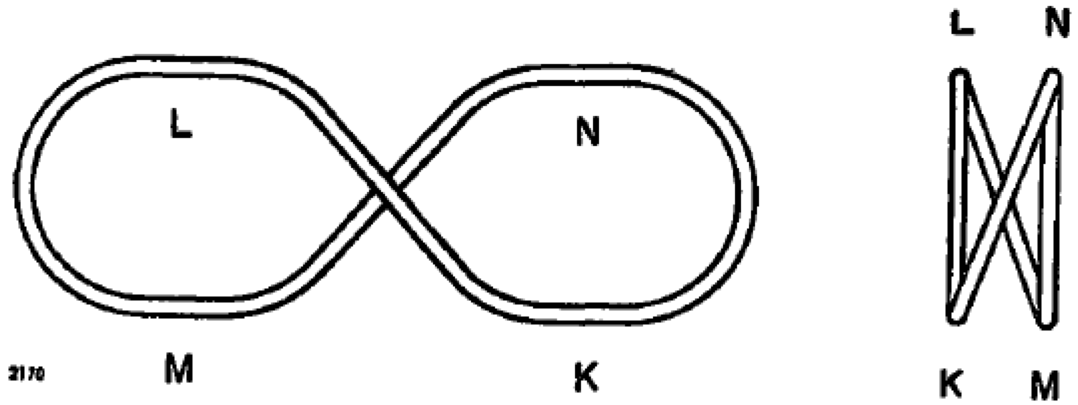

Figure 13 Top and end views of a figure-eight stellarator (Spitzer, 1958, p. 183).

The planes of the two halves are tilted at an angle to ensure that rotational transform is present. In addition, the twist makes the net drift of the charged particles small. This is a result as a particle that is on the outside of the center on one of the curved sections, will be at the inside of the next after traveling the straight part. Therefore, the upward drift on one side ideally cancels the downward drift on the other, but the twist to prevent the tubes from hitting when they cross makes it only a good approximation. Another way of achieving the rotational transform is to include additional helical windings to the outside of the tube. Groups of conductors are used in the setup, and the direction of the current are opposite in adjacent groups.

Tests conducted showed that:

> *"figure-eight stellarator tends to be generally unstable, but that the helical windings give a system that is completely stable hydromagnetically, provided that β, the ratio of material to magnetic pressure, is not too great."* (Spitzer, 1958, p. 191).

Spitzer also discusses the possible ways of heating the plasma to high enough temperatures. He sees two different ways of doing this, "ohmic heating" with electric field parallel to the magnetic field, and "magnetic pumping" with the electric field perpendicular to the magnetic field.

The first stellarator, the model A, was a figure-eight type of 5 cm in diameter and about 350 cm long, see Figure 14.

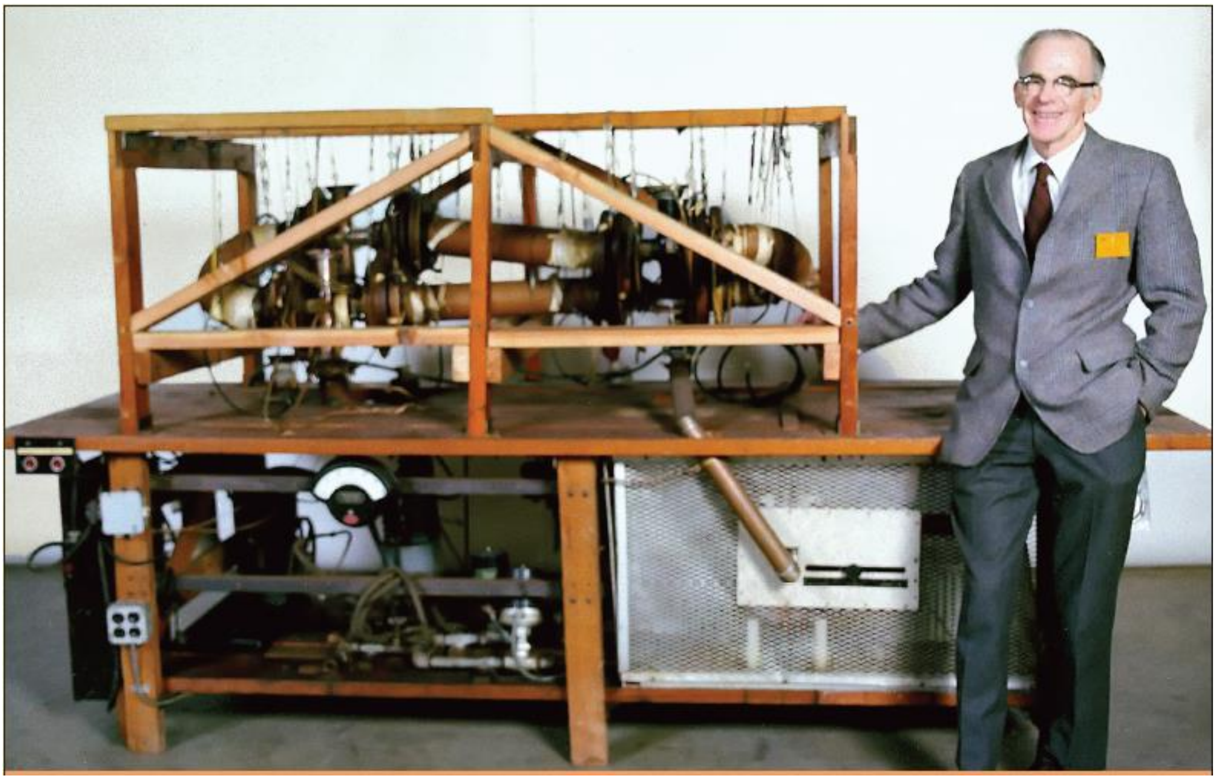

Figure 14 Lyman Spitzer Jr. with the model A stellarator (Greenwald, 2013).

Its magnetic coils were wound directly on the Pyrex glass tubes that made the vacuum chamber, and could produce a 1000-gauss steady-state field. It started operating in the early 1953 (Stix, 1998, p. 6).

Subsequently, several model B stellarators were made. The B-3 was the last of the figure-eight machines. It also had a 5 cm diameter, but a length of 468 cm and a magnetic field that were operated up to 40,000 gauss. B-3 also included helical windings for MHD-stability, but it did not help much for the rapid plasma loss, and the plasma confinement never exceeded a few tens of microseconds.

Tokamaks

The tokamak, named after the Russian toroidalnaya kamera magnitnaya katushka (toroidal chamber magnetic coil), is a toroidal confinement system where the toroidal field, B_ϕ, is set up externally by field coils. When current flows in the field coils a toroidal field is produced, represented in the plasma region using coordinates (r, θ, ϕ), see Figure 15, as

$$B_\phi(r,\theta) = \frac{B_\phi^0}{1+\frac{r}{R_0}cos\theta} \equiv \frac{B_\phi^0}{1+\varepsilon cos\theta} \quad (26)$$

where B_ϕ^0 is the toroidal field when r=0, R_0 is the radius of the minor axis relative to the major axis and $\varepsilon = \frac{r}{R_0}$.

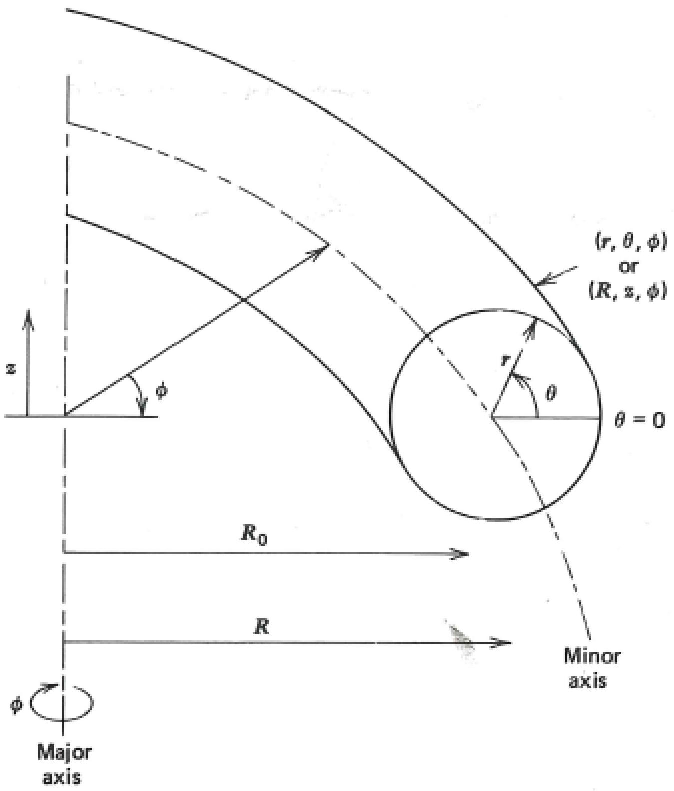

Figure 15 Toroidal (r,ϑ,φ) and cylindrical (R,z,ϕ) coordinate systems (Stacey, 2010, p. 46).

The drifts due to the ∇B and the curvature makes it impossible to have a purely toroidal field since, using equation 10 and equation 14,

$$\boldsymbol{v}_{\nabla B} = \frac{\frac{1}{2}mv_\perp^2}{qB^3}\boldsymbol{B}\times\boldsymbol{\nabla}B = \frac{\frac{1}{2}mv_\perp^2}{qB_\phi^2}\frac{\partial B_\phi}{\partial R}\boldsymbol{n}_z \quad (27)$$

$$\boldsymbol{v}_c = -\frac{mv_\parallel^2}{qB^2}\frac{\boldsymbol{B}\times\boldsymbol{n}_c}{R_c} = \frac{mv_\parallel^2}{qB_\phi R}\boldsymbol{n}_z\ . \quad (28)$$

The drifts go in opposite directions for electrons and ions. This separation of charges causes an electric field (downward in Figure 16) that makes a drift radially outwards for the plasma until it hits the chamber wall, using equation 6, see Figure 16,

$$\boldsymbol{v}_{E\times B} = \frac{\boldsymbol{E}\times\boldsymbol{B}}{B^2} = \frac{E}{B_\phi}\boldsymbol{n}_c \quad . \tag{29}$$

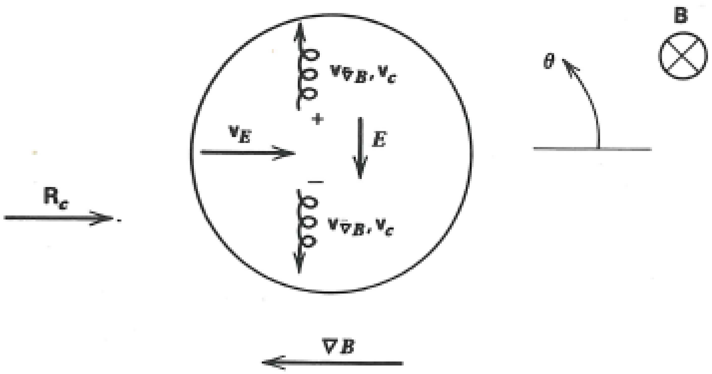

Figure 16 Drifts in the toroidal system (Stacey, 2010, p. 46).

This drift can be canceled by superimposing a poloidal field on the toroidal, see Figure 17. Then the radial displacement due to ∇B and curvature can be averaged out over a full circle since the ions sometimes will drift radially inwards and sometimes radially outwards. The tokamak makes the poloidal field by inducing toroidal currents in the plasma (The stellarator has a set of external coils).

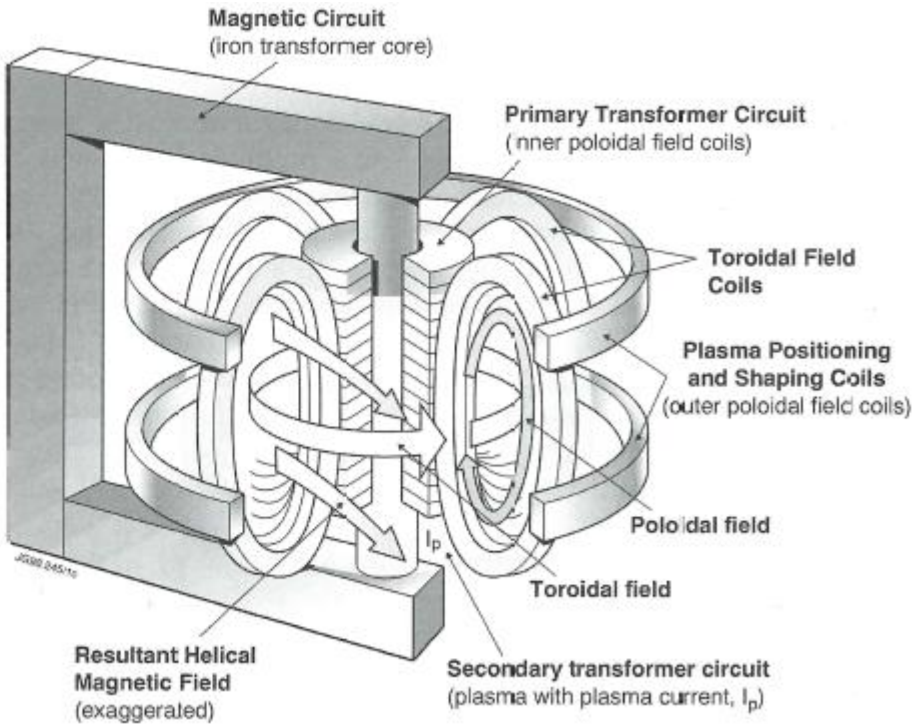

Figure 17 Schematics of a tokamak (Braams & Stott, 2002, p. 132).

Divertor

The hot plasma in a toroidal configuration must be as pure as possible. Since the magnetic confinement is not perfect, parts of the plasma will reach the wall and collide. This leads to erosion in the surface of the wall, and the eroded particles are mixed into the plasma. The physical sputtering is a measurement of how many atoms are ejected per incident particle, and Figure 18 shows the physical sputtering for deuteron incident on a number of different materials. At energies needed for fusion, many foreign ions will go into the plasma. These ions will cool the plasma by collision and radiation. The divertor bends the magnetic field by using a coil and makes the outermost field lines bend out and into the divertor, see Figure 19. In the divertor the impurities can be separated and taken out of the plasma. Spitzer proposed the first divertor in 1951, together with the schematics for the stellarator, see Figure 19.

Research on divertors for tokamaks started up around 1974 (Stacey, 2010, pp. 170-172). The divertors have changed during the years, having a bit different setup than Spitzer`s initial one, but the function has stayed the same.

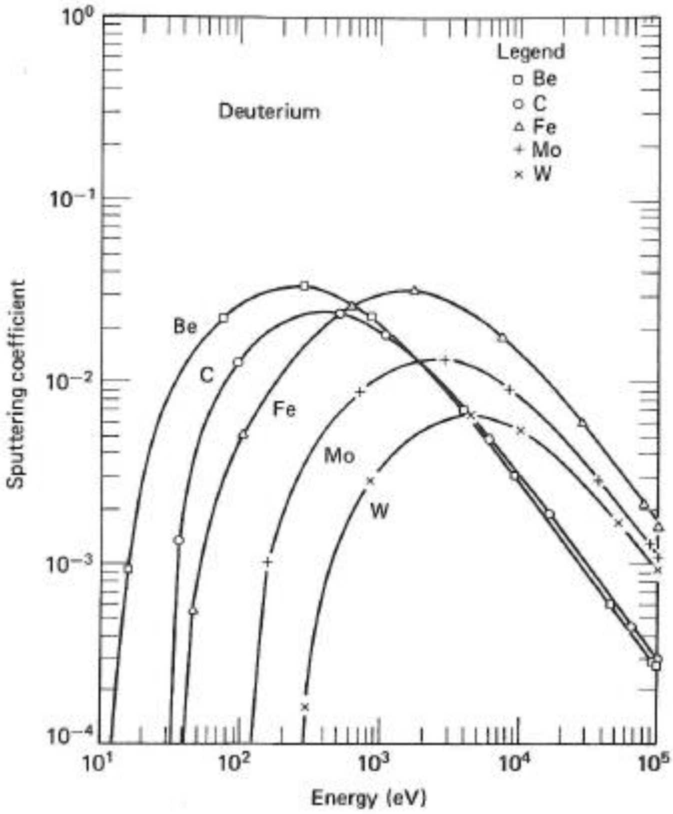

Figure 18 Physical sputtering yield for a number of materials for deuterons (Stacey, 2010, p. 82).

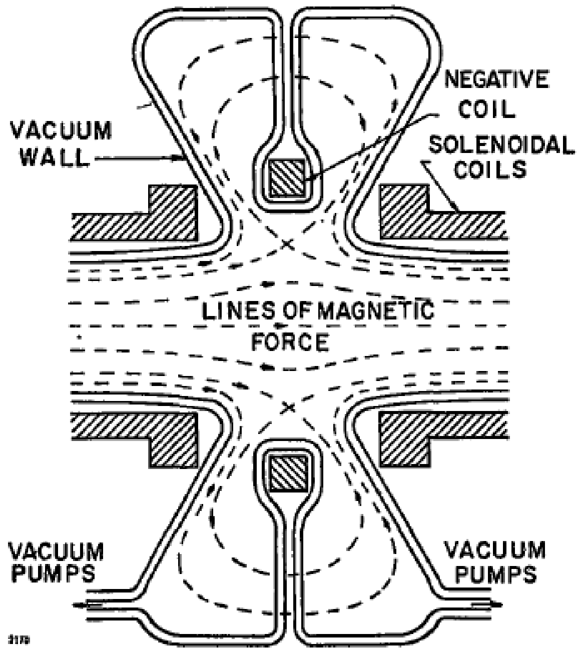

Figure 19 Divertor for the stellarator (Spitzer, 1958, p. 188).

Heating the plasma

Ohmic heating

In the confinement systems where a current flow through the plasma, like the tokamak, collisional friction gives an intrinsic heating mechanism. The power deposition, P_Ω in megawatts per cubic meter, can be written as

$$P_\Omega(\frac{MW}{m^3}) = 7\times10^{-2}\frac{Z_{eff}}{T_e^{\frac{3}{2}}(keV)}[\frac{1}{q(a)}]^2(\frac{B_\phi}{R_0})^2 \qquad (30)$$

where Z_{eff} is the effective charge average over all ions in the plasma, T_e is the electron temperature, $q(a)$ is the safety factor, B_ϕ the toroidal magnetic field and R_0 the radius of the minor axis relative to the major axis. This equation shows two important things. First, the heating power will saturate with increasing temperature, since it is divided by $T^{\frac{3}{2}}$. Secondly, it will be maximum with a strong field and a small radius, coming from the $(\frac{B_\phi}{R_0})^2$ part. Using the equation for P_Ω, and calculate it against the losses due to conduction and convection, it is found that the maximum temperature reached in a conventional tokamak ($B_\phi \simeq 5T, \frac{R_0}{a} \simeq 3-5, q(a) \simeq 2-4$) will be of order 1 keV (Stacey, 2010, p. 64). Therefore, ohmic heating can be used initially to heat the plasma, but to reach ignition temperature other types of heating must also be applied.

Neutral beam injection - NBI

Ions are produced by a source and accelerated by electrostatic fields to high energies. After they are accelerated, the ions are neutralized by going through a neutral gas. This is done in order to be able to inject the beam, since the strong magnetic field confining the plasma would bend an ion beam and consequently not reach the plasma center or destroy the reactor walls. When the neutral beam is injected into the plasma, the particles are ionized by collision with the plasma ions and electrons. The ions then deposit its energy through Coulomb scattering with the plasma particles. The beam is generally injected tangentially to the toroidal direction. To heat the plasma efficiently the fast ions must be confined long enough to transfer their energy and they must penetrate the core of the plasma.

Radio-frequency heating – RF-heating

Radio-frequency heating sends electromagnetic waves into the plasma. If the frequency of the wave is correct, it can convert its energy into heat by a resonant interaction between the wave and the plasma particles. A general wave will always give energy through collision, but the collisional absorption scales as in the same way as ohmic heating ($T^{-\frac{3}{2}}$) (Braams & Stott, 2002, p. 184), so only the collisionless process of resonance can be used to heat the plasma to high temperatures. Three frequency regimes are used for heating the plasma, each corresponding to a natural frequency part of the plasma. The first frequency ranges from 50 to 100 megahertz, corresponding to the ion cyclotron frequency (ICRH). The second one ranges from one to three gigahertz, where it resonates with frequency of fluctuations in the density of ions in the plasma (LHRH). The third ranges from 50 to 100 gigahertz, where it matches the electron cyclotron frequency (ECRH). All the radio-frequency heating systems are essentially a transmitting station. It includes a source for the wave, an amplifier, a transmission line and a launching structure (Conn, 1983, p. 48).

