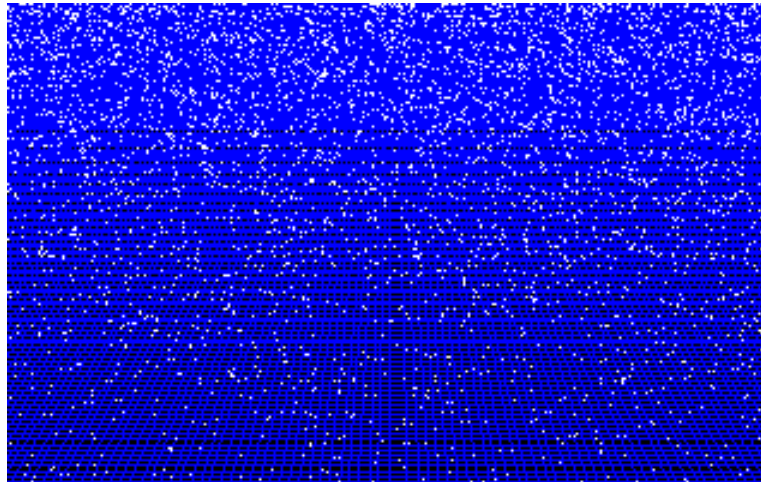


Energie

FEW cursus



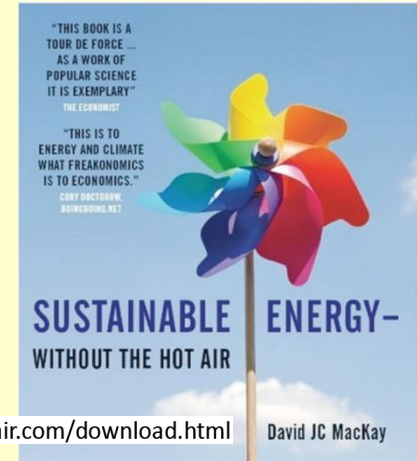
Jo van den Brand en Roel Aaij

www.nikhef.nl/~jo/energie

29 april 2013

Inhoud

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- **Roel Aaij**
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- **Beoordeling**
 - Huiswerk (20%), scriptie (20%), tentamen (60%)
- **Boeken**
 - Energy Science, John Andrews & Nick Jelley
 - Sustainable Energy – without the hot air, David JC MacKay
 - Elmer E. Lewis, Fundamentals of Nuclear Reactor Physics
- **Inhoud van de cursus**
 - Week 1 Motivatie, exponentiële groei, CO2 toename, broeikaseffect, klimaat
 - Week 2 Energieverbruik: transport, verwarming, koeling, verlichting, landbouw, veeteelt, fabricage
 - Week 3 Kernenergie: kernfysica, splijting
 - Week 4 Kernenergie: reactorfysica
 - Week 5 Kernfusie
 - Week 6 Energie, thermodynamica
 - Entropie, enthalpie, Carnot, Otto, Rankine processen, informatie
 - Energiebronnen: fossiele brandstoffen (olie, gas, kolen), wind, zon (PV, thermisch, biomassa), waterkracht, geothermisch
 - Week 7 Fluctuaties: opslag (batterijen, water, waterstof), transport van energie, efficiëntie
 - Energie: scenario's voor Nederland, wereld, fysieke mogelijkheden, politiek, ethische vragen, economische aspecten

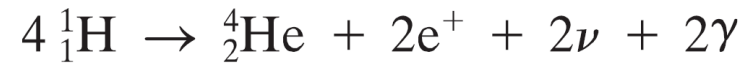
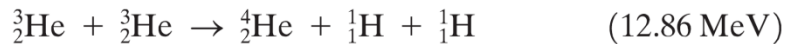
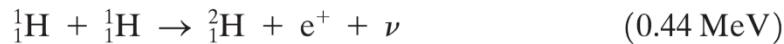


Gratis te downloaden

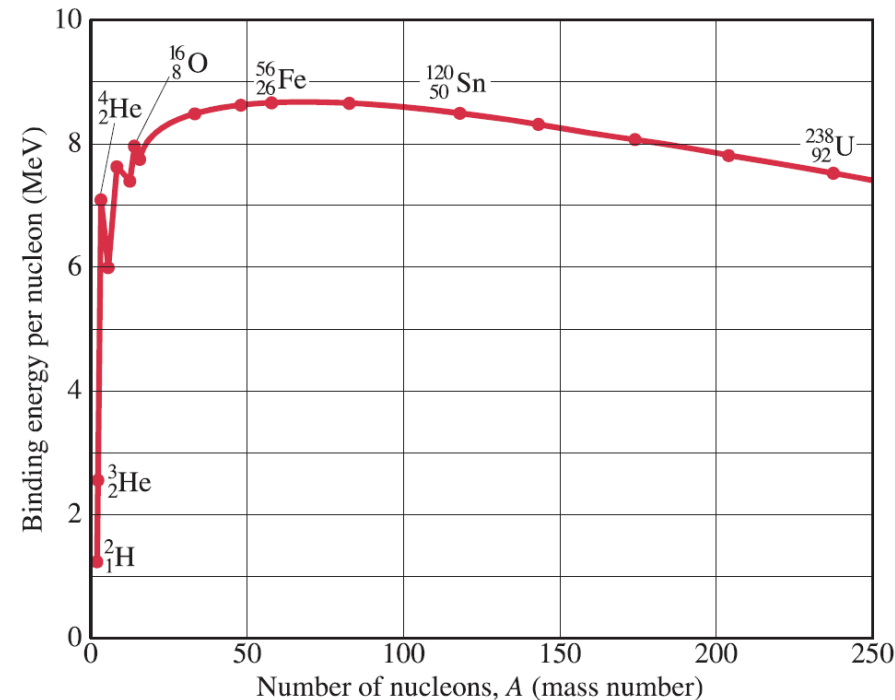
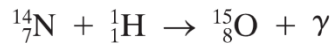
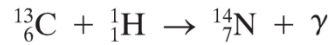
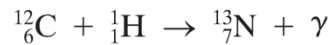
Kernfusie

Energie komt vrij bij de fusie van kernen

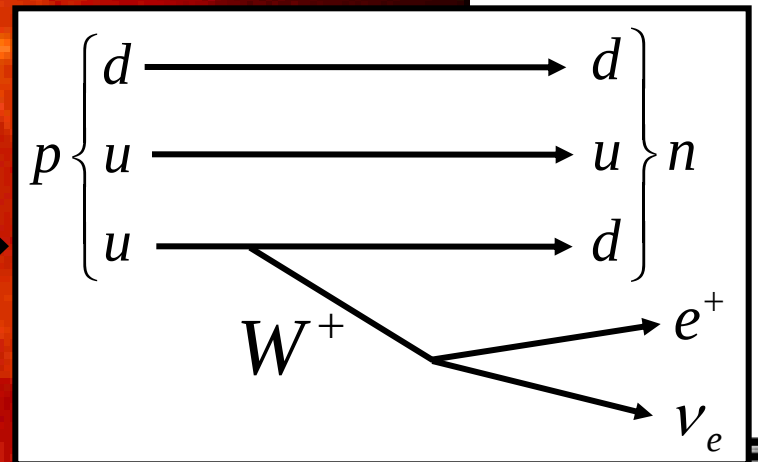
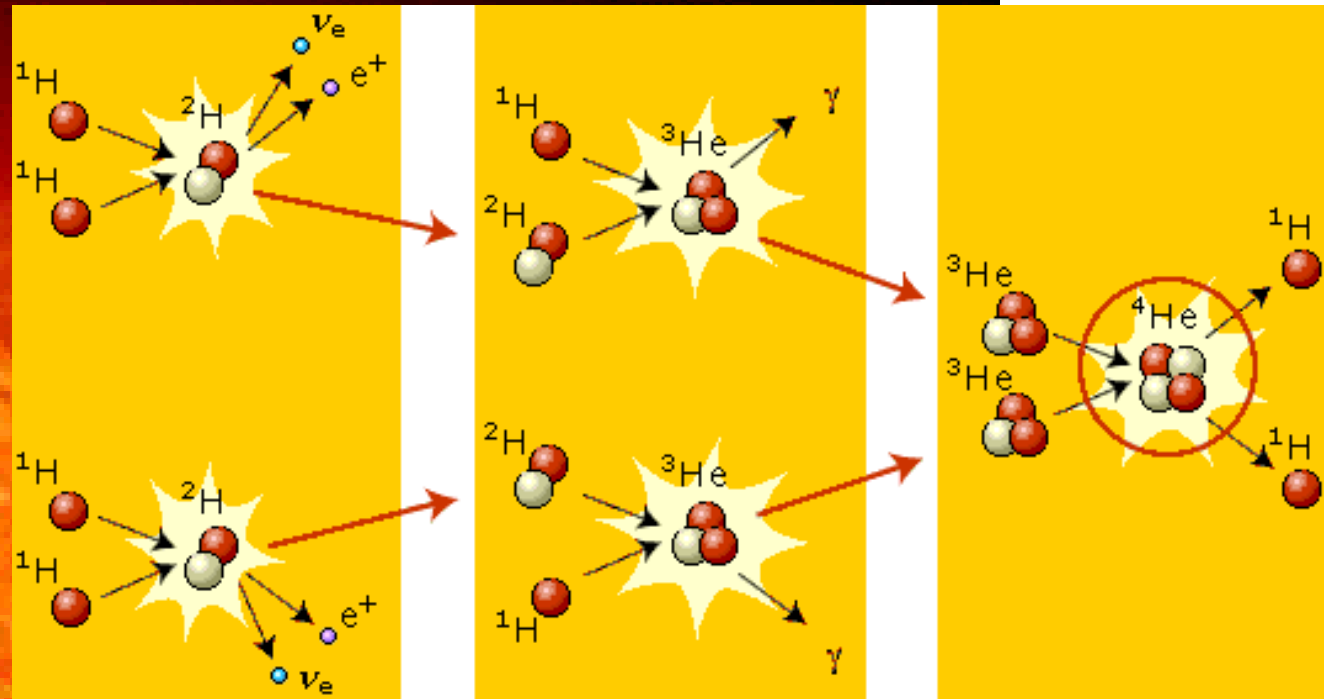
Proton – proton cyclus in de Zon levert 26.7 MeV



CNO cyclus (hete sterren)

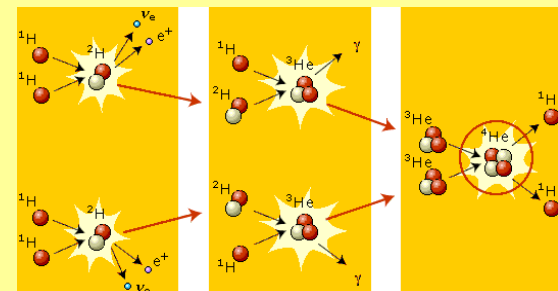


“Zwakke” wisselwerking



Fusie

- Mechanisme van energie productie in sterren
- Elke seconde wordt er ongeveer 600 miljoen ton waterstof omgezet door de *zwakke* wisselwerking



- Power dichtheid in de Zon is slechts 0.3 W/m^3

Temperatuur en kinetische energie

Temperatuur wordt altijd gebruikt om gemiddelde energie te geven. De eenheid is weer eV, i.e.

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

met T de temperatuur en T_k de temperatuur in Kelvin.

Merk op $1 \text{ eV} = 11605 \text{ K}$ $17.56 \text{ MeV} = 2 \cdot 10^{11} \text{ K}$

- De energie komt vrij in de vorm van kinetische energie
- De kinetische energie is niet gelijk verdeeld over de eindtoestanden, omdat zowel energie als impuls behouden moeten zijn

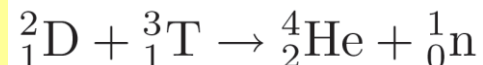
$$\begin{aligned} \frac{1}{2} m_A v_A^2 + \frac{1}{2} m_B v_B^2 &= E_{fus} \\ m_A v_A + m_B v_B &= 0 \end{aligned}$$

- Dez vergelijkingen kunnen opgelost worden en geven

$$E_A = \frac{1}{2} m_A v_A^2 = \frac{m_B}{m_A + m_B} E_{fus} \quad E_B = \frac{1}{2} m_B v_B^2 = \frac{m_A}{m_A + m_B} E_{fus}$$

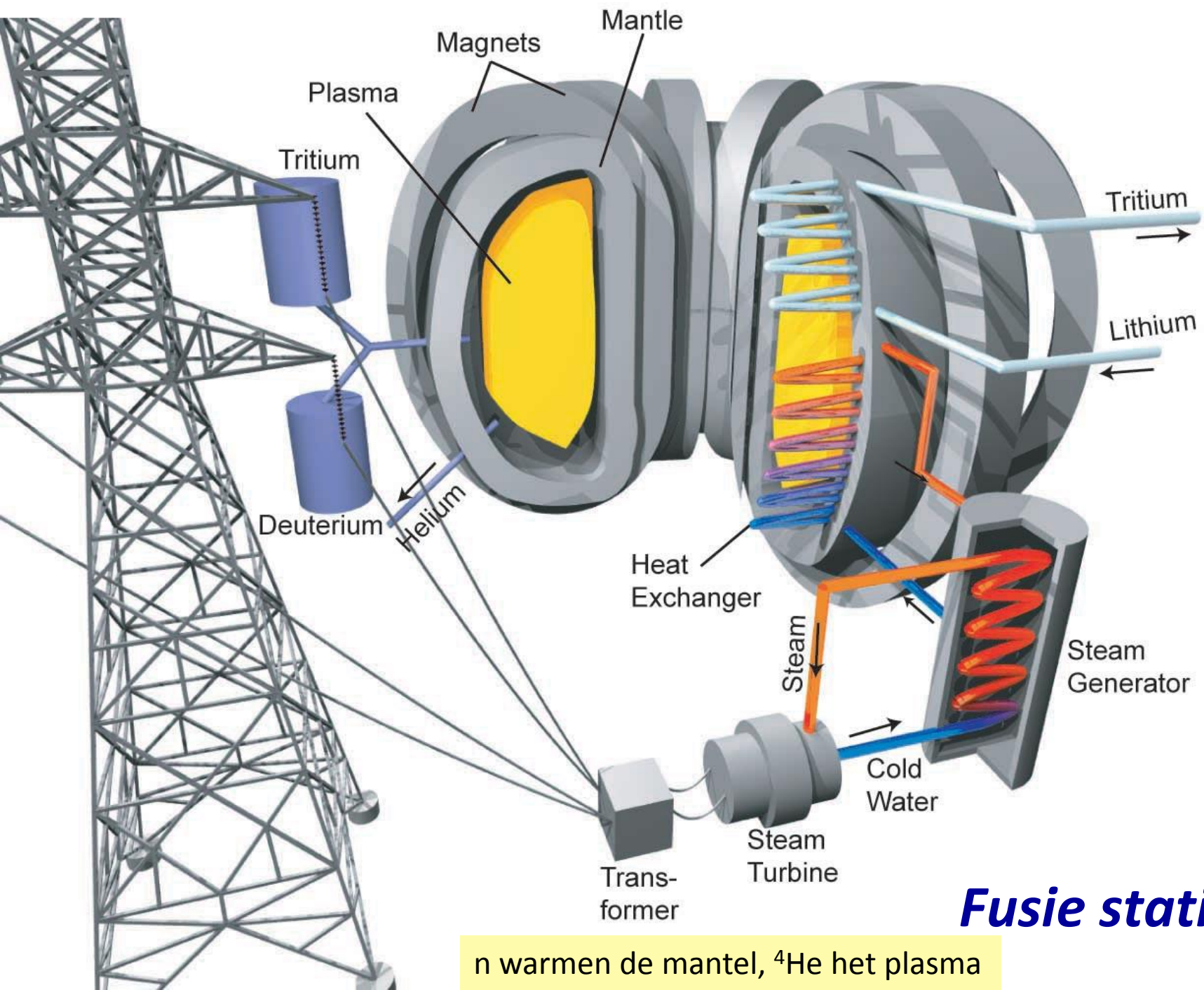
Lichtste deeltje heeft de meeste kinetische energie

