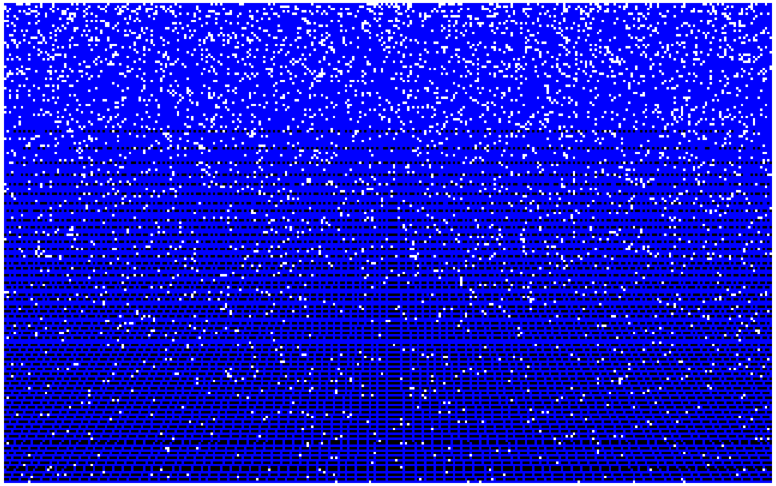
Energy Science

FEW course



Jo van den Brand

April 27, 2010

Overzicht

Algemene ontwikkeling
Tentamenstof
Ter informatie

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  - 0620 539 484 / 020 598 7900
  - Kamer: T2.69
- Rooster informatie
  - Dinsdag 13:30 – 15:15 in S655 (totaal 8 keer); HC vdB
  - Donderdag 15:30 – 17:15 in S345 (totaal 7 keer); WC Roel Aaij
- Boek en dictaat
  - Andrews & Jelley, Hoofdstukken 8 en 9
  - Zie website voor pdf van dictaat
- Cijfer
  - Huiswerk 20%, tentamen 80%

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  - Radiation shielding
  - Fast breeder reactors
  - Present day reactors
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- **Energy from fusion**
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  - Lawson, plasmas
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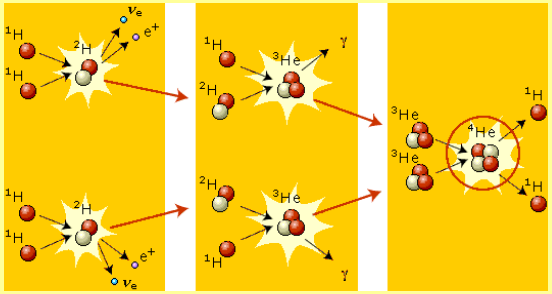
  - Magnetic mirror, tokamak
  - Plasma equilibrium
  - Energy confinement
  - Divertor tokamak
  - Inertial confinement
  - ITER

Nuclear fusion

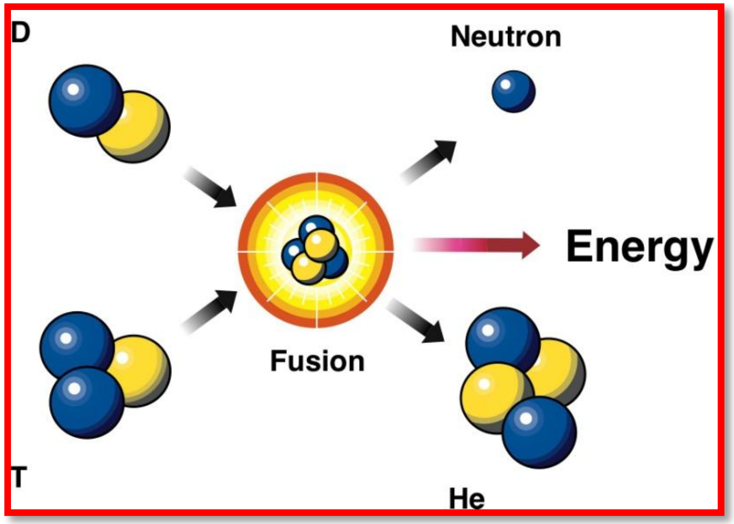
- Energy-producing mechanism in stars
- Each second about 600 million ton hydrogen is converted through *weak* interaction

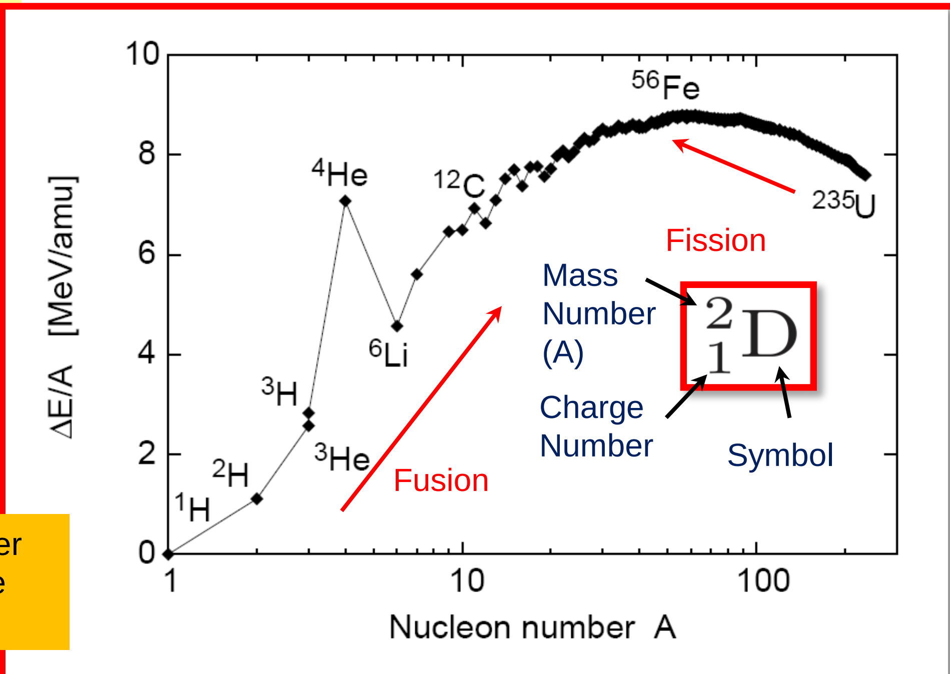


- Power density in Sun is only 0.3 W/m^3

Physics of fusion

- Fusion here refers to the controlled process in which two light atoms are fused together generating a heavier atom with the aim of generating energy.
- Binding energy is the energy that is released when a nucleus is created from protons and neutrons.
- It is released during the formation of a nucleus.
- The greater the binding energy per nucleon in the atom, the greater the atom's stability.





Binding energy (in MeV) per particle as a function of the mass number (A)

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Fusion reactions and energy released

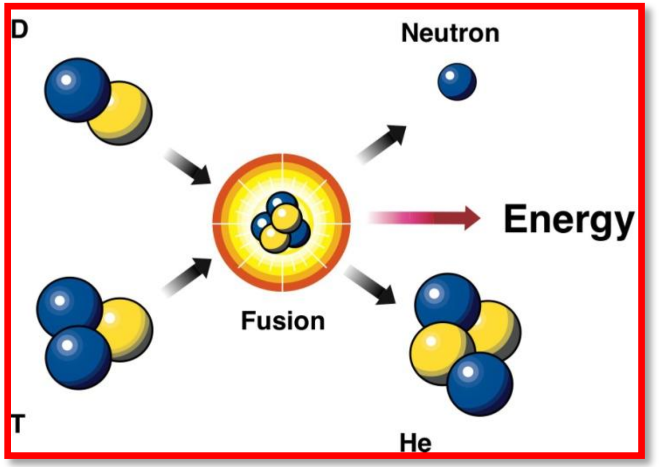
Often considered fusion reactions (note more than one reaction possible)

$$ {}^2_1\mathrm{D} + {}^3_1\mathrm{T} \rightarrow {}^4_2\mathrm{He} + {}^1_0\mathrm{n} + 17.6\ \mathrm{MeV} $$

$$ {}^2_1\mathrm{D} + {}^2_1\mathrm{D} \rightarrow {}^3_2\mathrm{He} + {}^1_0\mathrm{n} + 3.7\ \mathrm{MeV} $$

$$ {}^2_1\mathrm{D} + {}^2_1\mathrm{D} \rightarrow {}^3_1\mathrm{T} + {}^1_1\mathrm{H} + 4.03\ \mathrm{MeV} $$

$$ {}^2_1\mathrm{D} + {}^3_2\mathrm{He} \rightarrow {}^4_2\mathrm{He} + {}^1_1\mathrm{H} + 18.3\ \mathrm{MeV} $$



- The released energy follows from the mass deficit. Consider the reaction

$$ {}^2_1\mathrm{D} + {}^3_1\mathrm{T} \rightarrow {}^4_2\mathrm{He} + {}^1_0\mathrm{n} $$

- The masses of the different products are

$$ m_D = (2 - 0.000994)m_H \qquad m_T = (3 - 0.006284)m_H $$

$$ m_{He} = (4 - 0.027404)m_H \qquad m_n = (1 + 0.001378)m_H $$

- The mass deficit (initial mass minus total final mass) is

$$ \Delta m = 0.0187 m_H \qquad m_H = 1.6727 \cdot 10^{-27}\ \mathrm{kg} $$

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Calculation of the released energy

- The mass deficit is $\Delta m = 0.0187 m_H$ $m_H = 1.6727 \cdot 10^{-27}$ kg
- The energy then follows from Einstein's formula

$$E = mc^2 = 0.0187 m_H c^2 = 2.8184 \cdot 10^{-12} \ \mathrm{J}$$

- Used unit of energy is the electron volt (eV), kilo-electron volt (1 keV = 1000 eV) or Mega-electron volt (1 MeV = 10^6 eV)

$$E = \frac{2.8184 \cdot 10^{-12}}{1.6022 \cdot 10^{-19}} \mathrm{eV} = 17.56 \ \mathrm{MeV}$$

$$1 \ \mathrm{eV} = 1.6022 \cdot 10^{-19} \ \mathrm{J}$$

- 1 kg of a Deuterium/Tritium mixture would allow for a number of fusion reactions *N*

$$N = \frac{0.5}{2.5 \cdot 1.67 \cdot 10^{-27}} = 1.2 \cdot 10^{26}$$

- This amount of reactions would generate an energy

$$E = N 2.8184 \cdot 10^{-12} \ \mathrm{J} = 3.4 \cdot 10^{14} \ \mathrm{J}$$

- This is around 4 GW for 24 hours

Temperature and kinetic energy

Temperature is always used to express an averaged energy. The unit is again eV, i.e.

$$T = kT_k/e \text{ (eV)} = 8.617 \cdot 10^{-5} T_k \text{ (eV)}$$

where T is the temperature and T_k is the temperature in Kelvin.

Note 1 eV = 11605 K 17.56 MeV = 2 10^{11} K

- The energy is released in the form of kinetic energy
- The kinetic energy is not equally distributed over the products since both energy as well as momentum need to be conserved

$$\frac{1}{2} m_\mathrm{A} v_\mathrm{A}^2 + \frac{1}{2} m_\mathrm{B} v_\mathrm{B}^2 = E_{fus}$$

$$m_\mathrm{A} v_\mathrm{A} + m_\mathrm{B} v_\mathrm{B} = 0$$

- These equations can be solved to give

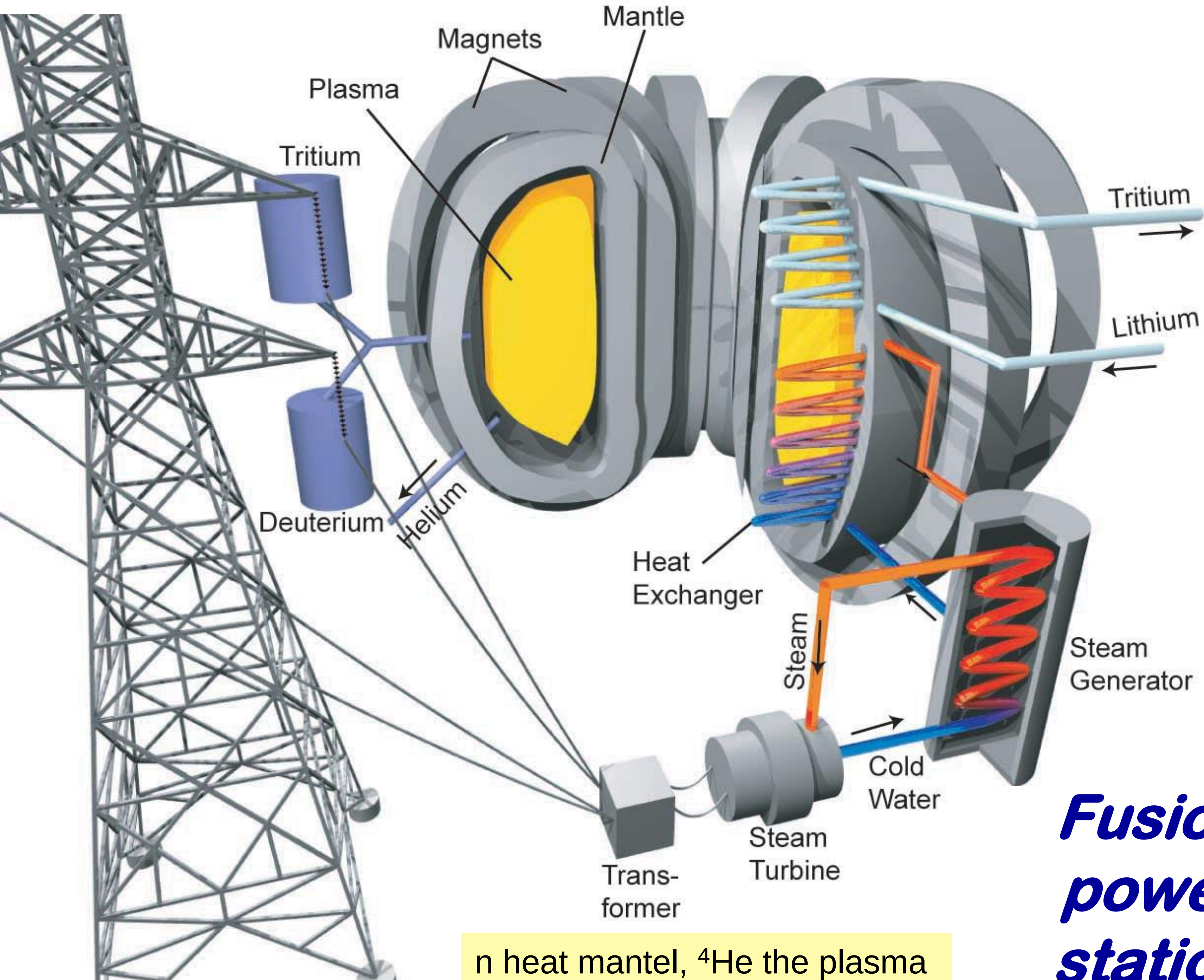
$$E_A = \frac{1}{2} m_\mathrm{A} v_\mathrm{A}^2 = \frac{m_B}{m_A + m_B} E_\mathrm{fus} \qquad E_B = \frac{1}{2} m_\mathrm{B} v_\mathrm{B}^2 = \frac{m_A}{m_A + m_B} E_\mathrm{fus}$$

Lightest particle takes most kinetic energy

- Take the now famous reaction

$$^2_1\mathrm{D} + {}^3_1\mathrm{T} \rightarrow {}^4_2\mathrm{He} + {}^1_0\mathrm{n}$$

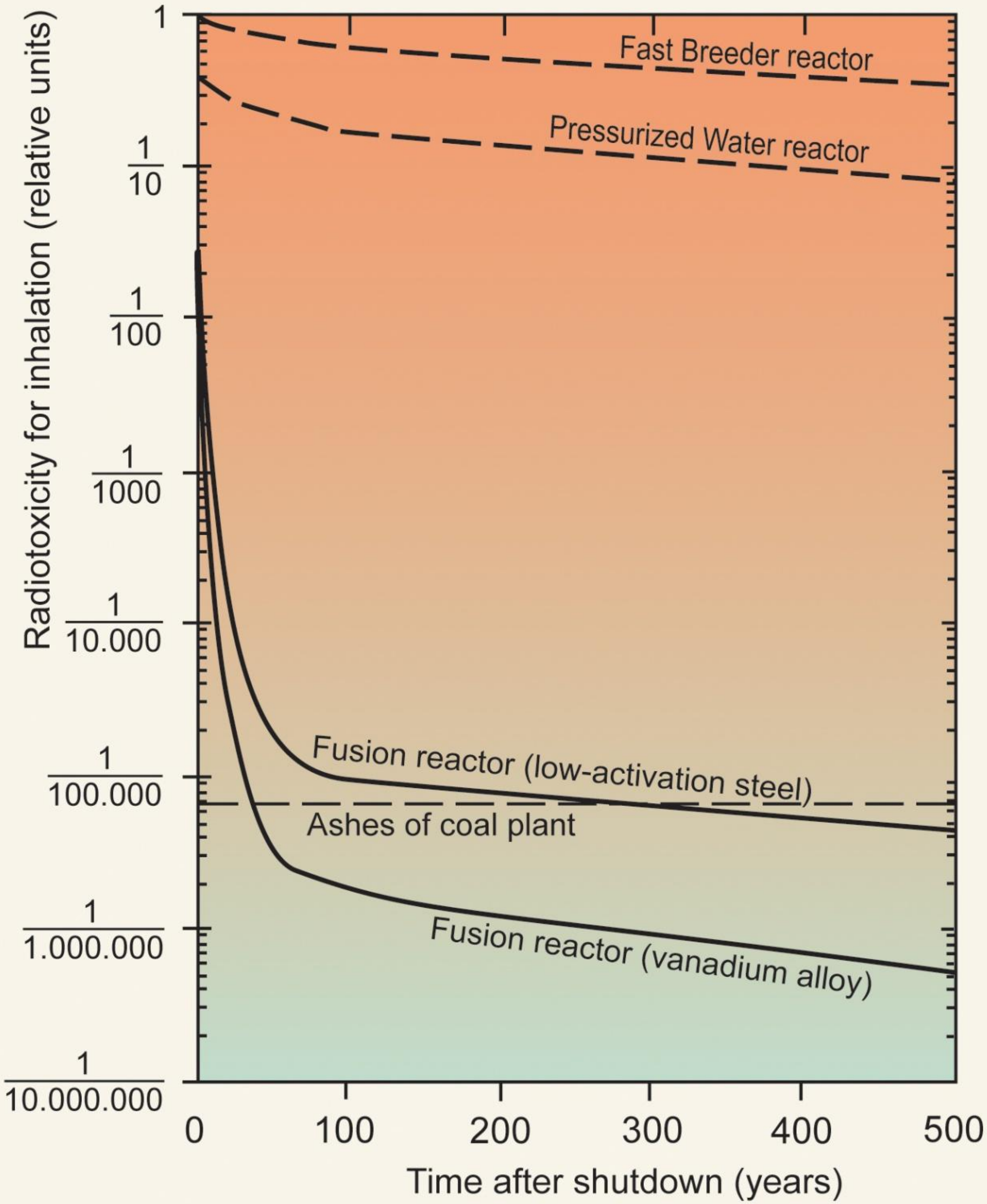
- Helium nuclei are roughly 4 times more heavy than the neutron and will thus acquire 20% of the energy (3.5 MeV) whereas the neutron obtains 80% (14.1 MeV)