The 1960`s

The Geneva conference in 1958 was a great step forward since it gave scientists from the different countries a chance to speak freely to colleagues across borders about breakthroughs and setbacks. Additionally, the conference had shown the scientists how they had come up with very similar solutions to the question of how to make a fusion power plant. This was maybe not a big surprise, since the laws of physics are the same, but more disappointing was the fact that the conference revealed the same problems for all countries and all machines. There were also decreasing support for fusion outside the scientific community. At a budget hearing in Washington in 1964 Senator John Pastore said:

> *"I am wondering in my own mind how long you have to beat a dead horse over the head to know that he is dead? … Is this not indeed a very expensive way of getting this basic knowledge? We can build these machines until the cows come home. Somewhere along the line somebody has to think that this is a lot of money and maybe we ought to be putting it into some other place where it may be more productive."* (Herman, 1990, p. 78).

Also the scientists working with fusion were more careful when talking about the future and what to expect, although the general consensus was that one would obtain fusion, but not necessarily as soon as previously believed. Fowler and Post ends an article about the progress towards fusion power in 1966 with the words:

> *"the efforts to obtain power from fusion is rather like the efforts of the blind men to describe the elephant by exploring its various parts. We are making steady progress in understanding our elephant, but we cannot yet claim to be able to draw a picture of it … we have little doubt that the beast exists, and that the dream of extracting unlimited energy from the seas will one day become a reality." (Fowler & Post, 1966, p. 31).*

At the IAEA conference in Culham in 1965, Spitzer held a speech talking about the future of fusion. He showed a careful optimism towards the ultimate goal, but had no doubt that the road towards a power plant would be long and challenging:

> *""Are we approaching the goal towards which many of us started with such high hopes a number of years ago - the release of controlled fusion power for the benefit of mankind?" I think the answer to this question is simple and obvious - we do not know. We cannot say what lies in territory that is unexplored and uncharted. Our course towards controlled fusion has encountered many obstacles in the past. Most of the serious ones have been overcome, sometimes after years of effort by a great number of scientists. We can be sure that there will be many other obstacles ahead but we have good reason to hope that these will be surmounted by the cooperative efforts of scientists in many nations."* (International Atomic Energy, 1966, p. 11).

In his concluding remarks of the IAEA conference in Novosibirsk in 1968, G. I. Budker talked about how scientists early thought that making a reactor would be achieved in a short period of time, but:

> *"experience soon showed that here we had a scientific rather than a technological problem and that it would be necessary to study in detail the physics of plasmas - which we have now been doing for over ten years."* (International Atomic Energy, 1969, p. 43).

This summarized much of a decade where most of the research had gone into understanding how the plasma was affected by different fields and trying to find ways to suppress the different instabilities. In all the papers presented at the conference only two mentioned the Lawson criteria, a feature most important when discussing the possibilities for a future reactor. Budker continued his talk with an encouragement to his colleagues. Now the basic physics had been studied for long enough, and even though not everything was understood completely, the research had to once more be directed towards a final power plant:

> *"Now, I feel that the progress achieved by the physicists during this period justifies our again thinking in terms of building a thermonuclear reactor. … Our generation, which gave the world atomic energy and thermonuclear energy in explosive form, now is responsible towards Mankind to solve the main problem - obtaining energy from water. The world expects it of us, and it is our duty towards mankind. It is a task which our generation must accomplish, and to do so we must now set forth on the road."* (International Atomic Energy, 1969, p. 44).

More instabilities

Although one had managed to avoid flutes in both the magnetic mirror and the toroidal devise, the plasma was still leaking at a rate more than 1000 times faster than what classical diffusion yields (Chen, 1967, p. 78). All the different unknown behavior was hard to describe or explain. It did not seem to agree with the current plasma theory, and for a long time they were lumped under the heading "cooperative phenomena" since it seemed like the plasma particles cooperated in some way to wiggle out of the magnetic bottle (Francis F Chen, 1967, p. 78).

Bohm diffusion

Another unexplained behavior was the Bohm diffusion, D_B. Classical diffusion, D_C, predicted that diffusion should be proportional to $\frac{1}{B^2}$ and have a $T^{-\frac{1}{2}}$ dependence. This prediction off the diffusion was great for the physicists. It gives a much lower value when the magnetic field is increased, and increasing the temperature to achieve ignition for the plasma would also decrease the plasma loss to the walls.

Bohm, on the other hand, made a semi-empirical formula based on the actually observed losses. Since the losses were far greater than what the classical predicts he came up with

$$D_B = \frac{kT}{16qB} \quad \text{(Braams \& Stott, 2002, p. 30)} \qquad (31)$$

This prediction became a great problem for plasma-physicists during the 1960`s since increasing the magnetic field would not help as much as classical diffusion predicts. It also says that the diffusion to the wall is dependent on the temperature, and not $T^{-\frac{1}{2}}$ as the classical diffusion yields. Therefore, increasing the temperature would, according to Bohm, increase the diffusion instead of decreasing it.

During the 1960`s more and more of the experimental devices could give a confinement time better than what Bohm diffusion predicted, but it was not until the 1968 Novosibirsk Conference that empirical data was great enough to discredit Bohm`s equation as the correct one for diffusion to the walls. As Artsimovich said in his opening speech at the conference in 1968:

> *" What, then, have we accomplished since Culham? In my opinion, at least one really important result has been achieved: we have rid ourselves of the gloomy spectre of the enormous losses embodied in Bohm`s formula and have opened the way for further increases*

in plasma temperature leading to the physical thermonuclear level." (International Atomic Energy, 1969, p. 17).

Kink instabilities

Other types of instability that troubled the early plasma physics was the kink and sausage instabilities. The kink instability is a small kink in the plasma, this will keep increasing since the magnetic pressure is stronger at the concave side of the kink (where filed lines are crowded together), se Figure 20 a. With the sausage instability the plasma pinches itself off at one or more places and thus creates several pieces. Here the field lines crowd up so that once a small sausage instability has started, it will just keep growing, se Figure 20 b. To stabilize the kink, it is possible to include a strong magnetic field in the plasma column to make it more rigid, se Figure 20 c and d. If a kink started to develop, the field would resist stretching and bending so the kink and sausage instabilities are stopped instead of increasing and destroying the plasma.

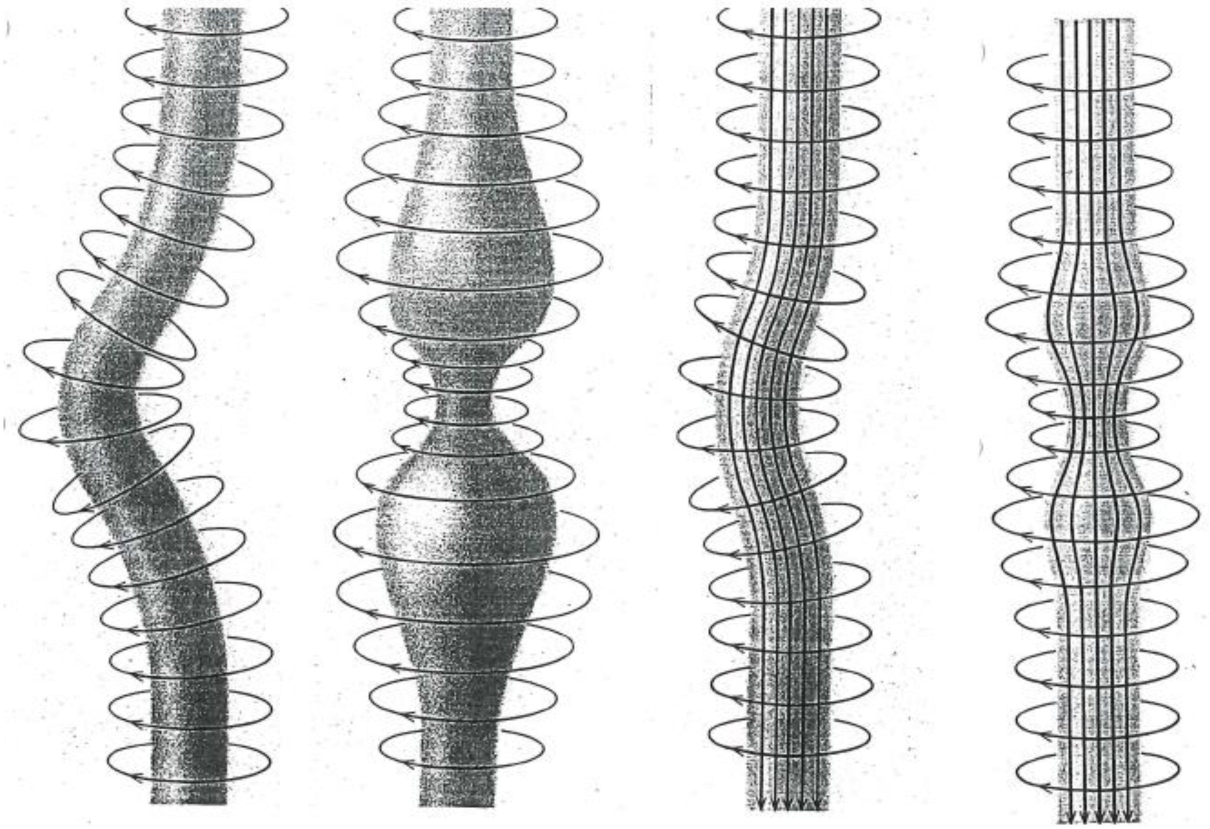

Figure 20 Kink (a) and sausage (b) instabilities with magnetic field inside to suppress the instability (c and d) (Richard F Post, 1957, pp. 80-81).

Landau damping

One process in the plasma that prevents wave-particle instabilities is Landau damping. It works opposite of an amplifying mechanism when a wave travels at a speed slightly higher than the average particle speed. When particles are caught in the trough of the wave, they speed up by extracting energy from the wave. This leads to an attenuating of the wave, and then also the instability that had started in the plasma (Fowler & Post, 1966, p. 29).

Magnetic mirror

When the idea of a magnetic well was shown to be highly successful in keeping the plasma in the magnetic container for a longer time, researchers turned to make even better configurations. The initial idea, Figure 10, was good for seeing whether it would work or not, but to achieve ignition the magnetic confinement system had to be as strong as possible. One of these configurations were the "baseball seam", se Figure 21, where the coil that makes the magnetic field looks like the seam on a baseball. This was invented at Culham in the winter of 1963 (Hiskes, 1967, p. 9) (first called the tennis ball), and was soon after used by Livermore and upgraded to the "yin-yang" coils who had better efficiency and gave greater access to the plasma center.

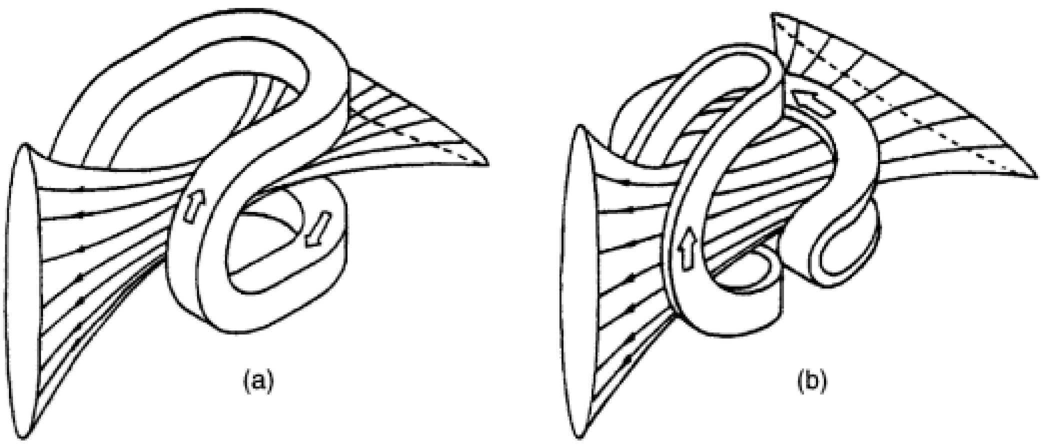

Figure 21 a) a "baseball seam" coil, b) a yin-yang coil set (Braams & Stott, 2002, p. 64).

At the Lawrence Radiation Laboratory, the 2X mirror machine used quadrupole magnetic coil to make the magnetic field configuration (Krall & Trivelpiece, 1973, p. 273). The plasma, 160 cm long and 6 cm in diameter, was injected axially to the magnetic field. It had a peak density of $5\times10^{13}cm^{-3}$, a mean ion temperature of 8 keV and electron temperature of 200 eV. The largest confinement time observed was $350\mu s$ (Krall & Trivelpiece, 1973, pp. 274-275). Livermore continued improving the magnetic mirror with the 2X II, which had greater density, ion and electron energy and confinement time, see Tabell 2.

	2X	2X II
Maximum D.C. Guide Field (kG)	2	4
Maximum Central Magnetic Field (kG)	16.3	14.5
Longitudinal Mirror Ratio	1.33	2
Radial Well Depth Measured At Wall (%)	2.5	21
Minimum Distance Along Field Line From Plasma To Wall (cm)	20	>300
Pulsed Magnetic Field Rise Time (μsec)	160	210
Magnetic Field Decay Time (msec)	8	30
Distance Between Mirror Points (cm)	160	100
Plasma Diameter (FWHM cm)	6	11
Maximum Plasma Density (cm^{-3})	5×10^{13}	10^{14}
Maximum Mean Ion Energy (keV)	8	20
Electron Temperature (eV)	100-200	>200

Tabell 2 Comparing parameters on 2X and 2X II (International Atomic Energy, 1971, p. 722).

Even though there were improvements in all the three parts of the Lawson criteria, plasma scattering into the loss cone were still a major problem that needed to be solved for the mirror machine to reach the confinement times needed in a fusion reactor. At the conference in Culham, V. V. Kadomtsev summarized the future for the single mirror with:

> *" Above all one can draw the conclusion that mirror traps with open mirrors suffer from an important defect relating to the existence of the "loss cone". Therefore these traps, without further modifications, and complications whose magnitude and extent I do not know, can scarcely be used for thermonuclear devices." (International Atomic Energy, 1966, pp. 30-31).*

Toroidal confinement

Stellarator

The new and improved Model C started operating in 1961, see Figure 22. It had the form of a racetrack with 12 m length and a minor radius of the plasma of 5 – 7.5 cm. When operated the magnetic field was about 35 000 gauss (Stix, 1998, p. 7). One of the straight legs of the racetrack had a divertor, the other one a section supplying 4 megawatts of 25 MHz ion cyclotron resonance heating. One of the main findings of the Model C stellarator was a confinement time consistent with Bohm diffusion.

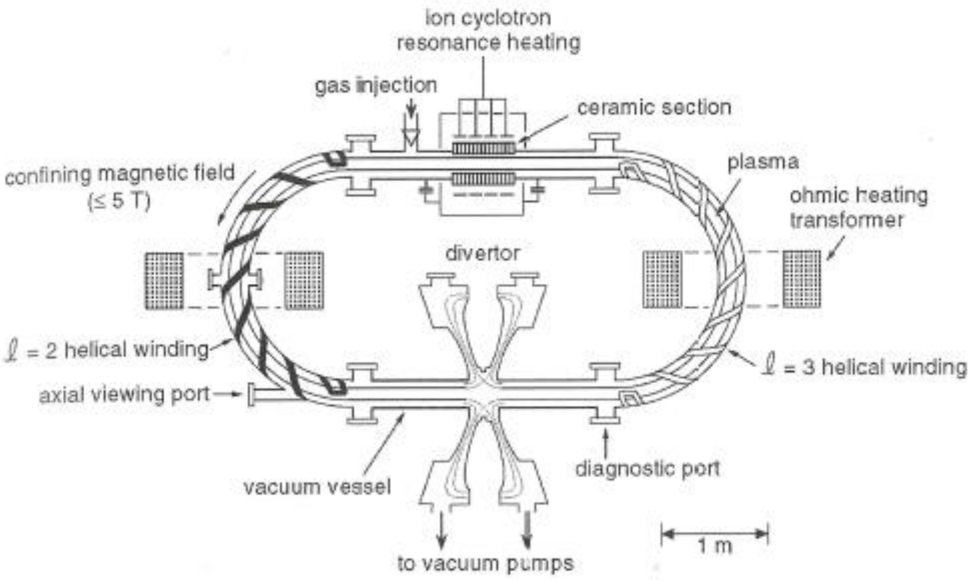

Figure 22 A simplified plan view of the C-stellarator showing major components (Braams & Stott, 2002, p. 125).

Tokamak

Soviet reported a great breakthrough at the conference at Novosibirsk in 1968. Their report from the tokamak T-3 showed better plasma confinement and higher temperature, both with a factor of ten greater than other toroidal configurations. With T in the temperature range of 700-1000 eV (here temperature, T, is electron + ion temperature) they could report of confinement time, τ_E, reaching 40-50 Bohm times, τ_B, see Figure 23.

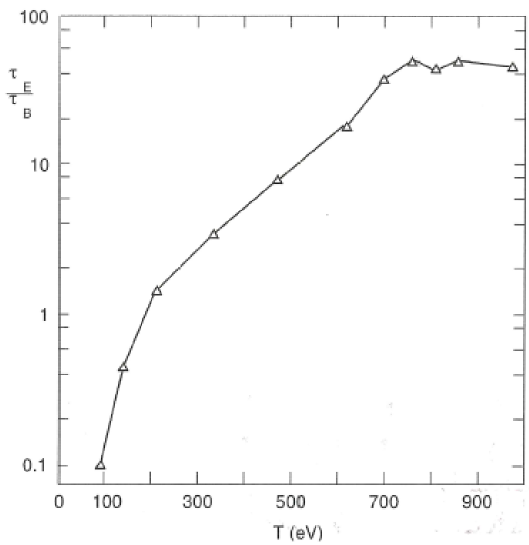

Figure 23 Results from T-3 showing the confinement time relative to Bohm confinement time for different temperatures (Braams & Stott, 2002, p. 133).

Scientists from Western countries was not convinced that the results could be trusted, but Lev Artsimovich, the head of the Soviet program, invited a group of British fusion scientists to the Kurchatov Institute to verify the results. During their visit, they got their findings confirmed. This lead to a great deal of other installations being transformed into tokamaks, in what has been known as the "bandwagon effect" (Dean, 2013, p. 23). US scientists turned away from their stellarators to convert them into tokamaks. Even the Model C stellarator at Princeton were made into a tokamak, now called ST, to further investigate the findings and breakthrough of the Soviet.

Inertial confinement fusion

The problem with magnetic confinement has been to confine the plasma for a long enough period so that the plasma can burn enough to produce a sufficiently high Q value. When the first lasers were operated in the early 1960`s (Lubin & Fraas, 1971, p. 22) it did not take long before it became clear that they could generate great amounts of energy in short time.

A laser is a devise that amplifies monochromatic and coherent beams of light. It can be made to have a very small divergence angle, so that it is focused in a spot with diameter of only a few hundred-millionths of a cm. Lasers can achieve power densities of more than 10^{17} watts per centimeter squared, giving a local electric field of order 10^{10} volts per centimeter (Lubin & Fraas, 1971, p. 21). This is an enormous amount, and the reason why lasers is a possible fusion ignition media.

Initially the laser were planned to heat plasma in already existing magnetic confinement systems, see Figure 24.