- Neem de beroemde reactie



- Helium kernen zijn ongeveer 4 keer zwaarder dan het neutron en krijgen dus 20% van de energie (3.5 MeV) terwijl het neutron 80% (14.1 MeV) krijgt





Fusie station

n warmen de mantel, ^4He het plasma

Kernfusie reactoren

Gebruik isotopen van waterstof



Abondantie van deuterium is 1 gram per 80 liter water

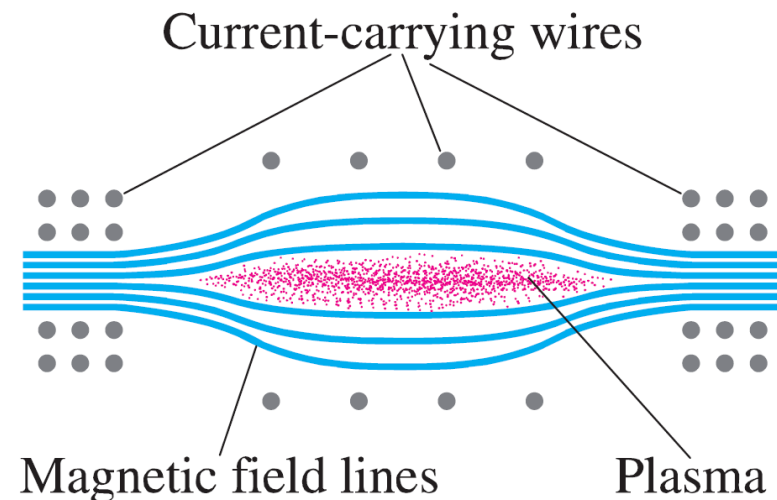
Praktisch probleem is het overwinnen van de Coulomb afstoting

Hoge temperatuur nodig in fusie reactor (paar honderd miljoen K)

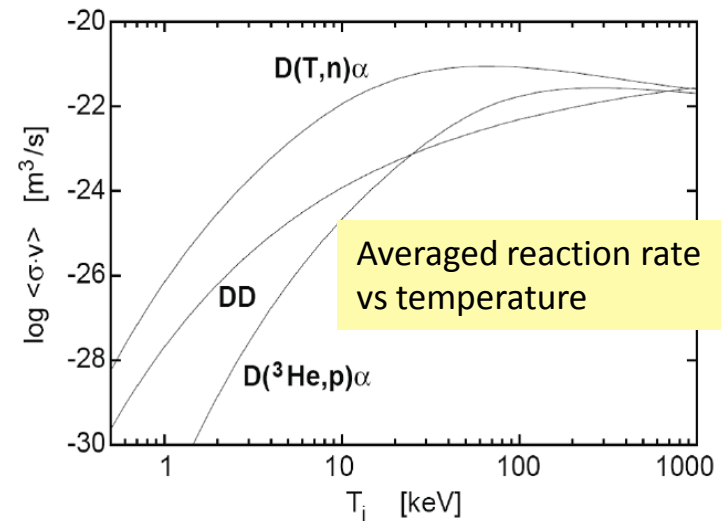
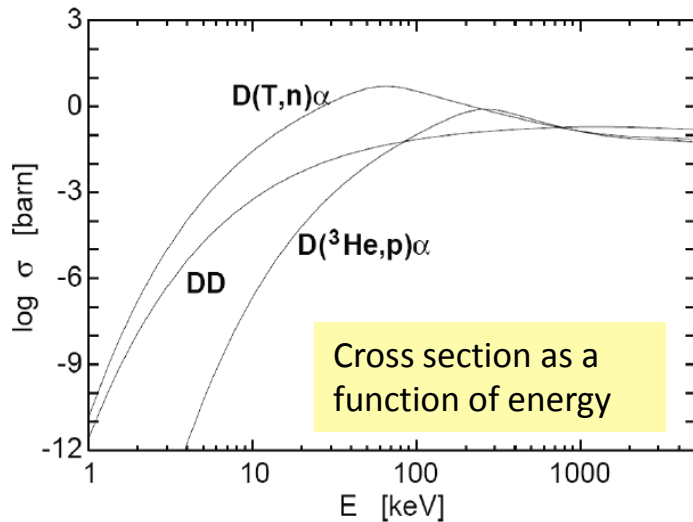
Opsluiting van het plasma is een uitdaging

Magnetisch opsluiting in een magnetisch fles

Plasma lekt weg aan de uiteinden



Werkzame doorsneden

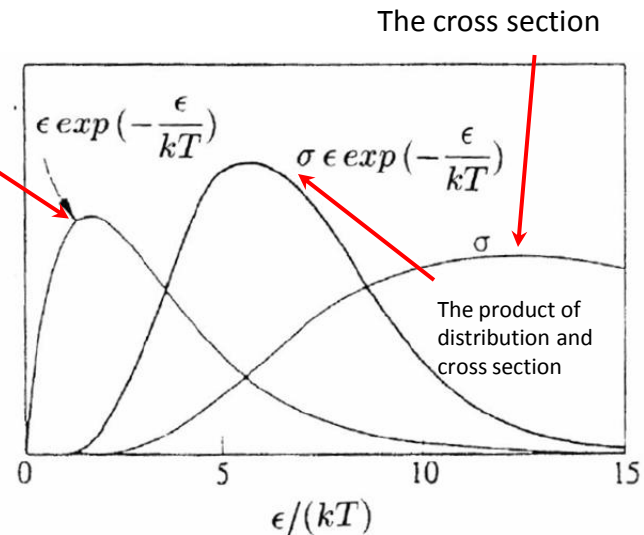


The averaged reaction rate does not fall of as strongly when going to lower energies

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)



Tokamak

Magnetisch opsluiting met toroidaal veld (langs de as van de toroide)

Elektrische stromen in het plasma produceren poloidaal magneetveld

Superpositie levert een helisch veld en dat sluit het plasma op

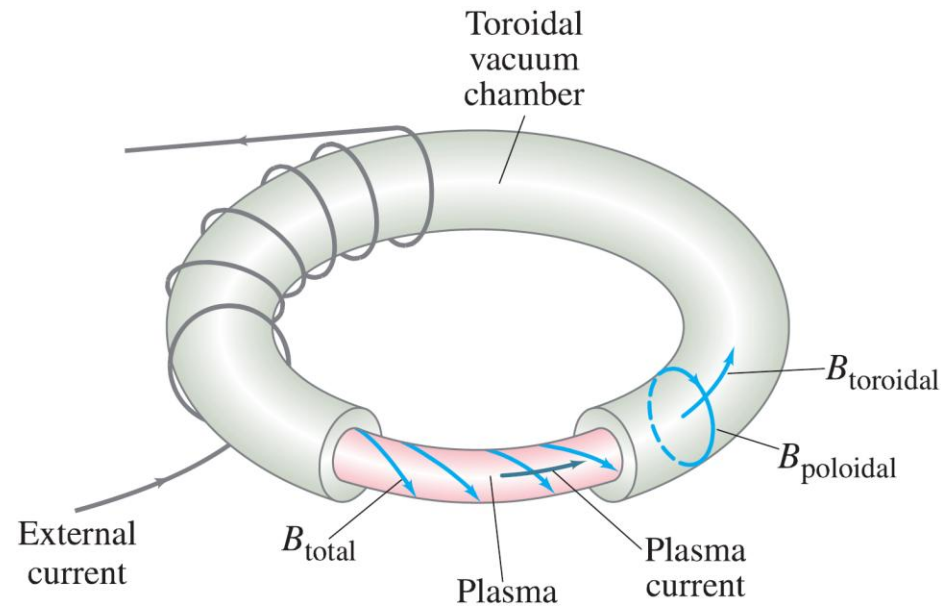
Lawson criterium voor ontsteking van het plasma

Typisch $t = 1 - 3$ seconde

$$n\tau \gtrsim 3 \times 10^{20} \text{ s/m}^3$$

Break-even wordt al een factor 10 lager bereikt (TFTR in Princeton, 1990)

ITER is het fusieproject van de toekomst (2016)



Gyro motion

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

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

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

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

$$\omega_c = \frac{|q|B}{m}$$

We will write the motion as

$$\mathbf{v} = v_{\parallel} \mathbf{b} + \mathbf{v}_g$$

Parallel and rapid gyro-motion

For 10 keV and B = 5T:

Larmor radius of deuterons ~4 mm

electrons ~0.07 mm

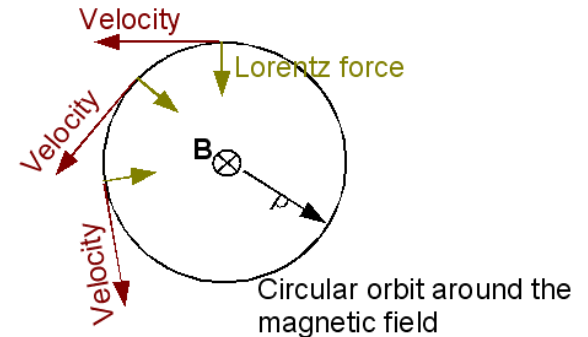
alpha particles (3.5 MeV) ~5.4 cm

Cyclotron frequency:

80 MHz for hydrogen

130 GHz for electrons

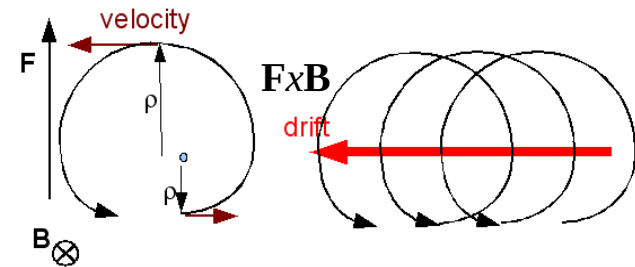
$$m \frac{d\mathbf{v}}{dt} = q\mathbf{v} \times \mathbf{B}$$



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

Physics picture
behind the drift
velocity

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



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

Parallel motion

Gyration

$\mathbf{E} \times \mathbf{B}$ drift

Polarization drift

Grad-B and curvature drift

Tokamak

Bend the theta pinch into a donut shape

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

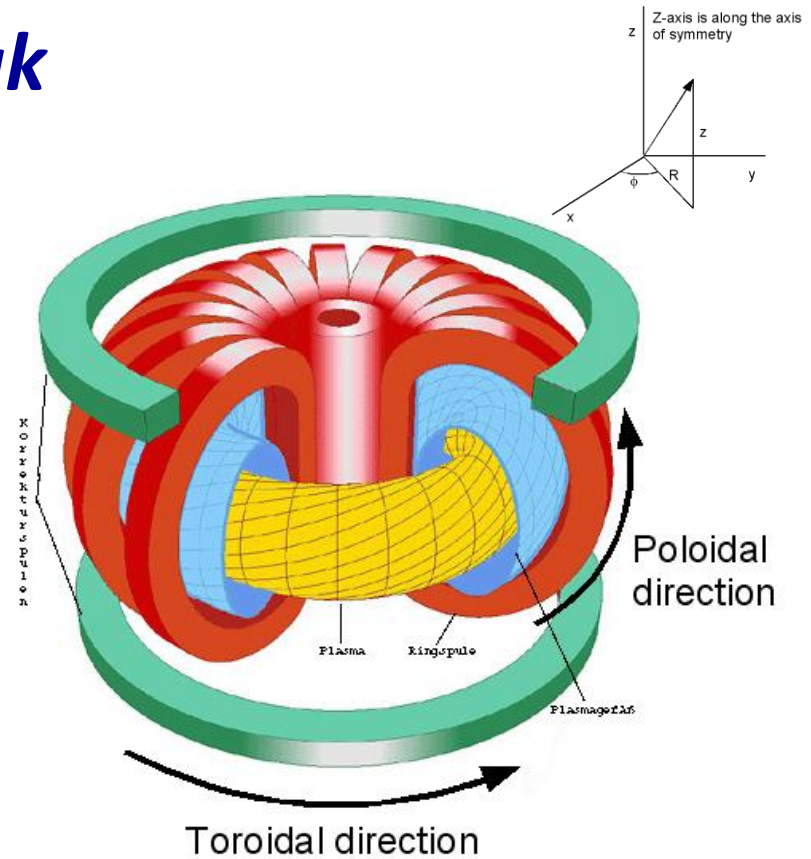
The magnetic field follows form

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

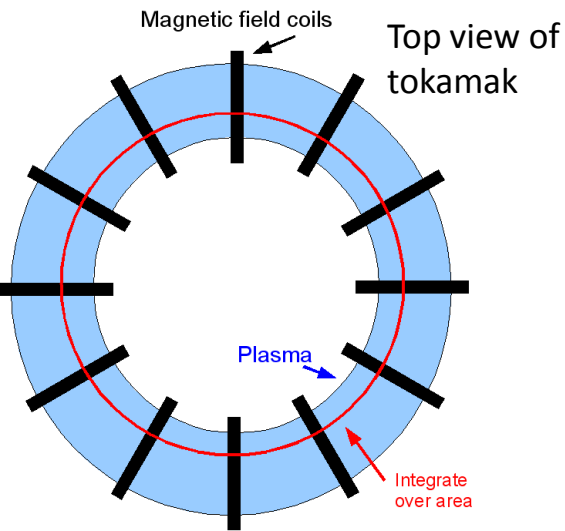
$$2\pi R B_\phi = \mu_0 I$$

And therefore varies with major radius R as

$$B_\phi = \frac{C}{R}$$



Schematic picture of the 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

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

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 $\mathbf{E} \times \mathbf{B}$ velocity