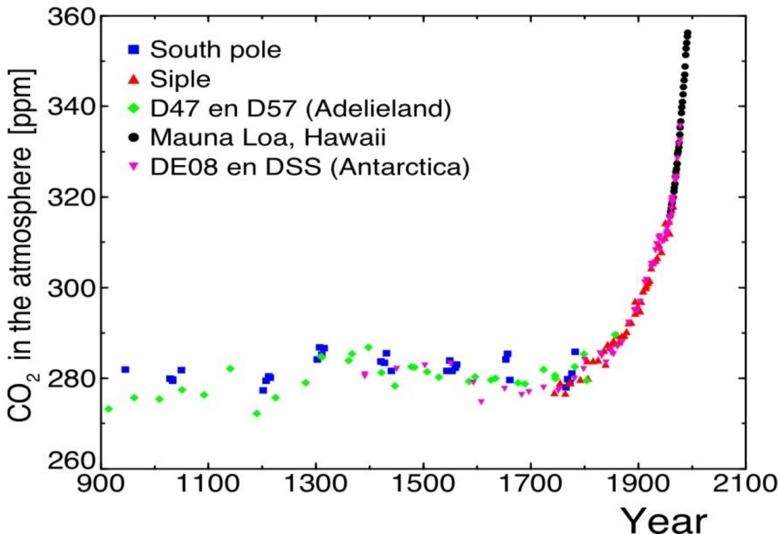


Fusion power station

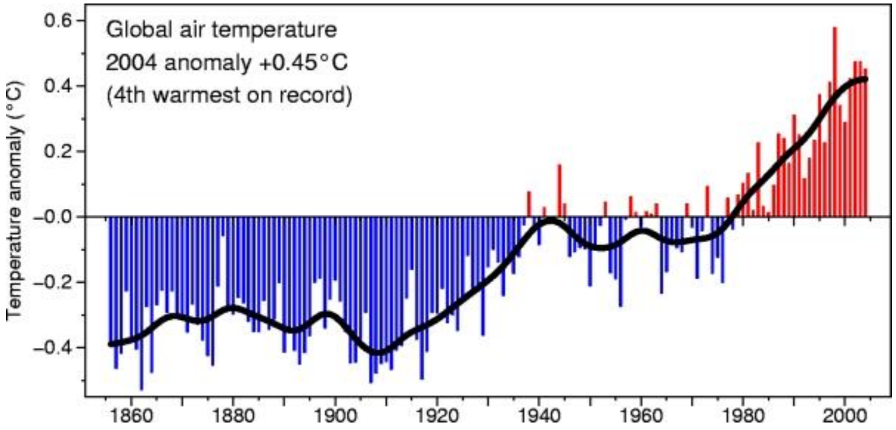
n heat mantel, ^{4}He the plasma

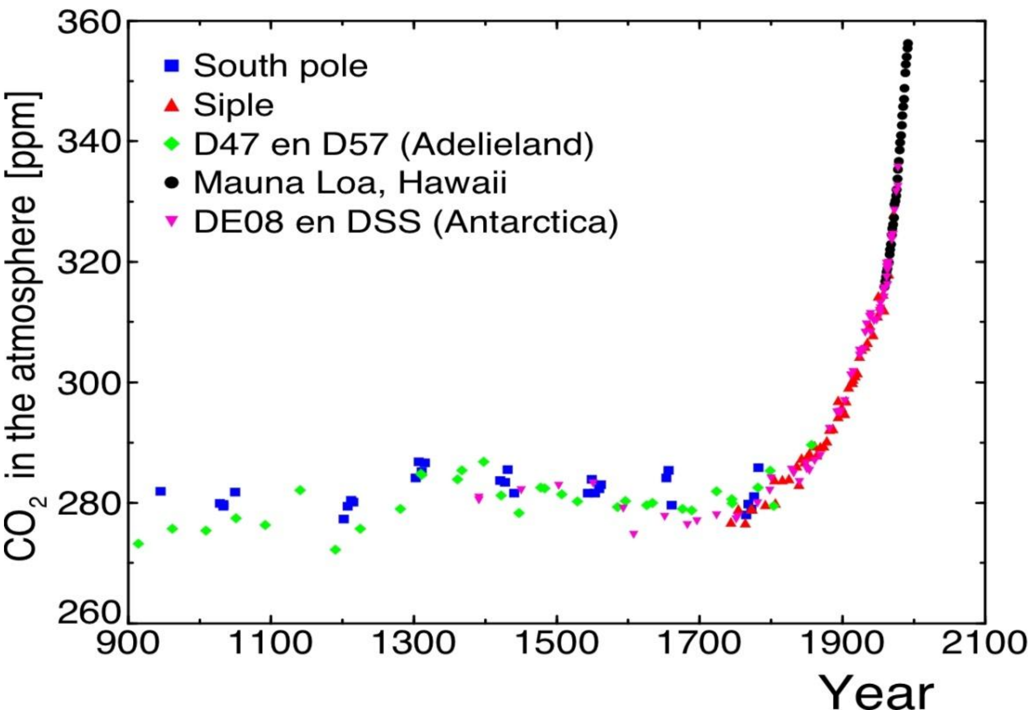
Radiotoxicity for inhalation





Climate issues





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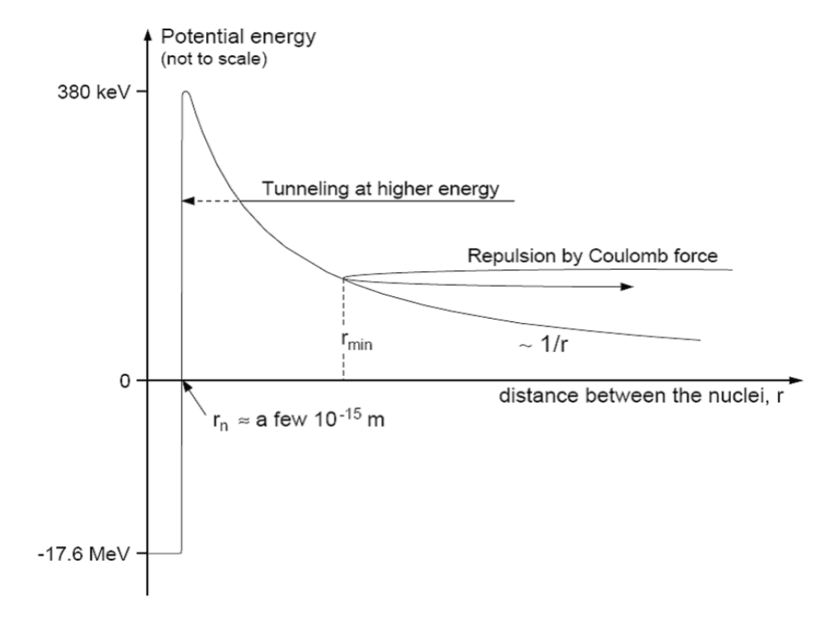
Cross section and Coulomb barrier

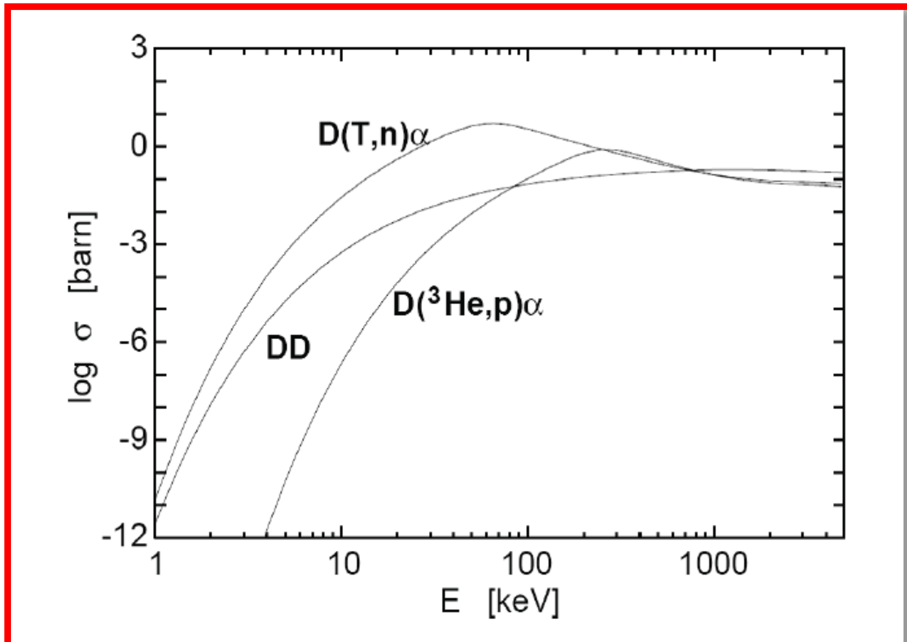


At large distances the deuteron and triton only experience the repulsive Coulomb force

At short distances there is attraction because of the strong force

Particles tunnel through the *Coulomb barrier*

The cross section of various fusion reactions as a function of the energy (note logarithmic scale)



- The cross section is the effective area connected with the occurrence of a reaction
- For snooker balls the cross section is πr^2 (with r the radius of the ball)

$$1 \text{ barn} = 10^{-28} \text{ m}^2$$

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Averaged reaction rate

- One particle (B) colliding with many particles (A)
- Number of reactions in Δt is

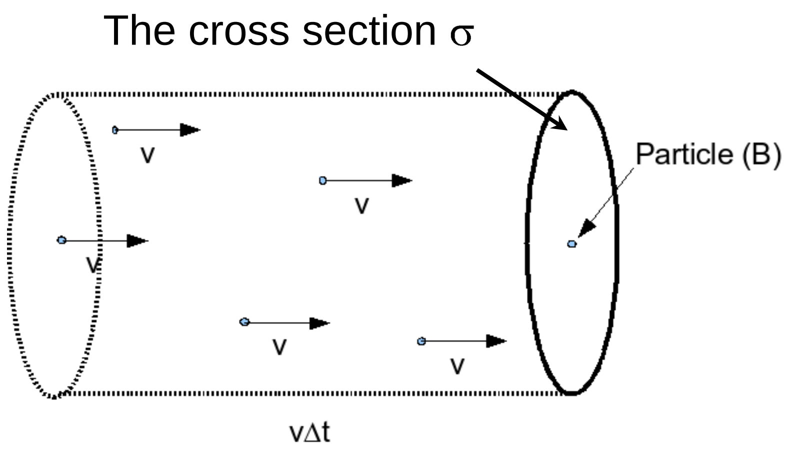
$$\Delta N = n_A \sigma v \Delta t \quad \rightarrow$$

- Both σ as well as *v* depend on the energy which is not the same for all particles. One builds the average

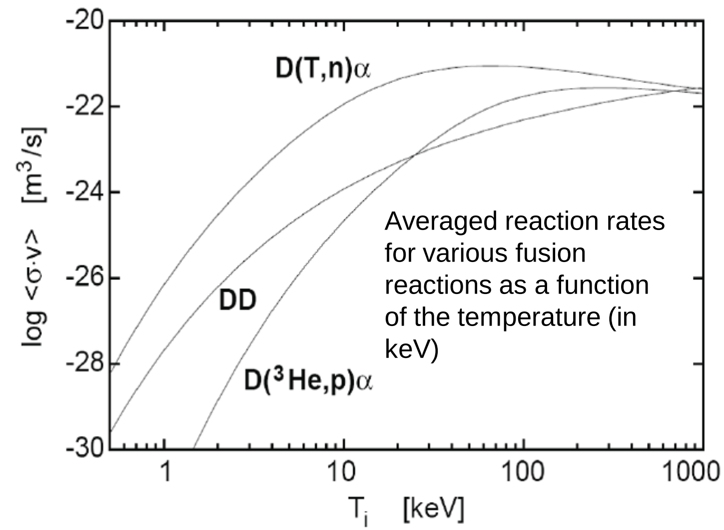
$$\frac{\mathrm{d}N}{\mathrm{d}t} = n_A \langle \sigma v \rangle$$

- The cross section must be averaged over the energies of the particles. Assume a Maxwell

$$F_M(v) = \frac{n}{(2\pi T/m)^{3/2}} \exp\left[-\frac{mv^2}{2T}\right]$$

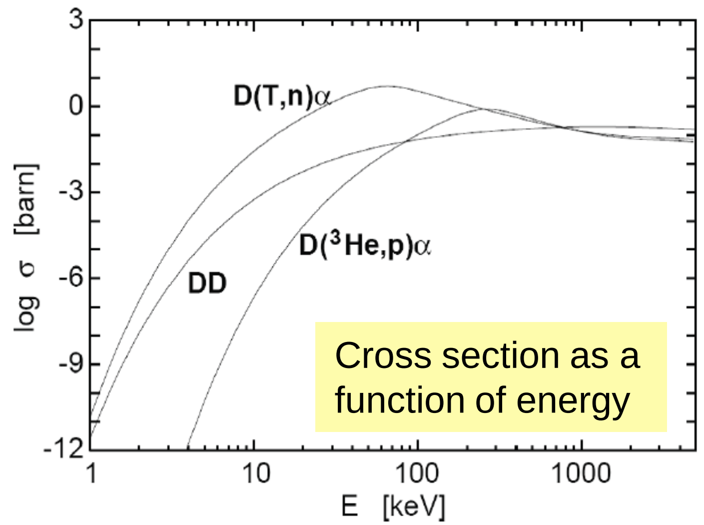


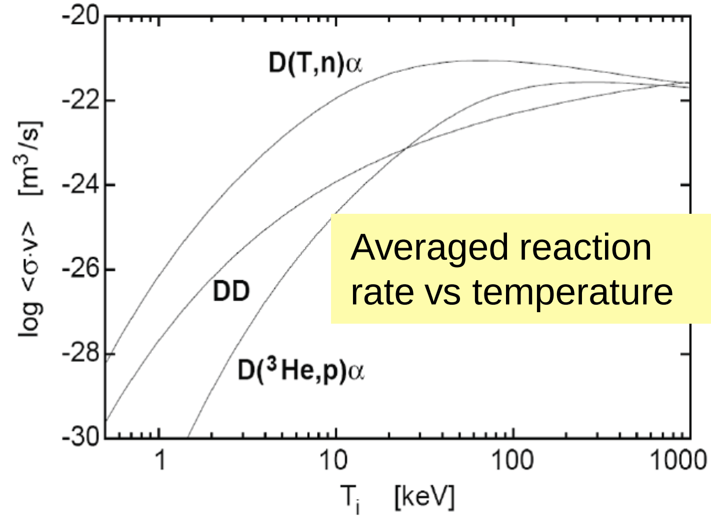
Schematic picture of the number of reactions in a time interval Δt



Averaged reaction rates for various fusion reactions as a function of the temperature (in keV)

Compare the two distributions



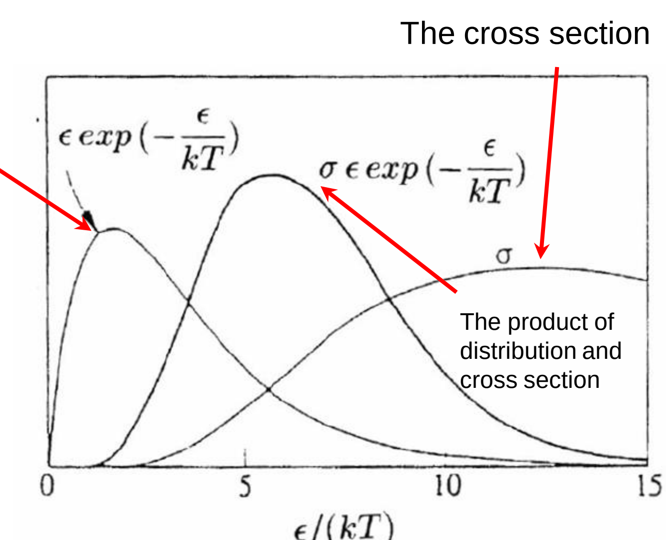


The averaged reaction rate does not fall of as strongly when going to lower energies

Even for temperatures below the energy at which the cross section reaches its maximum, there is a sufficient amount of fusion reactions due to the number of particles in the tail of the Maxwell distribution

The Maxwell (multiplied with the velocity)

Schematic picture of the calculation of the averaged reaction rate (Integrand as a function of energy)



Current fusion reactor concepts

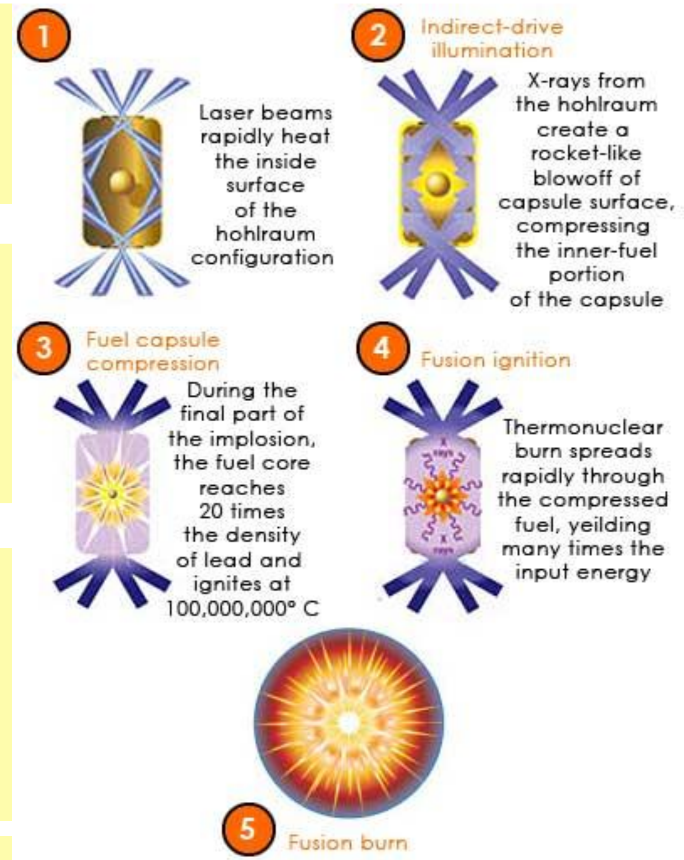
- Reactors designed to operate at around 10 keV (note this is still 100 million Kelvin, matter is fully ionized or in the plasma state)
- Are based on a mixture of Deuterium and Tritium
- Both are related to the cross section

- Some time scales can be estimated using the thermal velocity

$$v_{th} = \sqrt{2T/m}$$

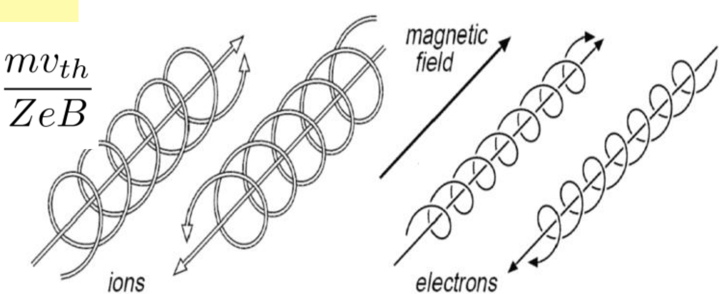
- This is 10^6 m/s for Deuterium and 6×10^7 m/s for the electrons
- In a reactor of 10 m size the particles would be lost in 10 μs.

- *Inertial confinement fusion* (ICF) is based on the rapid compression, and heating of a solid fuel pellet through the use of laser or particle beams. In this approach one tries to obtain a sufficient amount of fusion reactions before the material flies apart, hence the name,.



- *Magnetic confinement fusion* (MCF)
  - The Lorentz force connected with a magnetic field makes that the charged particles can not move over large distances across the magnetic field
  - They gyrate around the field lines with a typical radius

$$\rho = \frac{m v_{th}}{ZeB}$$



At 10 keV and 5 Tesla this radius of 4 mm for Deuterium and 0.07 mm for the electrons

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Availability of the fuel

- The natural abundance of Deuterium is one in 6700. There is enough water in the oceans to provide energy for 3×10^{11} years at the current rate of energy consumption (larger than the age of the universe)
- Deuterium is also very cheaply obtainable. Calculating the price of electricity solely on the basis of the cost of Deuterium, would lead to a drop of 10^3 in your electricity bill
- Tritium is unstable with a half age of 12.3 years. There is virtually no natural available resource of Tritium

- Tritium however can be bred from Lithium

$$ {}^6_3\mathrm{Li} + {}^1_0 n \rightarrow {}^4_2\mathrm{He} + {}^3_1\mathrm{T} + 4.8\ \mathrm{MeV} $$

$$ {}^7_3\mathrm{Li} + {}^1_0 n \rightarrow {}^4_2\mathrm{He} + {}^3_1\mathrm{T} + {}^1_0 n - 2.5\ \mathrm{MeV} $$

- Note that the neutron released in the fusion reaction can be used for this purpose
- The availability of Lithium on land is sufficient for at least 1000 if not 30000 years, and the cost per kWh would be even smaller than that of Deuterium.
- If the oceans are included it is estimated that there is enough fuel for 3×10^7 years.