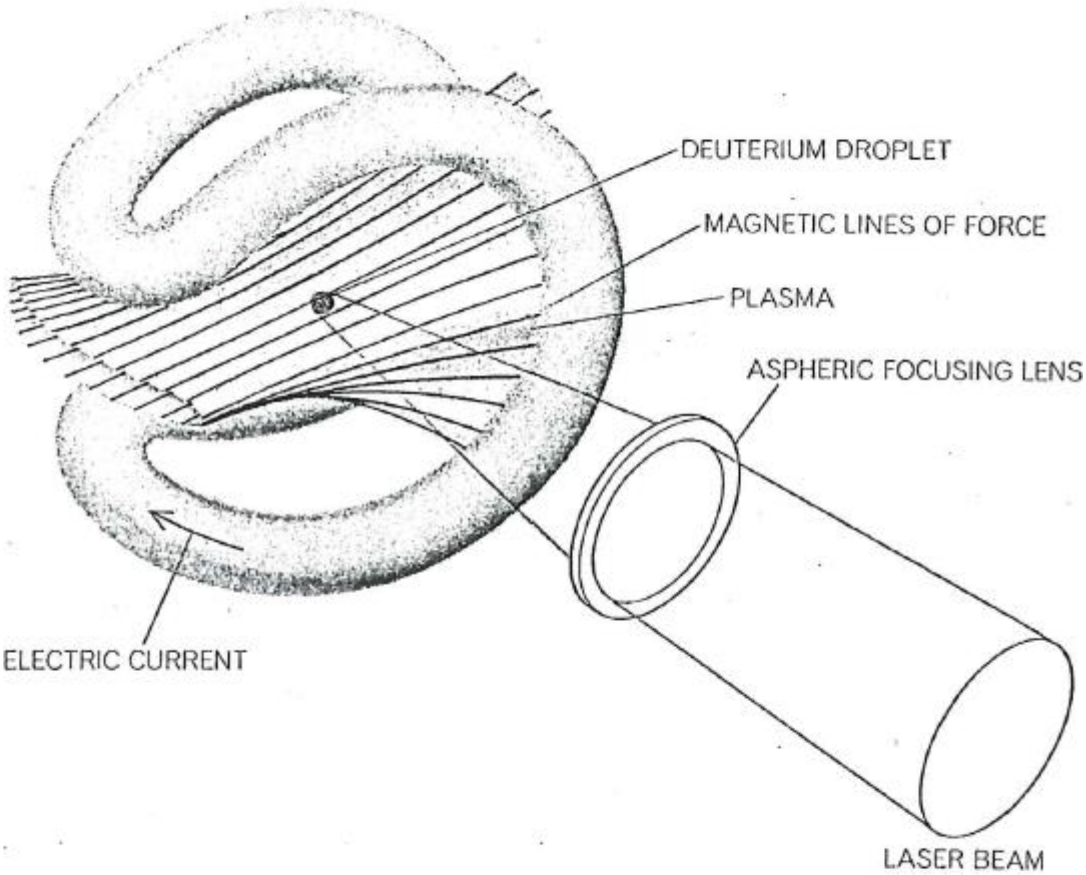

Figure 24 First use of lasers, heating within existing magnetic confinement (Lubin & Fraas, 1971, p. 25).

A setup like this got a temperature of 10 million K with density of 10^{13} ions per cubic centimeter at University of Rochester in 1968. However, the main study of fusion by inertial confinement ignition has been to make a small fuel pellet ignite and burn without the magnetic field confinement. This has the advantage of not having to use great amount of energy to create and maintain the field.

An alternative to using laser to heat the fuel pellet were filed for patent in 1960, and awarded to A. John Gale in 1963 (Yonas, 1978, p. 43). He proposed to ignite the fuel pellet with a particle beam and not lasers. The beam is easy to aim because it is charged (electron or ion), but for the same reason it is hard to focus.

To understand the basic idea of inertial confinement fusion we follow the thoughts of Lubin and Fraas (Lubin & Fraas, 1971, pp. 27-29). The laser is focused on a solid fuel pellet. Initially, a leading edge of the laser hits the pellet, vaporizing it without heating enough to ignite. When it has reached gaseous form, the main heating pulse is applied. This converts the gas to plasma and heats it to as high temperature as possible. For the goal of reaching a Q value greater than one, calculations in the 1960`s showed that input energies of around 10^5 to 10^6 joules is needed, while the highest energy possible to deliver in a properly shaped pulse was 10^3 joules. The energy must be delivered in a few nanoseconds because the plasma will start to expand and become dilute in this short time.

In order to make use of the energy released in the pellet, it must be converted in some way. A method for this was proposed by Oak Ridge National Laboratory in the early 1969 (Lubin & Fraas, 1971, p. 29). They wanted to use a pool of lithium to convert the kinetic energy of the neutrons into heat. Then use a heat exchanger to get the heat into a thermodynamic cycle, see Figure 25.

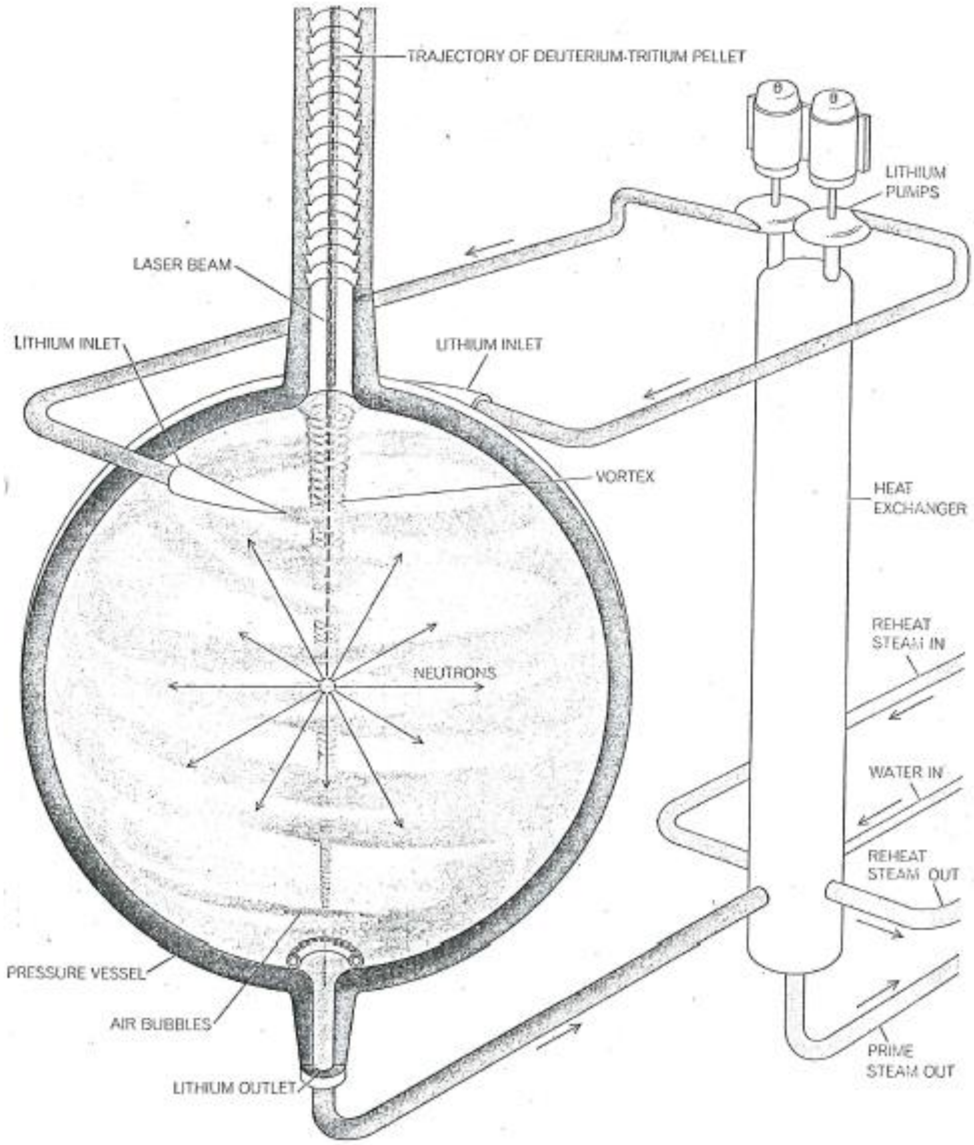

Figure 25 A proposed fusion reactor using laser and a frozen pellet of fuel (Lubin & Fraas, 1971, p. 28).

The pool of lithium would be contained in a spherical pressure vessel about four meters in diameter, and it would be swirled at a velocity high enough to form a free vortex around its vertical axis. A frozen pellet of deuterium-tritium is dropped into the center of the vortex and ignited by a laser pulse when it reaches the midplane. The heated lithium is taken out in the bottom and goes through the heat exchanger before being reentered at the top. The shockwave created in the fusion explosion could be attenuated by blowing air bubbles into the vessel, preventing the vessel from bursting. Tests made on smaller vessels with ordinary explosives extrapolates to a maximum output power of about 150 megawatts with this setup.

The 1970`s

The oil embargo in 1973, where several Arab countries affected western countries supporting Israel in the Yom Kippur war, significantly increased the oil prices. The US realized they were highly dependent on foreign energy, and dramatically intensified research on new ways of creating electric power (Yonas, 1978, p. 40). The budget for fusion research increased significantly as a result of this, as Figure 26 shows.

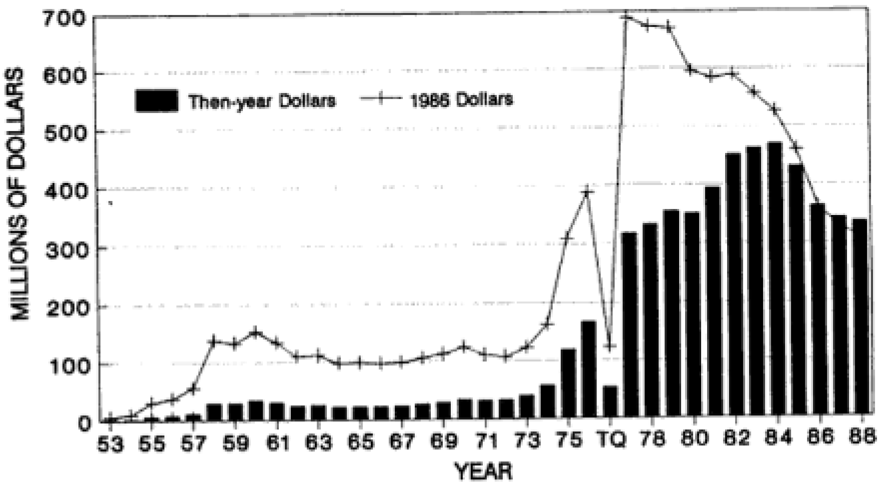

Figure 26 Budget for Magnetic confinement fusion in the US. The TQ is a transition between starting month of the fiscal years in 1976 (National Research Council & Policy, 1989, p. 20).

At the end of 1974 the Energy Research and Development Administration, ERDA, in the US, which included all energy sources, replaced AEC. Only a few years later, in 1977, ERDA changed into the Department of Energy, DOE (Dean, 2013, pp. 45,52).

In the start of the 1970`s, the US government ordered a plan for the development of the fusion program. When delivered in 1976 it contained a detailed plan for the future of fusion, with five scenarios, called Logics, for different funding. If the budgets were limitless and the scientists got to build what they wanted, the plan predicted Logic V. This should give a working demonstration power plant by 1990. The other end of the scenarios, Logic I, showed what no funding beyond basic understanding research would give. It predicted that a working power plant might never be built. Logic III was the scenario that was emphasized mostly in the report. It had the name "aggressive", and in the plan the description was:

> *"The levels of effort in physics and engineering are expanded according to programmatic need, assuming that adequate progress is evident. New projects are undertaken when they are scientifically justified. Many problems are addressed concurrently. Funding is ample but*

reasonably limited. (This program would be aimed at an operating demonstration reactor in the late 1990's.) (Administration, 1976, p. 8).

The different Logics were put together in a graph, Figure 27, showing a pessimistic, reference and optimistic year for the demonstration power plant.

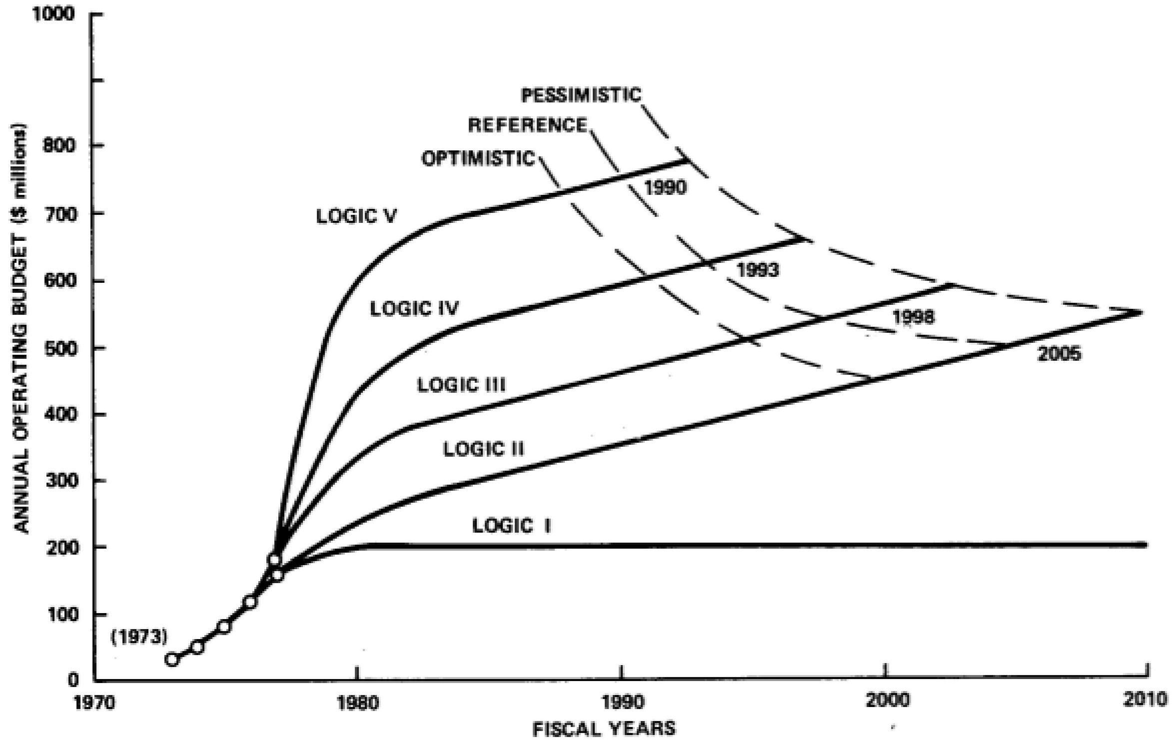

Figure 27 The five different Logics in the 1976 US fusion plan (Administration, 1976, p. 10).

As we can see from Figure 27, the most pessimistic estimate for a demonstration power plant, as long as the government funded fusion research in a moderate manner (Logic II), was 2010.

At his talk at the IAEA conference in Berchtesgaden in 1976 Pease summarized the findings for the toroidal pinches with a table, see Tabell 3, and the optimistic words:

> *"Table I* [Tabell 3] *indicates the general rate of progress that we have been reaching with tokamak systems over the past twenty years or so. One can see the surprisingly steady progress that has been maintained. Furthermore, looked at logarithmically, we have now covered the greater part of the total distance. What remains is difficult, but the difficulties are finite and can be summed up by saying that we do not yet have an adequate understanding of or control of the cross-field electron thermal conduction." (International Atomic Energy, 1977, p. 554).*

Year	τ_e (s)	T_i (K)	$n\tau_e$ ($cm^{-3}s$)
1955	10^{-5}	10^5	10^9
1960	10^{-4}	10^6	10^{10}
1965	2×10^{-3}	10^6	10^{11}
1970	10^{-2}	5×10^6	5×10^{11}
1976	5×10^{-2}	2×10^7	10^{13}
Needed for a reactor	10^0	10^8	10^{14}

Tabell 3 Plasma parameters in toroidal pinches (International Atomic Energy, 1977, p. 553).

Mirror

The increasing parameters in ion energy, temperature and plasma density from 2X to 2X II opened for further work on the machine. A group of experts recommended in 1972 to include neutral beam heating and other upgrades, and gave it the name 2X IIB (Bulmer, Calderon, Hibbs, & Kozman, 1975, p. 1). It included a yin-yang pair coil to make the magnetic confinement and started operating early 1975. It achieved an average β value of 70 %, mean ion energy of 10-20 keV and electron temperature up to 160 eV (T. Simonen, 2008, p. 24). Still the mirror leaked too much energy out of the ends, and it was clear that stronger magnets and better heating systems would not solve all problems for the mirror confinement system. Calculations showed that even in the best situation the maximum Q value would be no more than about unity (T. C. Simonen, 1981, p. 936). Something had to be done, and the solution to a better confinement were proposed independently by Soviet and the US in the mid-1970`s, the tandem mirror. The idea was to "plug" both ends of a long central solenoid with a mirror coil, see Figure 28.

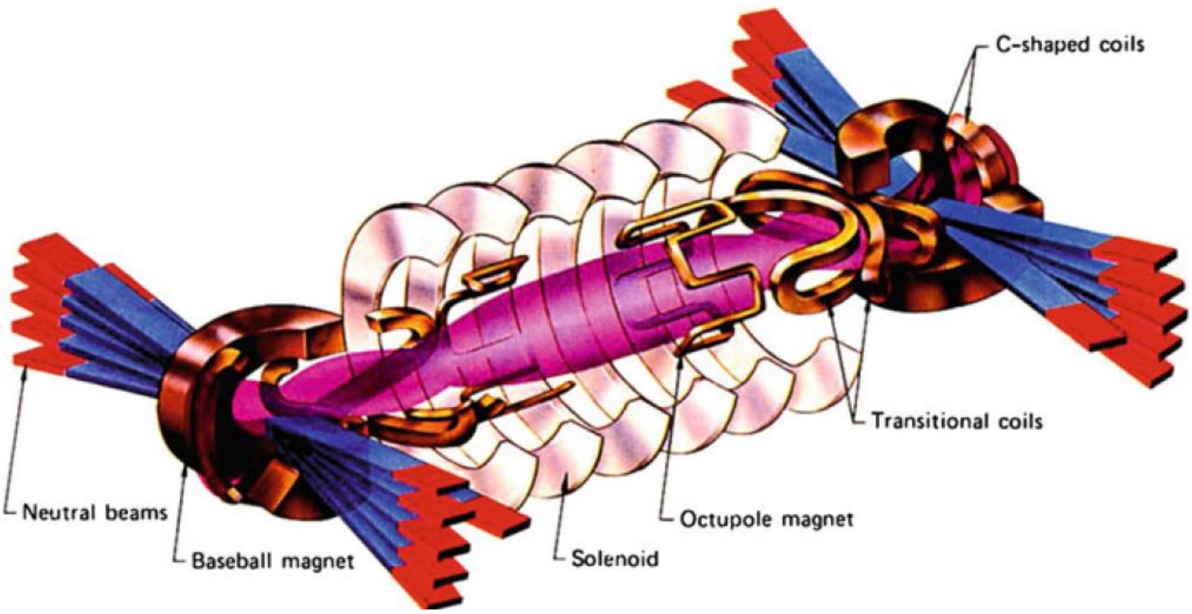

Figure 28 Schematics of Tandem Mirror Experiment, TMX (Dean, 2013, p. 55).

In any mirror the electrons scatter into the loss cone faster than the ions, leaving the mirror cell with a positive electrostatic potential. The tandem mirror makes use of this since the plasma potential, ϕ, in the plug mirrors will be positive compared with that of the central mirror, making the ions trapped in the central cell an thus increasing the confinement time, see Figure 29.

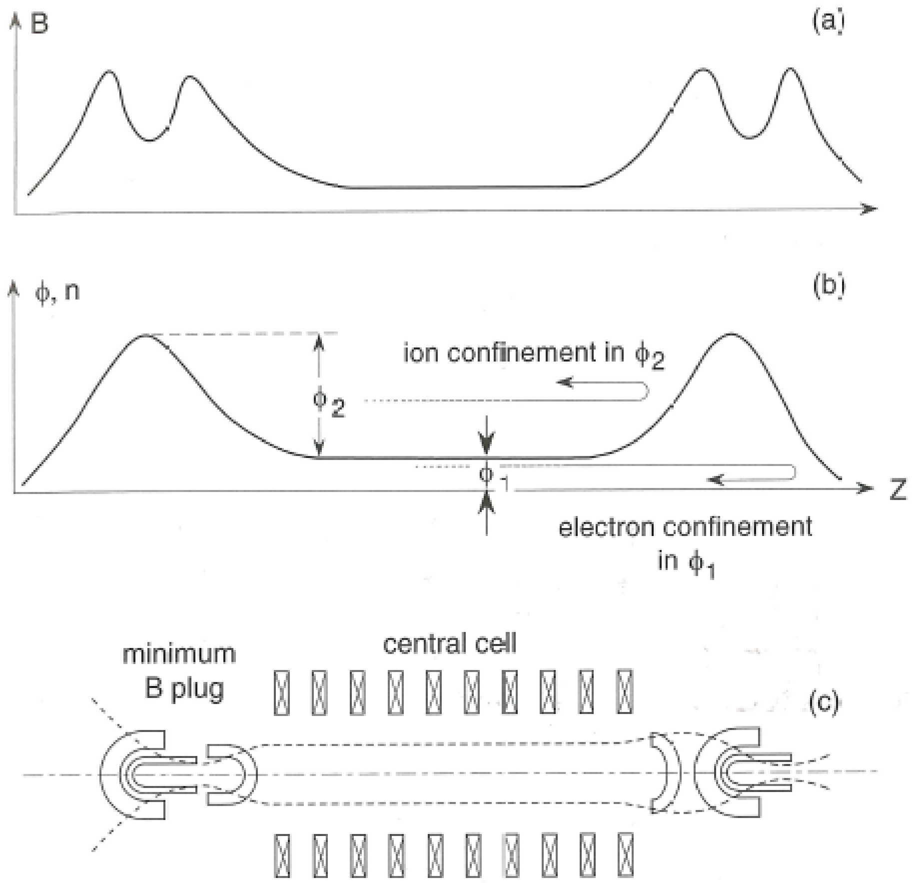

Figure 29 Principle of tandem mirrors. (a) Magnetic field on axis. (b) Plasma density potential on axis. (c) Coils for axisymmetric central cell and end plugs (Braams & Stott, 2002, p. 69).