The $\mathbf{E} \times \mathbf{B}$ velocity

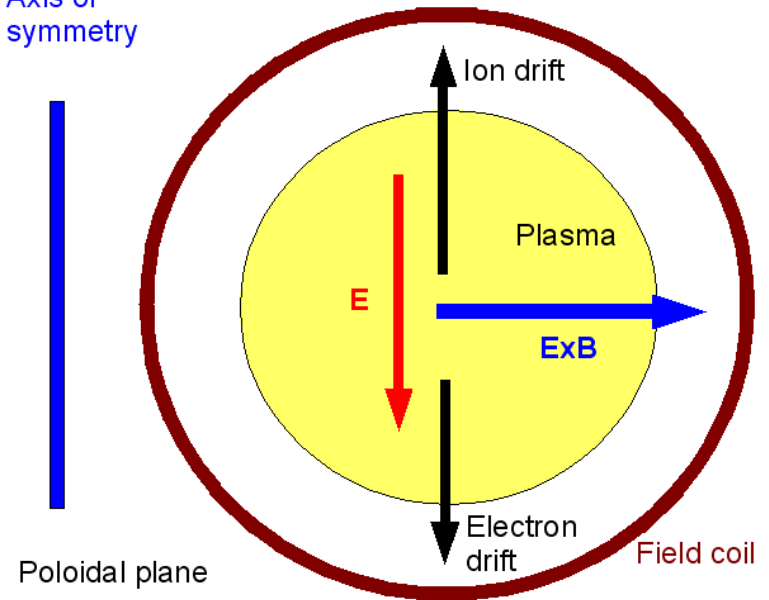
$$\mathbf{v}_E = \frac{\mathbf{E} \times \mathbf{B}}{B^2} = -\frac{E_z}{B} \mathbf{e}_R$$

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

This effect is no surprise since

$$F = -\mu \nabla B \longleftarrow B_\phi = \frac{C}{R}$$

Axis of symmetry



Poloidal cut of the tokamak.

Remedy: a toroidal plasma current will generate a poloidal field



The toroidal electric field

Plasma is the second winding of a transformer

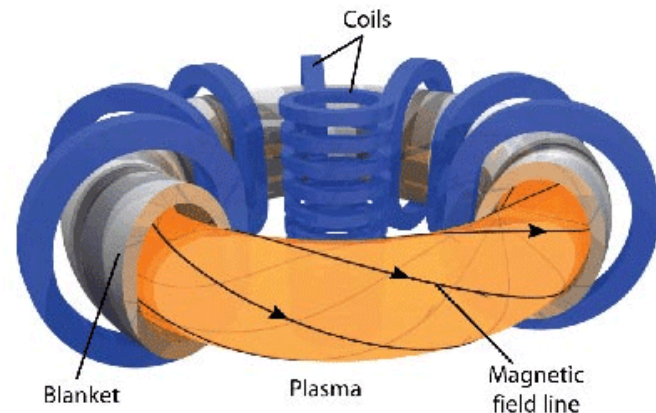
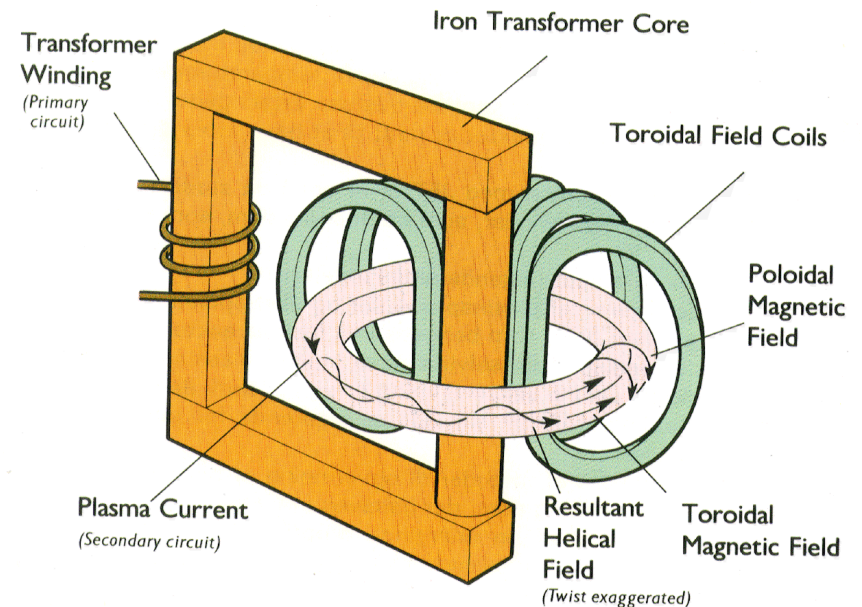
Flux in the iron core cannot be increased forever.
The tokamak is necessarily a pulsed machine

That is not good for energy production

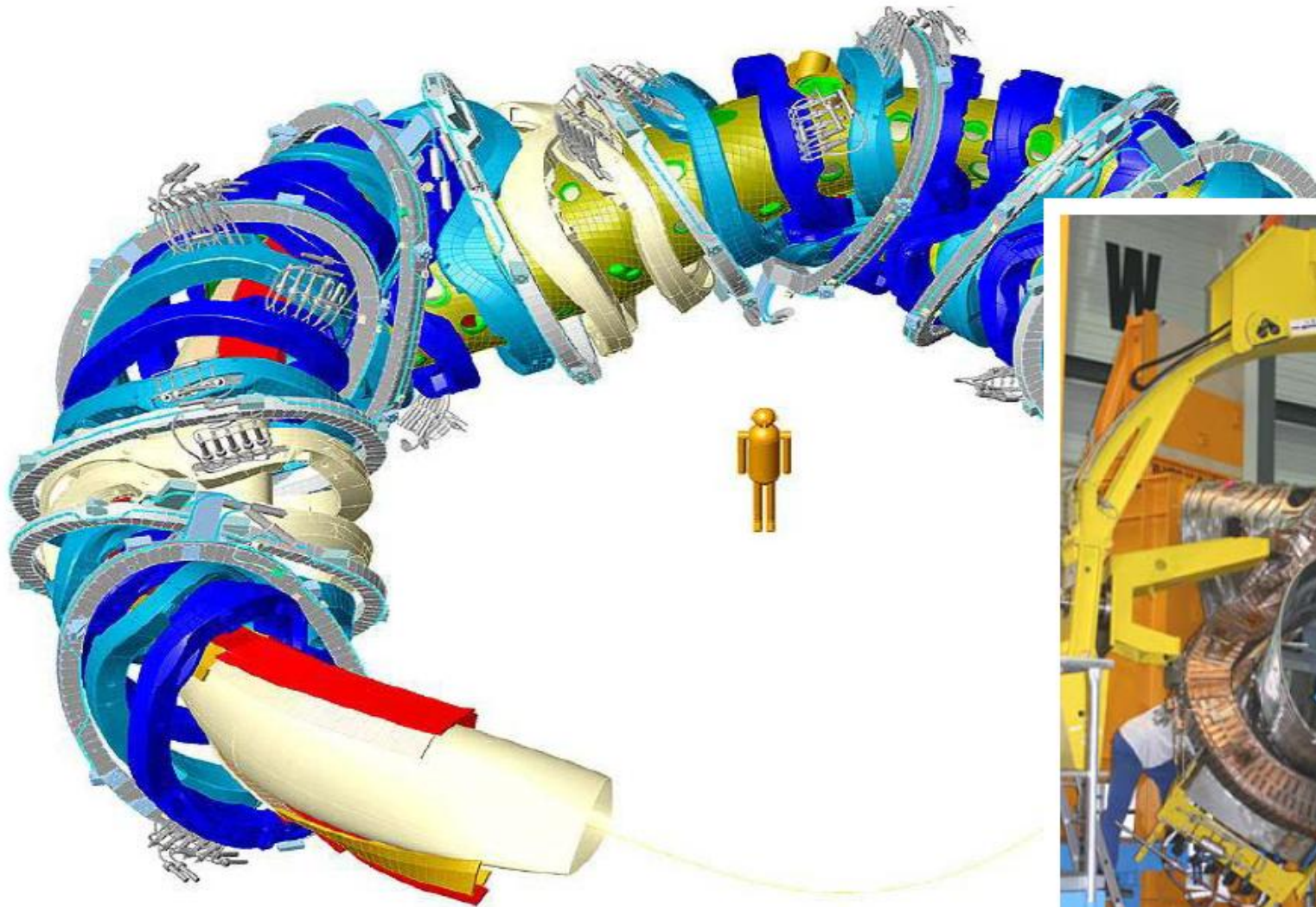
Also thermal stresses are associated with the pulsed character