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Quasi-neutrality and the Debye length

Using the Poisson equation

$$\nabla \cdot \mathbf{E} = -\nabla^2 \phi = \frac{\rho}{\epsilon_0}$$

And a Boltzmann relation for the densities

$$n_e = n_0 \exp\left[\frac{e\phi}{T}\right] \qquad n_i = n_0 \exp\left[-\frac{e\phi}{T}\right]$$

One arrives at an equation for the potential

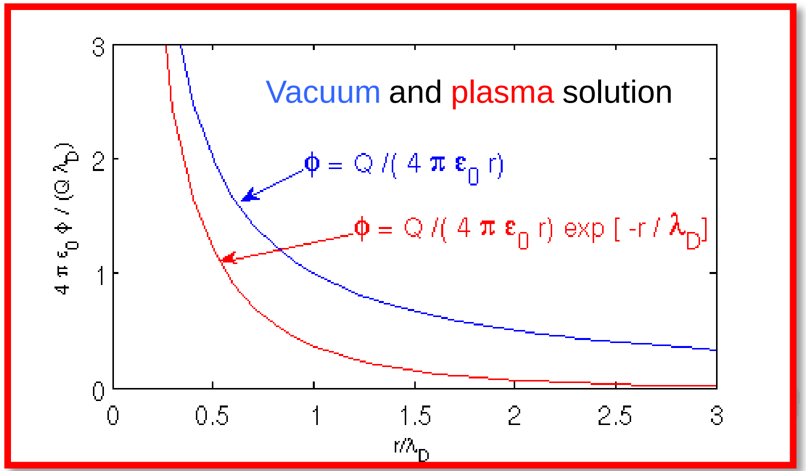
$$-\nabla^2 \phi = \frac{1}{\epsilon_0}\left[Q\delta(\mathbf{r}) - \frac{2e^2 n_0}{T}\phi\right]$$

Positive added charge — Response of the plasma

The solution of the Poisson equation is

$$\phi = \frac{Q}{4\pi r \epsilon_0} \exp\left[-\frac{r}{\lambda_D}\right] \qquad \lambda_D = \sqrt{\frac{\epsilon_0 T}{2e^2 n_0}}$$

Potential in vacuum — Shielding due to the charge screening



The length scale for shielding is the Debye length which depends on both temperature and density. It is around 10^{-5} m for a fusion plasma

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Quasi-neutrality

- For length scales larger than the Debye length the charge separation is close to zero. One can use the approximation of quasi-neutrality

  The charge density is assumed zero
  $$\sum_i Z_i n_i = 0 \qquad n_i = n_e$$

- Note that this does not mean that there is no electric field in the plasma

- Under the quasi-neutrality approximation the Poisson equation can no longer be used to calculate the electric field
  $$\nabla \cdot \mathbf{E} = \rho/\epsilon_0 \quad \rightarrow \quad \rho = 0$$
  since it would give a zero field

- Typical distance that particles are separated in a plasma $r_s \approx n^{-1/3}$

- Distance where relative kinetic energy (*kT*) equals Coulomb energy $U_c = e^2/(4\pi\varepsilon_0 r_c)$ is given by $r_c \approx e^2/(4\pi\varepsilon_0 kT)$

- In typical plasmas $r_s/r_c >> 1$ and binary Coulomb interactions are rare. These plasmas are called *weakly coupled* and we treat such plasmas as *collisionless.* Pressure exerted by the plasma is given by $p = nkT$.

- Length scales of the phenomena are larger than the Debye length

- The current is divergence free and displacement current is negligible

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Lawson criterion and fusion power

Derives the condition under which efficient production of fusion energy is possible

Essentially it compares the generated fusion power with any additional power required

The reaction rate of one particle B due to many particles A was derived

$$\frac{\mathrm{d}N}{\mathrm{d}t} = n_A \langle \sigma v \rangle$$

In the case of more than one particle B one obtains

$$\frac{\mathrm{d}N}{\mathrm{d}t} = N_B n_A \langle \sigma v \rangle = n_A n_B \langle \sigma v \rangle V$$

The total fusion power then is

$$P_{\mathrm{Fusion}} = n_A n_B \langle \sigma v \rangle E_{\mathrm{fusion}} V$$

Using quasi-neutrality

$$n_D + n_T = n_e = n$$

For a 50-50% mixture of Deuterium and Tritium

$$P_{\mathrm{fusion}} = \frac{1}{4} n^2 \langle \sigma v \rangle_{DT} E_{\mathrm{fus}}$$

To proceed one needs to specify the average of the cross section.
In the relevant temperature range 6-20 keV

$$\langle \sigma v \rangle_{DT} \approx 1.1 \cdot 10^{-24} T_k^2 \;\; \mathrm{m}^3/\mathrm{s}$$

The fusion power can then be expressed as with n_{20} in #/10^{-20} cm^3 and V in cm^3.

$$P_{\mathrm{Fusion}} = 7.7 n_{20}^2 T_k^2 V \;\; \mathrm{kW}$$

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Power loss

The fusion power must be compared with the power loss from the plasma

For this we introduce the energy confinement time τ_E

$$\frac{\partial W}{\partial t} = -\frac{W}{\tau_E} + P_{\text{heat}}$$

Where *W* is the stored energy

$$W = \left[\frac{3}{2}n_D T_D + \frac{3}{2}n_T T_T + \frac{3}{2}n_e T_e\right]V \approx 3nTV$$

If the plasma is stationary

$$W = 3nTV = P_{\text{heat}}\tau_E$$

$$nT = \frac{1}{3V}P_{\text{heat}}\tau_E$$

Combine this with the fusion power

$$P_{\text{Fusion}} = 7.7 n_{20}^2 T_k^2 V \ \ \text{kW}$$

One can derive the so called n-T-tau product

$$\frac{P_{\text{Fusion}}}{P_{\text{heat}}} = 0.16 n_{20} T_k \tau_E$$

Break-even and ignition

The *break-even* condition (*Lawson criterion*) : total fusion power is equal to the heating power

$$\frac{P_{\mathrm{Fusion}}}{P_{\mathrm{heat}}} = 0.16 n_{20} T_k \tau_E \quad \Rightarrow \quad n_{20} T_k \tau_E > 6 \ \ \mathrm{Break-even}$$

Note that this does not imply that all the heating power is generated by the fusion reactions

Ignition: energy produced by the fusion reactions is sufficient to heat the plasma

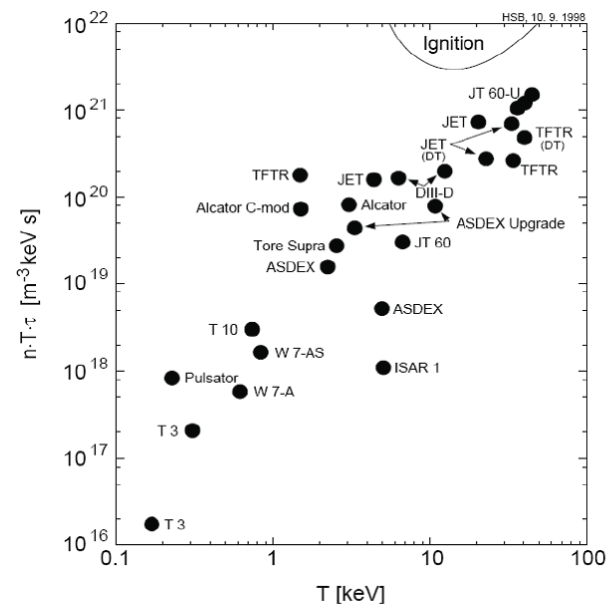
Only the He atoms are confined (neutrons escape the magnetic field)
Therefore, only 20% of the total fusion power is available for plasma heating

$$\frac{P_{\mathrm{Fusion}}}{P_{\mathrm{heat}}} = 0.16 n_{20} T_k \tau_E \quad \Rightarrow \quad n_{20} T_k \tau_E > 30 \ \ \mathrm{Ignition}$$

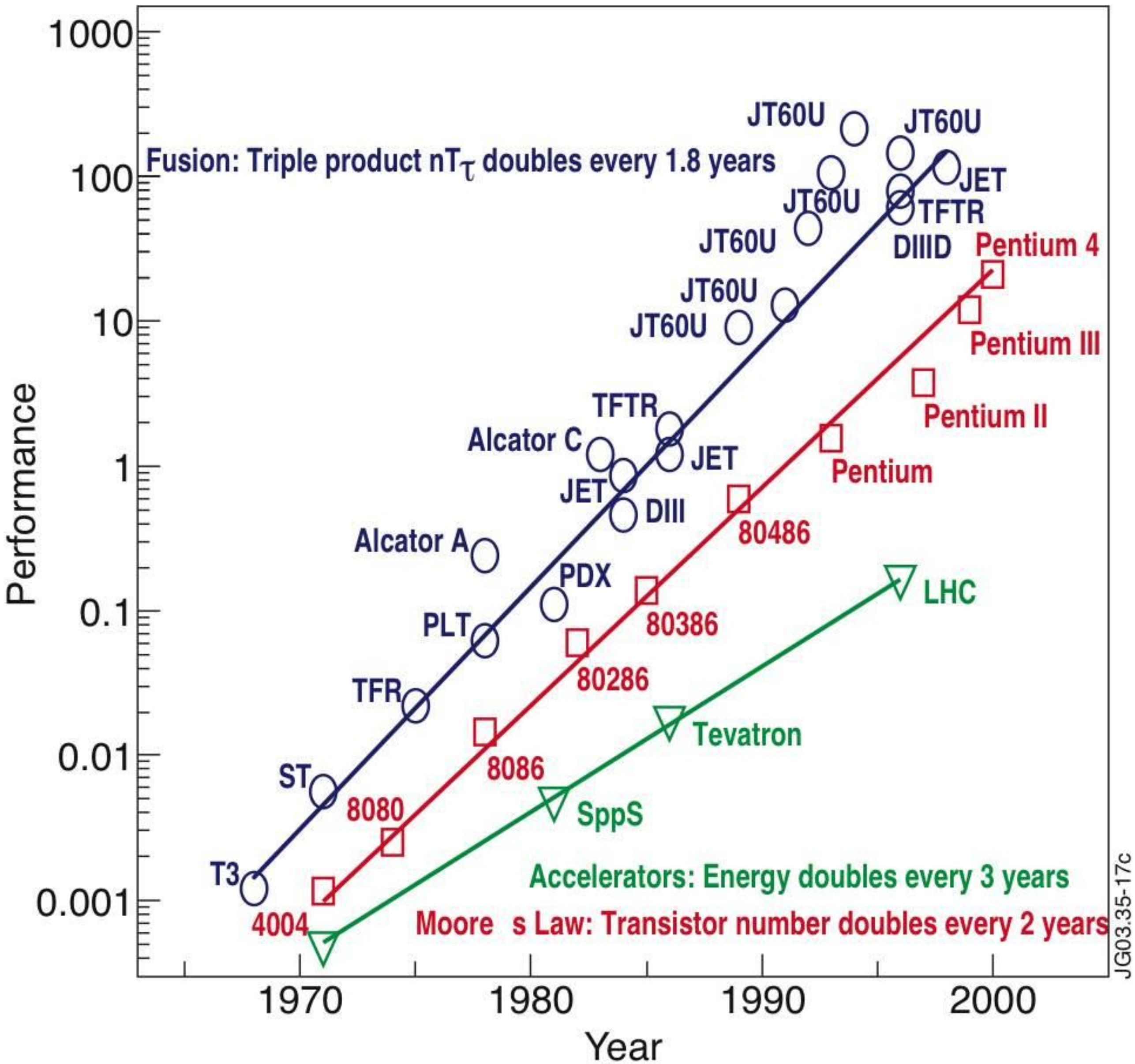
Over the years the n-T-tau product shows an exponential increase

Current experiments are close to break-even

The next step ITER is expected to operate well above break-even but still somewhat below ignition



Progress in fusion machines



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Force on the plasma

The force on an individual particle due to the electro-magnetic field (*s* is species index)

$$\mathbf{F}_i = Z_s e[\mathbf{E} + \mathbf{v}_i \times \mathbf{B}]$$

Assume a small volume such that $N_s = n_s V$

Then the force per unit of volume is $$\mathbf{F}_s = \frac{1}{V}\sum_{i=1}^{N_s}\mathbf{F}_i = \frac{1}{V}\sum_{i=1}^{N_s} Z_s e[\mathbf{E} + \mathbf{v}_i \times \mathbf{B}]$$

For the electric field $$\frac{1}{V}\sum_{i=1}^{N_s} Z_s e\mathbf{E} = \frac{N_s}{V} Z_s e\mathbf{E} = Z_s e n_s \mathbf{E}$$

Define an average velocity $$\mathbf{u}_s = \frac{1}{N_s}\sum_{i=1}^{N_s}\mathbf{v}_i$$

Then for the magnetic field $$\frac{1}{V}\sum_{i=1}^{N_s} Z_s e \mathbf{v}_i \times \mathbf{B} = Z_s e \frac{N_s}{V}\left(\frac{1}{N_s}\sum_{i=1}^{N_s}\mathbf{v}_i\right)\times\mathbf{B} = Z_s e n_s \mathbf{u}_s \times \mathbf{B}$$

Averaged over all particles $$\mathbf{F}_s = Z_s e n_s[\mathbf{E} + \mathbf{u}_s \times \mathbf{B}]$$

Now sum over all species $$\sum_{s=1}^{p} Z_s e n_s \mathbf{E} = e\mathbf{E}\sum_{s=1}^{p} Z_s n_s = 0 \qquad \sum_{s=1}^{p} Z_s e n_s \mathbf{u}_s = \mathbf{J}$$

The total force density therefore is $$\mathbf{F} = \sum_{s=1}^{p}\mathbf{F}_s = \mathbf{J}\times\mathbf{B}$$

For a fluid with a finite temperature one has to add the pressure force

$$\mathbf{F} = -\nabla p + \mathbf{J}\times\mathbf{B}$$

$$p = \sum_{s=1}^{p} n_s T_s$$

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Reformulating the Lorentz force

Using $\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$

The force can be written as $\mathbf{J} \times \mathbf{B} = \frac{1}{\mu_0}(\nabla \times \mathbf{B}) \times \mathbf{B}$

Then using the vector identity $\nabla(\mathbf{a}\cdot\mathbf{b}) = (\mathbf{a}\cdot\nabla)\mathbf{b} + (\mathbf{b}\cdot\nabla)\mathbf{a} + \mathbf{a}\times(\nabla\times\mathbf{b}) + \mathbf{b}\times(\nabla\times\mathbf{a})$

$$\mathbf{a} = \mathbf{B} \qquad \mathbf{b} = \mathbf{B}$$

$$\nabla(B^2) = 2(\mathbf{B}\cdot\nabla)\mathbf{B} + 2\mathbf{B}\times(\nabla\times\mathbf{B})$$

One obtains $-\nabla p + \mathbf{J}\times\mathbf{B} = -\nabla\left(p + \frac{B^2}{2\mu_0}\right) + \frac{1}{\mu_0}(\mathbf{B}\cdot\nabla)\mathbf{B}$

Magnetic field pressure   Magnetic field tension

Important parameter (also efficiency parameter) the plasma-beta $\beta = \frac{p}{B^2/2\mu_0}$

Theta pinch

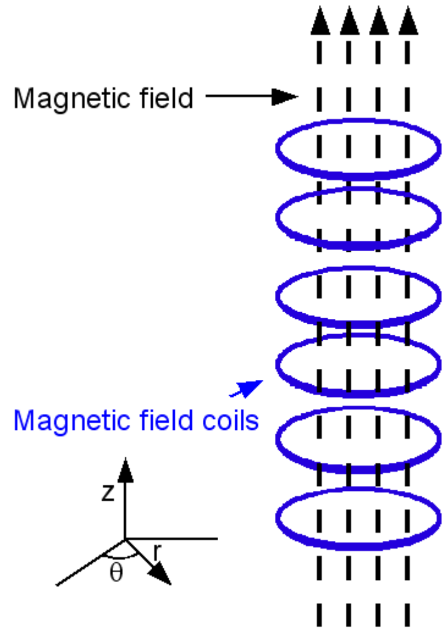
Straight magnetic field no tension

$$\nabla\left(p+\frac{B^2}{2\mu_0}\right)-\frac{\mathbf{B}\cdot\nabla\mathbf{B}}{\mu_0}=0$$

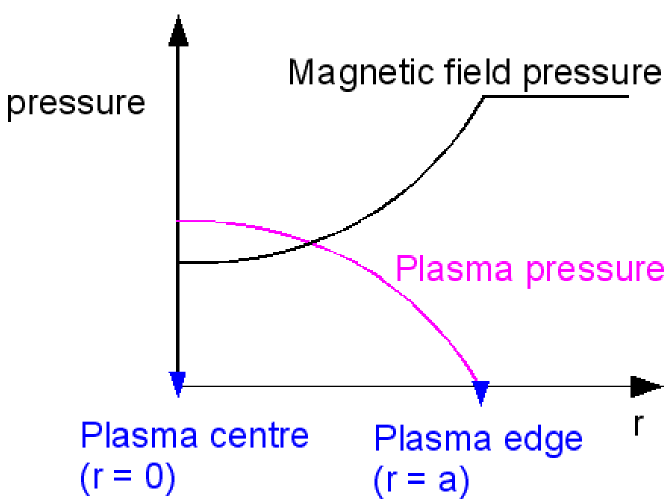
Equation gives constant total pressure

$$B_z\frac{\partial B_z}{\partial z}=0$$

Magnetic field is reduced inside the plasma
i.e. the plasma is diamagnetic



Plasma escapes at the ends; go toroidal …

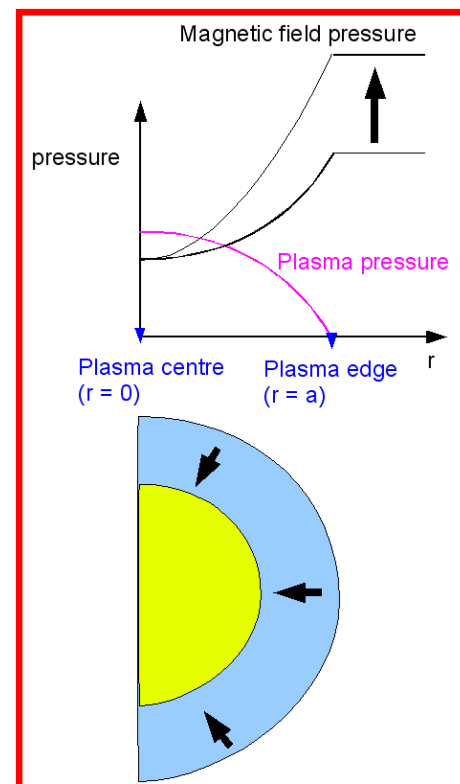


Ramp up the magnetic field by ramping the current in the coils

The magnetic field pressure will increase and is no longer balanced by the plasma pressure

The plasma is compressed

Compression leads to work against the pressure gradient force which will heat the plasma



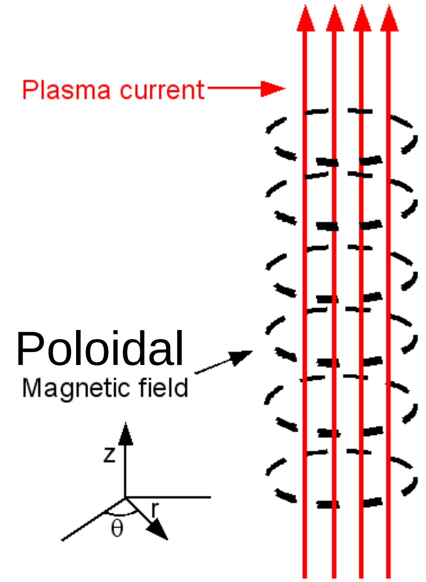
Z-pinch

A strong current is generated in the z-direction

This current generates a magnetic field in the θ direction

JxB force is then fully determined

Pressure gradient must balance the JxB force and is then also fully determined by the current



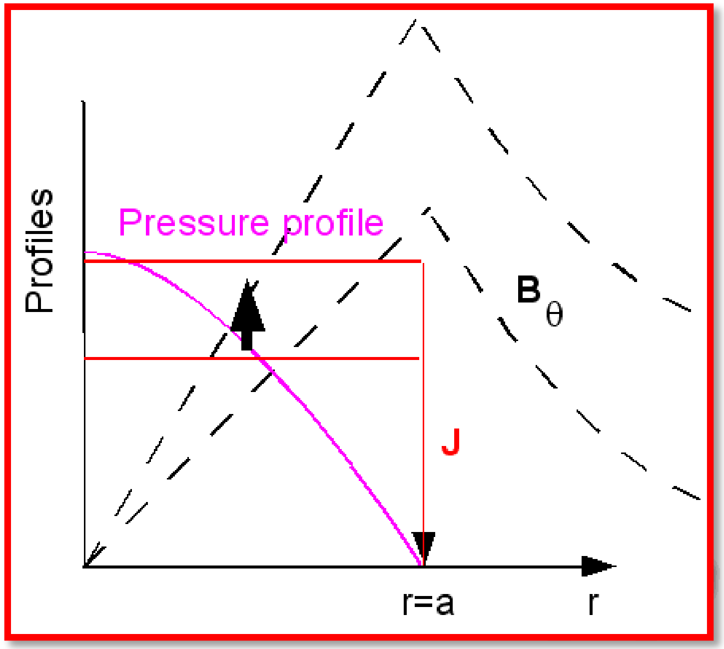
Current is the source of the magnetic field

$$\oint \vec{B}\cdot d\vec{l} = \mu_0 I_{enc} \Rightarrow 2\pi r B_\theta = \mu_0 \pi r^2 J$$

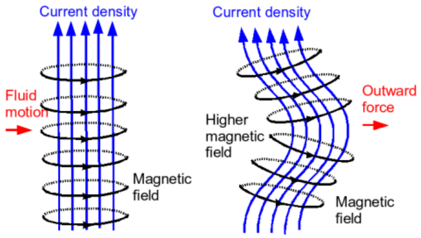
Magnetic pressure $p_B \approx \frac{F_B}{A} = \frac{IBL}{2\pi RL} = \mu_0 I^2 L / \{(2\pi R)^2 L\} = B^2 / \mu_0$

Ramping of the current will increase the magnetic field which will compress the plasma