Several new machines were built to verify the theory of the tandem mirror: TMX in the US, Ambal in Soviet and GAMMA-6 in Japan. The first results came already in a conference in Innsbruck in 1978 where the GAMMA-6 team summarized at the end of their paper that:

> *"These experimental results show an improvement of plasma confinement and suggest an increase of Q value."* (International Atomic Energy, 1979, p. 443).

The TMX, Figure 28, had central solenoid coils with baseball coils at each end as plugs. Neutral beams are injected with 13 keV per plug. The mean temperature of the central cell plasma was about 70 eV for both ions and electrons and confinement parameter was $n_e\tau_p \sim 3\times10^{10}cm^{-3}s$. The enhancement in confinement due to the electrostatic potential was approximately 4 (Miyamoto, 2007, pp. 169-170).

In the tandem mirror it was necessary to increase the density in the plug, n_p, in order to increase the plug potential, ϕ_c. This means that the power of the neutral beam injector that goes into the plug must be large. The plug potential is proportional to the electron temperature, T_e, so increasing the electron temperature would also increase the plug potential. If the electrons in the plug can be thermally isolated from the electrons in the central cell, the power input in the plug could be reduced. The solution to this was proposed in 1979 (Baldwin, Logan, & Fowler, 1979) where a thermal barrier is introduced between the central cell and the plug cell, see Figure 30. The dip in the potential formed by the thermal barrier thermally isolates the electrons in the central cell and the electrons in the plug cell.

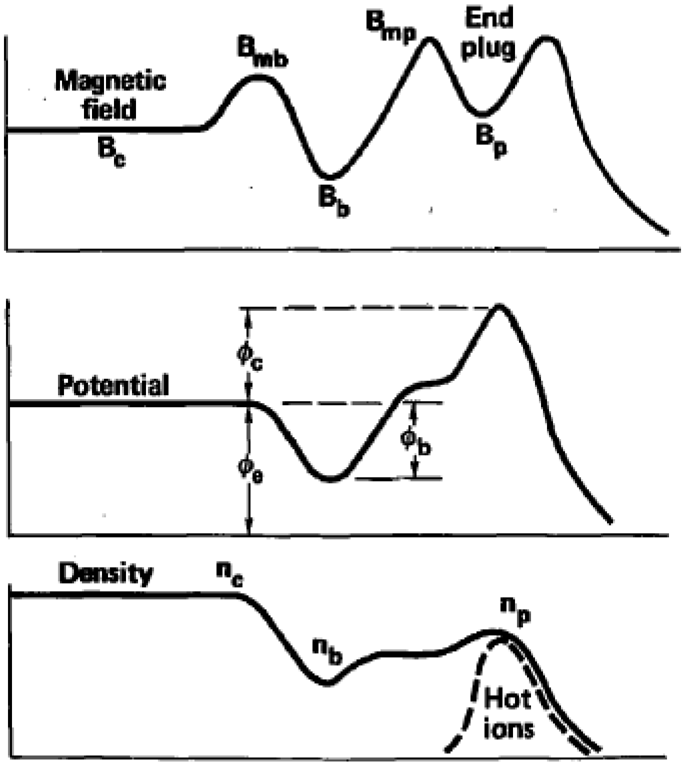

Figure 30 Magnetic field, electrostatic potential and density in a tandem mirror with thermal barrier. c is central mirror, b is thermal barrier, p is plug mirror and m means maximum (Baldwin et al., 1979, p. 41).

The thermal barrier had two advantages: it thermally isolated the electrons and at the same time made the density needed in the plug smaller. Both of these were advantages because it meant that the power needed to make the necessary potential in the plug would be much lower. This would then increase the Q-value since the energy put into the tandem mirror decreases. In the initial paper, Baldwin, Logan and Fowler estimated a Q-value between 10 and 20 for a tandem mirror fusion reactor with thermal barriers.

Tokamak

In the years after the Novosibirsk conference many new tokamaks were built, see Tabell 4. Together with the US, Soviet and Europe, Japan also became an important contributor to the tokamak research. Many of the new devises were relatively small and built to investigate one specific problem or method. Examples are the PDX at Princeton made to investigate poloidal divertors, the ISX at Oak Ridge investigating impurity problems and the T-5 in Moscow used to experimentally investigate theoretical predictions concerning plasma equilibrium (Braams & Stott, 2002, p. 153). The findings in all the different machines led the way towards the bigger and more expensive devices that was going to be most important in the coming decades. Many of them started planning, and some operating, in the late 1970`s, but they will not be covered until the 1980`s and forward section.

Location	Name	Operation	R_0 (m)	a (m)	B_t (T)	I (kA)
USA						
MIT [6]	Alcator A	1972–78	0.54	0.10	9.0	300
	Alcator C	1978–86	0.64	0.16	13	800
Princeton	ST	1970–74	1.09	0.14	4.4	130
	ATC [7]	1972–76	0.88	0.11	2.0	50
			0.38	0.17	4.7	118
	PLT [8]	1975–86	1.32	0.42	3.4	700
	PDX [9]	1978–83	1.4	0.4	2.4	500
Oak Ridge [10]	ORMAK	1971–76	0.8	0.23	2.6	230
	ISX-B	1977–84	0.93	0.27	1.6	250
GA [11], San Diego	Doublet II	1972–74	0.63	0.08	0.8–0.95	90–210
	Doublet IIA	1974–79	0.66	0.15	0.76	<350
	Doublet-III	1978–85	1.45	0.45	2.6	0.61
Europe						
Fontenay [12]	TFR	1973–78	0.98	0.20	6.0	400
	TFR-600	1978–86	0.98	0.22	6.0	600
Grenoble [13]	WEGA	1975–78	0.72	0.15	2.2	80
	Petula-B	1974–86	0.72	0.18	2.7	230
Garching	Pulsator [14]	1973	0.7	0.12	2.7	125
Frascati	TTF	1973	0.3	0.04	1.0	5
	FT [15]	1978	0.83	0.20	10.0	800
Culham	CLEO	1972–73	0.90	0.18	2.0	120
	Tosca [16]	1974	0.3	0.1	1.0	20
	DITE [17]	1975–89	1.17	0.27	2.7	260
Japan						
Naka [18]	JFT-2	1972–82	0.9	0.25	1.8	170
	JFT-2a/DIVA	1974–79	0.60	0.10	2.0	70
Nagoya	JIPP-T2	1976	0.91	0.17	3.0	160
Tokyo	TNT-A	1976	0.4	0.09	0.42	20
USSR						
Moscow [19]	T-4	1974–78	0.90	0.16	5	300
	T-7	1979–82	1.22	0.35	2.4	390
	T-5	1962–70	0.625	0.15	1.2	60
	T-6	1970–74	0.7	0.25	1.5	220
	T-11	1975–84	0.7	0.25	1.0	170
	T-9	1972–77	0.36	0.07	1.0	
	T-12	1978–85	0.36	0.08	1.0	30
	T-10	1975–date	1.5	0.39	5.0	
	TO-1	1972–78	0.6	0.13	1.5	70
St Petersburg [20]	TUMAN-2	1971–75	0.4	0.08	0.4–1.2	8
	TUMAN-2A	1977–85	0.4	0.08	0.7–1.5	12
	FT-1	1972–2002	0.62	0.15	0.7–1.2	30–50

Tabell 4 Tokamaks built in the first decade after Novosibirsk (Braams & Stott, 2002, pp. 154-155).

The PLT began operation in 1974, and by 1978 it was running on full operation. By the summer this year they exceeded the ideal ignition value of 5 keV of Lawson, an achievement viewed as a milestone in fusion physics (Dean, 2013, p. 55). As with the ZETA in Britain, the newspapers used great headings on the results. The Washington Post had:

> *" U.S. Makes Major Advance in Nuclear Fusion"*

at the top of the front page, and followed up with:

> *" "It is the first time we've produced the actual conditions of a fusion reactor in a scale-model device," said Dr. Stephen O. Dean, director of the Department of Energy's magnetic confinement systems division. "This is the biggest thing that has ever happened in fusion research," he said."* (Peterson, 1978, p. 1).

The article continues with a more detailed description where the scientists explains that much is still needed before this could be used in a commercial power plant, ending with that this is probably 20 to 30 years into the future.

The tokamaks continued to give better results and get closer to the parameters needed in a power plant. During his summary at the IAEA conference in Brussel in 1980, Rabinovich used a graph showing the increase in ion temperature, Figure 31, to show this progression from the start in the 1950`s and up to 1980.

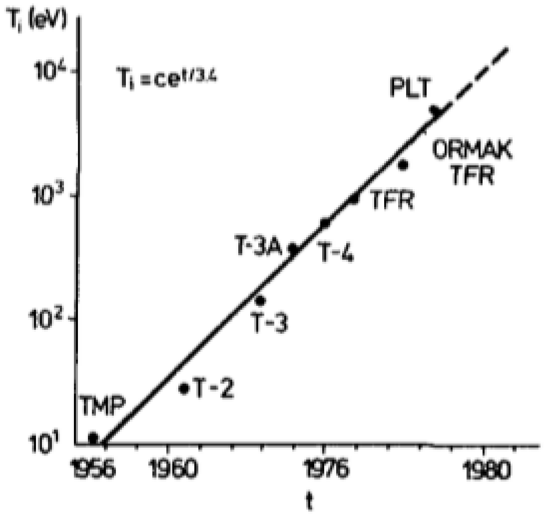

Figure 31 Increase in ion temperature for tokamaks in the years up to 1980 (International Atomic Energy, 1981, p. 770).

Sawteeth

The sawtooth instability differs from most of the other instabilities by the fact it does not end in a discharge of the plasma. The plasma core rather quickly recovers and the sawtooth repeats regularly. It was first reported in 1974 by Goeler, and soon after it was observed in most tokamaks. The complete cycle of the sawtooth can be described in three parts. First the ramp phase, a quiescent period where the plasma density and temperature increases linearly with time in the plasma core, see Figure 32 for a figure of all the phases. Secondly, the precursor oscillation phase, where a helical magnetic perturbation grows and it becomes a growing oscillatory behavior in the electron temperature and density. The third is the collapse phase where the electron temperature and density falls rapidly to lower values. The period for one complete cycle increases with the size of the tokamak (Hastie, 1997, p. 179).

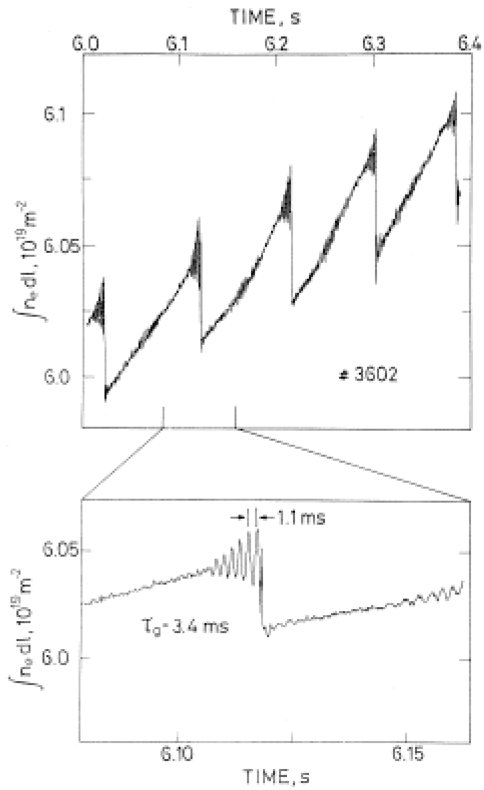

Figure 32 Sawtooth instability showing the ramp, precursor and collapse phases (from the tokamak JET) (Hastie, 1997, p. 180).

Inertial confinement fusion

Lasers

The crucial concepts of laser fusion was declassified by the AEC in 1972 (Emmett, Nuckolls, & Wood, 1974, p. 24).

Laser research increased significantly during the 1970`s, and DOE was planning to demonstrate fusion break even condition before 1985 (Yonas, 1978, p. 42). In the US, the funding for inertial confinement fusion was almost equal to that of magnetic confinement fusion during the mid-1970`s, before it once again decreased heavily at the end of the decade, see Figure 33.

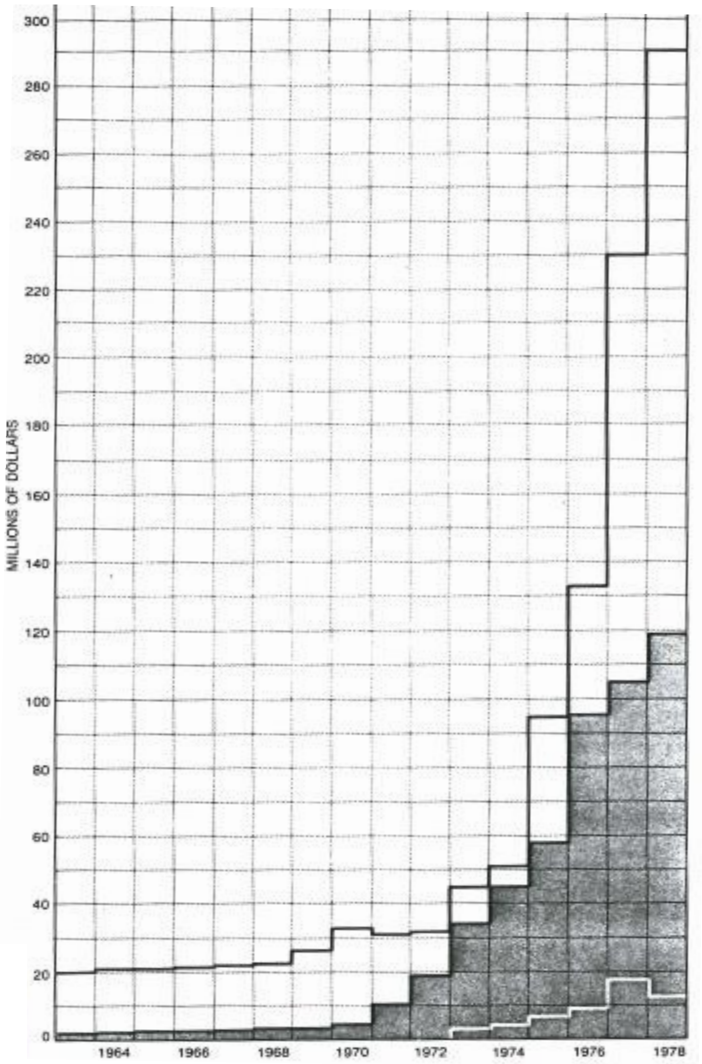

Figure 33 Annual funding levels for different kinds of fusion power research in the US. Black line is magnetic confinement, grey is inertial confinement and the white line is the portion of inertial confinement budget devoted to particle beam research (Yonas, 1978, p. 45)

The main research during the 1970`s was investigating the fuel pellet. Initially it was believed that the pellet could be solid and homogenous, but it turned out that the energy required to heat all the fuel was much higher than first believed. This led to the hot-spot concept, where the pellet consists of a shell filled with D-T gas. The shell has a material with high proton number on the outside and an inner region with solid D-T, see Figure 34.

The energy from the driver (laser) must be applied as symmetrical as possible, and it leads to ionization and vaporization of the shell immediately in a process called ablation. The inner parts, the D-T fuel, moves inwards with increasing velocity to conserve momentum. The result is a higher temperature in the inner part of the fuel compared to the outer parts. The fusion will then begin in the central area and a thermonuclear front propagates rapidly outward into the main fuel region.

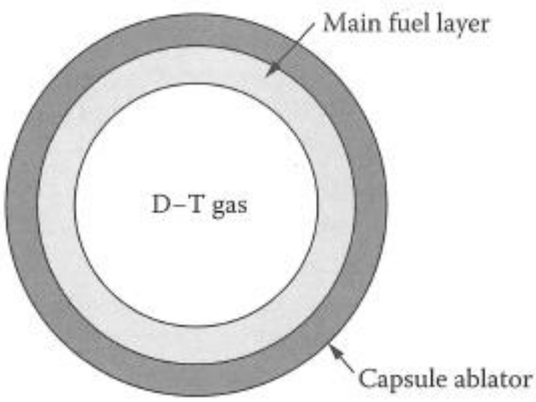

Figure 34 Schematic picture of target capsule (Pfalzner, 2006, p. 14).

The radius R of the capsule mainly determines the confinement time for the capsule. As the inward motion is driven by a shockwave which moves approximately at the speed of sound, c_s, the confinement time, t_c, can be estimated by the ratio of capsule radius over sound speed

$$t_c \simeq \frac{R}{c_s} \ . \tag{32}$$

Putting inn typical capsule radiuses in the equation gives confinement times in the order of $10^{-9}s$.

The Lawson criteria is often re-expressed for the inertial confinement fusion, using the capsule radius and the fuel density, ρ. For a freely expanding sphere, the disassembly time, τ, can be roughly estimated by

$$\tau \simeq \frac{R}{4c_s} \ . \tag{33}$$

The number density, n, is related to fuel density and mass, m, by

$$n = \frac{\rho}{m} \ , \tag{34}$$

and relating it to Lawson criteria, $n\tau$, gives

$$n\tau \simeq \frac{nR}{4c_s} = \frac{\rho R}{4c_s m} \ . \tag{35}$$

To get an efficient burn the $n\tau$ must be above the Lawson criteria, and using $n\tau \simeq 2\times10^{15}\frac{s}{cm^3}$ gives the estimate $\rho R \simeq 3\frac{gram}{cm^2}$ (Pfalzner, 2006, pp. 13-17).

Particle beams

The particle-beam approach of igniting the pellet came as a result of the low efficiency and high cost for lasers. During the 1960`s the US Department of Defense and AEC supported electron-beam accelerator research for military purposes, but it was not until 1973 that AEC supported the research for fusion using particle-beams (Yonas, 1978, p. 44). In the Soviet they started looking at electron beams in 1968, but it was not until 1971 they came up with the first proposal to use it as a fusion ignitor. One of the main areas of research during the 1970`s was to find a good design for the fusion pellet, as it was with the laser approach.

1980`s-present

The 1970`s were promising for the prospect of a fusion power plant. The funding had never been greater, many of the instabilities were being suppressed and the plans were aiming for a demonstration power plant by the end of the century.

In the US the 1980`s started promising as well. On October 7th 1980 president Carter signed the Magnetic Fusion Engineering Act, which was supposed:

> *"To provide for an accelerated program of research and development of magnetic fusion energy technologies leading to the construction and successful operation of a magnetic fusion demonstration plant in the United States before the end of the twentieth century to be carried out by the Department of Energy" (S. United, 1980, p. 1)*

To achieve this goal, the funding levels would have to be doubled within the next seven years to maintain the US as the world leader in magnetic fusion. The act followed up on the plan from 1976 and wanted a broad fusion approach with research on many different types of machines. Unfortunately, the Act was never put into action. Carter lost the presidential election in 1981 and the new president, Reagan, was not as positive towards fusion. The funding was cut every year and did not even follow the Logic II from 1976, see Figure 35 (Dean, 2013, pp. 84-85).