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

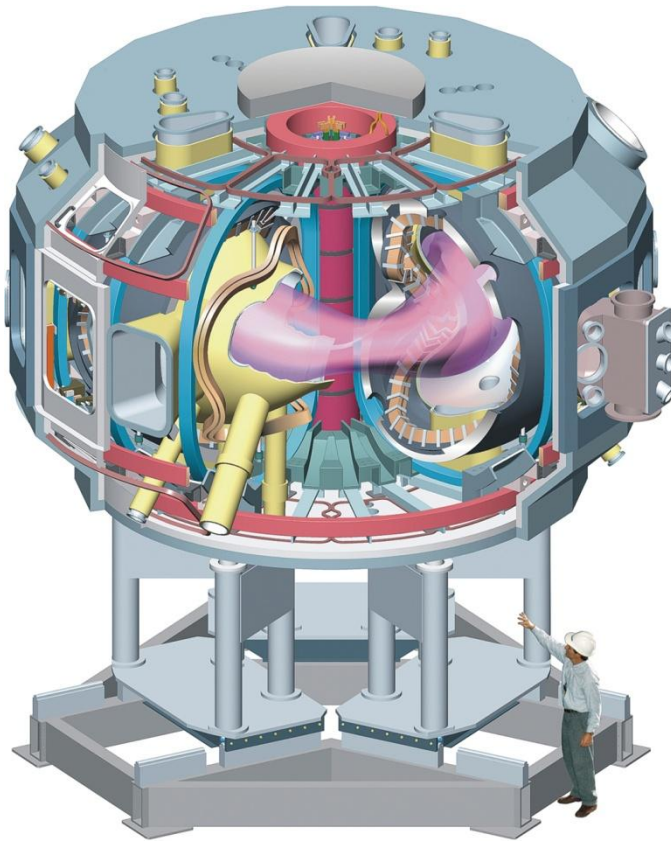


Tokamak niet enige oplossing: W7X

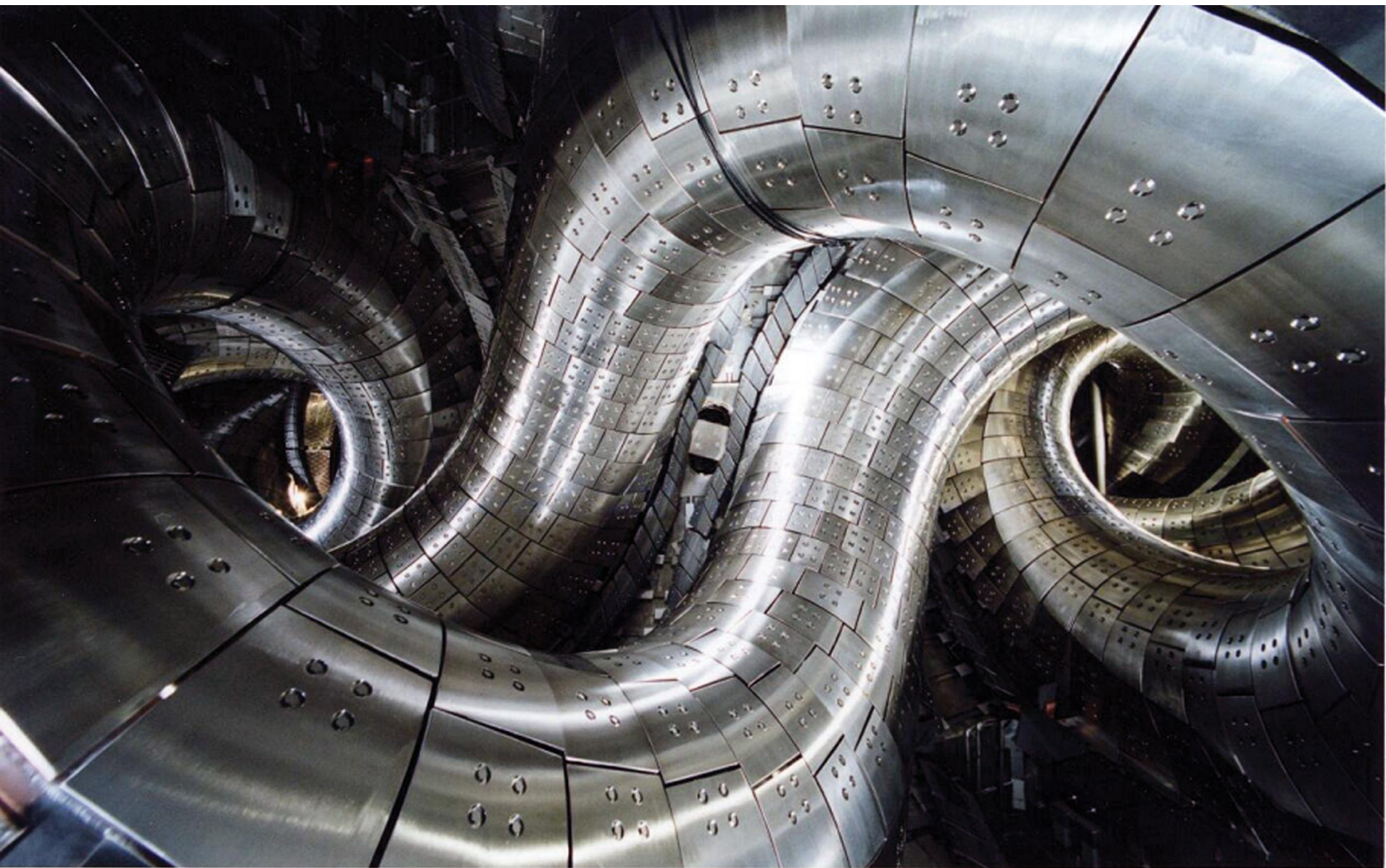


Compact stellarator NCSX princeton

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

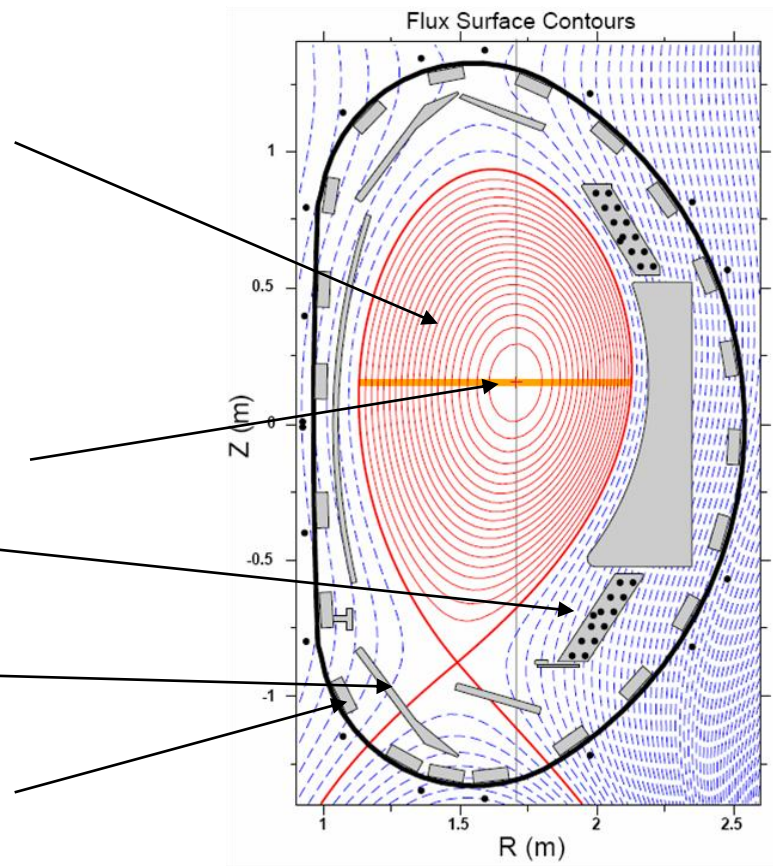


Stellarator – LHD in JAPAN



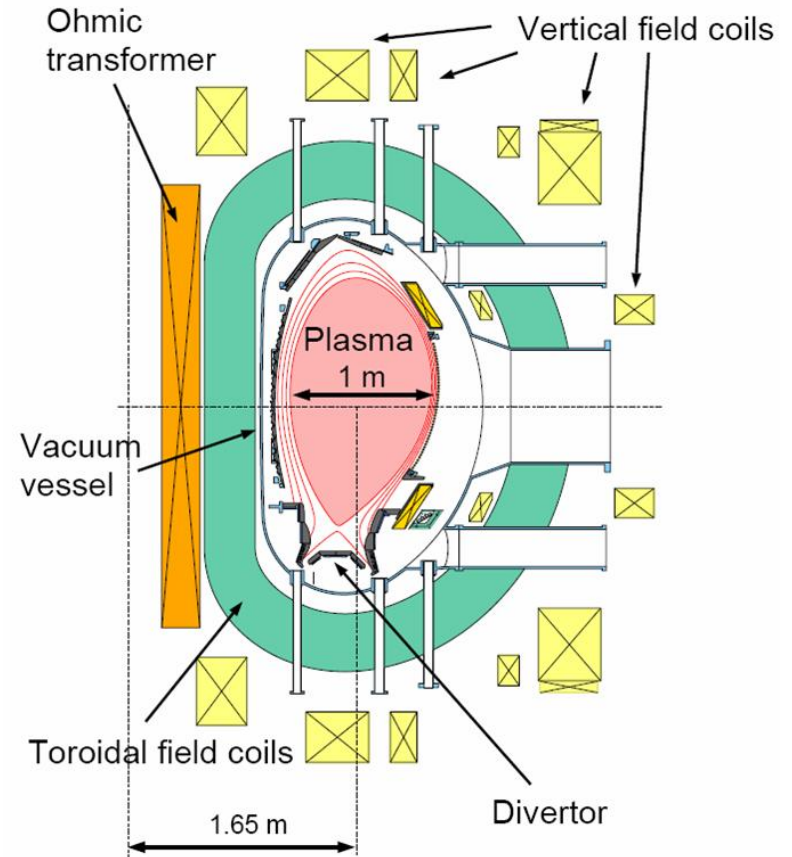
A tokamak

- 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

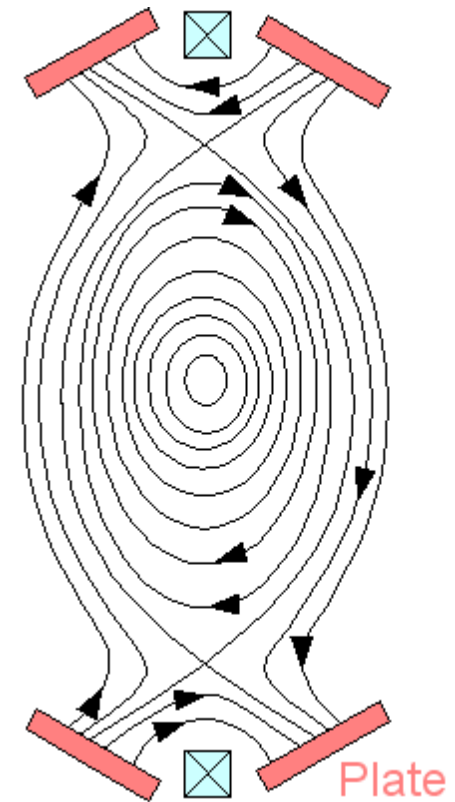
- Several coils around the plasma
- The vertical coils can shape the plasma and control its position
- Dominant shaping is the vertical elongation of the plasma



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



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 loss th

Plasma facing components have to be chosen carefully

Carbon / Beryllium have a low Z

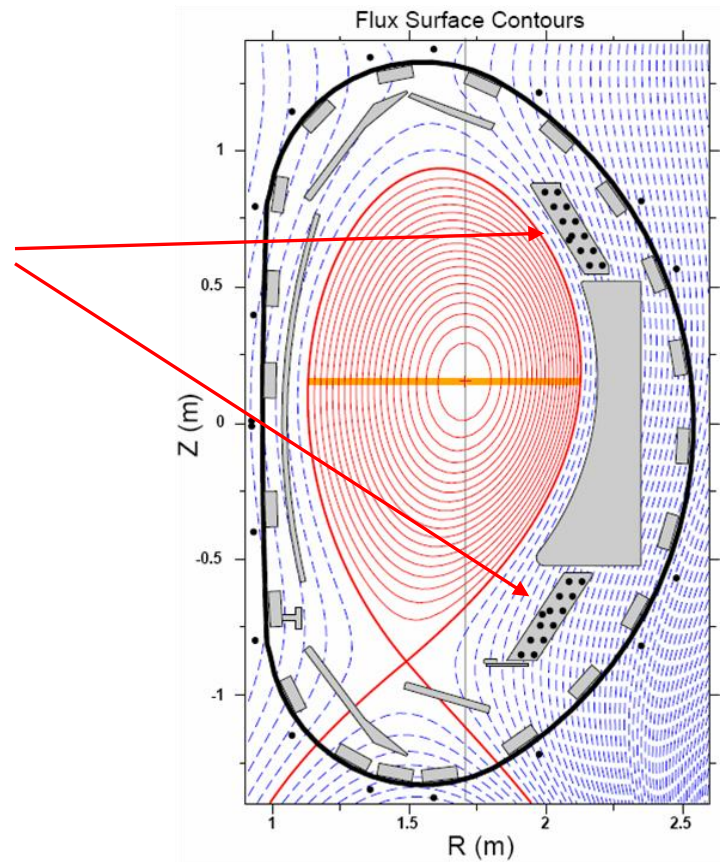
Carbon does not melt but has the problem that it binds well with Tritium (contamination of the machine)

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

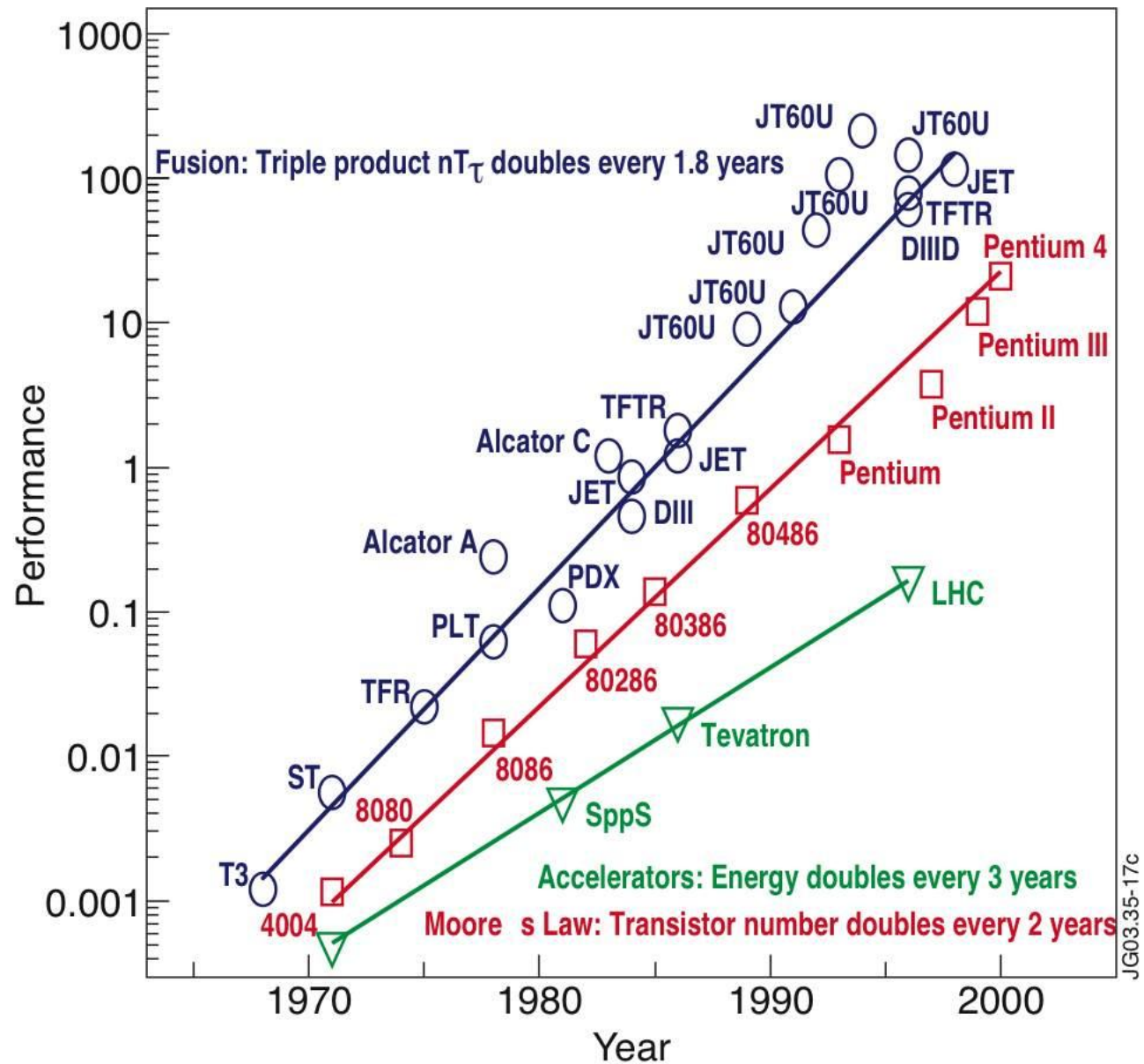


Plasma instabilities

- 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)



Voortgang in fusie onderzoek

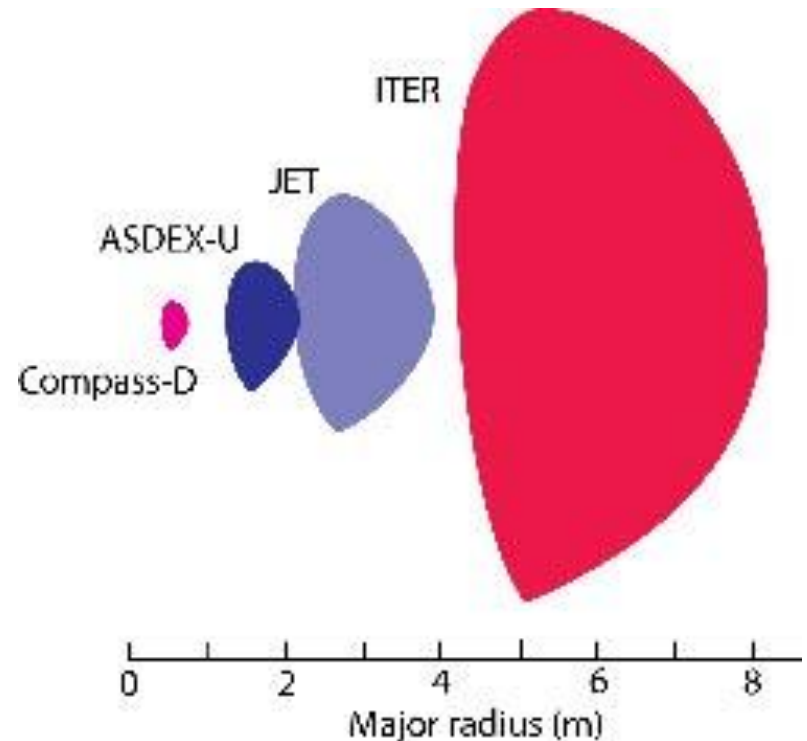


ITER



Wat is ITER?