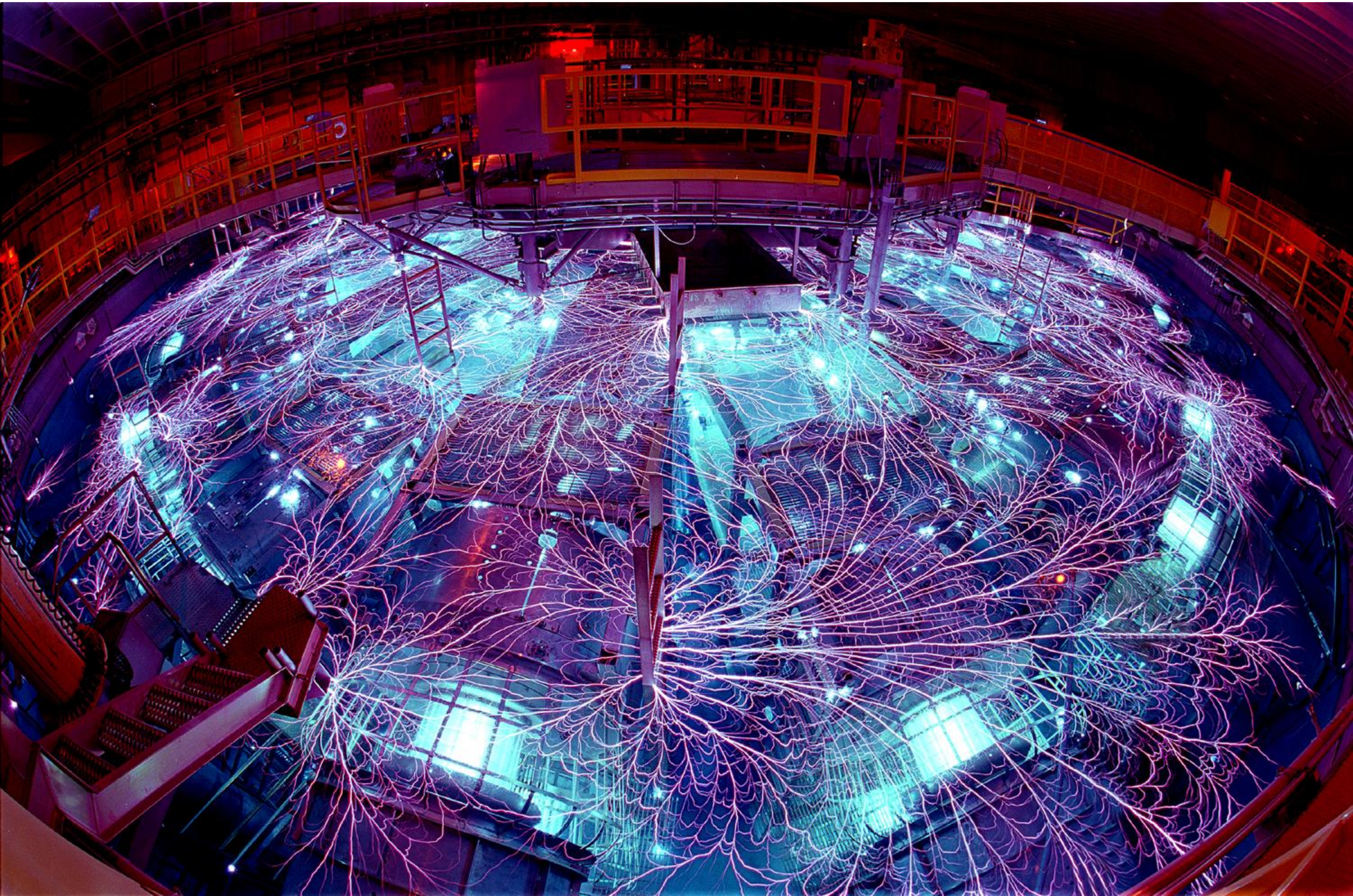
Besides the heating due to compression, the current will also dissipate heat when the plasma resistivity is finite



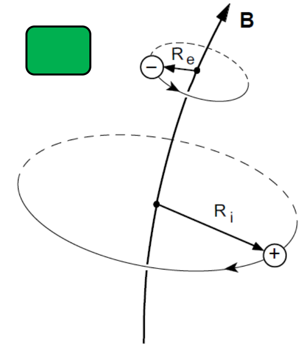
The Z-pinch is unstable. Most relevant instability is the kink



Sandia labs – Z pinch: 200 TW X-rays



Gyro motion



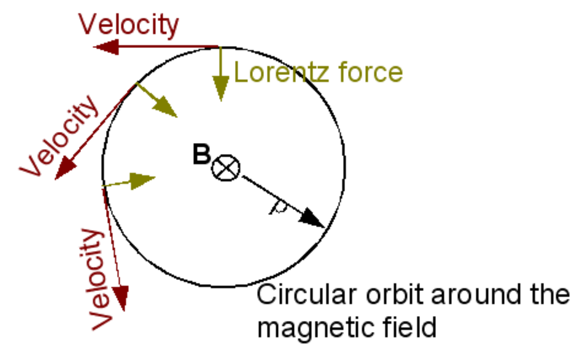
Lorentz force leads to a gyration of the particles around the magnetic field

$$x - x_0 = \rho sin \omega_c t$$

$$y - y_0 = \rho cos \omega_c t$$

$$\rho = \frac{mv_\perp}{|q|B} \qquad \omega_c = \frac{|q|B}{m}$$

$$m\frac{d\mathbf{v}}{dt} = q\mathbf{v} \times \mathbf{B}$$



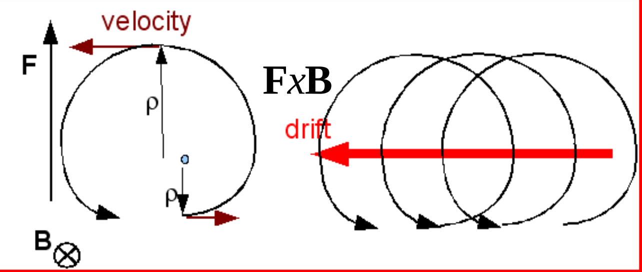
We will write the motion as $\mathbf{v} = v_{||}\mathbf{b} + \mathbf{v}_g$

Parallel and rapid gyro-motion

Finite additional force *F (=qE)* leads to drift

Physics picture behind the drift velocity

$$\rho = \frac{mv_\perp}{|q|B}$$



For 10 keV and B = 5T:

- Larmor radius of deuterons ~4 mm
- electrons ~0.07 mm
- alpha particles (3.5 MeV) ~5.4 cm

Cyclotron frequency:

- 80 MHz for hydrogen
- 130 GHz for electrons

$$\mathbf{v} = v_{||}\mathbf{b} + \mathbf{v}_g + \frac{\mathbf{E}\times\mathbf{B}}{B^2} + \frac{m}{qB^2}\frac{\mathrm{d}\mathbf{E}_\perp}{\mathrm{d}t} + \frac{mv_{||}^2 + mv_\perp^2/2}{qB}\frac{\mathbf{B}\times\nabla B}{B^2}$$

Parallel motion — Gyration — ExB drift — Polarization drift — Grad-B and curvature drift

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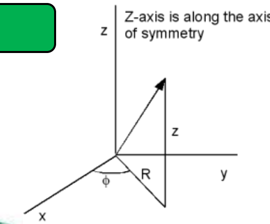
Tokamak



Bend the theta pinch into a donut shape

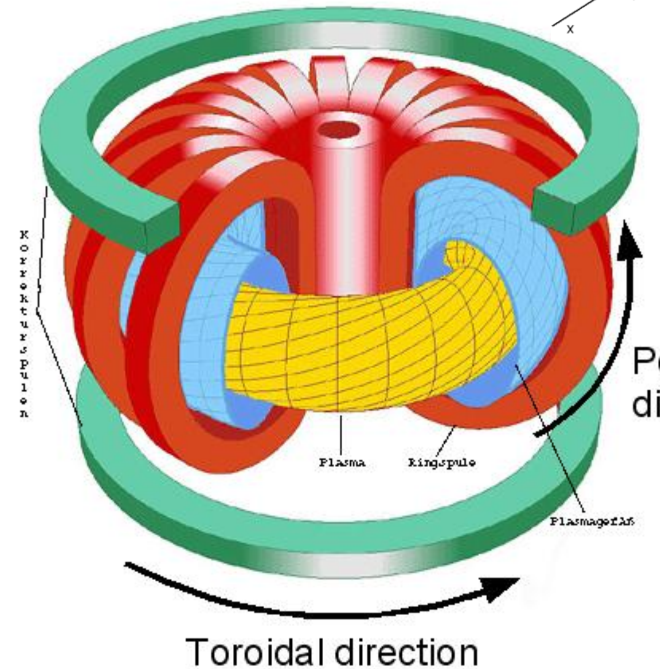
No end losses because the field lines go around and close on themselves

The magnetic field follows form

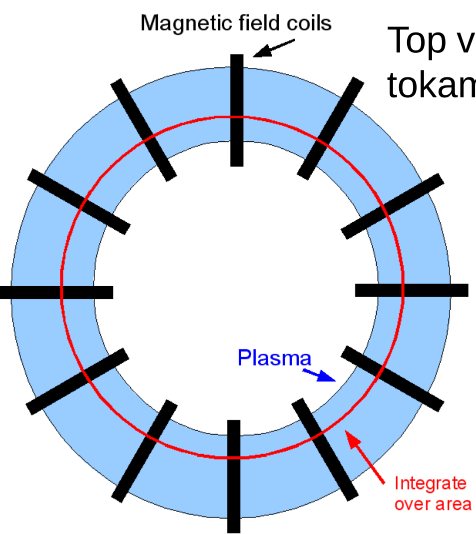
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$$

$$2\pi R B_\phi = \mu_0 I$$

And therefore varies with major radius *R* as $B_\phi = \dfrac{C}{R}$



Schematic picture of the tokamak



Top view of tokamak

Toroidal curvature has its price

The toroidal magnetic field has a gradient

$$B_\phi = \frac{C}{R} \longrightarrow \nabla B = \nabla\left(\frac{C}{R}\right) = -\frac{C}{R^2}\mathbf{e}_R = -\frac{B}{R}\mathbf{e}_R$$

Which leads to a drift in the vertical direction

$$\frac{\mathbf{B}\times\nabla B}{B^2} = \frac{1}{R}\mathbf{e}_z \qquad \mathbf{v}_d = \frac{mv_\parallel^2 + mv_\perp^2/2}{qBR}\mathbf{e}_z$$

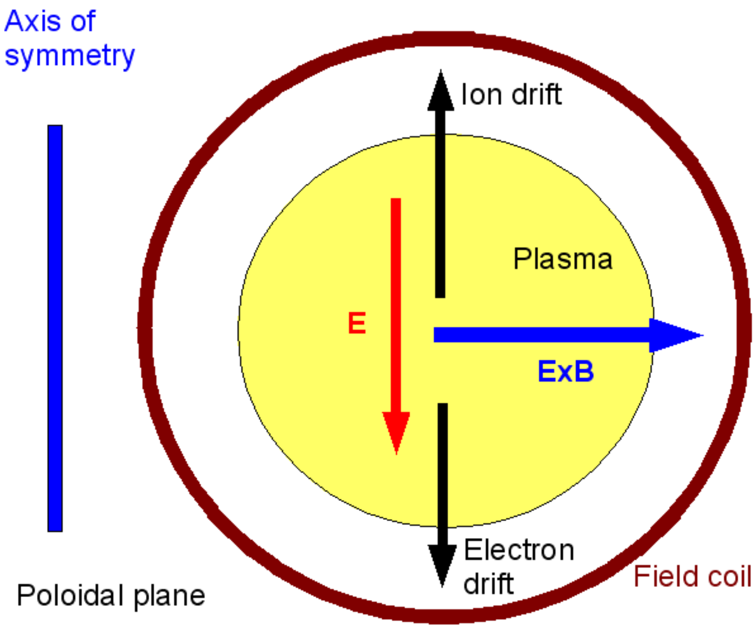
Note that the sign of the drift depends on the sign of the charge q

The drift $\mathbf{v}_d = \frac{mv_\parallel^2 + mv_\perp^2/2}{qBR}\mathbf{e}_z$

leads to charge separation

Build up of an electric field

and then to an ExB velocity



Poloidal cut of the tokamak.

The ExB velocity

$$\mathbf{v}_E = \frac{\mathbf{E}\times\mathbf{B}}{B^2} = -\frac{E_z}{B}\mathbf{e}_R$$

Is directed outward and will move the plasma on the wall in a short timescale

This effect is no surprise since $F = -\mu\nabla B \leftarrow B_\phi = \frac{C}{R}$

Remedy: a toroidal plasma current will generate a poloidal field

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The toroidal electric field

Plasma is the second winding of a transformer

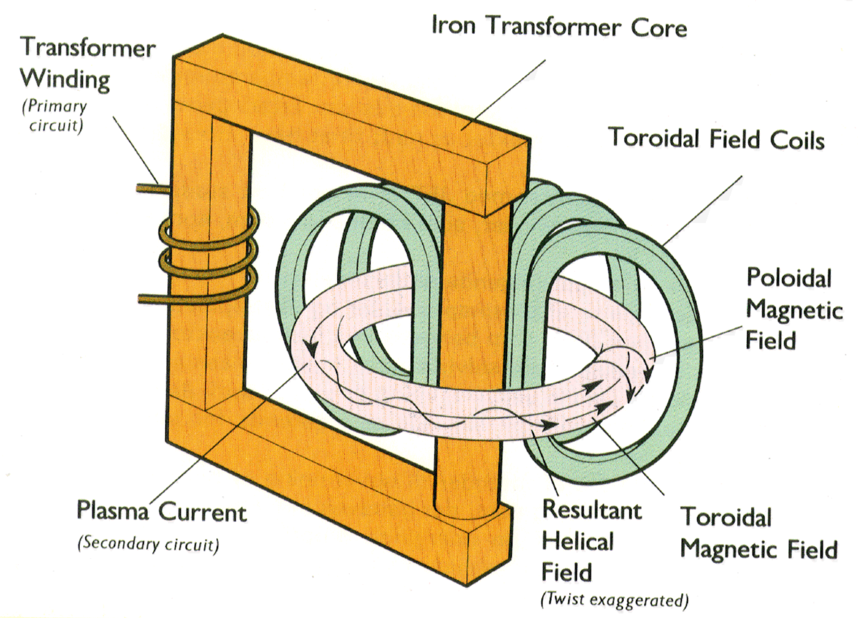
Flux in the iron core cannot be increased forever.
The tokamak is necessarily a pulsed machine

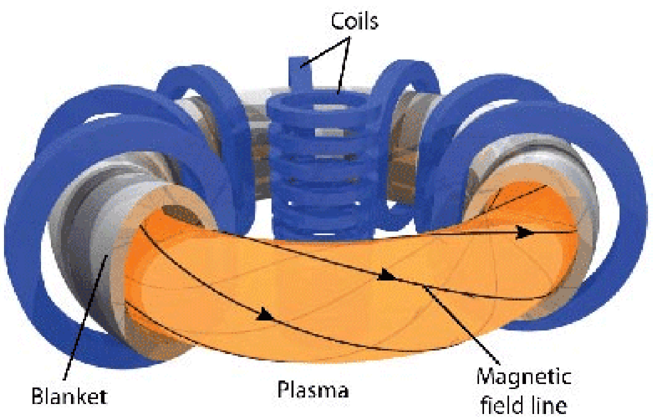
That is not good for energy production

Also thermal stresses are associated with the pulsed character

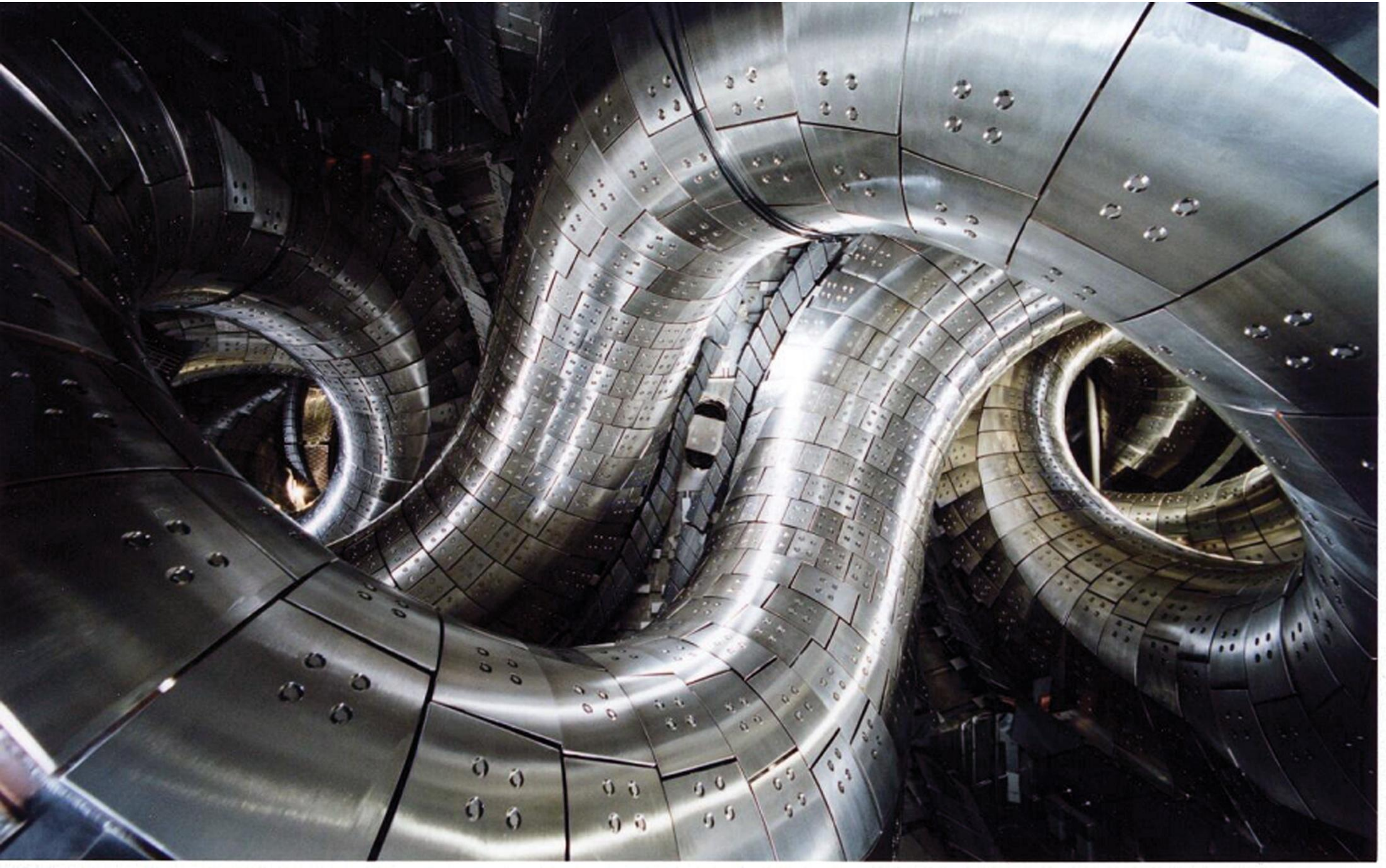
One can either: live with it / drive current another way / use a different concept