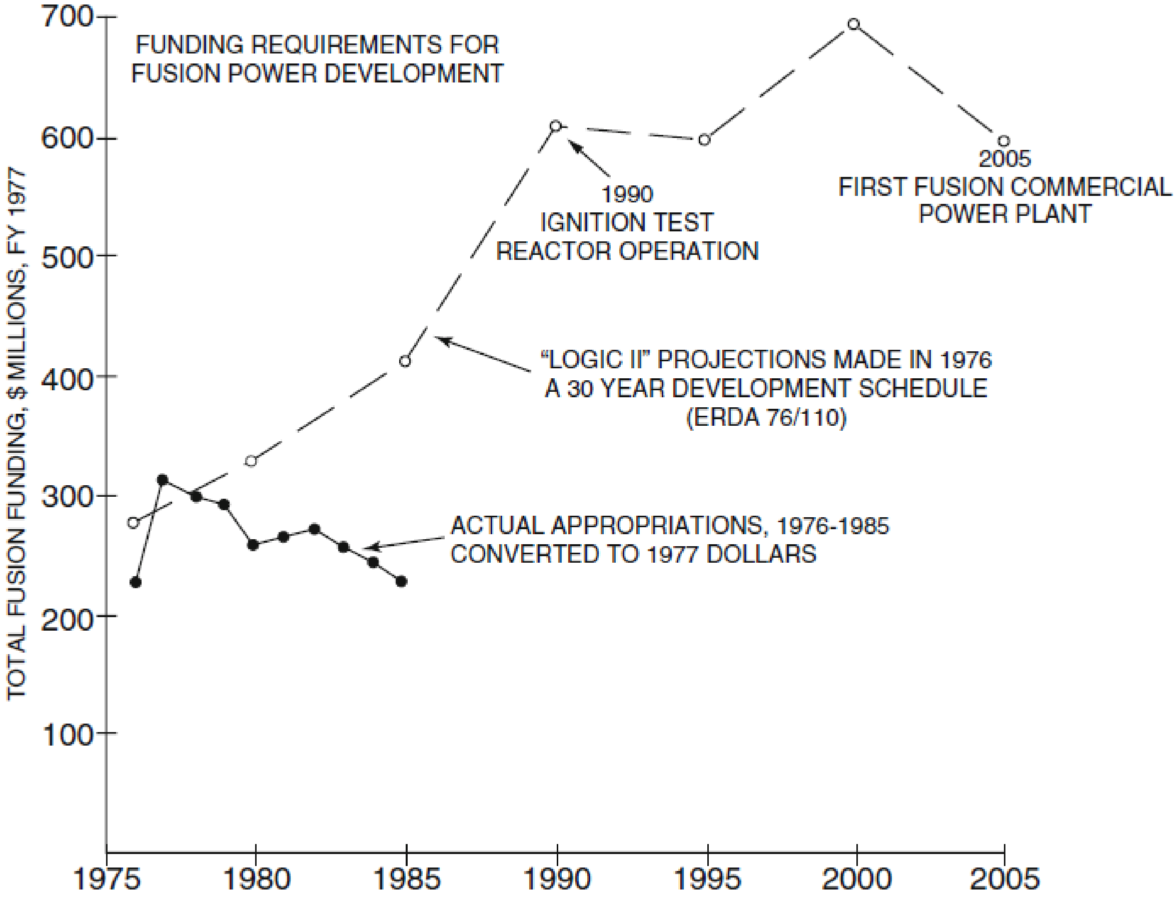

Figure 35 Fusion budget history 1975-1985. Upper curve shows funding required under the 1976 plan for Logic II. Lower curve shows actual fusion funding (Dean, 2013, p. 85).

The fundings were cut to a degree where they became less than Logic I, called "fusion never", from 1976, and several important machines were either stopped or canceled in the planning phase. The focus turned from a plan where the US would research and build a working fusion power plant on their own, to an international approach were the planning and funding would be distributed between several countries. Both the machines and the costs got bigger, and the US, Europe, Soviet and Japan worked more closely together to be able to afford and carry on with fusion research.

Magnetic confinement fusion

Magnetic mirror

The invention of the tandem mirror design was a great step forward for the mirror research, but it still had problems reaching even theoretical Q-values great enough for a fusion power plant. During the start of the 1980`s, several machines were built to investigate different aspects of the tandem mirror and the thermal barrier, see Figure 36. But even though they could show increasing results for one thing (confinement time, density, temperature, suppressing instabilities etc.) using the new principles of tandem mirror and plasma heating, one machine had not managed to demonstrate a complete set of operating conditions that the tandem mirror theoretically promised (Braams & Stott, 2002, p. 74).

			Central cell			Plugs		
Location	Name	Year	L (m)	B_0 (T)	Heating	B_{max}	Heating	Anchors
Tsukuba	GAMMA-10	1983	6	0.5	NBI/ICRH	3	NBI/ECRH	4-poles inside plugs
Livermore	TMX-U	1982	8	0.3	NBI/ICRH	2	NBI/ECRH	4-poles as plug
MIT	TARA	1984	5	0.2	ICRH	3	NBI/ECRH	4-poles outside plugs
Nagoya	RFC-XX-M		3	0.35	ICRH	2.1	ICRH	Cusps as plugs
Madison	Phaedrus-B	1987	3	0.6	ICRH	1	ICRH	4-poles inside plugs
Kyoto	HIEI		1.6	0.18	ICRH	0.8	ICRH	None
Novosibirsk	AMBAL-M	1962	13	0.45		6	NBI/ECRH	Cusps
Livermore	MFTF-B	1985	20	1.0	ICRH/ICRH	12	ICRH/ECRH	

Figure 36 The major tandem mirror machines built in the 1980`s (Braams & Stott, 2002, p. 71).

The device that should put all the different new inventions into operation and show whether the tandem mirror would work as a future power plant or not was the MFTF-B. It started as a bigger version of the 2XIIB in the 1970`s, but when the thermal barriers were invented it went through design upgrades before ending up as the final version. It was a big machine, the central cell was 54 meters long and 10 meters in diameter (Booth, 1987, p. 153). The goal was to come close to a value of D-D burn that corresponded to meeting Lawson criteria for D-T burn, so the hope was a Q value close to one. The actual expected parameters are given in Tabell 5.

Parameters	Value
Central-cell density, n_c	4.8×10^{13} cm^{-3}
Central-cell ion temperature, T_{ic}	15 keV
Central-cell electron temperature, T_{ec}	9 keV
Central-cell axial field, B_c	1-1.6 T
Effective central-cell length, L_c	13 m
Plasma radius/ion cyclotron radius, r_c/ρ_i	13
Confinement lifetime, τ	1 s
Density-lifetime parameter, $n\tau$	5×10^{13} cm$^{-3}\cdot$s
Axicell high-field peak, B_2	12 T
Axicell low-field peak, B_1	6 T
Yin-yang anchor central field, B_A	1 T
Yin-yang anchor mirror field, B_M	3 T
Plasma energy gain for D-T equivalent (depending on mode), Q	0.2-0.6
Central-cell plasma pressure, β_c	0.4-0.7

Tabell 5 Performance parameters expected for MFTF-B (Karpenko, 1983, p. 15).

The MFTF-B was, in many ways, a make it or break it-machine for the mirror program in the US. It was expensive and big, and the tokamak was showing much better results and had greater theoretical gain as a power plant. However, if MFTF-B would give the desired results and show that the tandem mirror design worked as hoped, then the mirror machines would still be an alternative as a fusion power plant.

The MFTF-B was planned and mostly built during the increase in fusion funding after the oil embargo and the fusion energy act of 1980. But as the 1980`s progressed, the funding was drastically cut and the US fusion program had to do some hard prioritizing. As the tokamak were the most promising one, and the new TFTR also was very expensive, the MFTF-B (together with almost all of the mirror fusion program in the US) were shut down. This happened on 21st February 1986, the same day as the machine was finished after nine years of construction and a prize of $ 372 million (Booth, 1987).

This was also a hard strike on the entire mirror fusion community in the world. The research continued in Soviet and Japan, but now more as a possible neutron source for other fusion concepts or as pure research on plasma behavior.

Tokamak

After the inflation in tokamaks during the decade after Novosibirsk, the information found in all the small devices was vast. However, they had all concentrated on one or a few new methods, and as with the mirror machines, the tokamaks needed to be built bigger to see whether all the improvements found separately in different machines could be put together and make one coming close to ignition. This resulted in three great machines, JET in Europe, TFTR in the US, and JT-60 in Japan.

Joint European Torus – JET

The planning of JET started already in 1973, with the first design proposal ready in 1975. It was an international collaboration of 16 countries in Europe. One of the main objectives was to investigate if scaling laws found in the smaller machines could be extrapolated to a big design. Therefore the size of JET had to be much bigger than the ones already operating, see Figure 37.

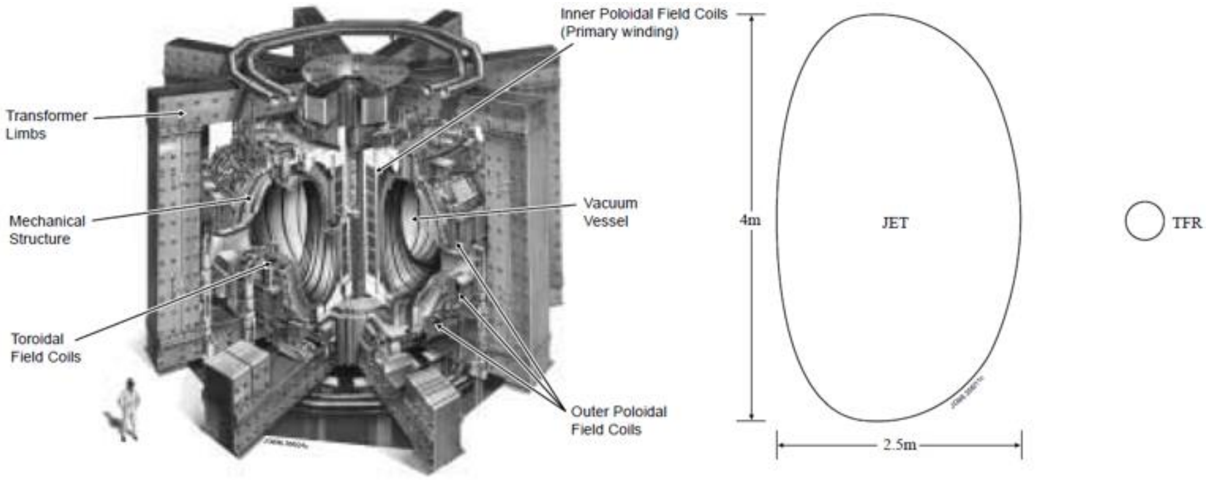

Figure 37 To the left a drawing of the JET design. To the right a comparison between JET and TFR (J Wesson, 1999, pp. 23,29).

JET has a torus radius of 3.1 m and a vacuum vessel 3.96 m high and 2.4 m wide. It can contain up to 100 m^3 plasma, so the upscaling from the tokamaks of the 1970`s was massive.

The original objective of the research was to:

> *" obtain and study a plasma in conditions and dimensions approaching those needed in a thermonuclear reactor. These studies will be aimed at defining the parameters, the size and the working conditions of a Tokamak reactor. The realisation of this objective involves four main areas of work:*
>
> *(i) the scaling of plasma behaviour as parameters approach the reactor range,*
>
> *(ii) the plasma-wall interaction in these conditions,*
>
> *(iii) the study of plasma heating and*
>
> *(iv) the study of α particle production, confinement and consequent plasma heating." (Commission of the European Communities, 1976, p. 25).*

The machine was completed in 1983, and the operation began on 25th June at the site in Culham, UK. After an initial phase of testing and slow increase in the input parameters, JET produced an ion temperature of 20 keV in 1988. This was achieved with the help of both ion cyclotron and neutral beam heating giving a total power of 35 MW, and when using only ohmic heating the confinement time reached 1 second.

In 1991, Jet started up a preliminary tritium experiment with only 10 % tritium (a 50-50 mix of deuterium and tritium is the best for achieving a highest possible fusion output). It gave a 1.7 MW of peak fusion power and a total energy output of 2 MJ. The machine went through a series of upgrades, which included divertor and new diagnostic equipment, before it in 1997 started up with full deuterium-tritium experiments.

The new upgrade, and a mix with 50% of both deuterium and tritium, gave a record high fusion power of 16.1 MW, see Figure 38. The input power was 22.3 MW of NBI and 3.1 MW of ICRF, leading to a Q value of 0.62. The high fusion performance lasted approximately 1.5 s. At a different plasma shot JET could maintain approximately 4 MW of fusion power for 3.5 s giving the largest total fusion energy of 22 MJ, but this had a Q value of only 0.18 (John Wesson, 2011, pp. 686-687).

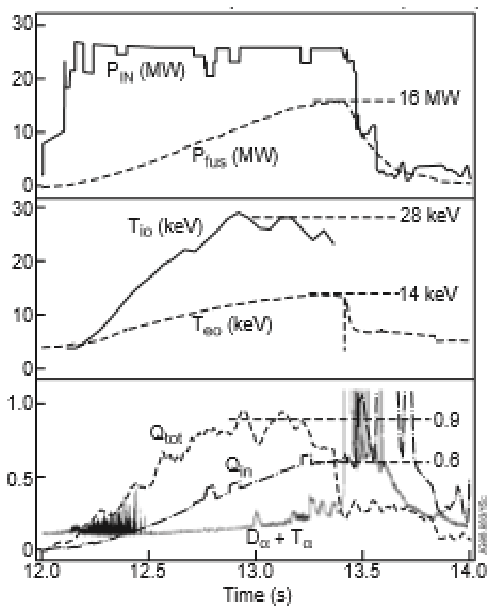

Figure 38 Input and fusion power, central ion and electron temperature and Q value (Q_{in} is the usual Q, Q_{tot} is a theoretical value if the plasma conditions could be obtained in steady state) from the record shot of 16.1 MW (Team, 1999, p. 9).

In 1999, the collaboration of countries that made JET stopped, but the machine continues to do experiments even today under the management of the European Fusion Development Agreement (EFDA). Now it is mainly doing experiments to prepare for ITER, the next great tokamak, and after having made several upgrades to become similar to ITER it is once again ready for Deuterium-Tritium experiments in 2017 (Litaudon & Horton, 2014, pp. 12-13). These will hopefully give important insight in what we can expect from ITER when it is functional and ready for operation.

The original objectives were made for the JET collaboration that ended in 1999, and JET had in several ways fulfilled the objectives. The scaling laws of plasma behavior was uncertain before JET since the previous machines were much smaller. With the help of JET and several other new machines the scaling laws have become better and more reliable than those they operated with earlier. The plasma-wall interaction was quite soon after operation started changed to divertor research. Initially JET had limiters, a solid surface that defines the edge of the plasma, to protect the wall from instabilities and disruptions. The problem with the limiter is that impurities leaving its surface as neutrals will penetrate the plasma and become ionized impurities. The solution to this problem was the divertor, which is more complex and expensive to use, but at the same time takes the problem to a place more remote of the plasma so the impurities are easier to control. The research of wall interaction in JET also solved the problem with beryllium being toxic. Beryllium has the lowest possible nuclear charge of the different alternatives for the wall panels facing the plasma and it has a high melting point. ITER`s first wall panels will be made of mainly beryllium and it will have a divertor similar to the one in JET, so the plasma-wall interaction objective can be seen as fulfilled.

The study of plasma heating was at a minimum when the planning of JET started in 1973. Most tokamaks only used ohmic heating, and the research in neutral beam injection and ion cyclotron heating was at a starting point with only a few hundred kilowatts of power injected. The heating in JET has been very successful and the available power has been increased over the years, see Figure 39.

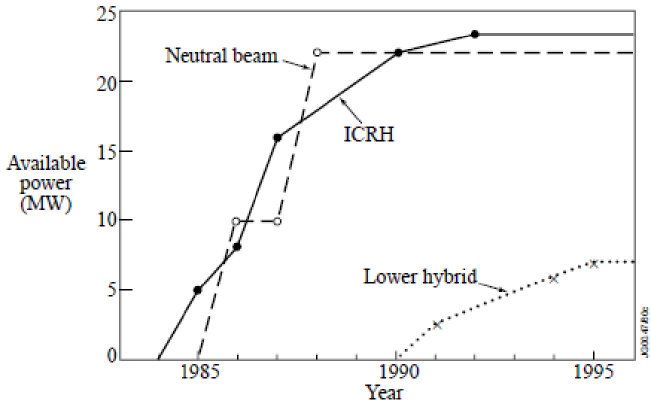

Figure 39 The available heating systems in JET. Both NBI and ICRH reached powers of over 20 MW (J Wesson, 1999, p. 167).

The study of α particle production, confinement and consequent plasma heating was maybe the objective scientists had the least knowledge of when JET started. One knew that α particles would be produced when the fusion started, the third equation in Tabell 1, but it was not known whether the particles would deposit its energy in the plasma by collision or generate an instability so that they get lost to the wall. The research done with JET indicates the α particles are confined for at least a long enough period to transfer the energy to the plasma, and there were not found any indications of instabilities created by them.

Tokamak Fusion Test Reactor – TFTR

TFTR was originally conceived in 1974, with the design report ready in 1976. Like JET, it was much bigger than the previous tokamaks, with the major radius of the plasma being 2.6 m. It used both NBI and ICRF to heat the plasma in addition to the ohmic heating, see Figure 40. The objectives were to achieve temperatures and densities relevant for a fusion reactor and to achieve approximately energy break even, meaning $Q \sim 1$ (Princeton Univ, 1976, pp. 2-3). The first operation of the machine started in December 1982.

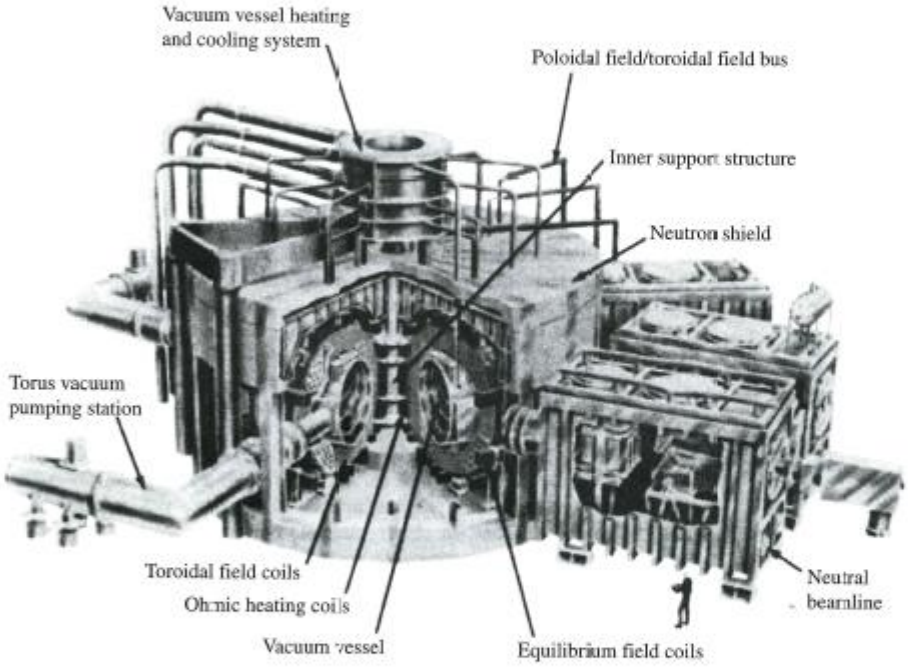

Figure 40 Overview of the most important parts of the TFTR machine (John Wesson, 2011, p. 637).

In 1993 TFTR started experiments using a fuel with 50:50 mixtures of deuterium and tritium, as the first of the big tokamaks. On December 9, the first shots were fired, producing a maximum of 3 MW of fusion power. Several journalists were invited to the happening, and the next days the results reached the front pages of several newspapers, see Figure 41. The New York Times had a big article about the day and possibilities for fusion in general. The newspaper described the scene as:

Figure 41 TFTR`s world record burst of fusion power on December 9 1993 made headlines in several newspapers (Greenwald, 2013b, p. 1).

> *"The atmosphere in the huge control room here was reminiscent of one at the National Aeronautics and Space Administration before a major space launching. As occasional snags in the countdown for the main fusion shot developed, scores of reporters, officials and scientists watched the tense proceedings from the windows of a balcony surrounding the control room. … Among the video displays was one showing the number of neutrons blasting away from each shot, measuring power output. For the final, full-power shot of the night, the*

screen was almost blanked out with a pattern of white snow -- clear evidence that a powerful fusion reaction had occurred." (Browne, 1993).

The greatest result was made in 1994 with a shot that generated a peak fusion power of 10.7 MW. This was a record for the time, but the input power was 39.5 MW of NIB so the Q value was only 0.27, see Figure 42.