- ITER = (International Tokamak Experimental Reactor) is de volgende stap in tokamak research.
- Grootste tokamak in de wereld
- Project is gestart in Cadarache, France
- Samenwerking tussen Europa, China, Japan, Korea, Rusland (en de US).



Doorsnede van het plasmavolume

Meer over ITER

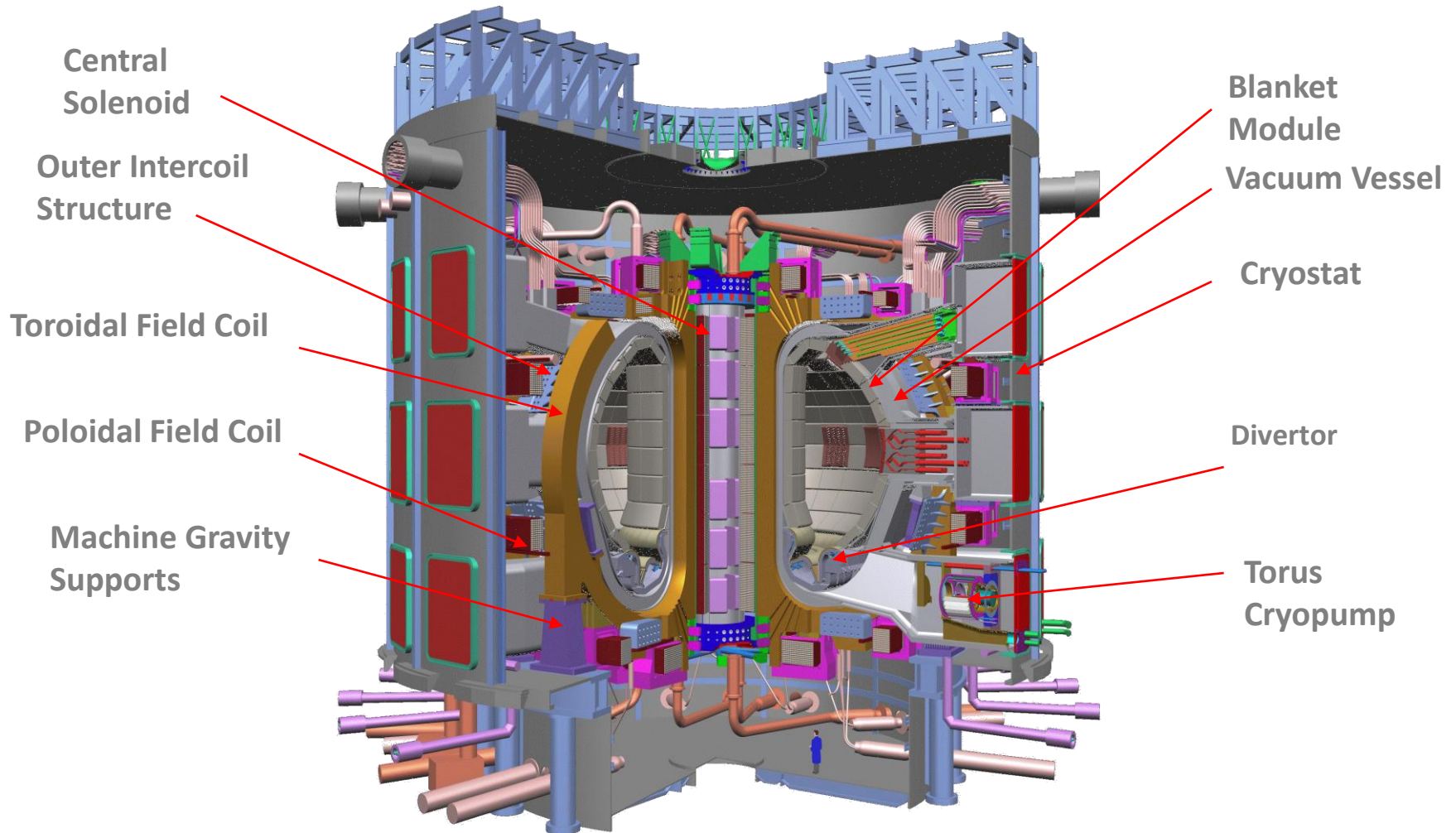
Belangrijkste missie

- Demonstreer dat het mogelijk is een fusiereactor te bedienen. Dit omvat het genereren van een plasma dat door fusie reacties verwarmd wordt, maar ook dat aan de technische eisen voldaan kan worden.

Project

- Kosten 5 miljard Euro constructie + 5 miljard Euro voor bedrijf (het duurste experiment op Aarde)
- Constructie van het gebouw is begonnen in 2008 / Assemblage begint in 2012
- Assemblage gaat ongeveer 7 jaar duren
- 20 jaar bedrijf is geplanned

Ontwerp – belangrijkste eigenschappen



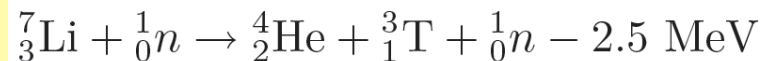
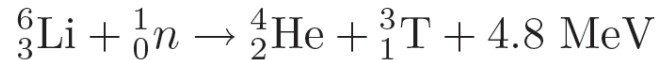
ITER parameters

• Total fusion power	500 MW
• Q = fusion power/auxiliary heating power	≥ 10 (inductive)
• Average neutron wall loading	0.57 MW/m^2
• Plasma inductive burn time	$\geq 300 \text{ s}$
• 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)

Availability of the fuel

- The natural abundance of Deuterium is one in 6700. There is enough water in the ocean 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



- 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.

Theta pinch

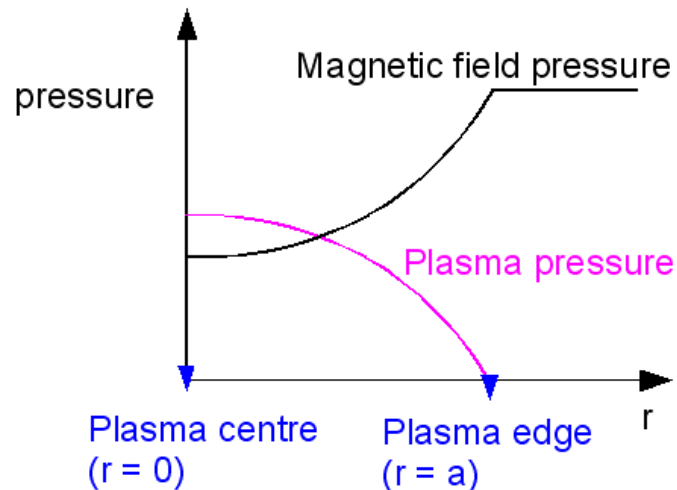
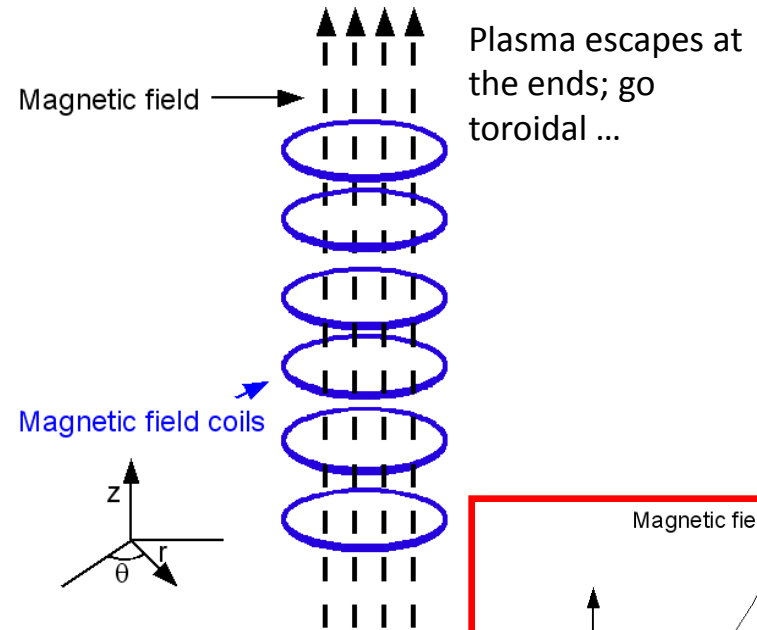
Straight magnetic field no tension

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

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

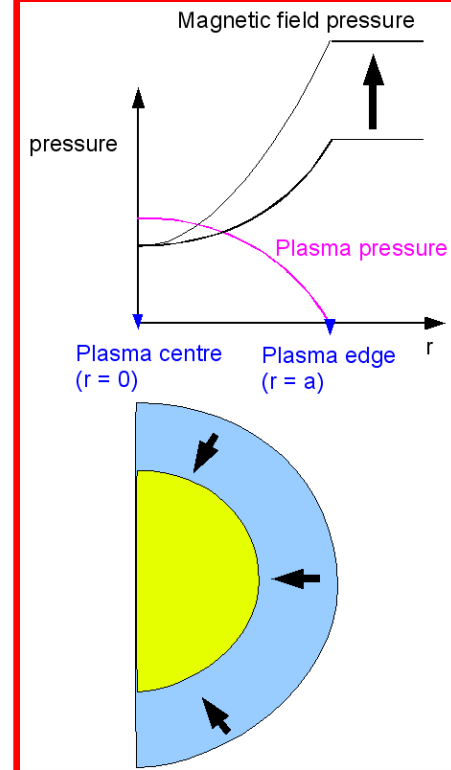


Ramp up the magnetic field by
ramping the current in the coils

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

$\mathbf{J} \times \mathbf{B}$ force is then fully determined

Pressure gradient must balance the $\mathbf{J} \times \mathbf{B}$ force and is then also fully determined by the current

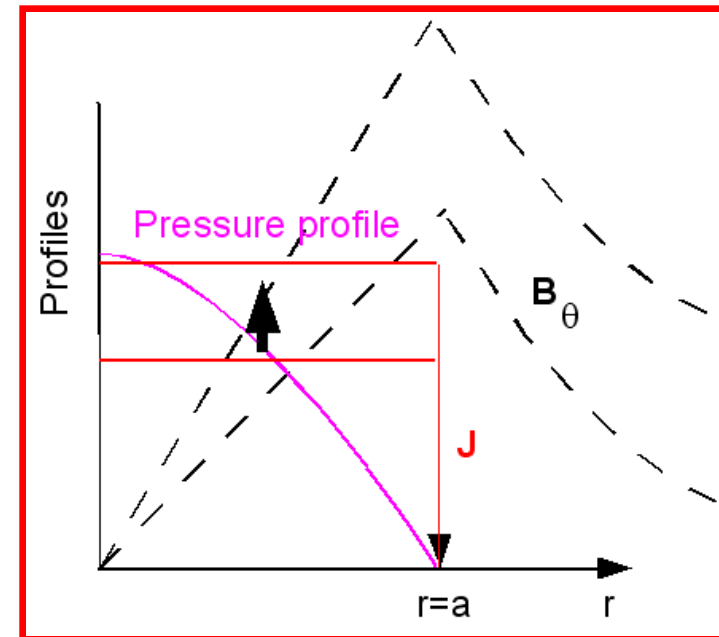
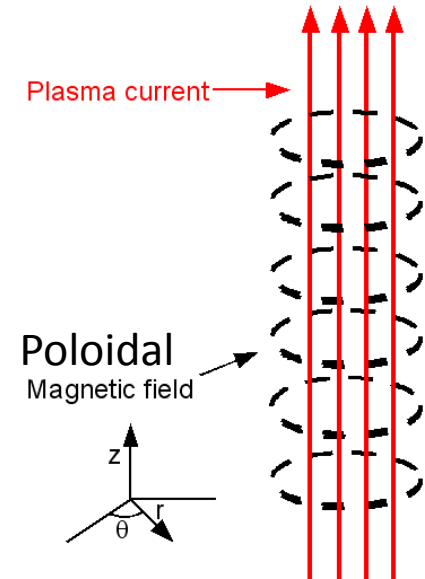
Current is the source of the magnetic field

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

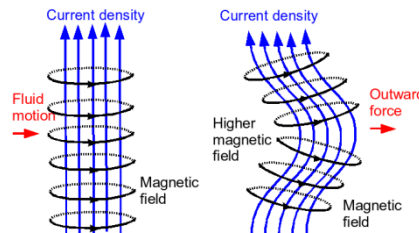
Magnetic pressure $p_B \approx \frac{F_B}{A} = \frac{IBL}{2\pi RL} = \mu_0 I^2 L / \{(2\pi R)^2 L\} = B^2 / \mu_0$