Because of the plasma current the field lines wind around helically





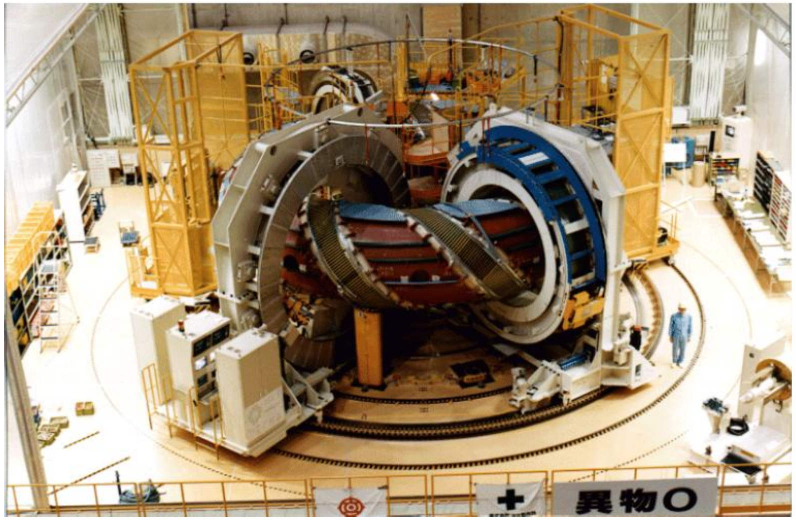
Stellarator – LHD in JAPAN



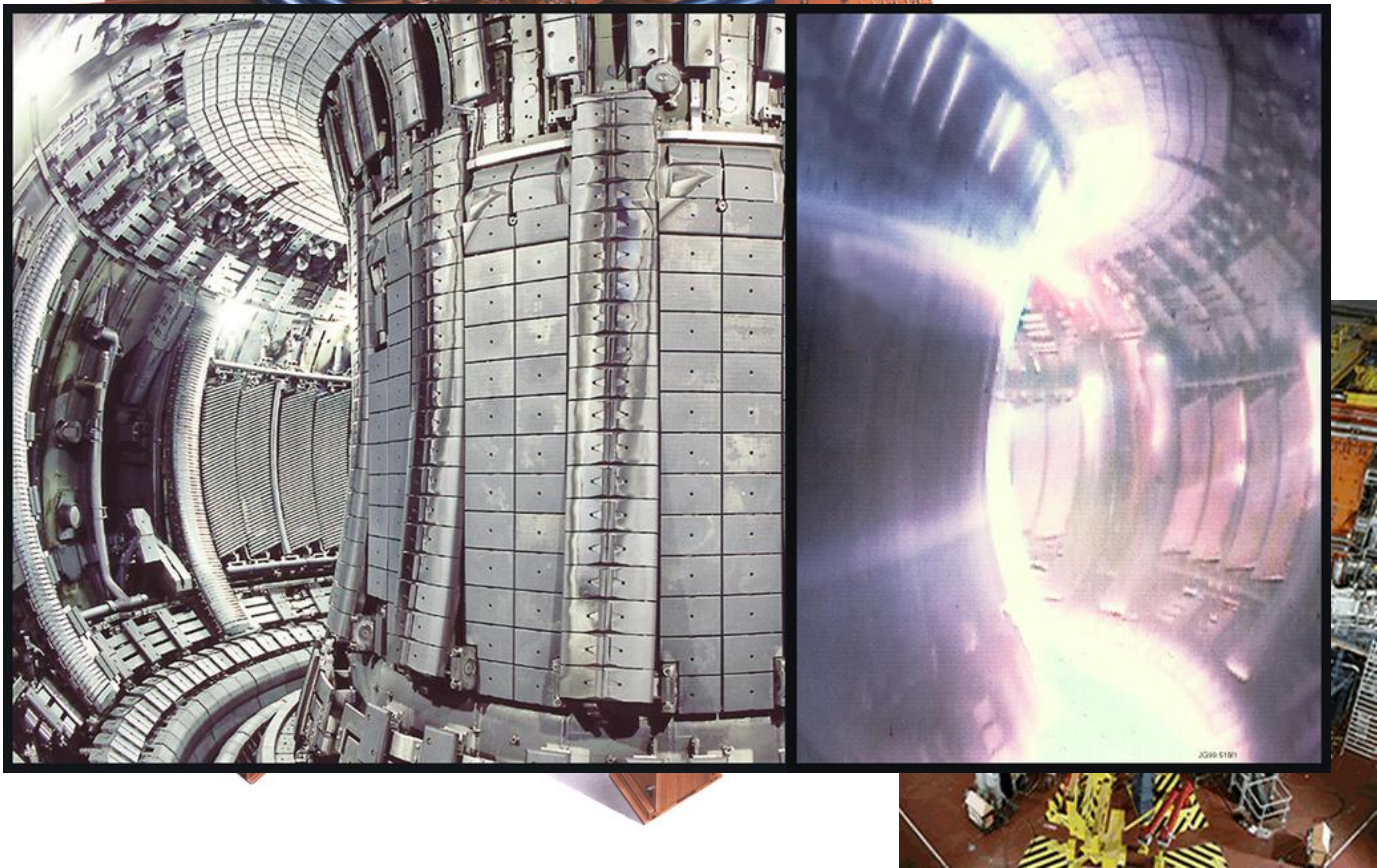
Large Helical Device (LHD,Japan)

Specifications of LHD devices

	Phase I (II)
Major radius	3.9 m
Coil minor radius	0.975 m
Plasma radius	0.5–0.65
Plasma volume	20–30 m^3
I/m	2/10
i (0)/i (a)	< 0.5/1
Helical ripple	0.2
Bo/Bmax	3/6.6 T (4/9.2 T)
Helical coil current	5.85 MAT (7.8 MAT)
LHe temp.	4.4 K (1.8 K)
Poloidal coil (IV/IS/OV)	5.0/−4.5/− 4.5 MAT
Magnetic energy	0.9 GJ (1.6 GJ)
Plasma duration	10 s
Repetition time	5 min
Heating power	
ECRH	10 MW
NBI	15 MW (20 MW)
ICRF	3 MW (12 MW)



JK)



Comparison of confinement time

Confinement times of LHD are below those of the large tokamaks

This is mostly due to the smaller plasma volume

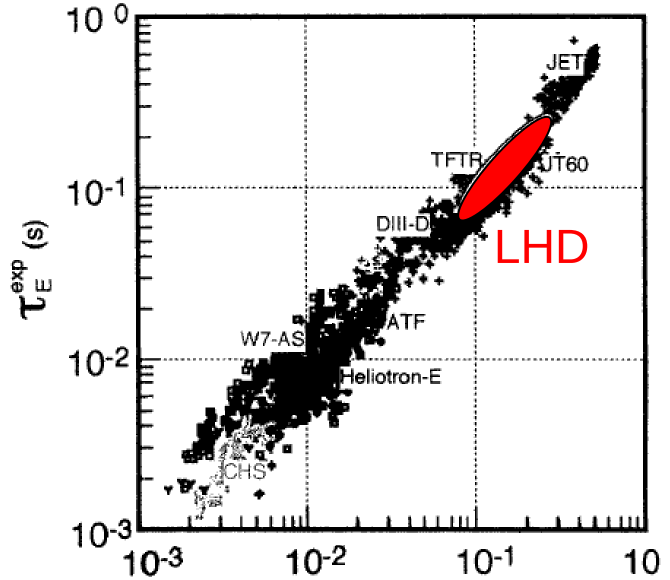
Advantage of the stellarator

- Stationary plasma operation
- No current in the plasma, and therefore no current driven instabilities

Disadvantage

- Complex magnetic field coils
- Curved coils lead to large forces (strong supporting structures)
- Difficult to make compact devices

Confinement time of tokamaks and stellarators compared

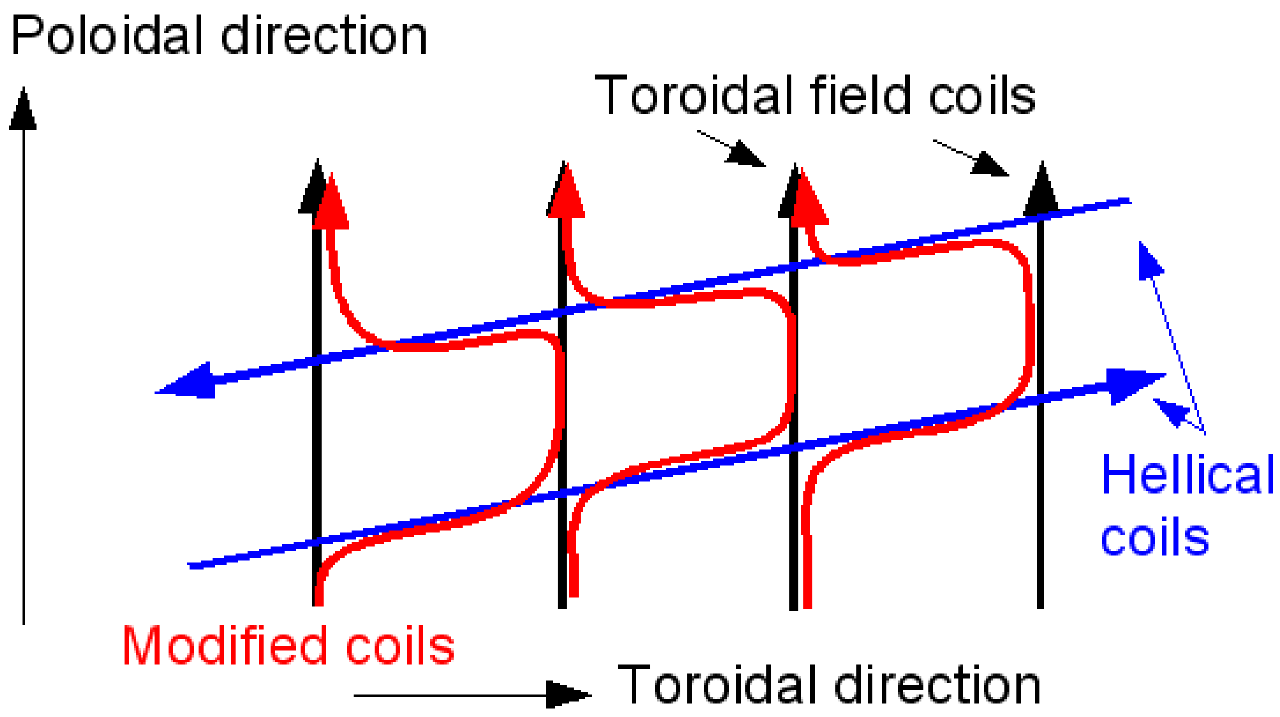


$\tau_E^{ISS95} = 0.08\, a_p^{\,2.21}\, R_0^{\,0.65}\, P_{abs}^{\,-0.59}\, \bar{n}_e^{\,0.51}\, B_0^{\,0.83}\, \iota_{2/3}^{\,0.40}$

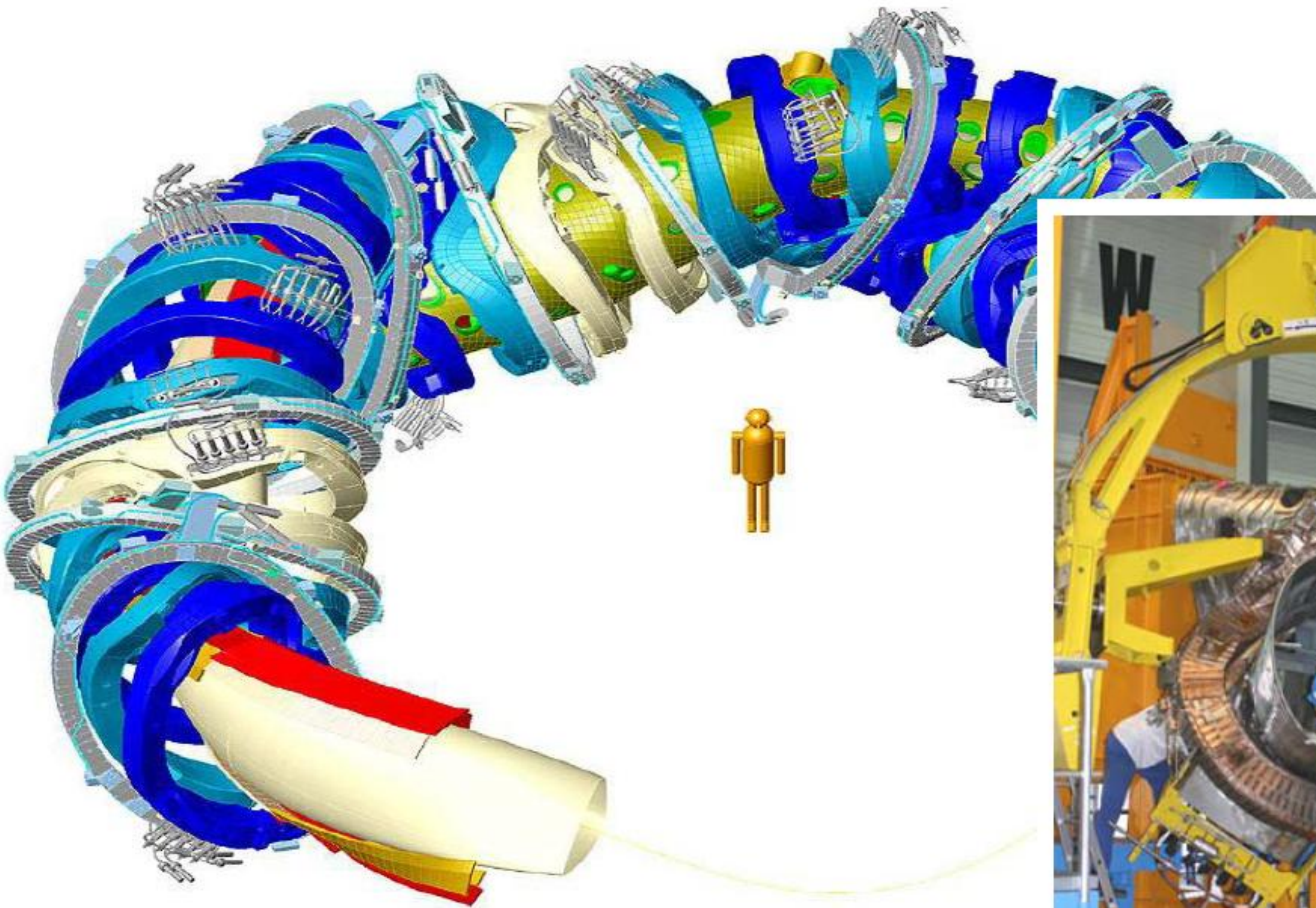
τ_E^{ISS95} (s), a_p (m), R_0 (m), P_{abs}(MW), $\bar{n}_e(10^{19}m^{-3})$, B_0 (T)

Helical coils can be simplified

- **The picture shows how the combination of helical coils and toroidal field coils can be changed to use modular coils**

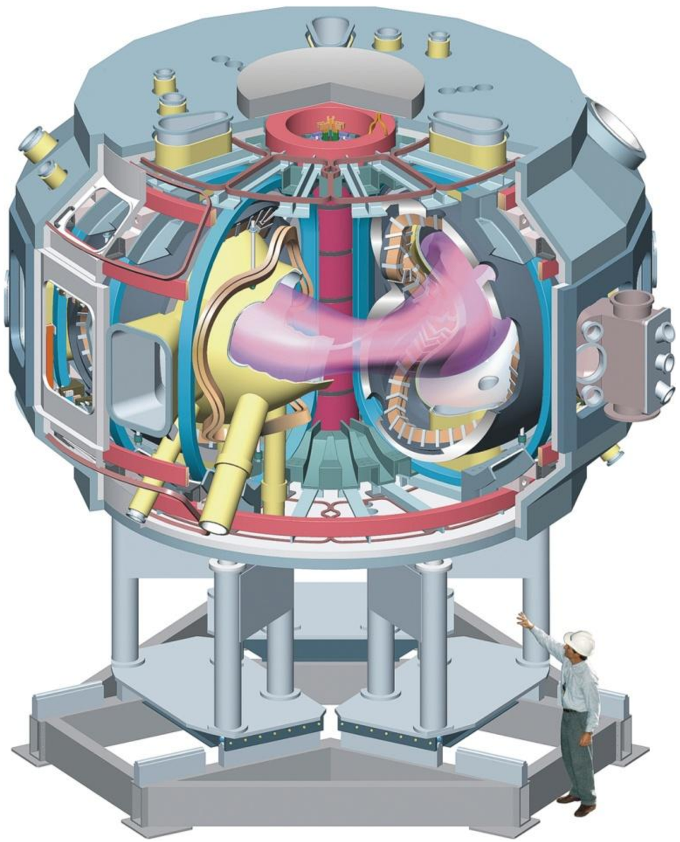


Applied in W7X



Compact stellarator NCSX princeton

Compact stellarators are a challenge.
The plasma current in this device is not driven by a transformer.



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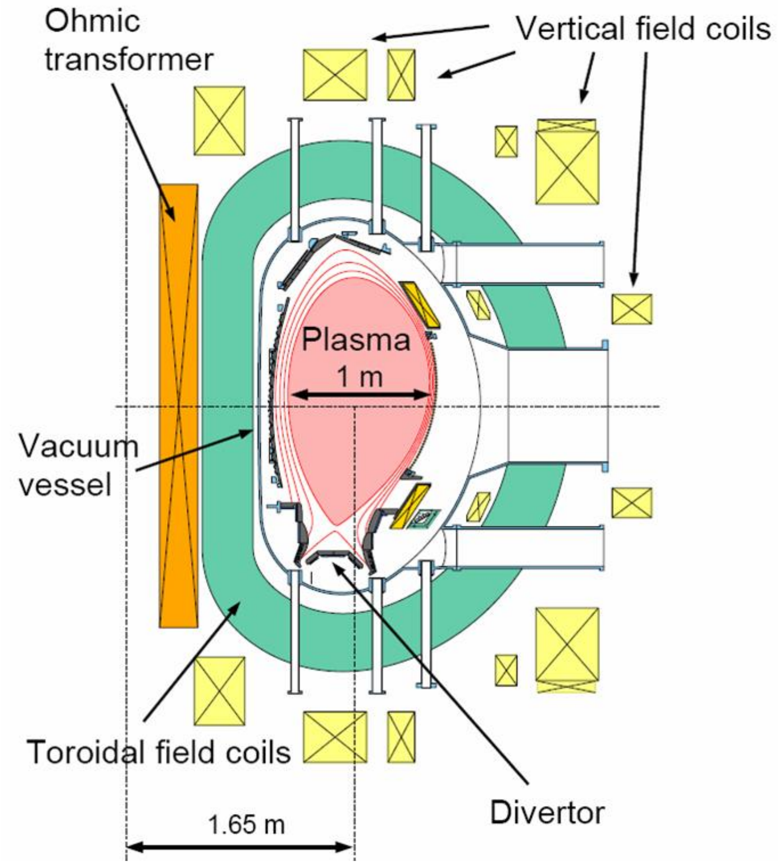
A tokamak

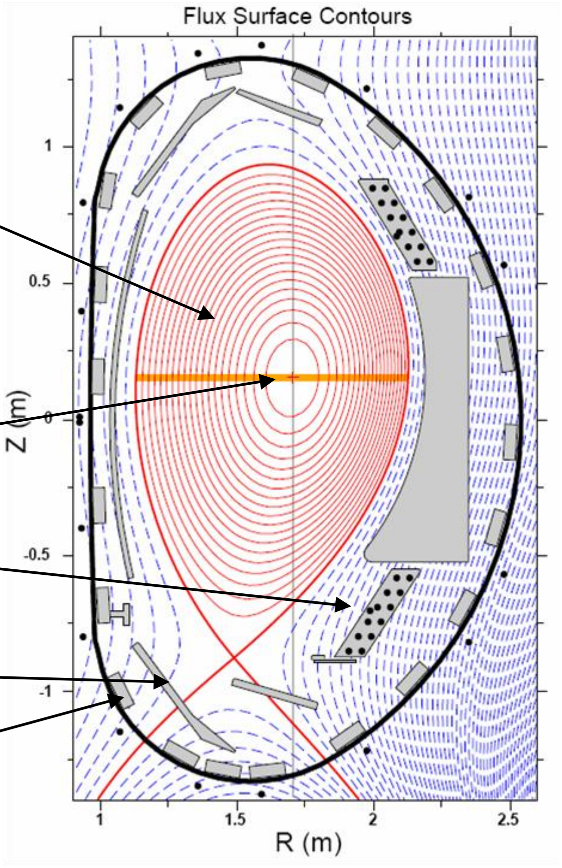
- Plasma (purple) Notice the shape
- Surrounded by plates
- Vessel (pumps)
- Coils mostly outside vessel (finite reaction time)
- Ohmic transformer / toroidal field coils (green)



Schematic Drawing of the poloidal cross section of the ASDEX Upgrade tokamak

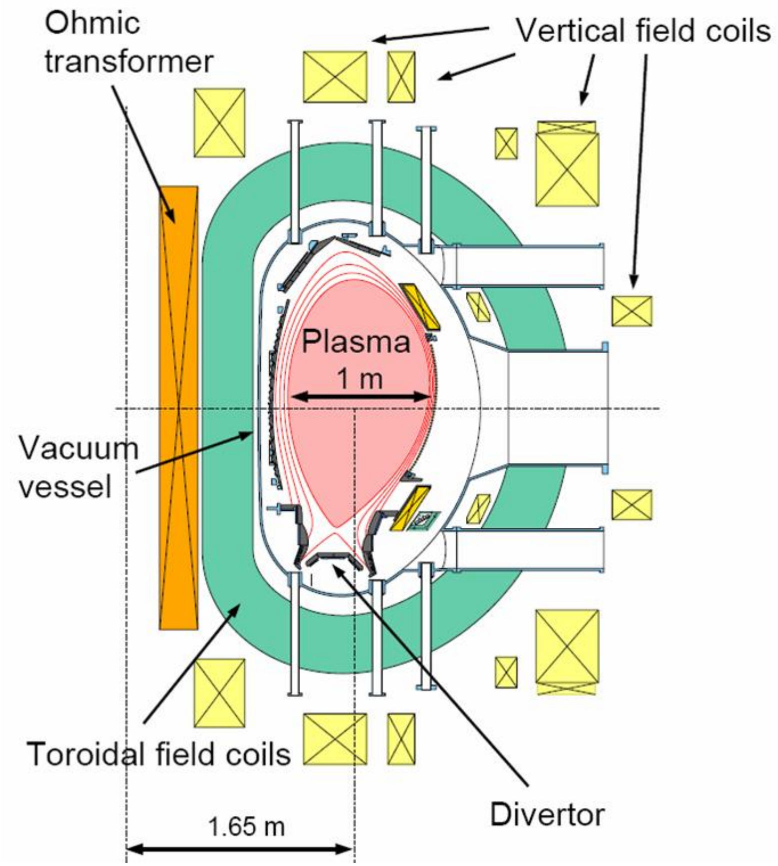
A tokamak

- Magnetic surfaces are the surfaces traced out by the magnetic field
- They are nested (best confinement)
- Centre is shifted outward
- Large passive coils
- Magnetic field ends on a set of plates
- Large set of small coils for diagnostic purposes