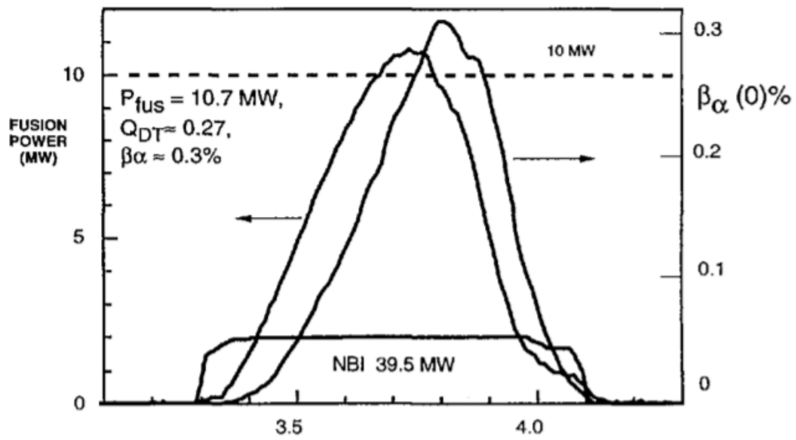

Figure 42 The record shot giving 10.7 MW of fusion power in 1994 (International Atomic Energy, 1997, p. 22).

TFTR was taken out of operation in late 1997. The machine had managed to achieve temperatures and densities relevant for a fusion reactor, and had shown α particle heating in the deuterium-tritium plasma experiments. The Q value were not achieved as high as hoped, peaking at a bit below 0.3 for several of the experiment.

JT-60 / JT-60U / JT-60SA

The JT-60 was the next generation tokamak in Japan. Construction started in 1975, and the first ohmic heating experiments started in April 1985. With a major radius of 3.0 m it was as big as the other tokamaks, see Figure 43. To heat the plasma JT-60 used both NBI, LHRF and ICRF. The machine was only designed to use deuterium as a fuel, not tritium as JET and TFTR.

The main objectives for JT-60 were to investigate plasma physics, heating and fusion technology at breakeven plasma conditions. Since the machine only used deuterium, the Q value would be calculated into what an equivalent result using deuterium-tritium fuel would give, called Q_{DT}.

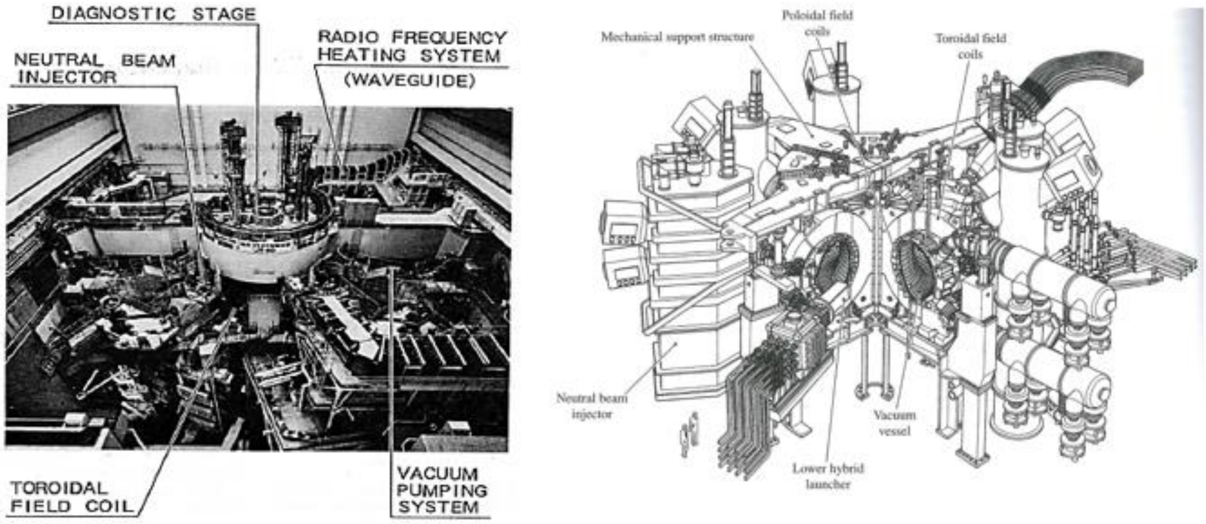

Figure 43 JT-60 (left) (Yoshikawa, 1989, p. 198) and JT-60U (right) (John Wesson, 2011, p. 690).

Since JT-60 were made only for deuterium experiments, the machine needed to have some other features that would be unique compared to JET and TFTR. One important difference is that JT-60 were built with a divertor and not only a limiter. The divertor was considered a better solution to get impurities out of the plasma, this leading to reduced temperature loss. The length that the machine could maintain the plasma was also longer than JET and TFTR, making it possible to better study stable plasma and obtain equilibrium.

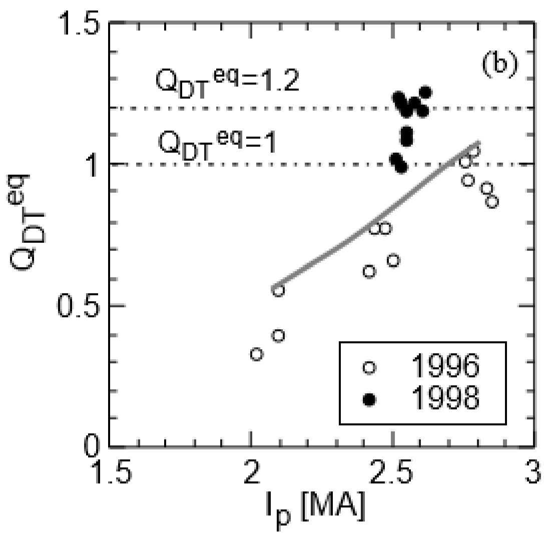

Figure 44 Q_{DT} as a function of plasma current, showing that there were several shots achieving a Q_{DT} value higher than 1.2 (Fujita et al., 1999, p. 6).

During the first years of operation, JT-60 showed great results in the temperature, density and confinement time. The parameters were already reaching the areas defined in the initial objectives, and the divertor showed good impurity control (Yoshikawa, 1989, p. 203). However, it turned out that the machine was unable to work in the newly discovered H-mode, which gave an increase in confinement time. To fix this, it was redesigned and upgraded from 1988 to 1991, see Figure 43, and renamed to JT-60U. When the operation restarted, the transition to H-mode was possible and the machine gave several great results, especially after a new divertor was installed in

1997. The highest achieved value for $n_D(0)T_i(o)\tau_E$, the central deuterium density, central ion temperature and energy confinement time, was $8.59\times10^{20}m^{-3}keVs$. This corresponds to Q_{DT}=1.25, a value more than satisfying the objectives for the machine, see Figure 44 (Fujita et al., 1999).

Other tokamaks

Several other tokamaks were built in the years after 1980, but none was as big and important as the three described above. However, many of them provided important insight into areas that needed to be resolved before building a working reactor.

The H-mode

During a NBI experiment on the German ASDEX tokamak in 1982, the researchers observed a rapid transition to higher confinement. The increased confinement, giving a higher β -value (H-mode), was typically twice as big as the previous low confinement, with low β -value (L-mode), see Figure 45 (Wagner et al., 1982, p. 1409). The transition only occurs after a given power threshold, which increases with plasma size, density and toroidal magnetic field. The increasing confinement is first apparent at the edge of the plasma, and even though the confinement is seen across the whole plasma, the major improvement is at the edge.

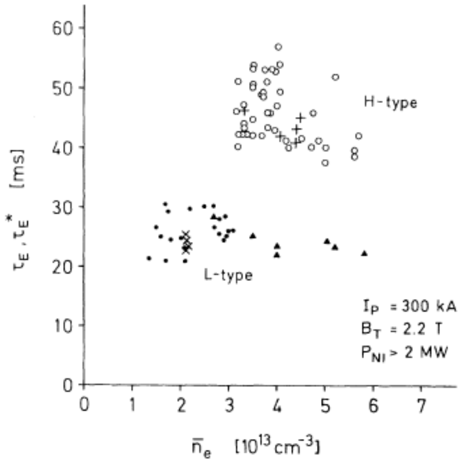

Figure 45 Energy confinement time against average density for H-mode and L-mode, showing the improved confinement time in H-mode (Wagner et al., 1982, p. 1410).

ELMs

With the discovery of the new H-mode came an observation of a new instability, the Edge Localized Mode, ELM. As the name suggests the instability occurs at the edge of the plasma, and it is similar to the sawtooth since it is repetitive and leaves the plasma in a state of lower temperature and density, see Figure 46. The ELMs are commonly divided into three categories.

Type I ELMs are giant ELMs. They occur as single outbursts of plasma from the edge. The heat loss pulse that is sent out from the plasma is problematic because it leads to a very high heat load on the divertor.

Type II ELMs does not lead to the high heat pulse from Type 1, and it does not give a severe loss to general confinement, but it only occurs in a limited range of operational spaces.

Type III ELMs are small but continuous, and generally leads to a severe loss of confinement due to the high occurring frequency (John Wesson, 2011, pp. 416-417).

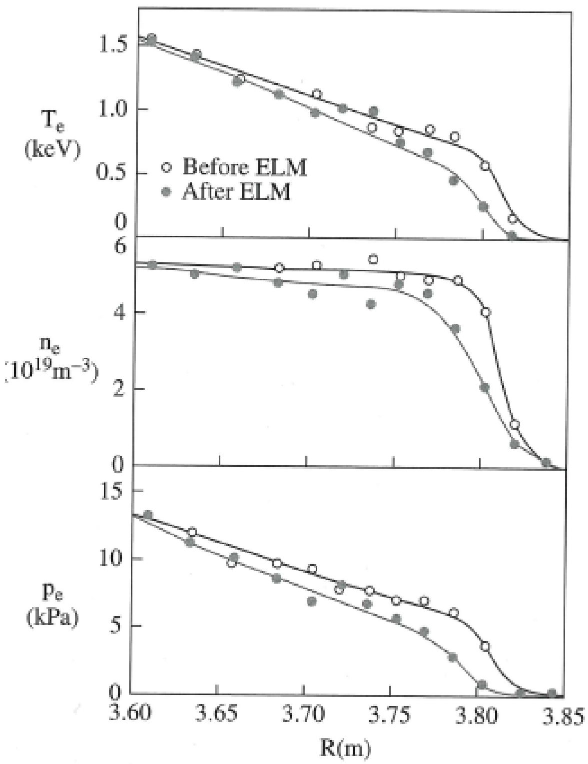

Figure 46 Showing the fall in electron temperature, density and pressure resulting from an ELM in JET (John Wesson, 2011, p. 416).

Even if the ELMs are problematic for several reasons listed above, they can also be beneficial for reaching a fusion power plant. Impurities builds up in the plasma through plasma-wall and divertor interactions, and the impurities cools the plasma, preventing fusion from happening. ELMs have turned out to be effective at expelling impurities from the edge of the plasma, given high enough frequency on the ELMs (Kirk, 2016, p. 10).

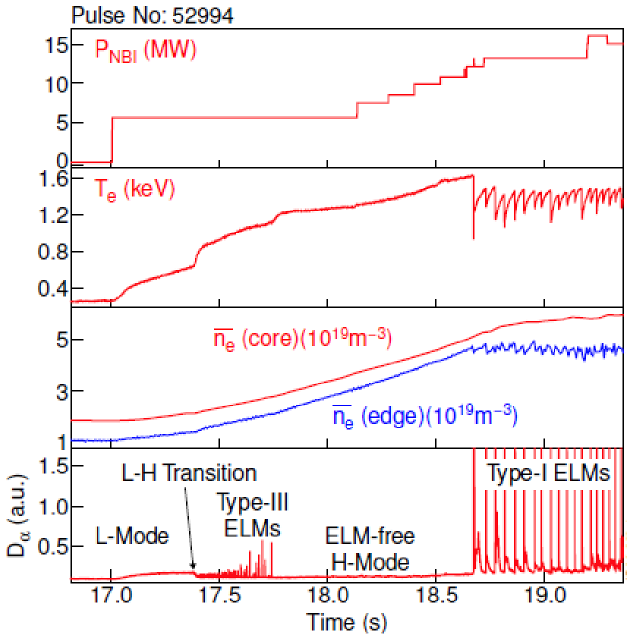

Figure 47 A JET fusion shot showing ELMs type I and III. top plot shows applied NIB power, second plot the electron energy at the plasma edge, third plot the electron densities for the plasma core and edge and bottom plot the D_α -emission in the inner divertor (Pérez & Forschungszentrum, 2004, p. 22).

A typical fusion H-mode shot from JET is shown in Figure 47. The D_α - emission at the bottom plot is from the inner divertor and is a way to measure ELMs. At the beginning the plasma is in L-mode, but after 17.39 s there is a step-like increase in edge temperature and rate of increase of plasma density indicating a transition to H-mode. After the transition there is a phase of high frequency spikes in the D_α -signal, this is the Type III ELMs. Then there comes an ELM-free H-mode where the temperature and density increases. Without an increase in heating power, the plasma would collapse. However, if the power is increased, there occurs several quite regular spikes in the D_α -signal. This is the Type I ELMs.

The setup with using H-mode confinement and keep it in a quasi-steady state by means of repetitive ELMs are often referred to as ELMy H-mode (Pérez & Forschungszentrum, 2004, pp. 20-22).

Alpha-particle heating

Once the fusion has started, the neutrons mainly carry the energy released away, and since they are neutral, they do not interact with the plasma on the way. However, the charged alpha particle carries one fifth of the energy. The 3.5 MeV energy is transferred to the plasma through collisions. It is important that this energy is deposited in the plasma as an additional heating source, in order to minimize the power needed from outside sources.

Wendelstein 7-X

With the great results from the tokamak T-3 presented at Novosibirsk in 1968, most of the toroidal confinement studies turned towards the tokamak setup. However, the stellarator studies were never completely stopped, and during the decades several new devices were built and operated. They were all relatively small with much of the same problems with instabilities as the tokamaks, but the main advantage of the stellarator remained. Since the magnetic field is made solely by external coils, the plasma can theoretically be confined for as long as needed, unlike the tokamak where part of the field is set up by inducing a current in the plasma. So in the tokamak the confinement will only hold in a time period given by the length the magnetic field can be made by the current in the plasma.

The research were carried out in several countries, with Germany, the US and Japan as main contributors. With the increasing computing power of the supercomputers, it became possible to first define the shape of the magnetic field to contain the plasma, and then have the computer design a set of magnets to produce the field. The first machine to use such a method was the Wendelstein 7-AS, located near Munich, Germany. It was in operation from 1988 to 2002 and broke all of the stellarator records for a machine of its size (Clery, 2015). Several new stellarators have been built since, the largest is the LHD in Japan, but the next big step to see whether the stellarator concept of Spitzer can be used as a fusion power plant is Wendelstein 7-X, see Figure 48.

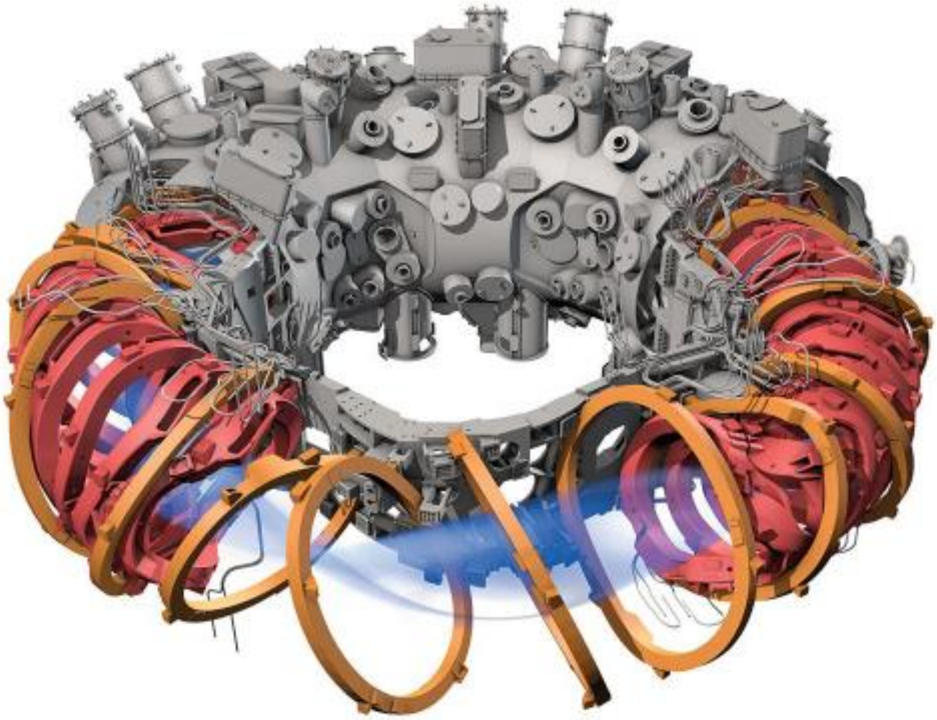

Figure 48 Schematics of the Wendelstein 7-X. The blue shows the plasma, the red rings are superconducting coils making the magnetic cage for the plasma and the orange rings are superconducting coils making fine adjustments to the magnetic field (Clery, 2015).

Wendelstein 7-X consists of 50 non-planar superconducting magnet coils, each about 3.5 m high and weighing about 6 ton. The coils are placed in an extremely complex arrangement that looks quite random, but is actually optimized to millimeter precision by supercomputers to make the desired magnetic field. The first results from the machine actually shows that the topology of the measured magnetic field has a deviation from the desired one that are less than one part in 100 000 (T. Sunn Pedersen et al., 2016).

In addition, the machine has 20 planar superconducting coils to do fine adjustments to the magnetic field. To keep the temperature sufficiently low for the superconducting coils to work, supercritical helium circulates through the voids between the strands that makes the coil.

To heat the plasma the machine uses mainly ECRH, with additional ICRH and NBI heating. To extract impurities the stellarator has a divertor. It should be able to confine the plasma for up to 30 minutes at a time (Wanner & Team, 2002).

Wendelstein 7-X was planned to start up in 2006, at a cost of €550 million. However, budget shortfall and problems with construction and cooling of the coils delayed the construction. The machine was close to be cancelled, but got additional funding with a cost ceiling of €1.06 Billion, and the first helium plasma was produced and heated to about 1 million˚C on December 10, 2015 (Hambling & Webb, 2016, p. 36).

The first operation phase of Wendelstein 7-X lasted for 10 weeks, with hydrogen plasmas created from 5th February 2016. It ended at 10th March after more than 2000 plasma discharges (Sieber & Henze, 2016, p. 59). The results are still preliminary, but they show that the process mainly work as the theory predicts. However, several important features have not been added to the machine yet, so only plasma pulse lengths up to 500 ms with electron temperature at 80 keV and ion temperature at 2 keV has been achieved, while the longest plasma pulse, with lower temperature, is 6 s. The machine is currently in shutdown, to upgrade and install parts for the next operation, scheduled spring 2017.

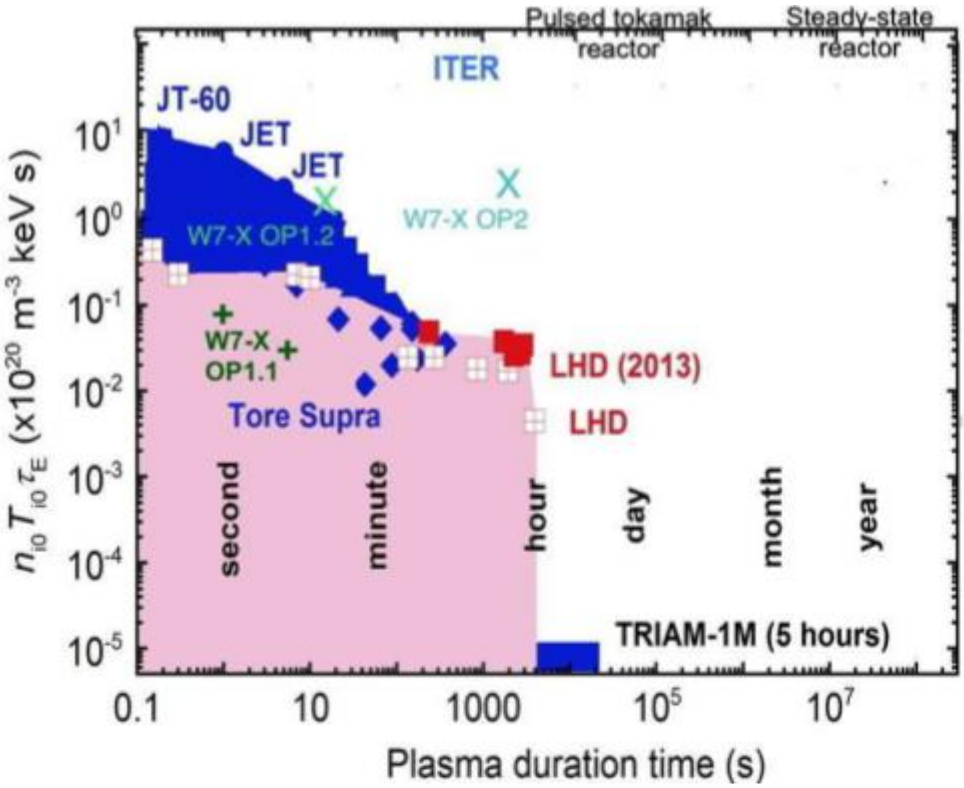

Figure 49 The triple product plotted versus pulse length. W7-X OP1.1 is the results from the finished operation phase, while OP1.2 and OP2 are expected values for the coming operations phases (T.S Pedersen et al., 2017, p. 9)

In the years to come a divertor, surfaces that can take a much greater heat load and greater heating power will be installed in the machine. This will make it possible to greatly increase the plasma pulse length and the fusion power from Wendelstein 7-X (T.S Pedersen et al., 2017, p. 2).