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

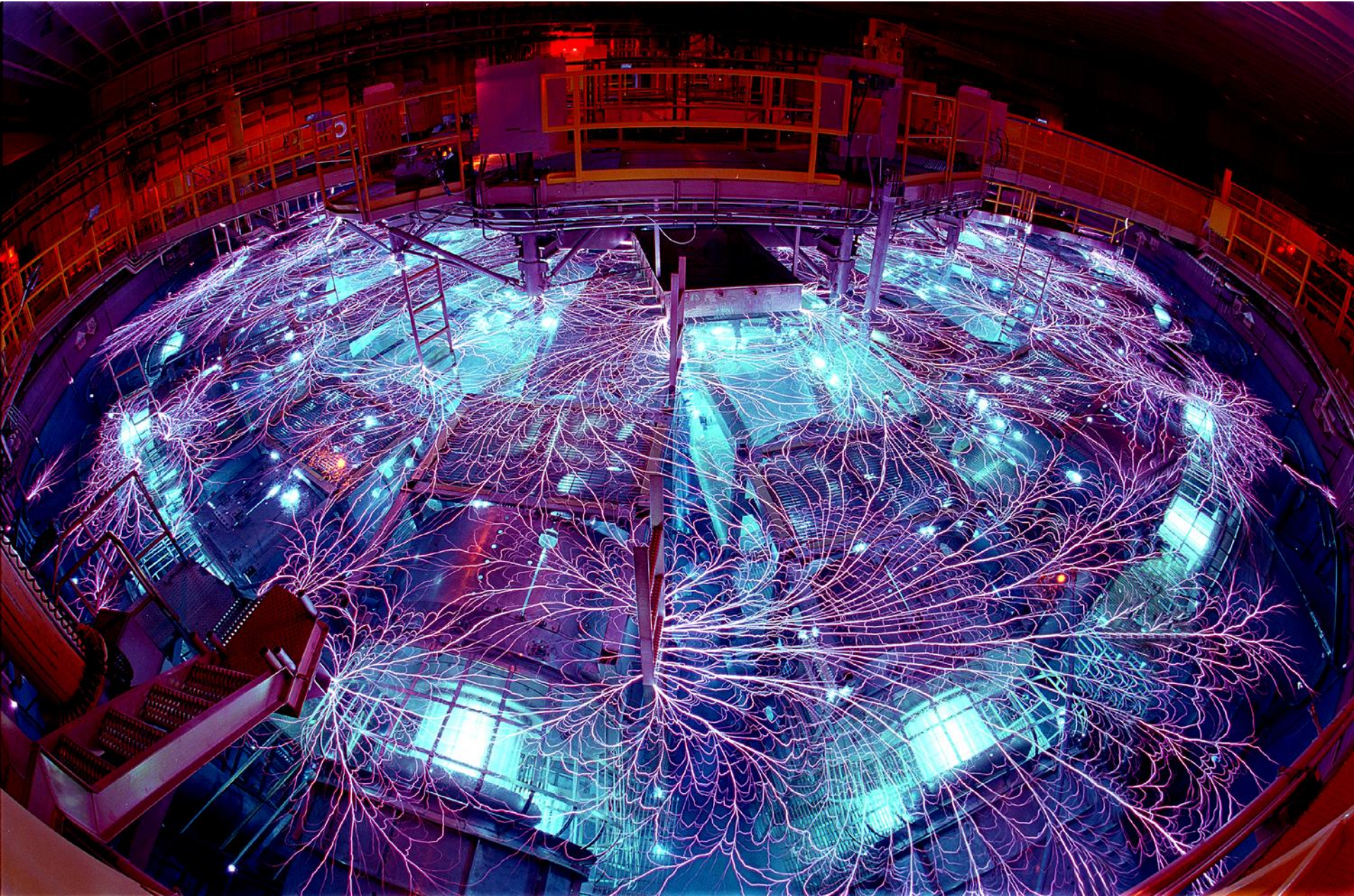
Besides the heating due to compression, the current will also dissipate heat when the plasma resistivity is finite



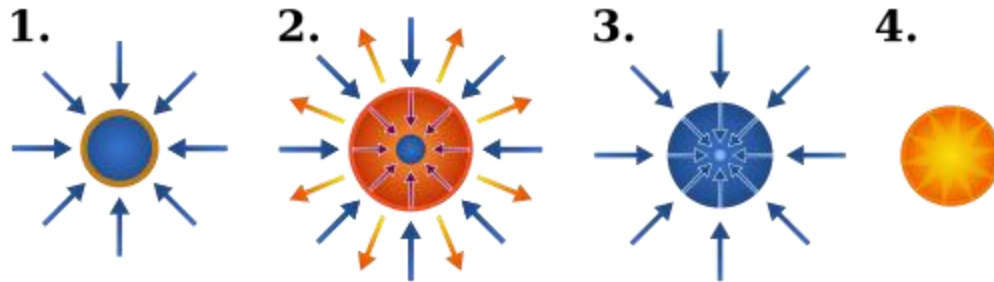
The Z-pinch is unstable.
Most relevant instability is the kink



Sandia labs – Z pinch: 290 TW X-rays



Sandia labs – Z pinch IFE



Laser of X-ray straling

Materiaal verdampt

Back-reaction comprimeert sample

Kernfusie treedt op

Sandia Z pinch

27 miljoen ampere

95 nanoseconde

350 Terawatt (80x wereld)

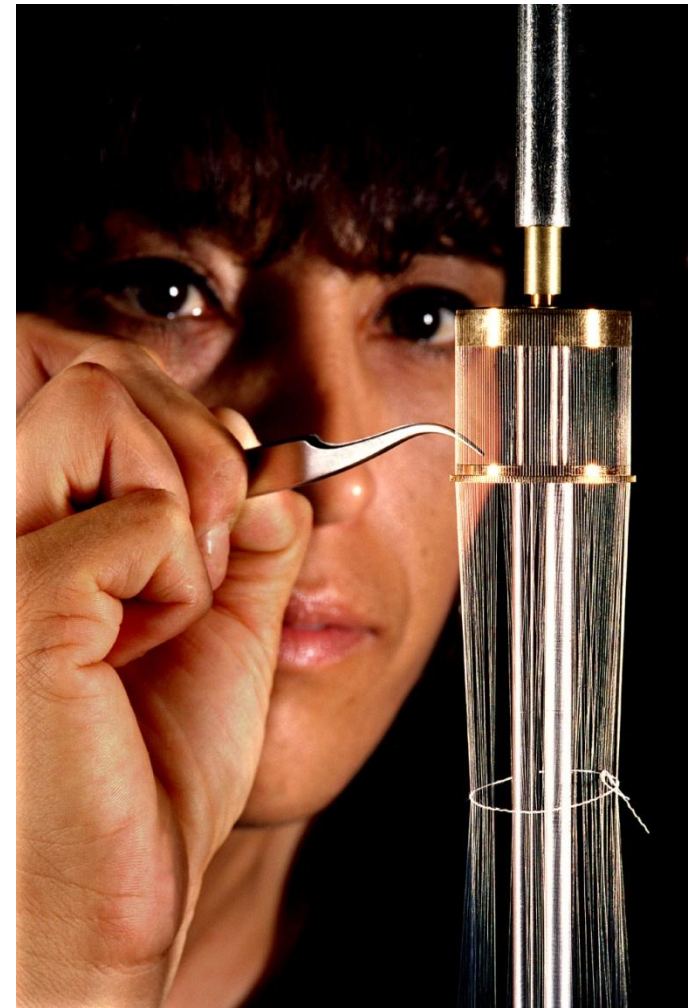
2.7 MJ X-ray energie

3.7 GK temperatuur bereikt

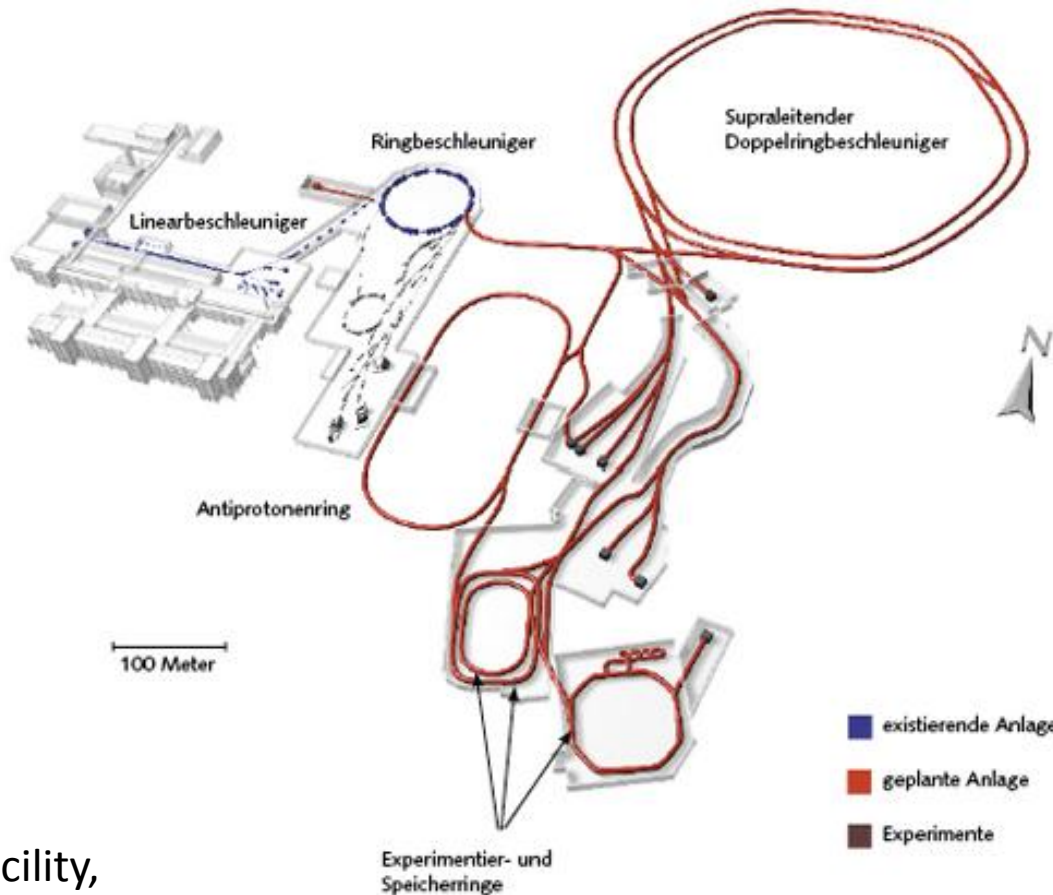
deuterium fusie gerealiseerd in 2006

metalen platen versneld tot 34 km/s

ZN (Z neutron fusie machine: $p - 7\text{Li}$)



Possible drivers: ion beams



Advantages:

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

Disadvantages:

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

FAIR facility,
Darmstadt, Germany

10 to 20 rings needed
for fusion power plant!

Possible drivers: lasers (best shot)



National Ignition Facility (NIF), Livermore, USA

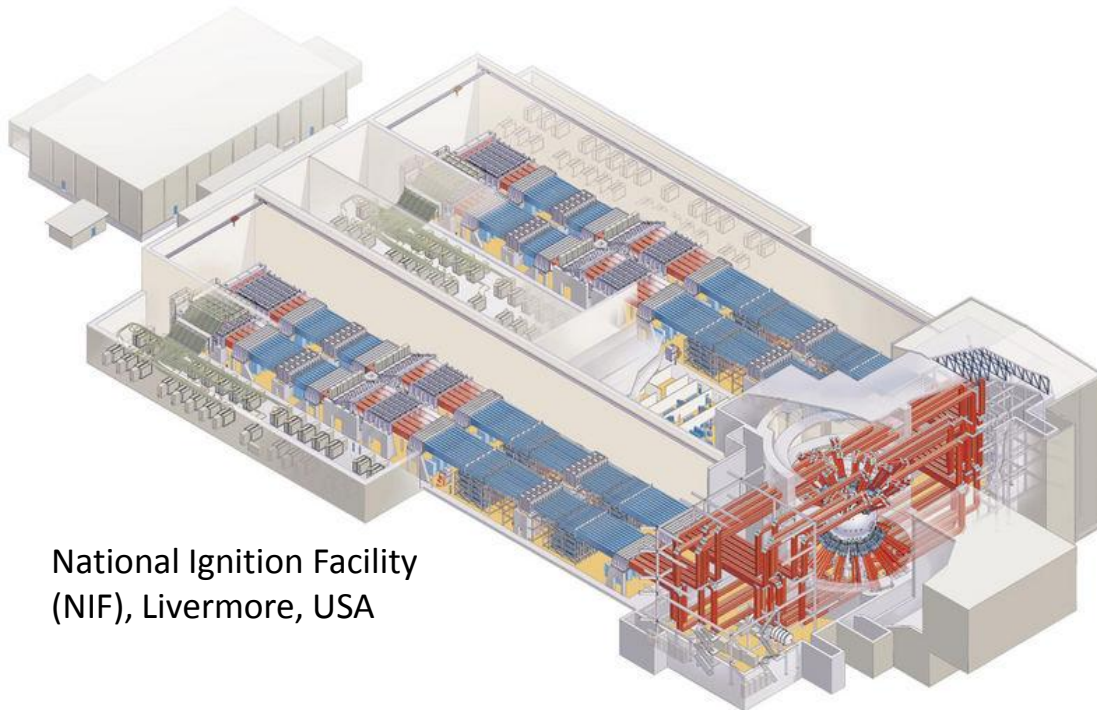
Advantages:

- Well advanced technology
- Good control of energy release

Disadvantages:

- **Bad energy conversion**
- Very expensive to build

Possible drivers: lasers



National Ignition Facility
(NIF), Livermore, USA

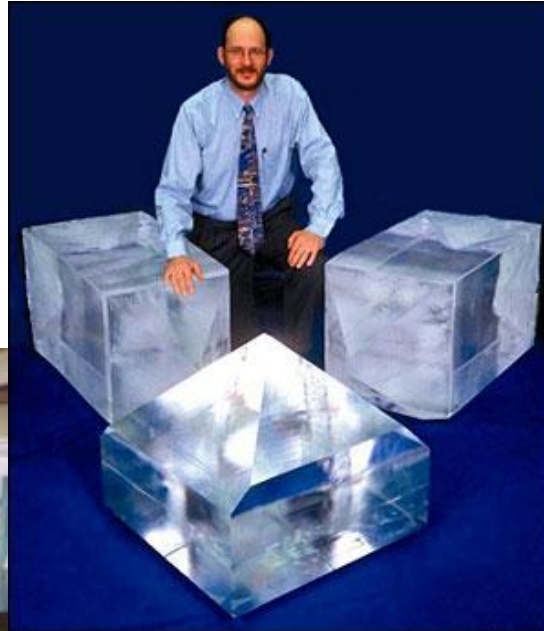


Target chamber, NIF with 192
laser beams

Possible drivers: lasers

~1000 large optics:

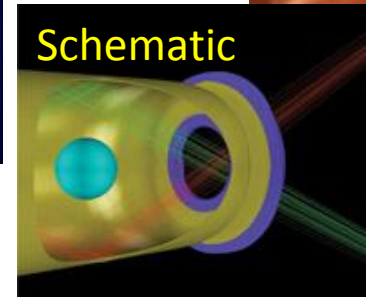
192 beam lines:



real NIF target

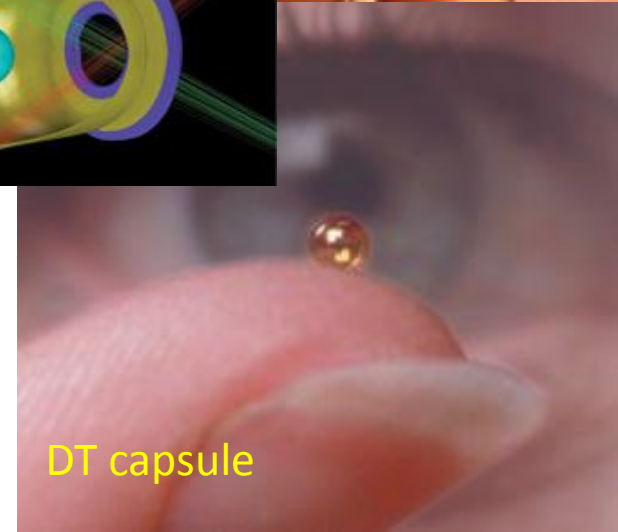


Schematic



Engineering challenges at NIF

DT capsule



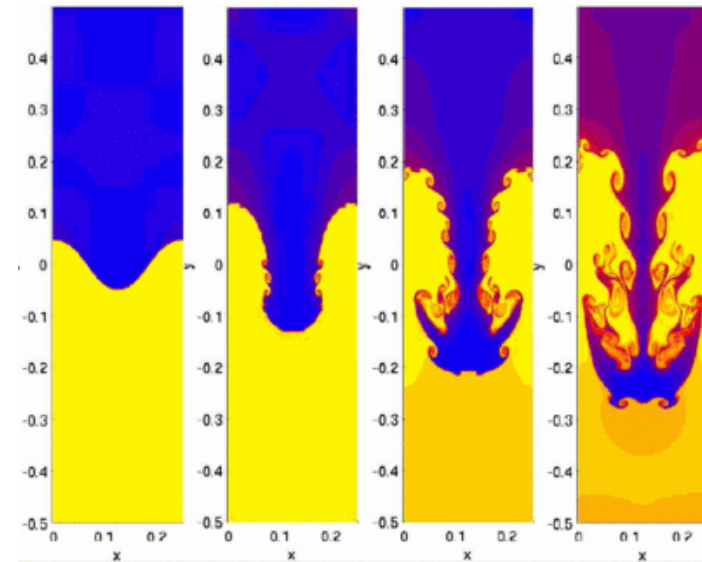
Problems blocking fusion energy

Technical and engineering problems

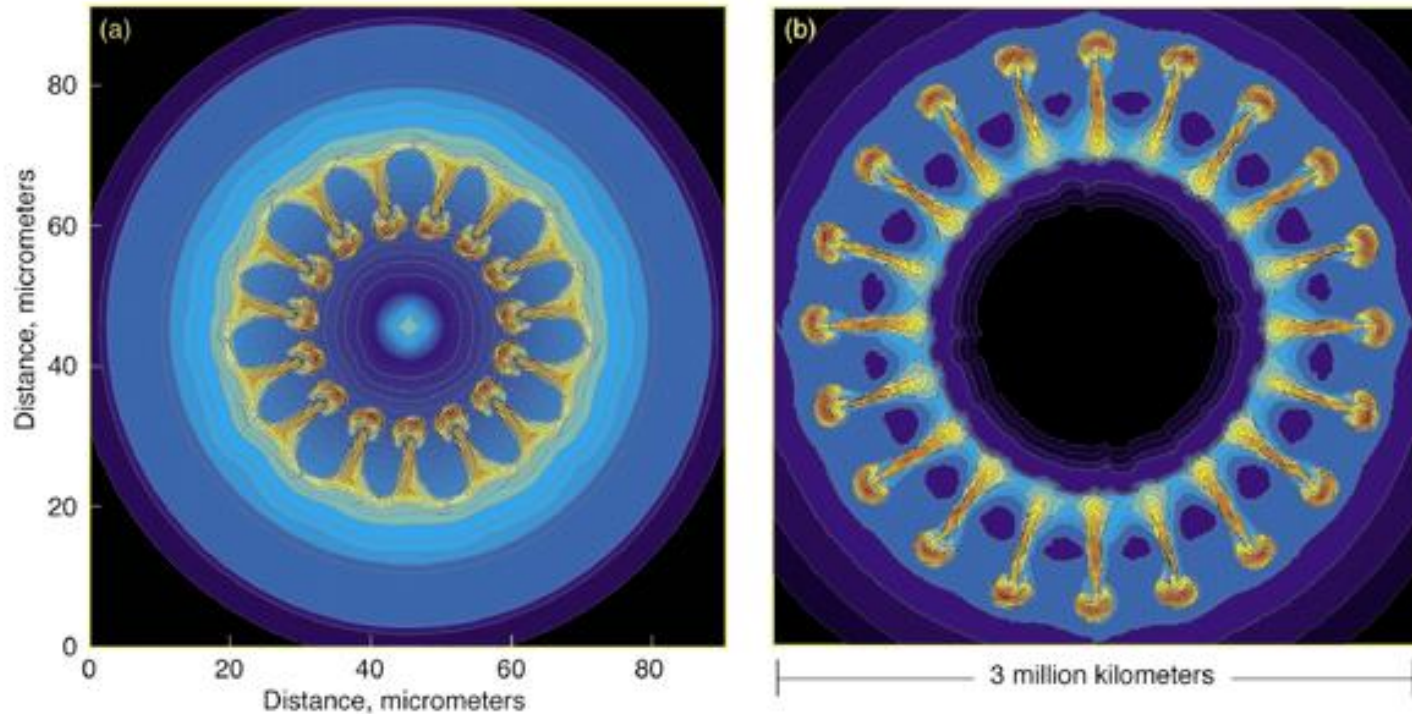
- High energy drivers are expensive and untested
- Energy conversion is too low (gain of >100 needed now)
- Repetition rate of drivers are too low (3-10 Hz needed)

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?



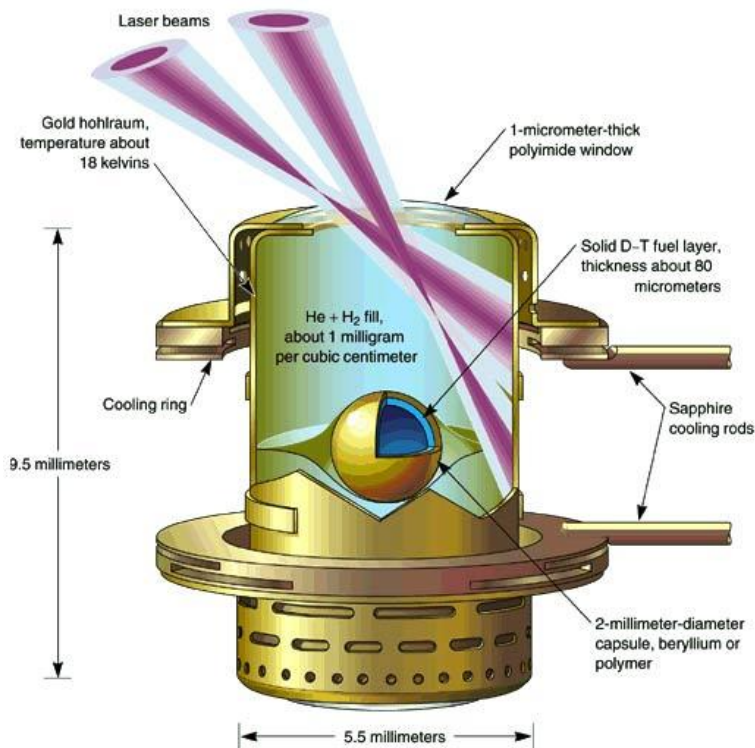
Rayleigh-Taylor Instability – spherical implosions / explosions



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 symmetric as possible!

Relaxing the symmetry conditions – indirect drive



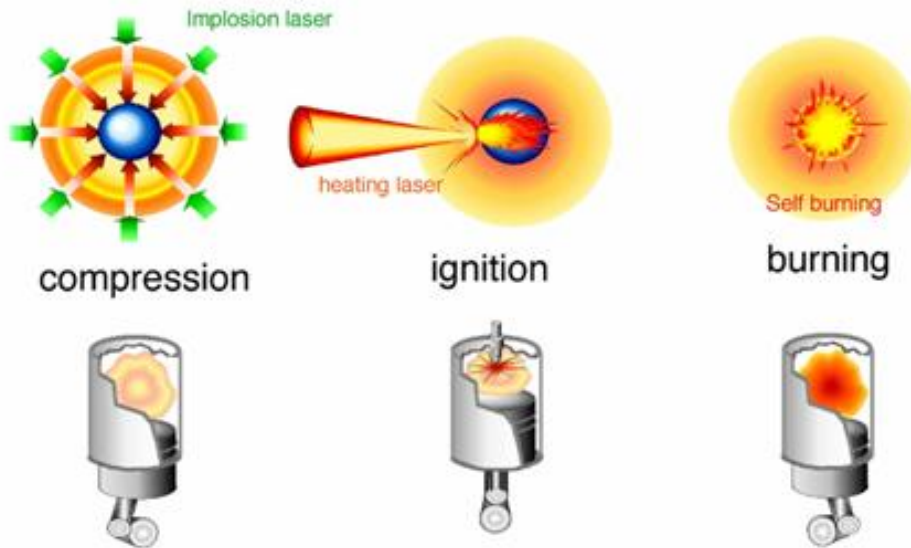
NIF design (laser)

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!

Relaxing the symmetry conditions – fast ignition

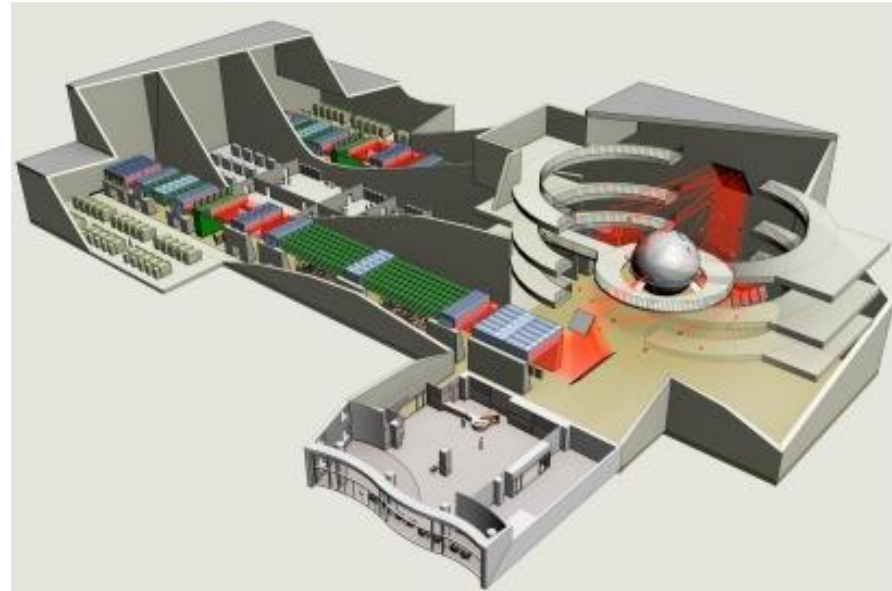


Fast ignition scheme
with many facets

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

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



Stralingsschade

Stralingsschade

Geladen deeltjes (alfa en beta stralen, protonen, ionen) ioniseren het medium waar ze doorheen gaan

Fotonen: foto-elektrisch effect, Compton effect en paarvorming

Neutronen: kernreacties

Materialen worden bros

Biologische schade: ionisatie in cellen, DNA schade

Bron activiteit in curie of becquerel (SI)

$$1 \text{ Ci} = 3.70 \times 10^{10} \text{ decays per second}$$

$$1 \text{ Bq} = 1 \text{ decay/s}$$

Activiteit neemt af in de tijd $\left| \frac{dN}{dt} \right| = \lambda N = \frac{0.693}{T_{1/2}} N$

Geabsorbeerde dosis [gray] (energie per kg materiaal)

$$1 \text{ Gy} = 1 \text{ J/kg} = 100 \text{ rad}$$

Relative biological effectiveness (RBE), ook wel QF

Effectieve dosis in rem of sievert (SI)

$$\text{effective dose (Sv)} = \text{dose (Gy)} \times \text{QF}$$

Natuurlijke achtergrond ongeveer 3 mSv

X-rays, scans ongeveer 0.6 mSv (limiet 1.0 mSv)

Fatale dosis: 4 Sv in korte tijd (50% fataal)

TABLE 42–1 Quality Factor (QF) of Different Kinds of Radiation

Type	QF
X- and γ rays	1
β (electrons)	≈ 1
Fast protons	1
Slow neutrons	≈ 3
Fast neutrons	Up to 10
α particles and heavy ions	Up to 20

Stralingstherapie

Gebruik van straling om mensen met kanker te behandelen

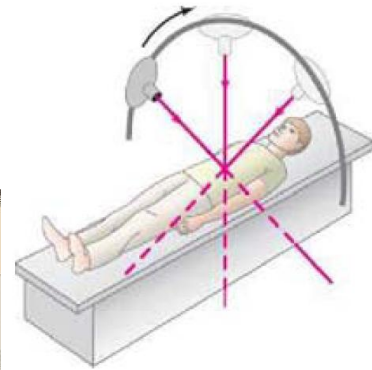
Relatief grote dosis nodig voor effectieve bestrijding

Kleine bundel g straling voor behandeling goed gelokaliseerde tumoren

Roteer bron om schade aan gezond weefsel te minimaliseren

Bron: $^{60}_{27}\text{Co}$ of een X-ray machine voor 200 keV tot 5 MeV

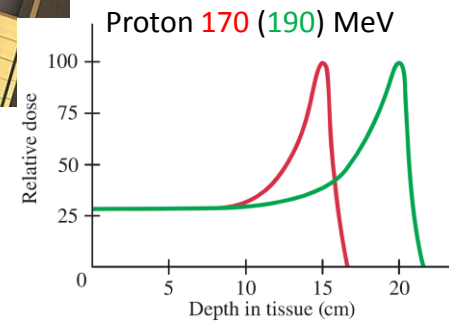
Actueel: proton- en (koolstof) ionentherapie



Clinical Aspects and Potential Benefits of PROTON THERAPY: A New Era in Radiation Oncology

Symposium ter ere van de oratie van Prof.dr.ir. J.M. Schippers
(Leerstoel: Toegepaste Fysica Partikel Therapie)

16 december 2008
Van 9.30 uur tot 15.00 uur



BLAUWE ZAAL
Universitair Medisch Centrum Groningen (UMCG)
Hanzeplein 1
Groningen, Nederland