Plasma manipulation

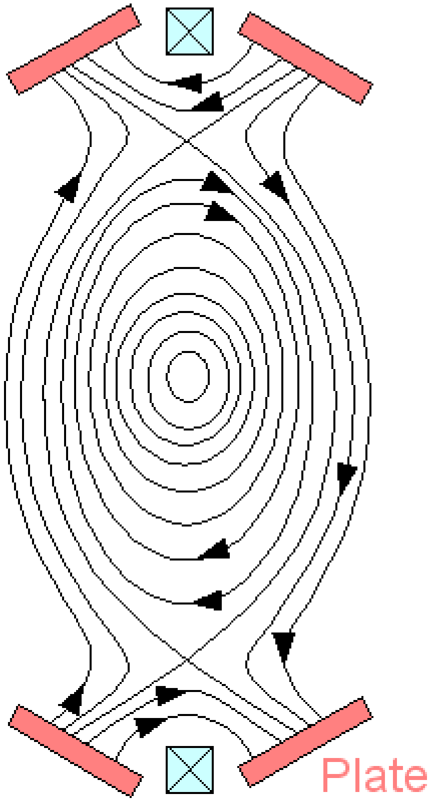
- Several coils around the plasma
- The vertical coils can shape the plasma and control its position
- Dominant shaping is the vertical elongation of the plasma



Schematic Drawing of the poloidal cross section of the ASDEX Upgrade tokamak

Plasma elongation

- Plasma can be diverted onto a set of plates
- Close to the coils the field of the coils dominates
- In between the field is zero resulting in a purely toroidal field line
- This shows up as an X-point in the figure of the magnetic surfaces
- Surfaces outside the one with the X-point are not close with the field ending on the plates



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Preventing impurities – divertor

Given a fixed electron density, impurities dilute the fuel

$$n_e = n_D + n_T + Z n_I$$

Density of the impurity with charge *Z*

Acceleration of electrons by the ions in the plasma lead to radiation losses known as 'Bremstrahlung'

The radiation scales with the average charge. High Z impurities enhance the radiation
High Z-impurities also lead to energy los

Plasma facing components have to be chosen carefully

Carbon / Beryllium have a low Z

Carbon does not melt but has the proble
that it binds well with Tritium (contamina
of the machine)

Tungsten has very high Z, but takes the
heat loads very well

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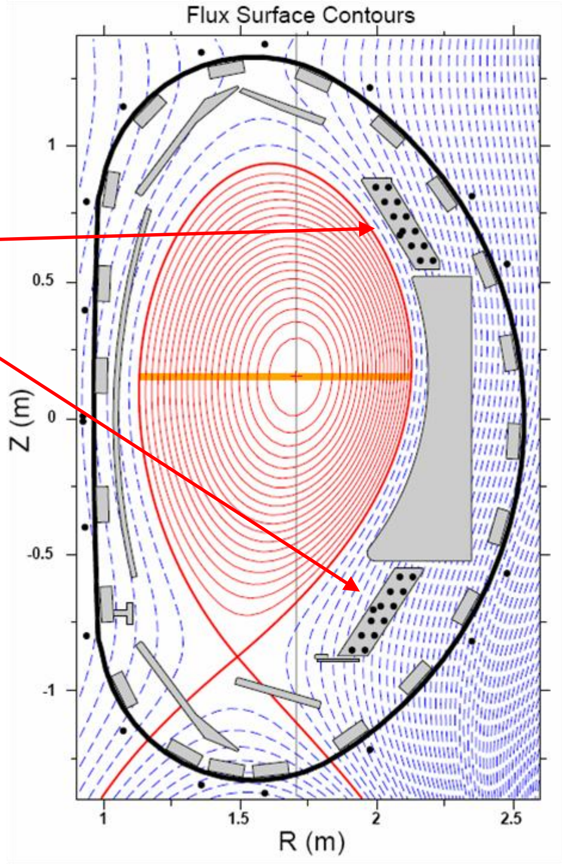
Plasma instabilities

- Plasma vertical instability with growth rates of the order 10^6 s^{-1}
- For this reason the passive coils have been placed in the plasma
- When the plasma moves it changes the flux through the coils which generates a current that pushes the plasma back
- Growth rate is reduced to the decay time of the current in the coils (ms)



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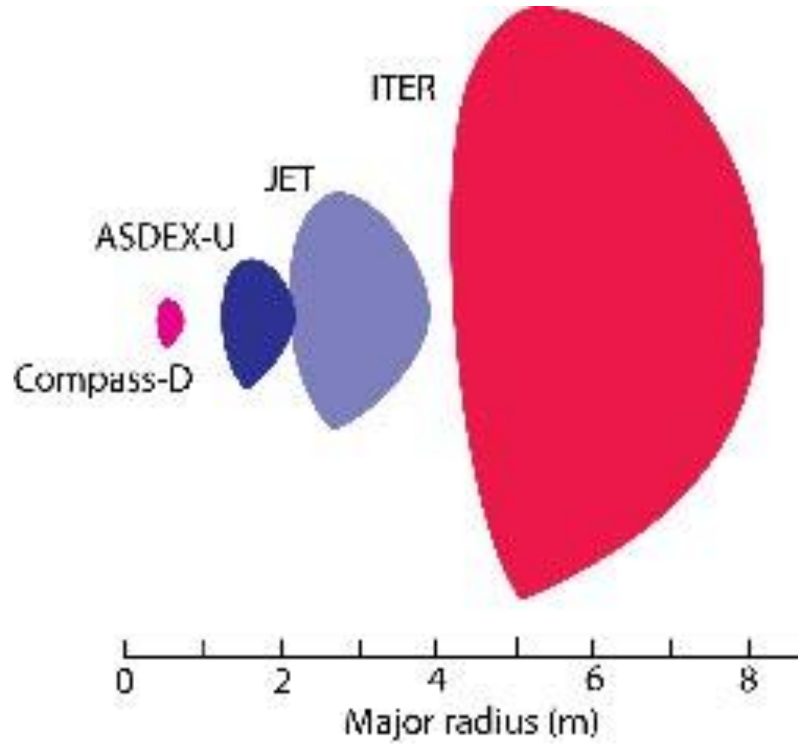
ITER

What is ITER?

- ITER = (International Tokamak Experimental Reactor) is the next step in tokamak research.
- Largest tokamak in world
- Project has started in Cadarache, France
- Joint project of Europe, China, Japan, Korea, Russia (and the US).



Cross section of the plasma area in the poloidal plane for different devices

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More on ITER

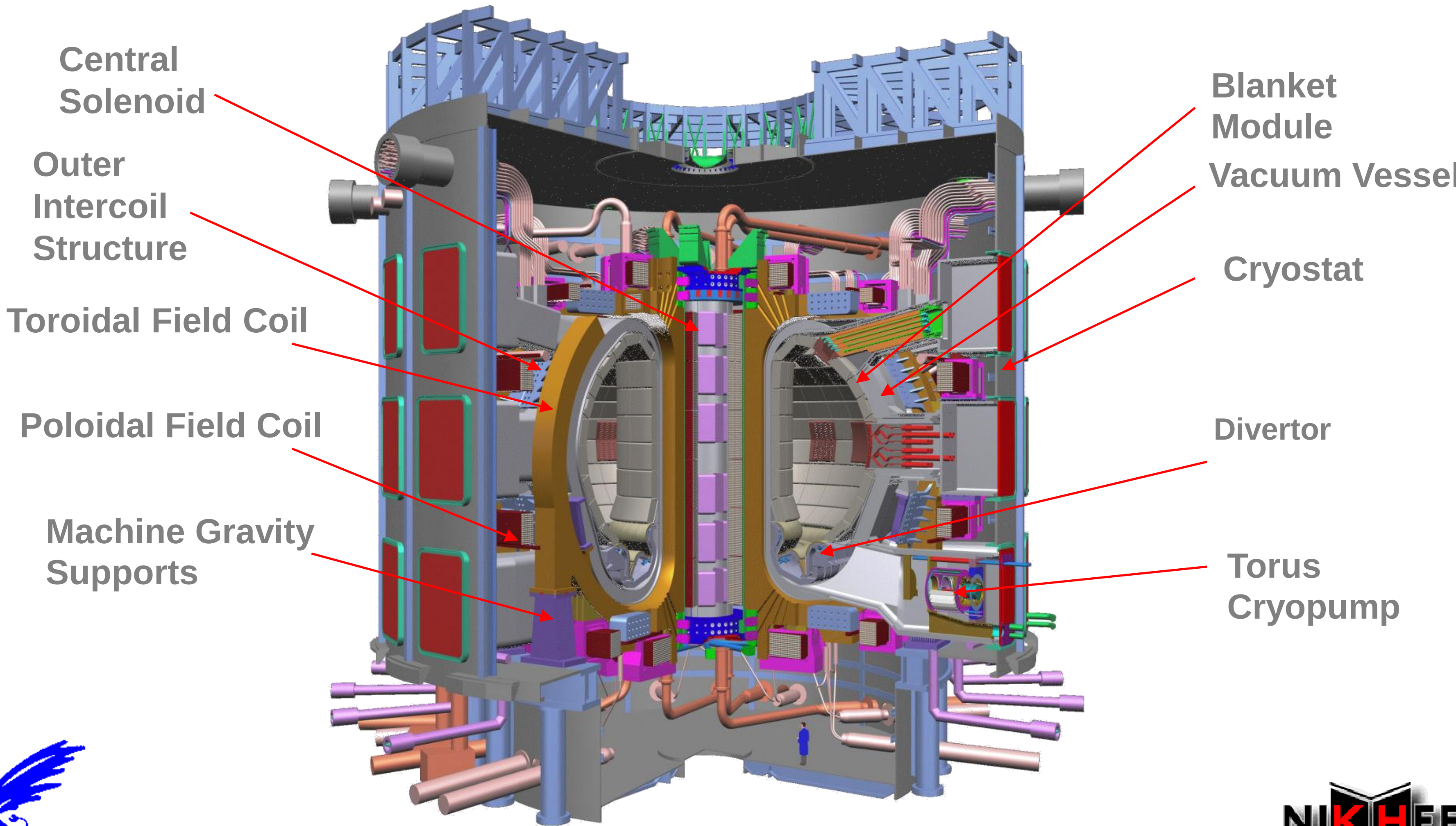
Main objective

- Demonstrate the feasibility of a fusion reactor. This includes generating a plasma that is dominantly heated by fusion reactions, but also demonstrating that an integrated design can meet the technological constraints

Project

- Cost 5 billion euro construction + 5 billion euro for operation (most expensive experiment on earth)
- Construction of building started in 2008 /Assembly starting on 2012
- Assembly estimated to last 7 years
- 20 years of operation planned

Design - main features



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ITER parameters

• Total fusion power	500 MW
• Q = fusion power/auxiliary heating power (inductive)	≥10
• Average neutron wall loading	0.57 MW/m^2
• Plasma inductive burn time	≥ 300 s
• Plasma major radius	6.2 m
• Plasma minor radius	2.0 m
• Plasma current	15 MA
• Vertical elongation @95% flux surface/separatrix	1.70/1.85
• Triangularity @95% flux surface/separatrix	0.33/0.49
• Safety factor @95% flux surface	3.0
• Toroidal field @ 6.2 m radius	5.3 T
• Plasma volume	837 m^3
• Plasma surface	678 m^2
• Installed auxiliary heating/current drive power	73 MW (100 MW)

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Main differences ....

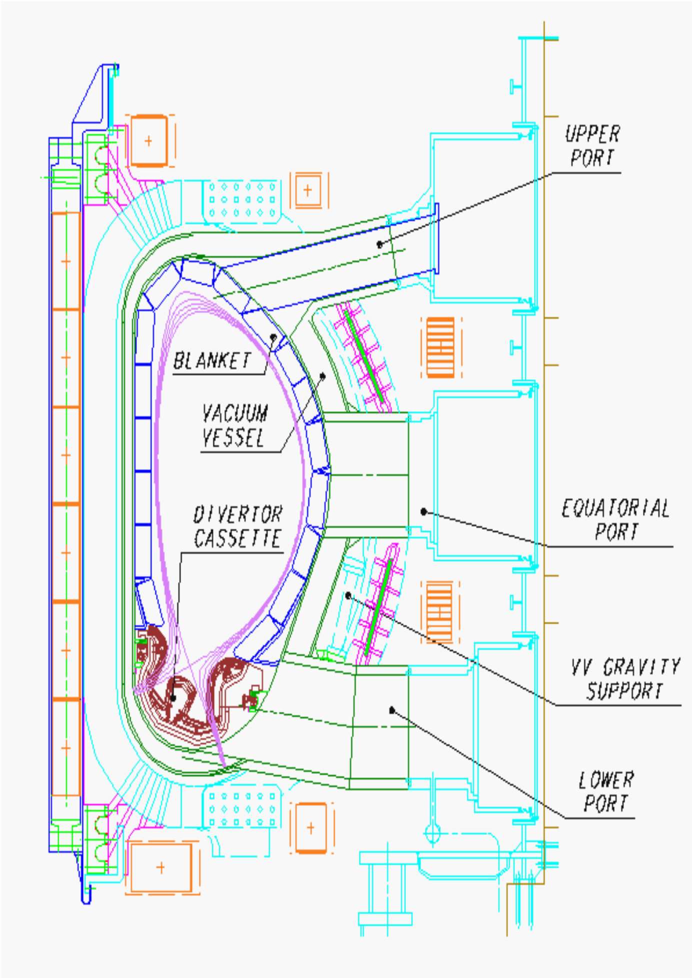
- All components must be actively cooled
- Superconducting coils. For 5 T and a major radius of 6 m one can work out the total current in the toroidal field coils

$$I = \frac{2\pi}{\mu_0} B_t R \rightarrow 150 \text{ MA}$$

- If the electric field is 1 V/m this will lead to a dissipation (EJ Volume) of 4.5 GW. Much more than the fusion power.
- The best superconductor has a critical magnetic field of around 11 T. This limits the field in the plasma to 5 T !!!!
- Neutron shielding. Superconducting coils must be shielded from the neutrons, which could damage the material or lead to the quenching of the superconductor

Design - vessel

- The double-walled vacuum vessel is lined by modular removable components, including divertor cassettes, and diagnostics sensors, as well as port plugs for limiters, heating antennae, and diagnostics.
- The total vessel/in-vessel mass is ~10,000 t.
- These components absorb most of the radiated heat and protect the magnet coils from excessive nuclear radiation. The shielding is steel and water, the latter removing heat from absorbed neutrons.



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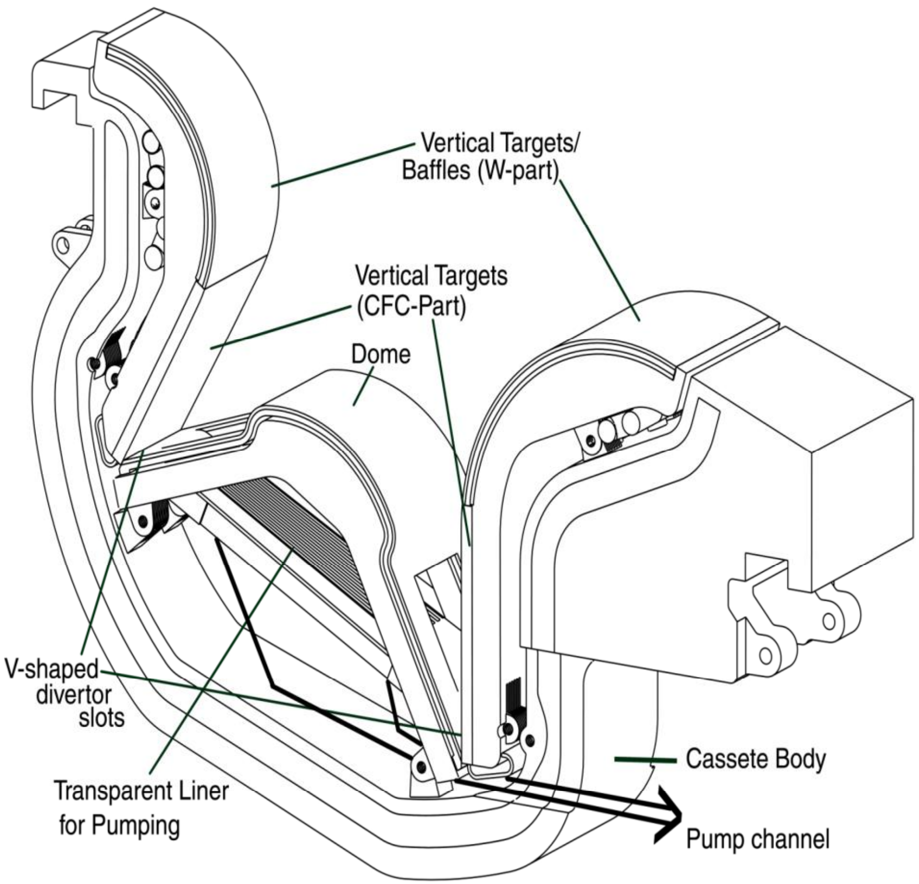
Design - divertor



•The divertor is made up of 54 cassettes. The target and divertor floor form a V which traps neutral particles protecting the target plates, without adversely affecting helium removal. The large opening between the inner and outer divertor balances heat loads in the inboard and outboard channels.

•The design uses C at the vertical target strike points. W is the backup, and both materials have their advantages and disadvantages. C is best able to withstand large power density pulses (ELMs, disruptions), but gives rise to dust and T co-deposited with C which has to be periodically removed. The best judgement of the relative merits can be made at the time of the experiments.

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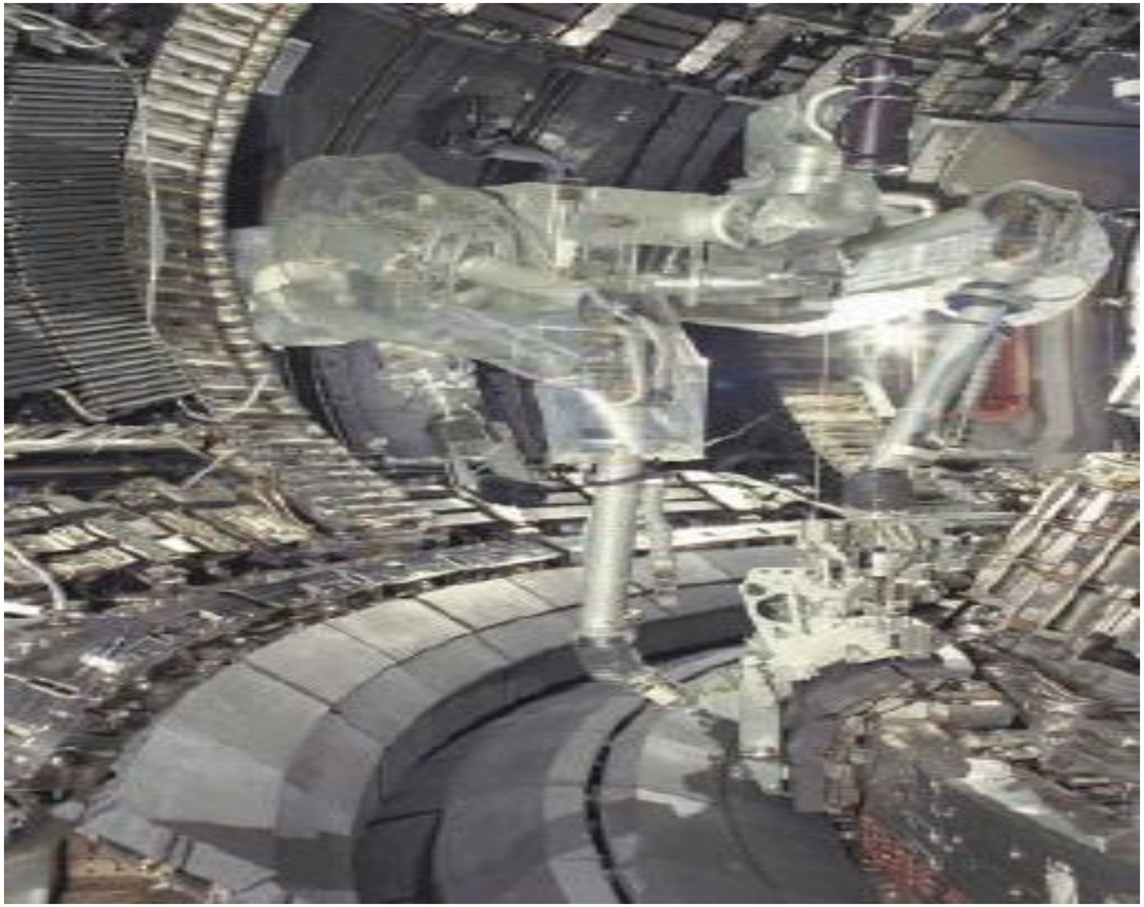
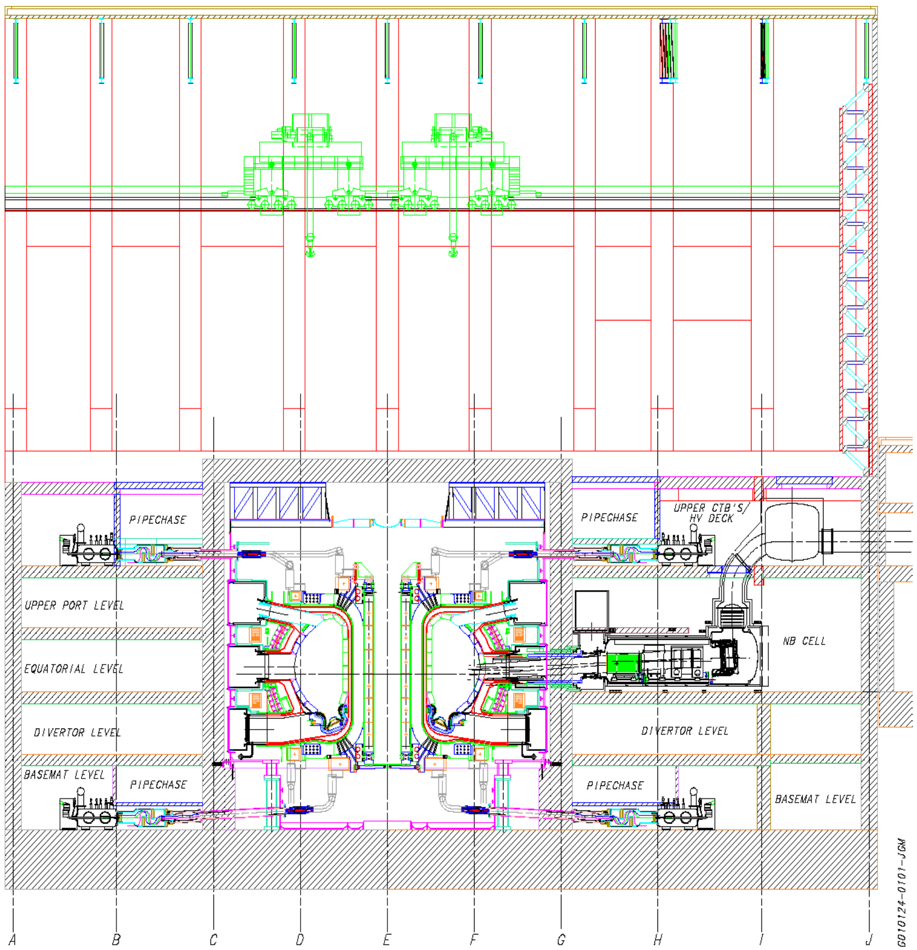
Remote handing to replace to cassettes