ITER

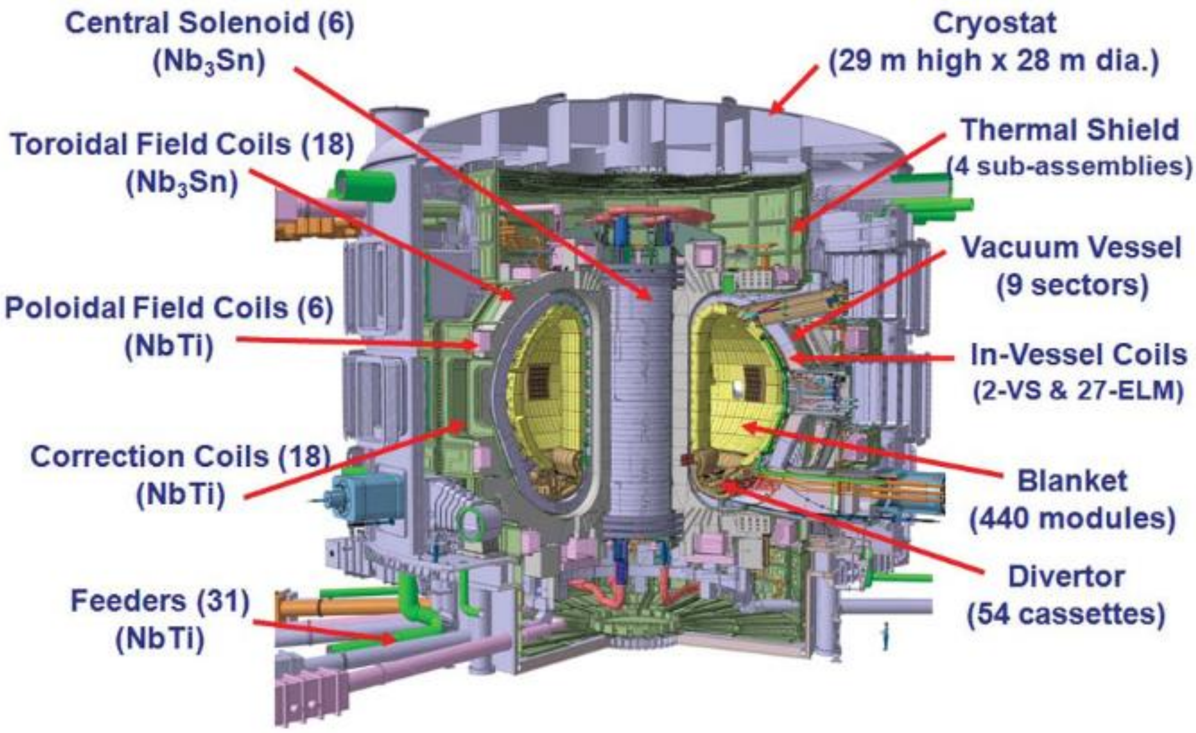

Figure 50 Schematic diagram of some of the component in ITER. Pay attention to the human in the lower right corner to as a reference for the size (Authority, 2014).

During the late 1970`s and early 1980`s the international fusion community had been discussing the possibility to collaborate on building the next generation tokamak. The design got the name INTOR and was significantly bigger than JET and aimed for ignition, see Tabell 6. However, the participating countries could not agree on design and purpose for the machine, so INTOR was canceled in the planning phase (Braams & Stott, 2002, p. 249).

The idea of an international collaboration for a great tokamak was lit, and during a meeting between the American and Soviet leaders Reagan and Gorbachov in Geneva in 1985, the idea was once more pursued. The diplomatic relationship between the two countries was bad during the cold war, and a scientific collaboration for the benefit of all mankind was seen as a possible way of communication between them. The initiative in 1985 led to the signing of the ITER agreement between the US, Soviet, the European community and Japan in 1987. ITER was initially both an acronym for the International Thermonuclear Experimental Reactor and a Latin word meaning "the way".

The greatness of the project, and the number of participants, led to a project that was divided into phases. The first phase, the Conceptual Design Activities (CDA), started in 1988. The goal of this phase was to come up with the general parameters for ITER, with realistic design for both the science and the budget, as well as a preliminary schedule and cost estimate.

At the end of the CDA phase, a conceptual design of ITER was ready. The aim was to reach ignition, and therefor the size, current and heating power had to be much greater than previous tokamaks, see Tabell 6. The cost of the machine was estimated at $4.9 billion, with an additional $270 million per year of operation. The construction was scheduled to take approximately seven years when the final plan was ready, giving an estimated commissioning in 2004. Some of the greatest scientific goals were to achieve the first controlled, ignited burn in a deuterium-tritium plasma, and to approach steady-state operation with Q > 5 (International Atomic Energy, 1991, pp. 22,85).

	INTOR 1986	ITER CDA 1990	ITER 1998	ITER 2001
Plasma current, I (MA)	8	22	21	15 (17)*
Major radius, R_0 (m)	5.0	6.0	8.14	6.2
Plasma radius, a (m)	1.2	2.15	2.8	2.0
Elongation, κ	1.6	2.0	~1.6	1.7–1.85
Toroidal field on axis, B_t (T)	5.5	4.85	5.68	5.3
Safety factor, q	1.8	3.1	3.0	3.0
Average $\langle n_e \rangle$ (10^{20} m^{-3})	1.6	1.23	0.98	1.0
Average $\langle T_i \rangle$ (keV)	10	10	12.9	8.1
Average $\langle \beta \rangle$ (%)	4.9	4.2	2.2–3.0	2.5
Confinement time, τ_E (s)	1.4	3.6	5.9	3.7
Energy multiplication, Q	Ignition	Ignition	Ignition	10
Nominal fusion power, P_{th} (MW)	600	1000	1500	500 (700)
Neutron wall load (MW m^{-2})	1.3	1.0	1.0	0.57 (0.8)

Tabell 6 A comparison of INTOR and the three different designs made for ITER (Braams & Stott, 2002, p. 251).

The CDA was followed by the six-year Engineering Design Activities (EDA) phase. Now the detailed plan for design and parameters had to be made, to prepare for the next construction phase. The new report, then called "Final Design Report", was ready in 1998. The research from other tokamaks in the period made it necessary to increase the size of the machine, see Tabell 6, and this increased the cost. The new estimate was at $5.2-5.7 billion (International Atomic Energy Agency, 1998, p. 606). Even though the increase in cost was not very high, it became a problem to get all of the participants to sign for the new construction phase. The US was the most negative towards ITER, and funding cuts in their national budget forced them to pull out of the project after the EDA phase.

The reduced number of participants in the project made it necessary to reduce the cost by modifying the design. The main objective of ITER is to demonstrate the technical and scientific feasibility of fusion power, and one important thing to manage is to operate with the alpha particles as the dominant source of plasma heating. It turned out that to achieve this it is required that Q ≥ 10. This became the boundary condition for the reduced size, see Tabell 6 (Braams & Stott, 2002, pp. 258-259).

ITER final design- EDA-FEAT

The final design of ITER was presented in 2001. By reducing the size, the cost had nearly been cut in half from the 1998 estimate, and was now at about $2.7 billion (International Atomic Energy, 2001, p. 71). The biggest scientific cutback was going from ignition to at least achieving Q = 10.

The main objective for ITER was still to demonstrate the scientific and technological feasibility of fusion power for peaceful purposes. The performance specifications for the machine was not as high as the 1998 EDA, but still the increase from JET and other tokamaks was massive. A summary of the performance required of ITER when operating was given in the summary of the ITER final design report:

"· to achieve extended burn in inductively-driven deuterium-tritium plasma operation with Q

≥ 10 (Q is the ratio of fusion power to auxiliary power injected into the plasma), not precluding ignition, with an inductive burn duration between 300 and 500 s;

· to aim at demonstrating steady state operation using non-inductive current drive with Q ≥ 5;

In terms of engineering performance and testing, the design should

· demonstrate availability and integration of essential fusion technologies,

· test components for a future reactor, and

· test tritium breeding module concepts; with a 14 MeV-neutron power load on the first wall ≥ 0.5 MW/m^2 and fluence ≥ 0.3 MWa/m^2.

In addition, the device should:

· use as far as possible technical solutions and concepts developed and qualified during the previous period of the EDA, and

· cost about 50% of the direct capital cost of the 1998 ITER Design." (International Atomic Energy, 2001, p. 10).

As the performance specifications shows, the design of ITER do not preclude ignition, even though the scaling from smaller tokamaks estimates Q = 10. The duration of this burn is also much longer than the duration of the maximum Q value of earlier tokamaks, with ITER aiming for 300-500 seconds while JET only held it for a few seconds. This can also be seen in the expected fusion power for ITER. While the record currently held by JET is at 16.1 MW, it is expected that ITER gain about 500 MW of fusion power in the high performance scenario.

Additionally, the aim of demonstrating steady state with Q ≥ 5 is a great step forward compared to the earlier machines where steady state have only been achieved at low Q values. The plan is to maintain the plasma for as long as 3000 seconds with a high enough fusion power to get Q ≥ 5.

The engineering performance and testing requirements goes on preparing for the demonstration fusion power plant that should follow ITER. To include all the new research and technology in one machine, and demonstrate that they function as predicted, is important for the continuous development of the fusion community. One important concept that has to be in place for a power plant is tritium breeding. The tritium can be bred from lithium as shown in Tabell 1, and requires a neutron from the fusion reaction. The neutron will have high speed when reaching the wall where the lithium is placed in the blanket, and an important task for ITER will be to investigate how this can be done without the neutrons damaging the rest of the tokamak.

After a discussion on location and funding, several new participants joined ITER. The US decided to rejoin, together with China, Korea and India. The seven participants, often called the parties, reached an agreement at a meeting in Moscow in 2005 about location and funding. They decided that the construction site should be located in Europe, at the Cadarache facility in Saint-Paul-Lèz-Durance, in France. The host party should fund about 45 % of the construction and the other parties about 9 % each (Matsuda & Tobita, 2013, p. 331).

The construction of ITER started formally in October 2007 when the site was prepared for construction. The assembly of the actual tokamak did not start until 2014. After several delays, the plan is now to have the machine ready for first plasma in 2025 and first D-T plasma in 2035, but there is fear these dates could also be pushed further into the future. The costs have also increased much since the estimated $ 2.5 billion in 2001. Since the parts for ITER are built separately by the different parties as part of the payment of the machine, it is hard to set an exact price for the tokamak so far. However, according to estimates, the price has at least tripled, if not more. This could be due to the fact that the initial price was given without the final design being completely finished. In addition, the numbers were given mainly to be able to divide the work between the parties, not as real-world manufacturing expenses, see Figure 51. As an ITER official said during an interview:

> *"“Of course, bureaucrats wanted to get ITER approved, and politicians were happy to turn a blind eye,” an official told me. “If they would have said, ‘Oh, instead of five billion this will be fifteen billion,’ then probably nobody would have wanted to build it.”" (Khatchadourian, 2014).*

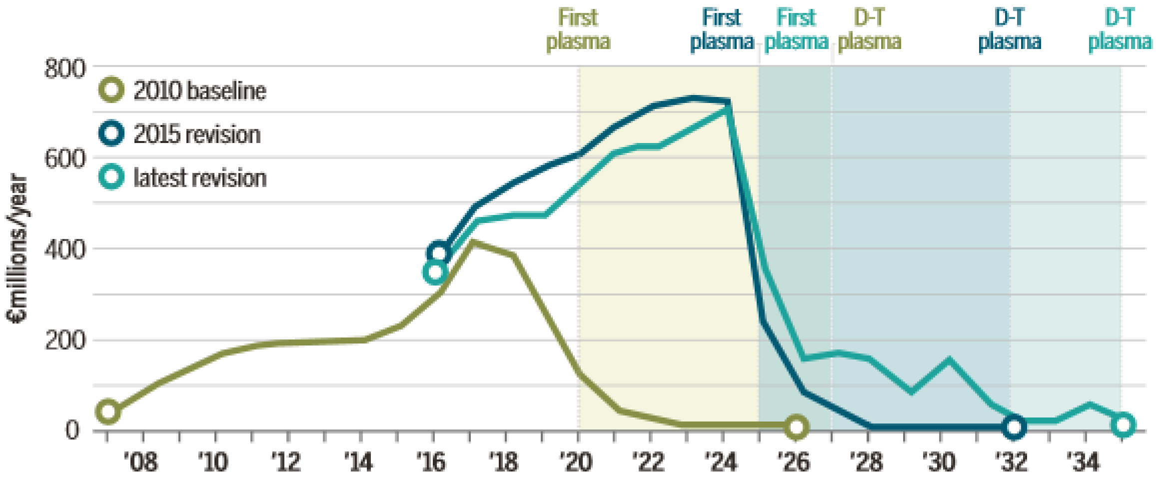

Figure 51 Schedule and yearly funding for ITER showing the 2010 plan together with the revised plans (Clery & Cho, 2016, p. 637).

Operation

ITER is an experimental machine that is built with the possibility to run several different settings and scenarios. The two main scenarios when entering the deuterium-tritium phase will be the inductive and the steady state.

The inductive operation will use a high inductively driven current and heating power to reach the highest possible fusion power, the aim is to produce 500 MW. In this scenario, the Q value should be at least 10 and the inductive current limits the burn time to about 400 s. Figure 52 shows a calculated time evolution for plasma parameters in an inductive operation. The current reaches 15 MA and the fusion power 400 MW. The external heating power is 34 MW neutral beam heating and 7 MW of RF heating, giving Q = 10 in this calculated scenario.

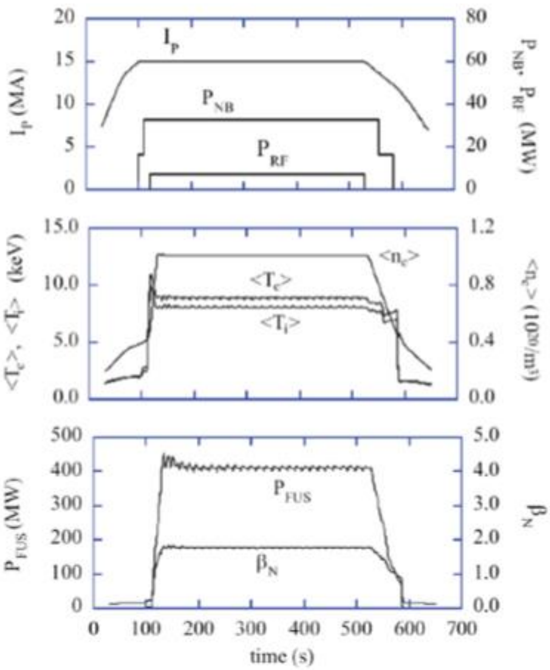

Figure 52 Calculated time evolution of ITER plasma parameters for an inductive operation. At top Plasma current and neutral beam and RF power, in the middle electron density and electron and ion temperatures and at the bottom fusion power normalized beta (How & Reichle, 2009, p. 156).

The inductive operation will be based on the type I ELMy-H mode, where repetitive ELMs with high energy heat losses obtain a quasi-steady state. This requires the divertor to be able to handle the great power dissipation. Because a too great heat load will destroy the plasma facing components, ITER can control the ELMs in two ways. The first is to inject pellets at a high enough frequency, $f_{pellet} > 20-40Hz$, to trigger the ELM with small enough energy, $\Delta W_{ELM} < 1MJ$, instead of waiting for an ELM with greater energy, but smaller frequency. The second is to perturb the magnetic field near the edge. Coils placed in the vacuum vessel have been shown to increase the frequency of the ELMs leading to a decreased ELM energy loss (How & Reichle, 2009, pp. 199-200).

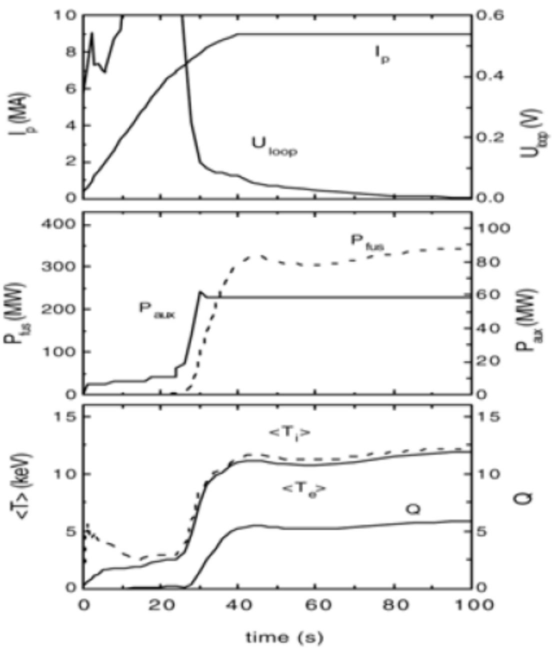

Figure 53 Calculated time evolution of ITER plasma parameters, showing a steady-state scenario with weak negative shear. At top plasma current , in the middle fusion power and added power and in the bottom Q value and electron and ion temperatures (How & Reichle, 2009, p. 163).

The steady state operation will consist of several different configurations to investigate how to achieve the best possible confinement of the plasma. Plasma current will be much smaller and not inductive, making the burn time considerably longer, the aim is at 3000 s. It will be important to investigate different types of magnetic shear in the machine, and to determine which setup is the best for achieving the longest possible burn time. Figure 53 shows a calculated time evolution of plasma parameters in a steady-state scenario with weak negative shear.

Inertial confinement fusion

The inertial confinement depends a lot on the laser, and how much energy the laser can deliver to the pellet. Therefore, the fusion research was limited to computer models and target design for several years. When the US decided to make a laser with much more power than any other in the world, the fusion community viewed it as a possibility to experimentally investigate the theories and models made.

The laser facility got the name National Ignition Facility (NIF) and has a 1.8 MJ laser with 192 laser beams to distribute the energy as evenly as possible. It is located at Lawrence Livermore National Laboratory, and can in addition be used for astrophysical experiments, military purposes and other basic studies (Hogan, 1998, p. 1).

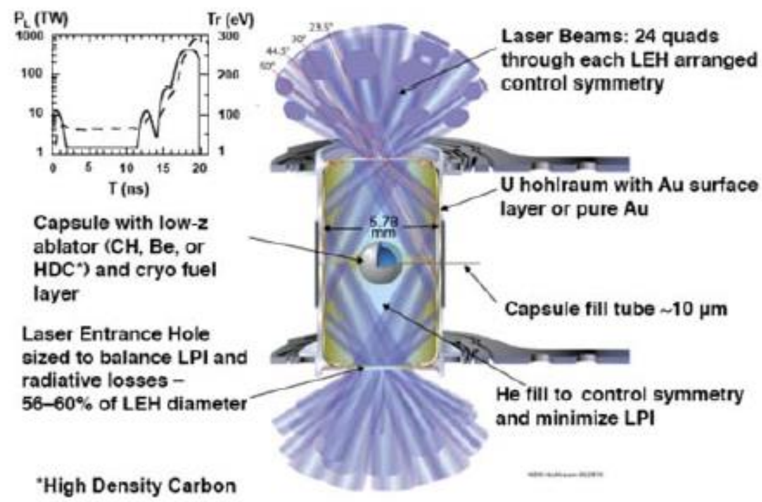

Figure 54 The indirect drive of NIF. Also shown is the laser pulse shape and hohlraum radiation temperature reached (Lindl, Landen, Edwards, & Moses, 2014).