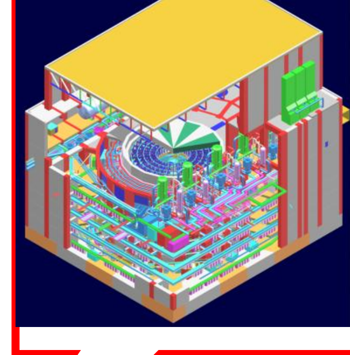


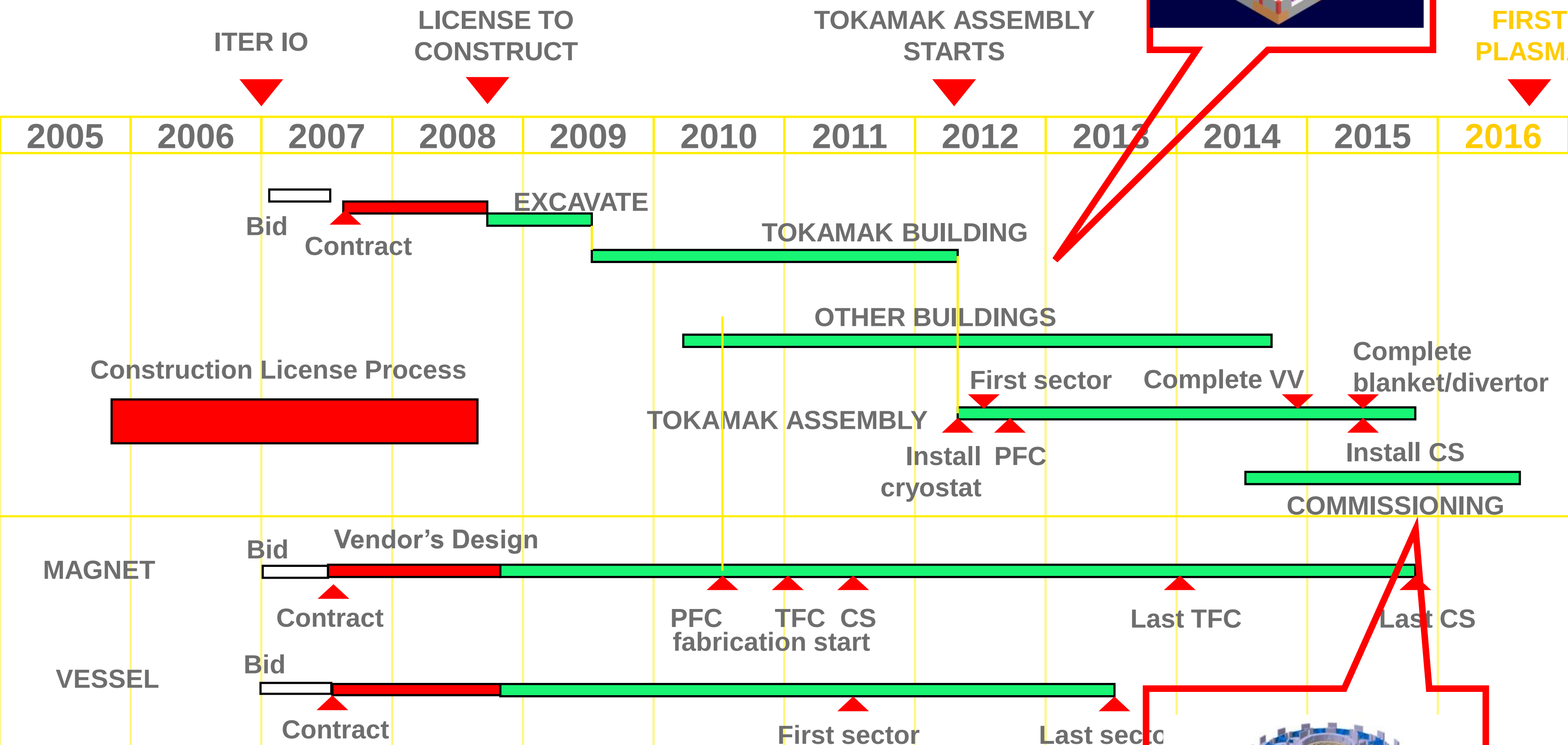
Design – Tokamak building

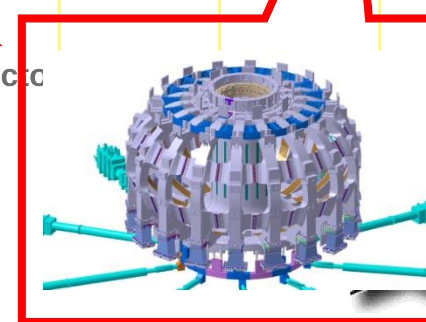


- Provides a biological shield around cryostat to minimize activation and permit human access.
- Additional confinement barrier.
- Allows contamination spread to be controlled.
- Provides shielding during remote handling cask transport.
- Can be seismically isolated.

Schedule







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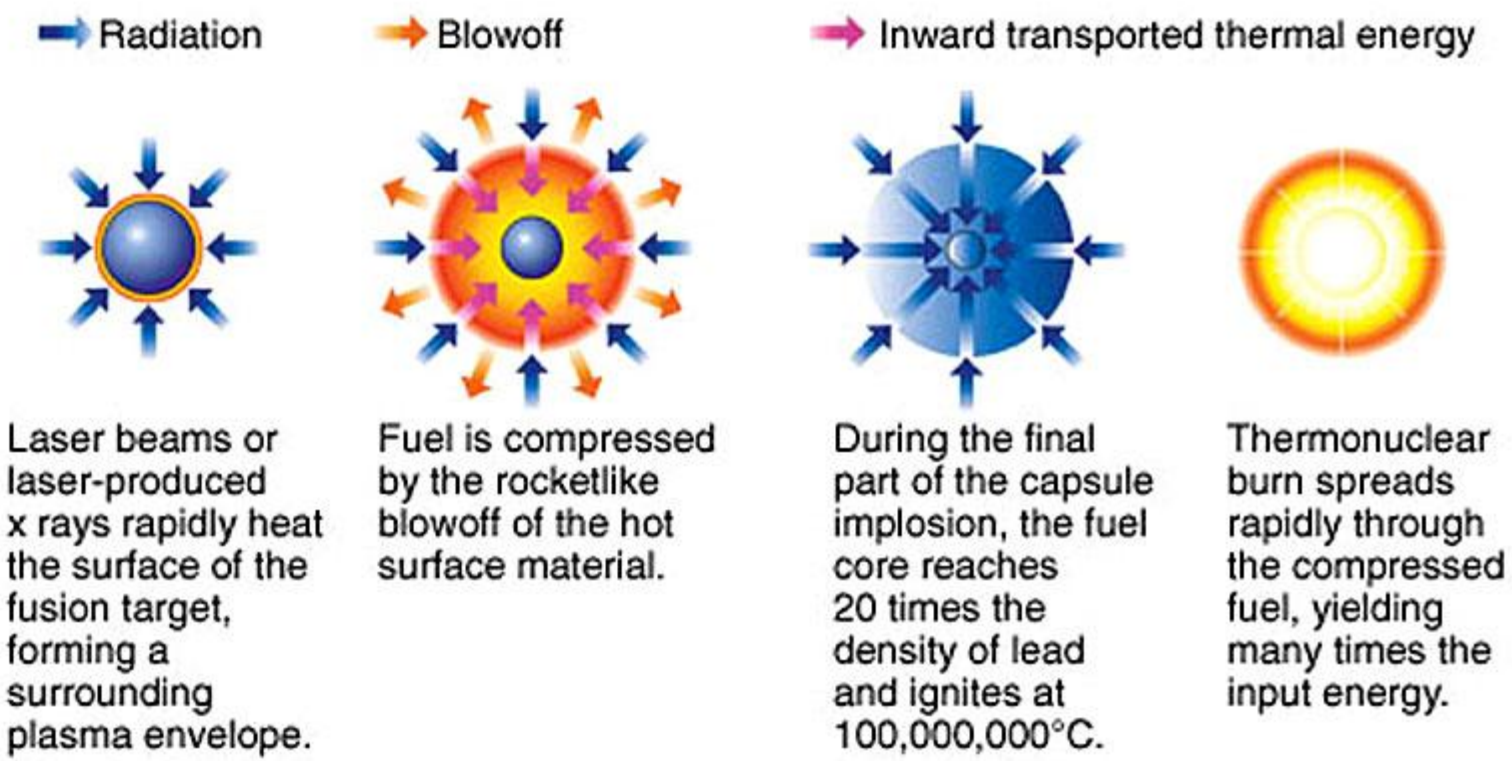
Inertial confinement fusion concept



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Plasma conditions during ICF

- Before compression and ignition

Density:	solid DT ice at 0.225 g/cm^3 and gas
Temperature:	few Kelvin

- During the burn phase

Density:	300 to 1000 times liquid density
	300 to 1000 g/cm^3 ≈ 10^{26} cm^{-3}
Temperature:	around 10.000.000 K or 10 keV
Pressure:	around 10^{12} bar

- Confinement time needed: around 200 ps

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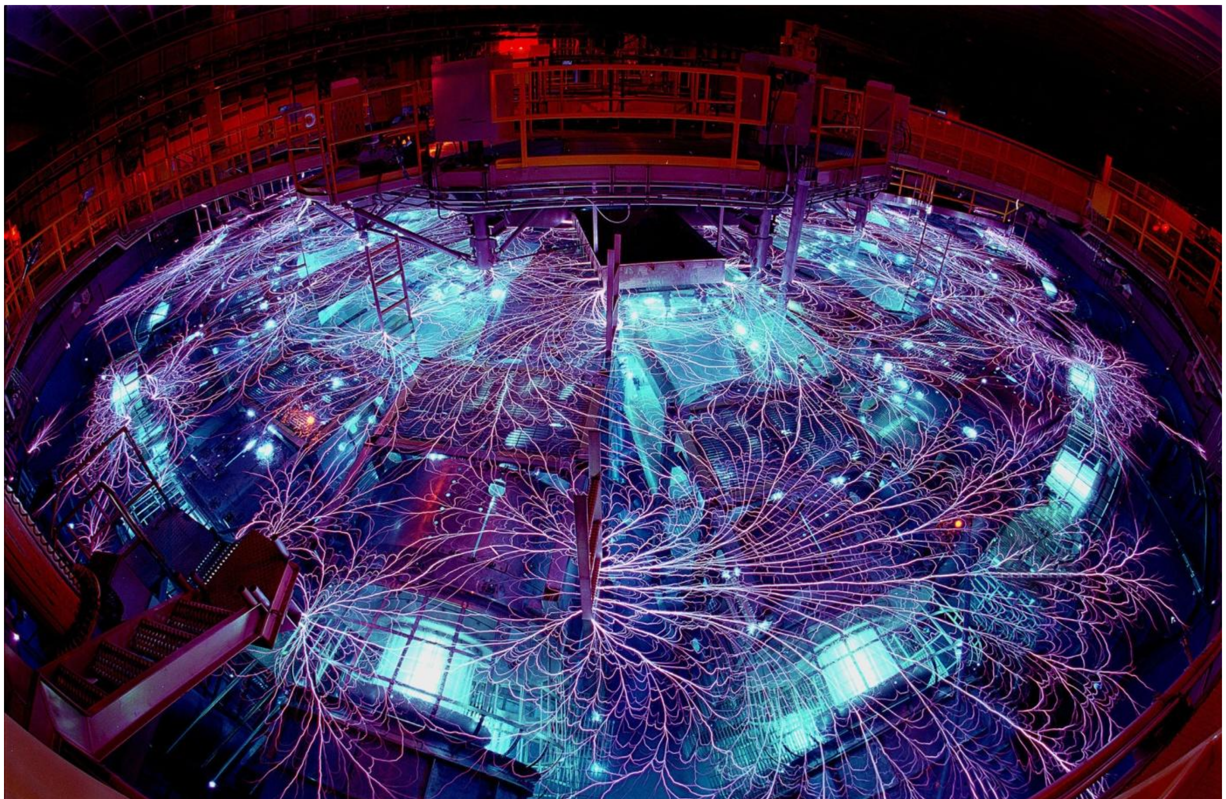
Possible drivers: Z - pinches



Z-Machine, Sandia labs, Albuquerque USA

Advantages:

- Good energy coupling (many x-rays)
- Large Targets

Disadvantages:

- Very slow (one shot / day)
- Only one device worldwide

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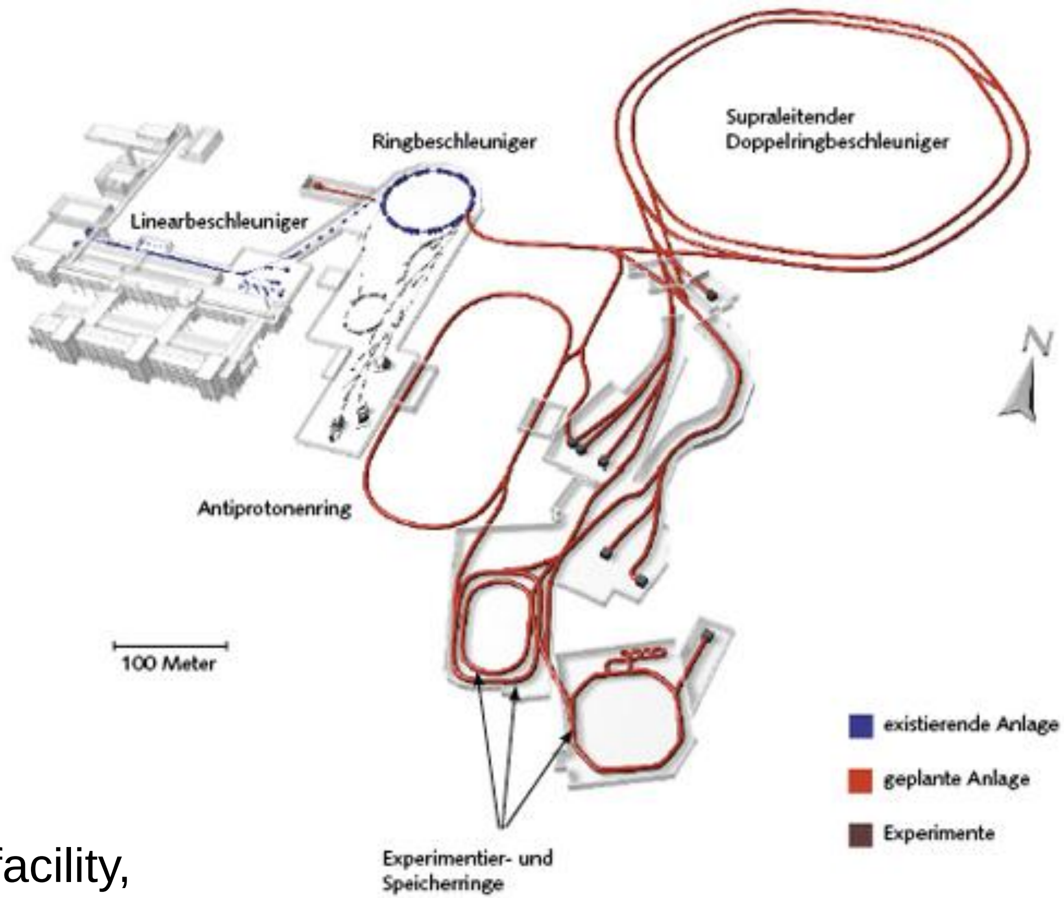
Possible drivers: ion beams



FAIR facility, Darmstadt, Germany

10 to 20 rings needed for fusion power plant!