The models predicted results close to break even, or even ignition, with the increased energy available in NIF, so the goal of the first three years of research (2010-2012), called the National Ignition Campaign (NIC), was to achieve ignition (Lindl et al., 2014, p. 2). NIF uses a method called indirect drive to heat the capsule, see Figure 54. Here the laser heats up a cylinder, called a hohlraum, which sends out x-rays that heats the capsule. This method gives a more uniform heating than the direct drive, where the laser is used directly at the capsule, but it has a lower efficiency since energy is lost in the transfer from laser to x-rays.

When the NIC ended in 2012, most of the goals for the campaign had been met, with the exception of reaching ignition. The laser had deposited the expected energy and the hohlraum had been heated enough to give the required x-rays, but the density and pressure in the hot spot were much lower than what the models predicted, see Tabell 7. The difference between calculated and achieved values were mainly expected to come from instabilities being more dominant than first thought.

	1-D	2-D	3-D	expt.
DSR (%)	4.41	4.60	4.24	4.3±0.2
T_{ion} (keV)	2.90	2.91	3.29	3.4±0.16
HS density (g/cc)	75	82	71	44±8
HS pres. (Gbar)	195	202	175	102±20
Neutrons (no alpha deposition)	22.9	17.8	16.2	4.8 (est)
Neutrons (10^{14}) (13-15 MeV)	39.2	29.8	23.6	5.6±0.2

Tabell 7 Comparison of calculated and measured performance for a DT shot during the NIC, showing that density and temperature in the hot spot were lower in the experiment (Lindl et al., 2014, p. 56).

A way to suppress the instabilities better was found not long after. A method called "high-foot", were the laser pulse is shaped with a higher power at the start and a lower overall duration, increases the density and the pressure in the hot spot. This also makes self-heating by alpha particles more dominant, leading to a much greater fusion power coming from the pellet. This new method gave great results, see Figure 55, and late 2013 the laboratory reported of a shot showing scientific break-even.

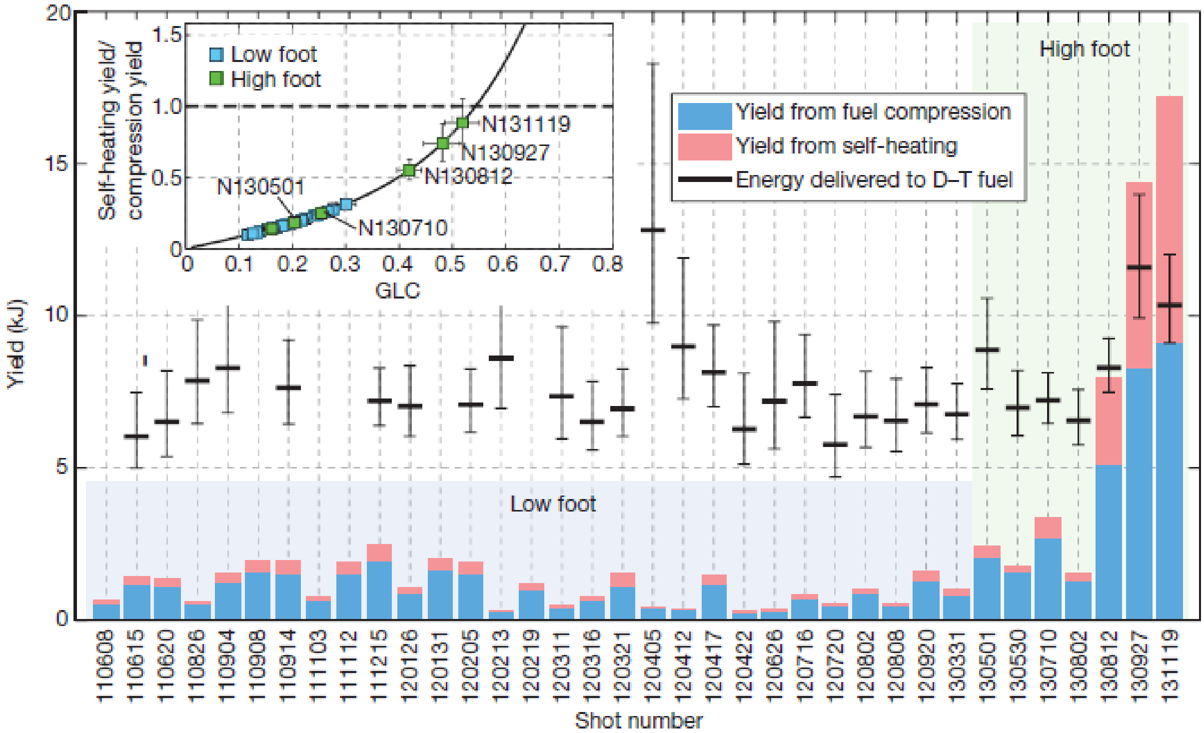

Figure 55 Fusion yield and energy delivered to the fuel plotted versus shot number (so increasing time). The energy delivered are plotted with error bars. From shot 130501 are the high-foot shots, before are low-foot shots (Hurricane et al., 2014, p. 346).

It is important to understand what the meaning of scientific break-even means in this statement. The usual method of measuring this is to look at total energy put in and total energy coming out of the fusion device. However, in the NIF experiment they only take into consideration the energy actually delivered to the pellet as energy into the reaction. Therefore, the energy "lost" in making and shaping the laser pulse, and in making the x-rays in the hohlraum, are not taken into consideration, only the energy delivered of the x-rays to the pellet. When the total energy of the laser, 1.8 MJ, is compared to the energy output, 14 kJ, the Q value ends up at only 0.0078.

This shows that there is still a long road ahead for the inertial confinement fusion. The first goal is to achieve ignition, which was the initial goal of NIF and with the high-foot method they are not far from completing it. The next step however, is bigger, with increasing the energy output, the rate of pellets ignited and collecting the energy in a good way. These are all important and difficult issues that needs to be solved if a power plant based on inertial confinement fusion should be an alternative in the future.

Power plants

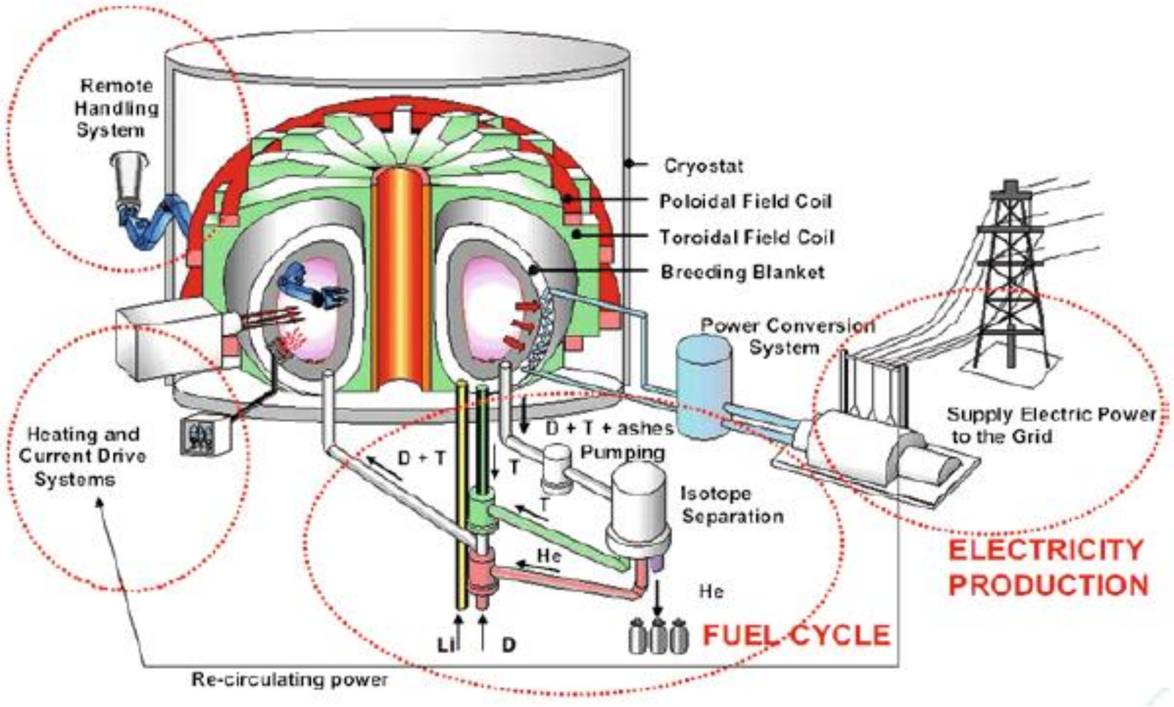

Figure 56 A Schematic of how researchers believes the main parts of a fusion power plant will be (F. F. Chen, 2011, p. 351).

The ultimate goal for fusion research is a commercial fusion power plant. The journey towards this goal has been longer and harder than what most researchers believed when the first attempts towards gaining energy from fusion started. However, every time a new problem has occurred, the fusion community has eventually been able to find a solution to it. Some problems are yet to be resolved, and much of the further research will depend on how ITER behaves compared to how the current models expect it to behave. If ITER can show good results in fusion power and burn time, the next step will be a demonstration power plant. Over the years there has been several proposals for the design and method of extracting the energy, the most favored today are several designs called DEMO.

DEMO

There is no single design plan for the DEMO power plant, but rather several different designs building on assumptions of funding, ITER results and other research done in the near future. However, a general aim for a "fast track programme"-concept has been made. Here, DEMO is the only step between ITER and a commercial power plant (Batistoni et al., 2010, p. 7).

In this concept, DEMO should be able to demonstrate significant net (~several hundred of MW) electric production over an extended period of time (a few months). This will make DEMO a steady state electric source. There is however a discussion on whether the aim should be to also operate the plasma in steady state or if the plasma should be operated in a few hours followed by a downtime of 15-20 minutes. The latter scenario would then require an energy storage for the downtime. Another important aim in this scenario is to integrate breeding blankets in DEMO that can supply the machine with all the tritium it needs for the fusion. The blankets must also absorb as much as possible of the neutron energy, and transport the heat produced from the blanket to the rest of the power plant.

Europe have made a power plant conceptual study (PPCS) where four different power plant models are identified to keep a range of possibilities open. The models, PPCS A-D, all have different designs and solutions to problems, taking into account different levels of funding the next decades, see Figure 57 and Tabell 8. The fusion power scales to $\beta^2 B_T^{\ 4}$, where B_T is the toroidal magnetic field, so fusion power models typically tries to achieve a high β or a high B_T. In the PPCS study the Models A and B focuses on the high B_T approach, while Models C and D focuses on achieving a high β. The fusion power also scales after the major radius cubed, so Model A will have the highest fusion power of the power plants (Costley, 2016, p. 2).

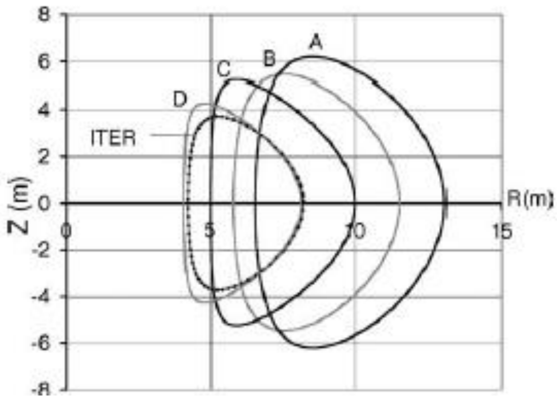

Figure 57 The size and shapes of the different PPCS models, with ITER as a reference (Maisonnier et al., 2005, p. 1175).

Parameter	Model A	Model B	Model C	Model D
Unit size (GW_e)	1.55	1.33	1.45	1.53
Blanket gain	1.18	1.39	1.17	1.17
Fusion power (GW)	5.00	3.60	3.41	2.53
Plant efficiency[a]	0.31	0.36	0.42	0.60
Aspect ratio	3.0	3.0	3.0	3.0
Elongation (95% flux)	1.7	1.7	1.9	1.9
Triangularity (95% flux)	0.25	0.25	0.47	0.47
Major radius (m)	9.55	8.6	7.5	6.1
TF on axis, on the conductor (T)	7.0, 13.1	6.9, 13.2	6.0, 13.6	5.6, 13.4
Plasma current (MA)	30.5	28.0	20.1	14.1
β_N (thermal, total)	2.8, 3.5	2.7, 3.4	3.4, 4.0	3.7, 4.5
Average temperature (keV)	22	20	16	12
Average density (10^{20} m^{-3})	1.1	1.2	1.2	1.4
H_H (IPB98y2)	1.2	1.2	1.3	1.2
Bootstrap fraction	0.45	0.43	0.63	0.76
P_{add} (MW)	246	270	112	71
n/n_G	1.2	1.2	1.5	1.5
Q	20	13.5	30	35
Average neutron wall load	2.2	2.0	2.2	2.4
Divertor peak load (MWm^{-2})	15	10	10	5
Z_{eff}	2.5	2.7	2.2	1.6

[a] The plant efficiency is defined as the ratio between the net electric power output and the fusion power.

Tabell 8 Main parameters of the PPCS models (Maisonnier et al., 2005, p. 1175).

In the US, the leading program for a power plant is called ARIES. There has been several different proposals during the years, changing as new knowledge and technology has been available, and the latest are actually cheaper than the older. This is a result of research showing the possibility to have a greater β (and therefore smaller radius, magnetic field and current), smaller recirculating power fraction (how much power is used to run the plant and therefore not sold) and a greater thermal efficiency. The cost of the electricity coming from the power plant has also halved, from the first to one of the last ARIES design, see Figure 58.

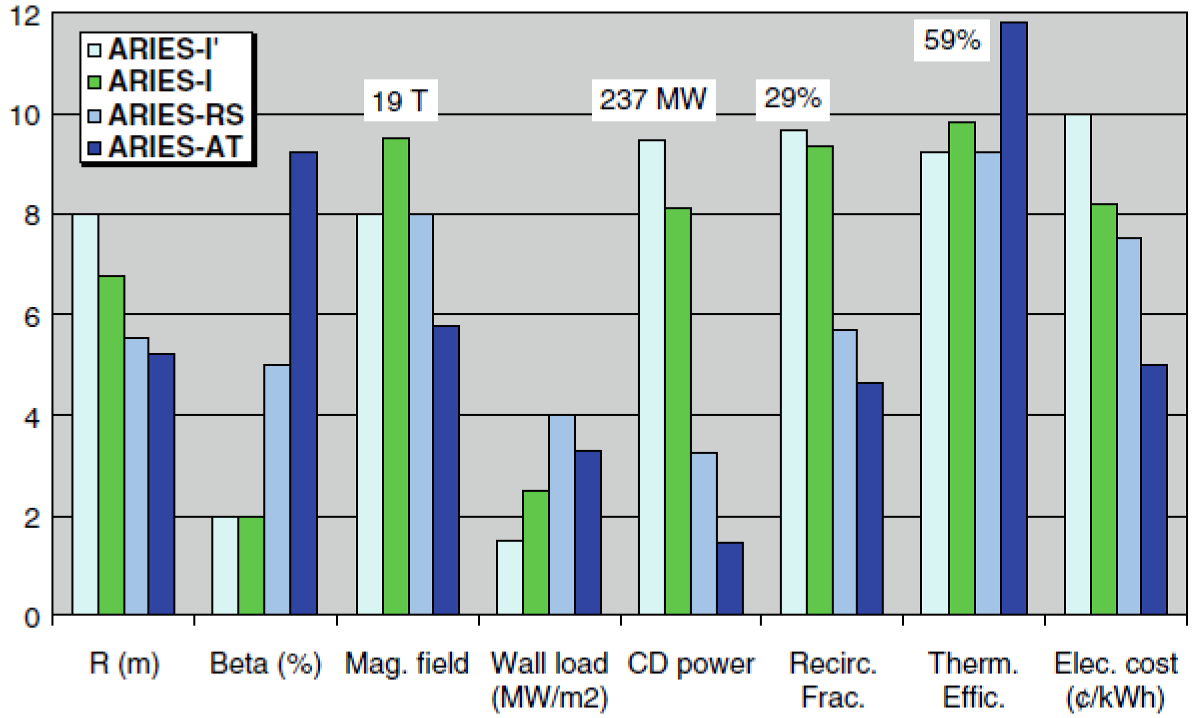

Figure 58 Evolution of ARIES reactor design, going oldest to newest from left to right. Some bars are rescaled to the chart, in these cases the maximum values are shown (F. F. Chen, 2011, p. 352).

The latest study, called ARIES-ACT, is divided into four designs, ACT 1-4. As the PPCS from Europe the different designs plan for different scenarios, here called advanced or conservative physics and technology. The most advanced has high β, small radius and complex materials, while the conservative have the opposite. All the power plants are designed to produce about 2,000 MW of fusion power and 1,000 MW of net electric power, see Tabell 9 (Kessel et al., 2015, p. 4). The plants are planned to run for 50 years, and the radioactive waste is of low-grade radioactivity that needs to be stored for only 100 years.

	ACT1	ACT2	ACT3	ACT4
	Adv phys / adv tech	Con phys / con tech	Adv phys / con tech	Con phys / adv tech
R, m	6.25	9.75	8.50	8.0
a, m	1.56	2.44	2.13	2.0
B_T, T (B_{Tcoil})	6.0 (11.8)	8.75 (14.4)	6.25 (10.6)	9.0 (15.97)
β_N^{th}, β_N^{fast}	4.75, 0.85	2.25, 0.35	4.00, 0.83	2.25, 0.22
P_{fusion}, MW	1813	2637	2538	1848
Q	42.5	25.0	32.5	27.5
P_{elec}	1006.0	989.3	989.8	994.6

Tabell 9 Parameters for the different ARIES-ACT power plant studies. The table is shortened from the full table in the scource (Kessel et al., 2015, pp. 4-5).

Conclusion

The dream of imitating our sun has been alive for more than 60 years, and the need for a new, long lasting and environmentally friendly energy source has never been greater than today. Several renewable sources like solar and wind have made great progress and can supply much energy at certain locations. However, these sources do have several drawbacks that makes them less reliable other places.

Fusion is an energy source that can supply energy for several million years, with only limited impact on the environment. The initial estimate of 20 years before a method to extract the energy from fusion should be ready has been long passed, and there is a saying amongst some scientists that fusion is always 20 years from happening, but the reason for the delay is understandable. There was hardly any research made on hot plasma behavior when the initial attempts were made in the early fusion machines, and most believed that it would behave as a liquid. As the results were analyzed, it became clear that the plasma behaved in a much more complex way with several instabilities propelling the plasma to the walls much faster than what the classical theory predicted. Most of the research since have been focusing on learning the basic physics of hot plasma and how to suppress the instabilities so that the plasma can be maintained for a long enough time.

All the work has given great results. Several instabilities are completely eliminated, while others are controlled in a way where their impact is limited. Some instabilities are even helpful in extracting impurities from the plasma. Scaling laws for how a machine will behave depending on several variables has been developed for the tokamak design, and this tells us that we need a bigger machine to reach the goal.

ITER is the next step towards a fusion power plant, with a greater volume, current and magnetic field than any of the previous tokamaks. The scaling from smaller machines estimates an energy gain of at least 10, and that alpha particles produced is the main heating source. The power produced and confinement time of plasma are also expected to increase drastically, from 16.1 MW for a few seconds in JET to 500 MW for several hundred seconds in ITER. This is a massive increase, but still far from enough to make it economically viable to build a power plant on the design. Therefore, a demonstration power plant must first be designed, built and tested before fusion can become a reliable energy source in a great scale.

The future of fusion research depends on the results from ITER. As the parameters have been considerably increased, no one knows exactly how the machine will behave. Extrapolating from smaller devices with scaling laws is not necessarily exact, and new instabilities may occur when ITER is running full power. On the other hand, increasing the power was the way H-mode was discovered, so ITER may also give better results than estimated.

Whether ITER gives the desired results or not will become clear earliest at the start of the 2030`s. This has made it necessary to design several proposals for the next step demonstration power plant. But even though we are prepared for many outcomes of ITER, the earliest hope for the power plant to become a reality is about 2050, and the delays on ITER has shown that there will probably be delays in this as well.

It is hard to say exactly what fusion will bring to humanity in the future. It is clear that it will not be the energy source that will provide the almost free electricity the early fusion scientists dreamed of. The costs of building, running and maintaining a future power plant will be too high for that. However, it is without a doubt that it can become a great alternative for todays fossil fuel. When this will happen depends a lot on funding and ITER results. A famous quote of Lev Artsimovich from the

1970`s says that "*Fusion will be there when society needs it*" (Stott, 2004, p. 13). This quote holds truth to it today as well. Many of the questions still remaining could be answered in a shorter time if the funding for new machines are increased. When the need for more and cleaner energy becomes even higher, hopefully fusion will be the answer.

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