Advantages:

- Excellent conversion from electric power to beam energy
- Large targets

Disadvantages:

- Concept was never tested
- Beam intensity is still too low

NIKHEF

Possible drivers: lasers (best shot)

National Ignition Facility (NIF), Livermore, USA

Advantages:

- Well advanced technology
- Good control of energy release

Disadvantages:

- Bad energy conversion
- Very expensive to build

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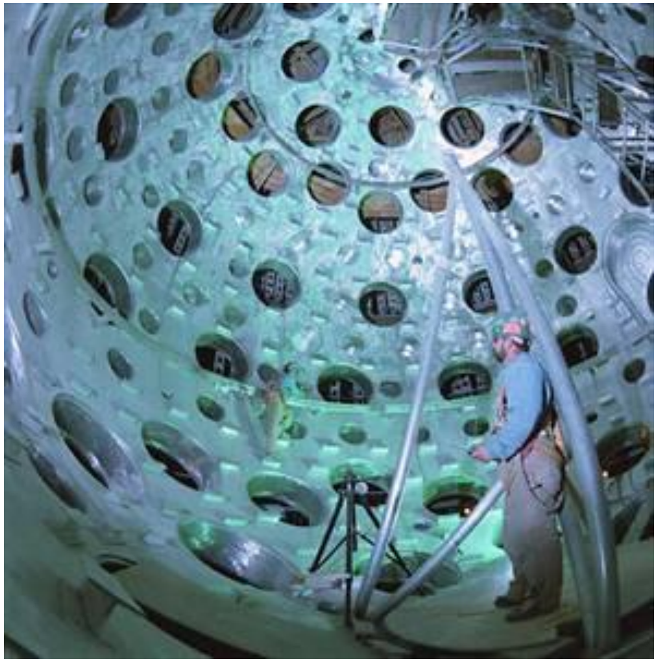
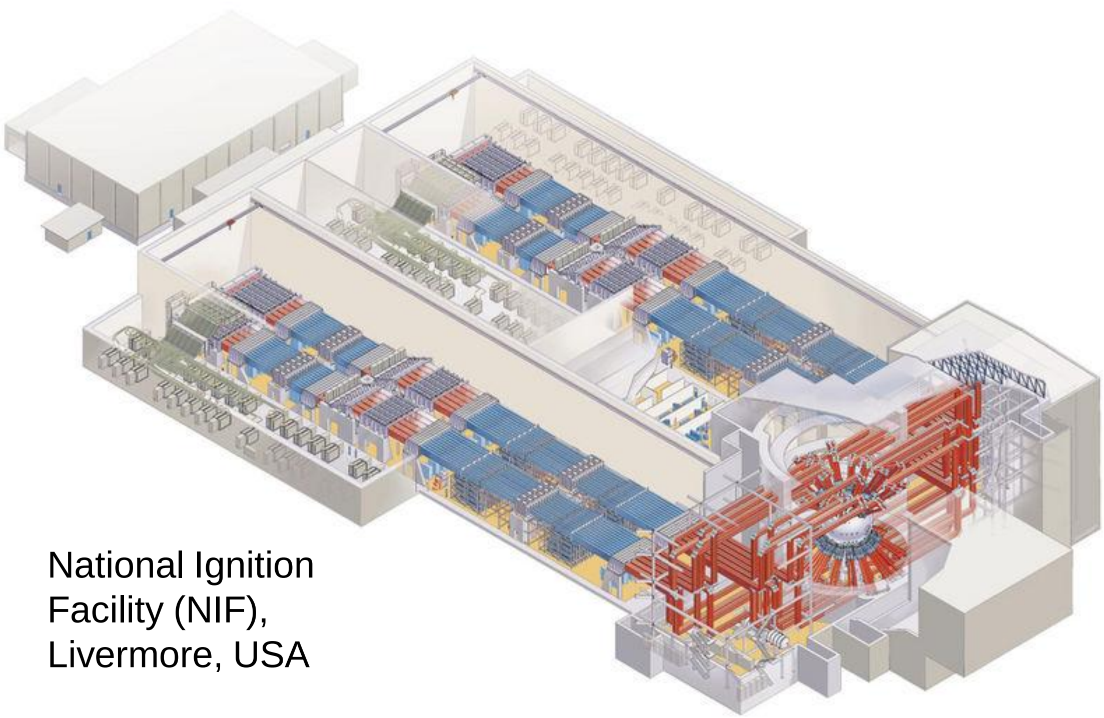
Possible drivers: lasers



Target chamber, NIF with 192 laser beams



National Ignition Facility (NIF), Livermore, USA

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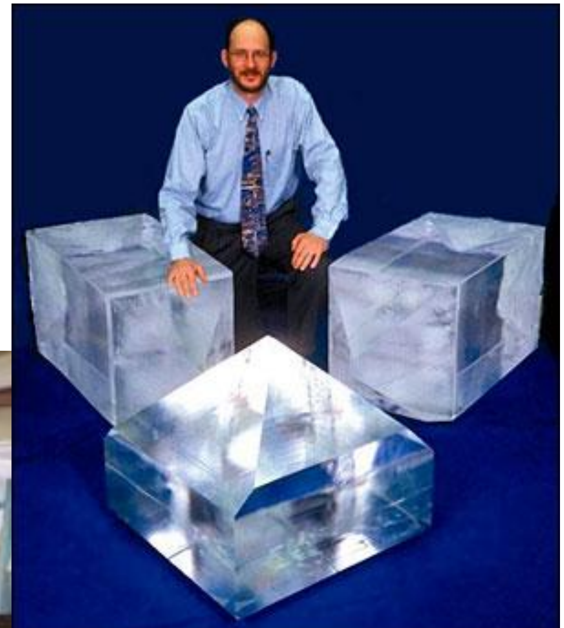
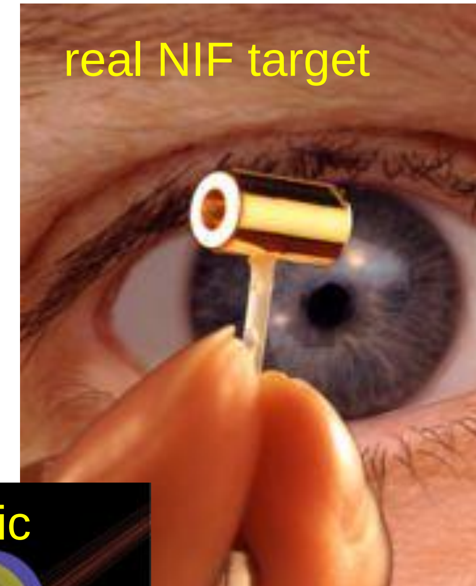
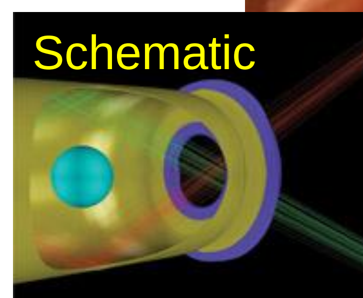
Possible drivers: lasers

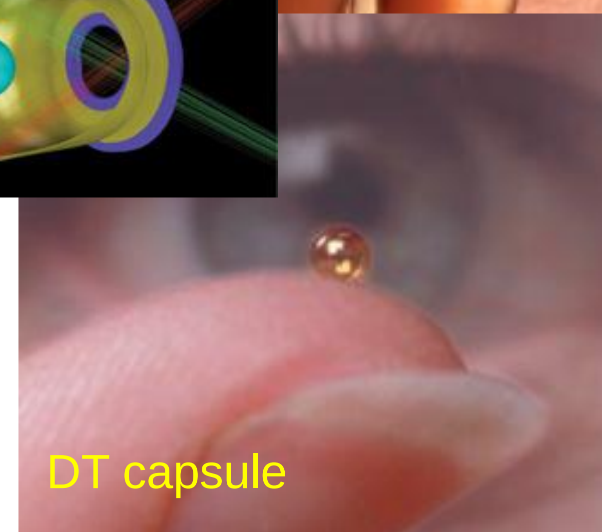
~1000 large Optics:



192 beam lines:







Engineering challenges at NIF

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Problems blocking fusion energy

Technical and engineering problems

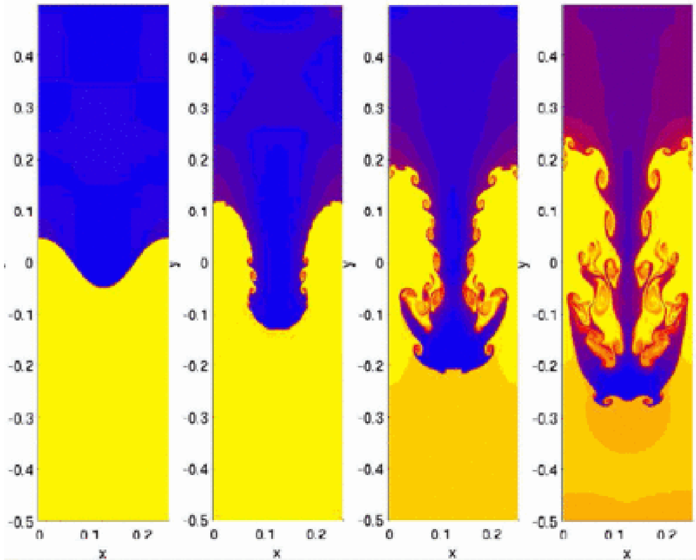
- High energy drivers are expensive and untested
- Energy conversion is too low (gain of >100 needed now)
- Repetition rate of drivers are too low (3-10 Hz needed)

Physics Problems

- Instabilities and Mixing

  Rayleigh-Taylor unstable compression
  Break of symmetry destroys confinement

- How to improve energy coupling into target
- What is the best material for the first wall?



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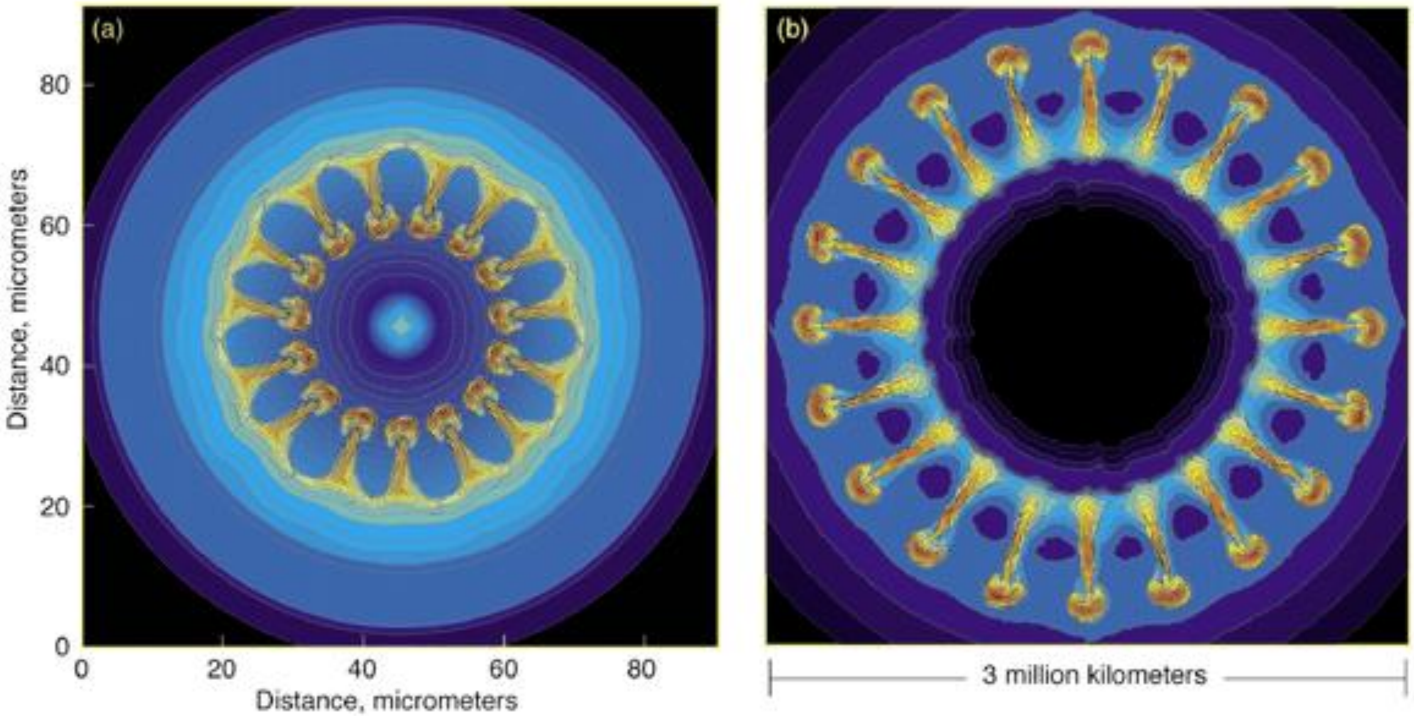
Rayleigh-Taylor Instability – spherical implosions / explosions



Striking similarities exist between hydrodynamic instabilities in (a) inertial confinement fusion capsule implosions and (b) core-collapse supernova explosions. [Image (a) is from Sakagami and Nishihara, *Physics of Fluids B* **2**, 2715 (1990); image (b) is from Hachisu et al., *Astrophysical Journal* **368**, L27 (1991).]

➢**Energy must be delivered as sysmmetric as possible!**

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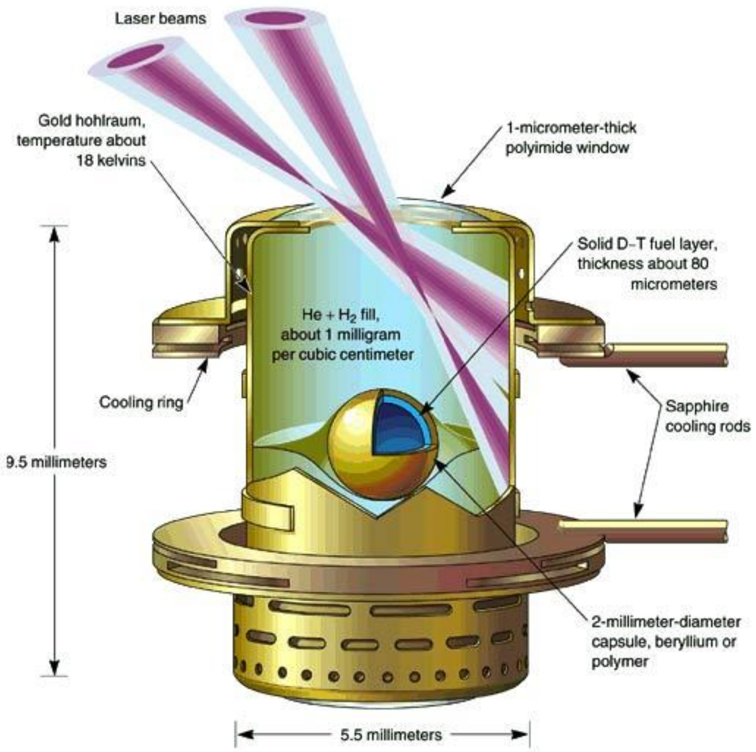
NIKHEF

Relaxing the symmetry conditions – indirect drive



NIF design (laser)

Hohlraum for the Z-machine

- Laser beams heat walls
- Walls emit thermally (X-rays)
- X-rays compress and heat the fusion capsule
- X-rays highly symmetric!

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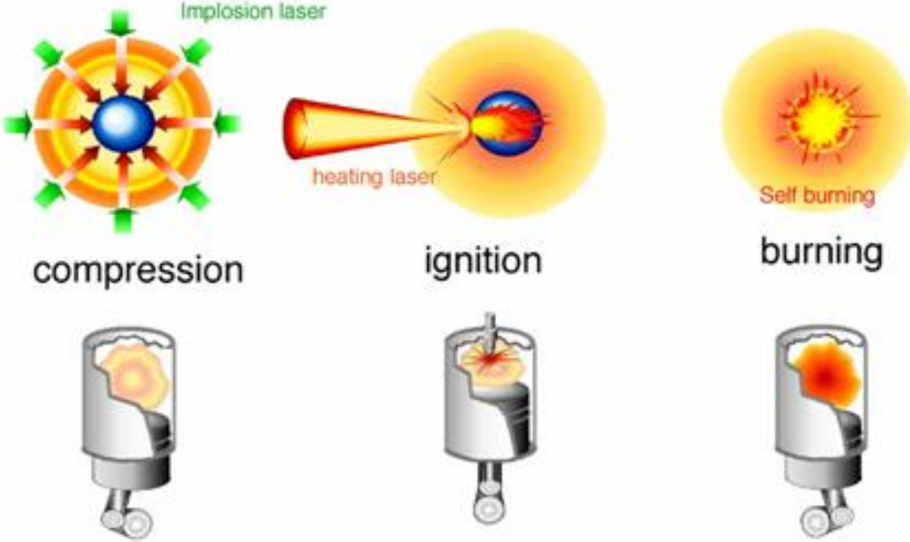
NIKHEF

Relaxing the symmetry conditions – fast ignition



Fast ignition scheme
with many facets

- Idea: separate compression and ignition with two pulses
- ➢ Less compression, cooler targets, lower densities
- Problem: How can energy be transferred to hot spot?

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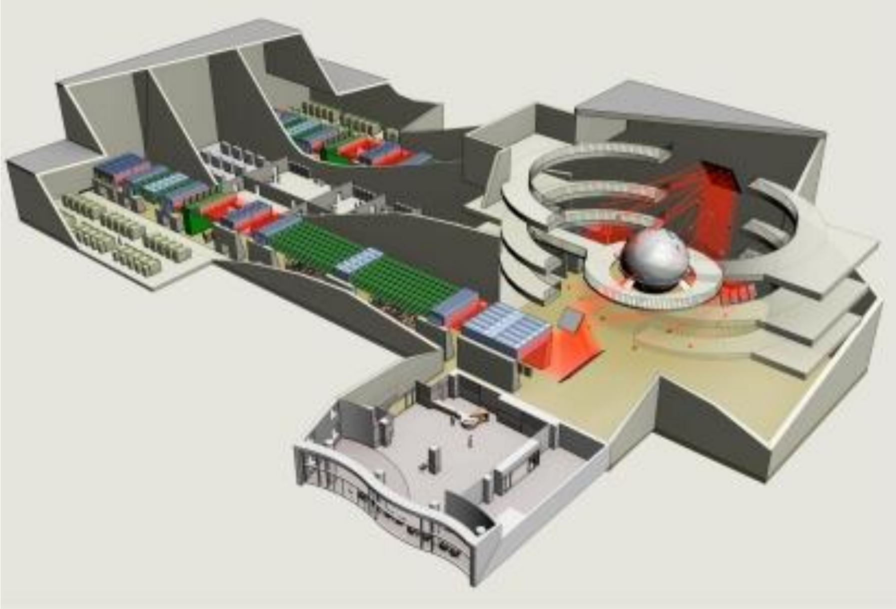
NIKHEF

Interesting experiments to come

- National Ignition Facility (NIF, Livermore, USA)
  - More than 90% completed, first tests done
  - First full scale experiments this year; ignition in 2010?
- Laser Mega-Joule (LMJ, France)
  - Commissioning (full scale) in 2011
- FIREX I and FIREX II (ILE, Osaka, Japan)
  - Fast ignition experiments showed prove-of-principle
  - Fully integrated experiments in 2010 / 2011
- HiPER project (Europe)
  - Fast ignition proposal
  - Full funding pending
- ITER



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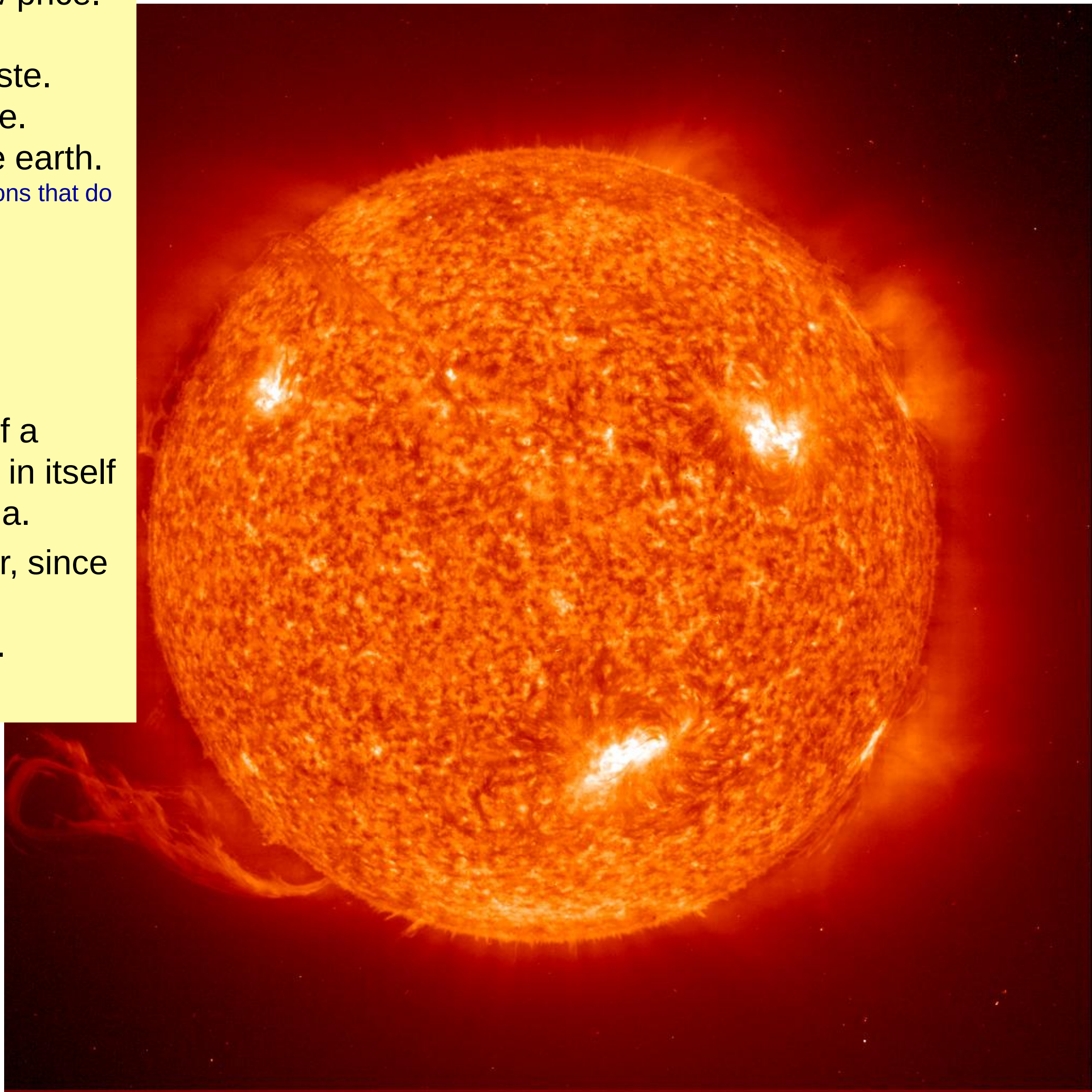
Summary

Advantages

- Large amount of fuel available, at low price.
- Fusion is CO_2 neutral.
- Only small quantity of radioactive waste.
- No risk of uncontrolled energy release.
- Fuel is available in all locations of the earth.
  - Fusion is of interest especially for those regions that do not have access to other natural resources.
  - Geo-political importance
- Non-proliferation of weapon material

Disadvantages

- To be demonstrated. The operation of a fusion reactor is hindered by several, in itself rather interesting, physics phenomena.
- The cost argument is not all that clear, since the cost of the energy will be largely determined by the cost of the reactor.



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