Tracers

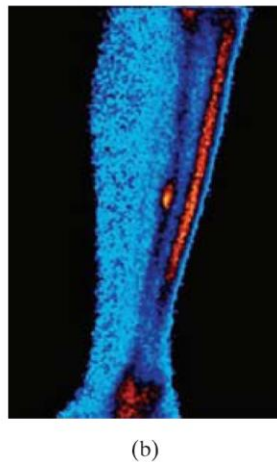
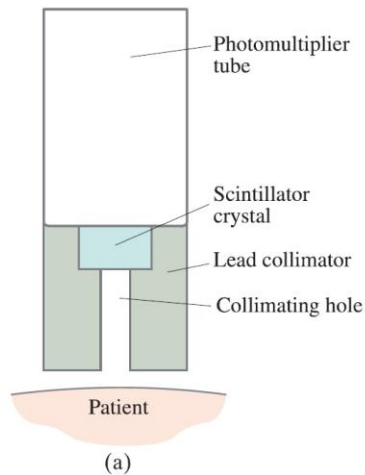
Radioactieve isotopen zoals $^{14}_6\text{C}$ of ^3_1H

Autoradiografie met planten in een CO_2 omgeving

Medische diagnose met technetium-99 met levensduur van 6 uur $^{99\text{m}}_{43}\text{Tc}$

Technetium-99 kan in diverse verbindingen gebruikt worden, die specifiek zijn voor verschillende organen

Gamma camera's maken dynamische studies mogelijk



(a)



(b)

Tomografie: CT en PET

Conventionele X-ray (een soort schaduw-opname)

CT: computed (axiaal) tomografie (beeld slices af)

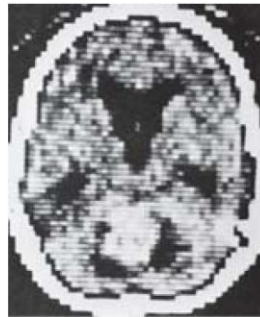
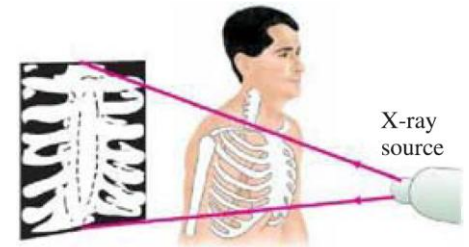
Een smalle bundel gaat door het lichaam

Bron en detector maken slices

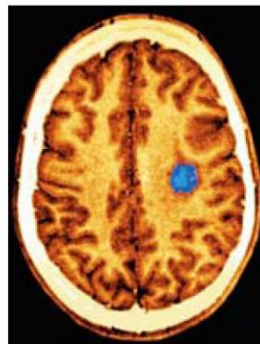
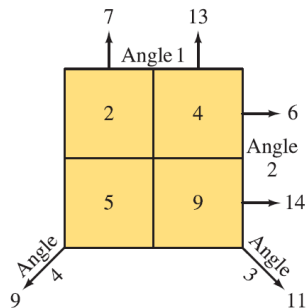
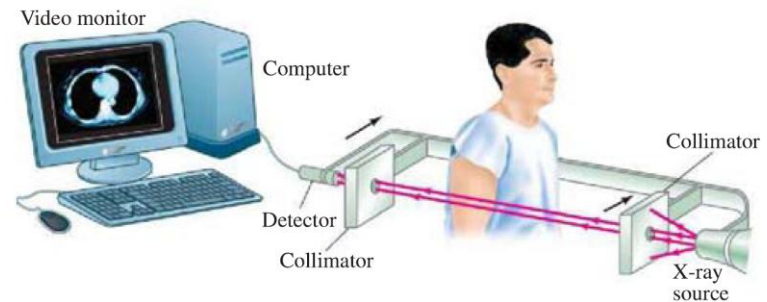
Roteer apparaat met 1° en maak slice

Fan-beam scanner

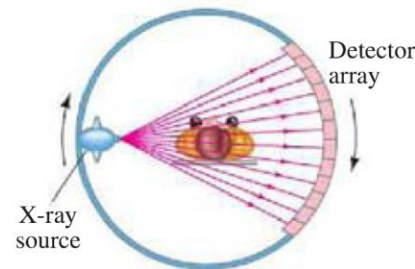
Beeldverwerking: pixels



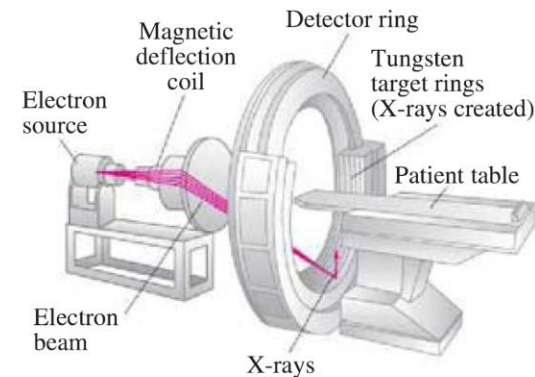
(a)



(b)



(a)



(b)

Emissie tomografie

Single photon emission (computed) tomografie: SPET of SPECT

Meet X-rays van een tracer en doe CT

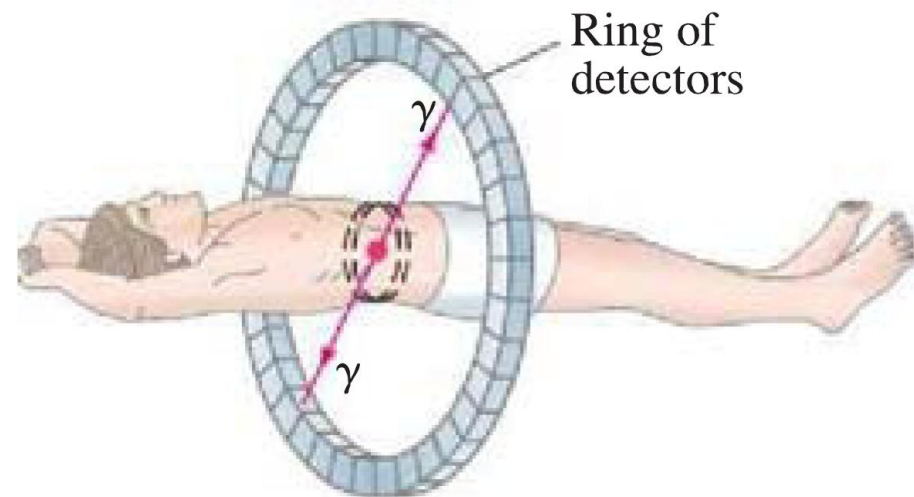
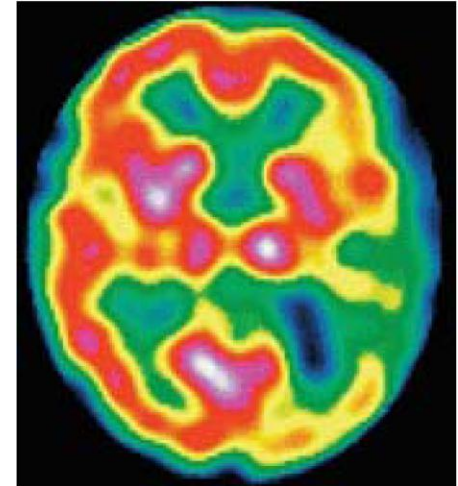
Positron emission tomografie (PET)

Gebruik positron emitters: $^{11}_6\text{C}$, $^{13}_7\text{N}$, $^{15}_8\text{O}$, and $^{18}_9\text{F}$

Positron annihileert met elektron

Er worden 2 fotonen geproduceerd

Gebruik een ring van foton detectoren



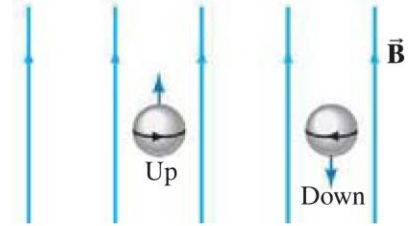
Kernspinresonantie (NMR)

Kern in magnetveld heeft energie $\vec{\mu} \cdot \vec{B}$

Proton spin kan twee instellingen hebben (up, down)

Dit leidt tot twee energieniveaus

Er geldt $\Delta E = 2 \mu_p B_T$



In NMR opstelling plaatsen we een sample in een statisch veld B

Vervolgens geven we een RF pulse met frequentie f , zodat $hf = \Delta E = 2\mu_p B_T$

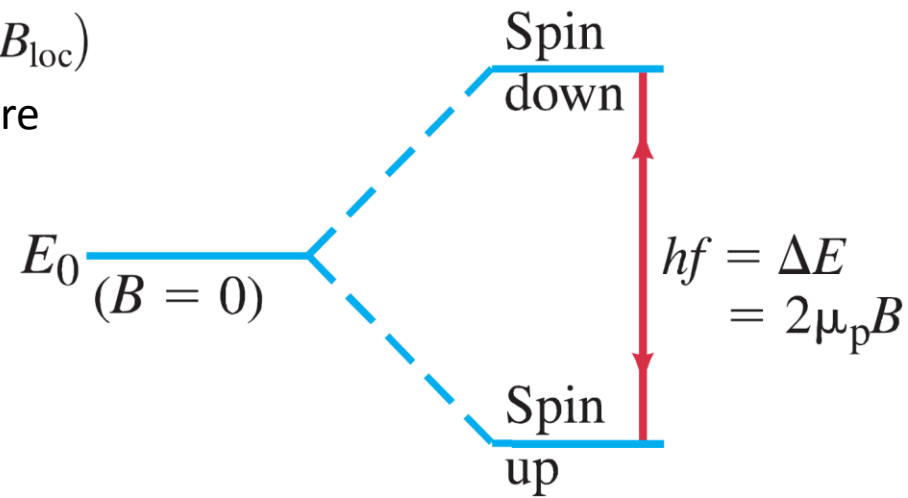
Op deze wijze induceren we overgangen tussen beide niveaus

Voor een proton hebben we 42.48 MHz voor een 1.0 T veld

Voor een gebonden proton geldt

$$hf = 2\mu_p(B_{\text{ext}} + B_{\text{loc}})$$

De frequentieverandering t.g.v. de moleculaire binding noemen we *chemical shift*



Magnetic Resonance Imaging (MRI)

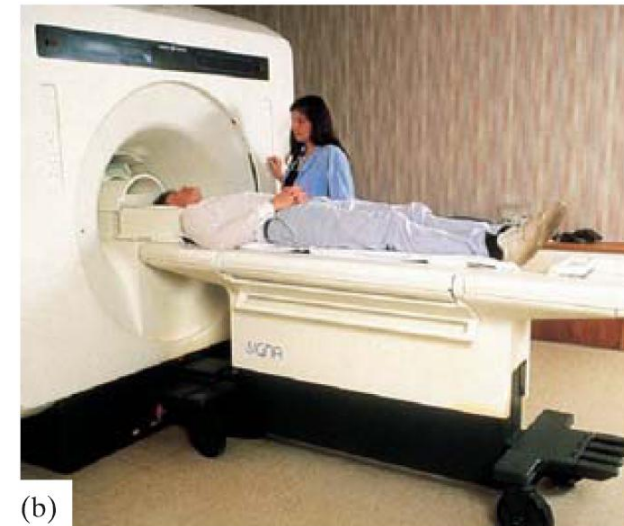
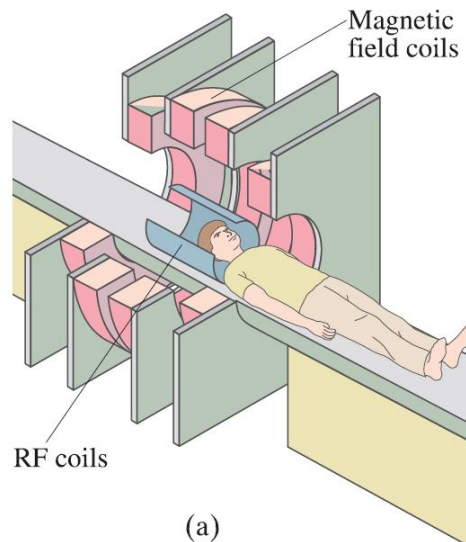
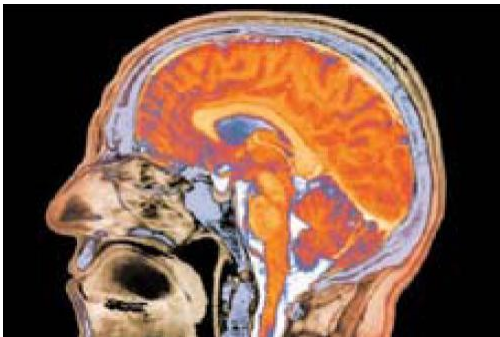
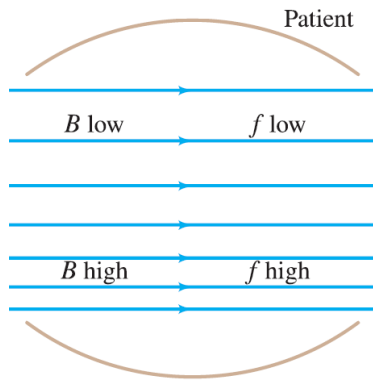
MRI maakt beelden op basis van de proton spin (NMR principe)

CT technieken worden gebruikt in de 2D of 3D beeldproductie

Statisch magneetveld heeft een gradient

Hierdoor is resonantie beperkt tot slechts 1 plaats (voor 1 frequentie)

De plaats van resonantie wordt gevarieerd (door gradienten of frequentie)



Samenvatting

Voordelen

- Grote hoeveelheden brandstof (lage prijs).
- Fusie is CO₂ neutraal.
- Kleine hoeveelheid radioactief afval.
- Geen risico van snelle energie afgifte.
- Brandstof is overal op Aarde beschikbaar.
 - Fusie is dus van belang voor iedereen die geen natuurlijke energiebronnen heeft.
 - Geo-politiek belang.
- Geef proliferatie van materiaal voor wapens

Nadelen

- Nog niet gedemonstreerd. Het bedrijf wordt gehinderd door allerlei, op zichzelf interessante natuurkundig fenomenen.
- Het kostenplaatje is onduidelijk. Met name de kosten van de reactor.

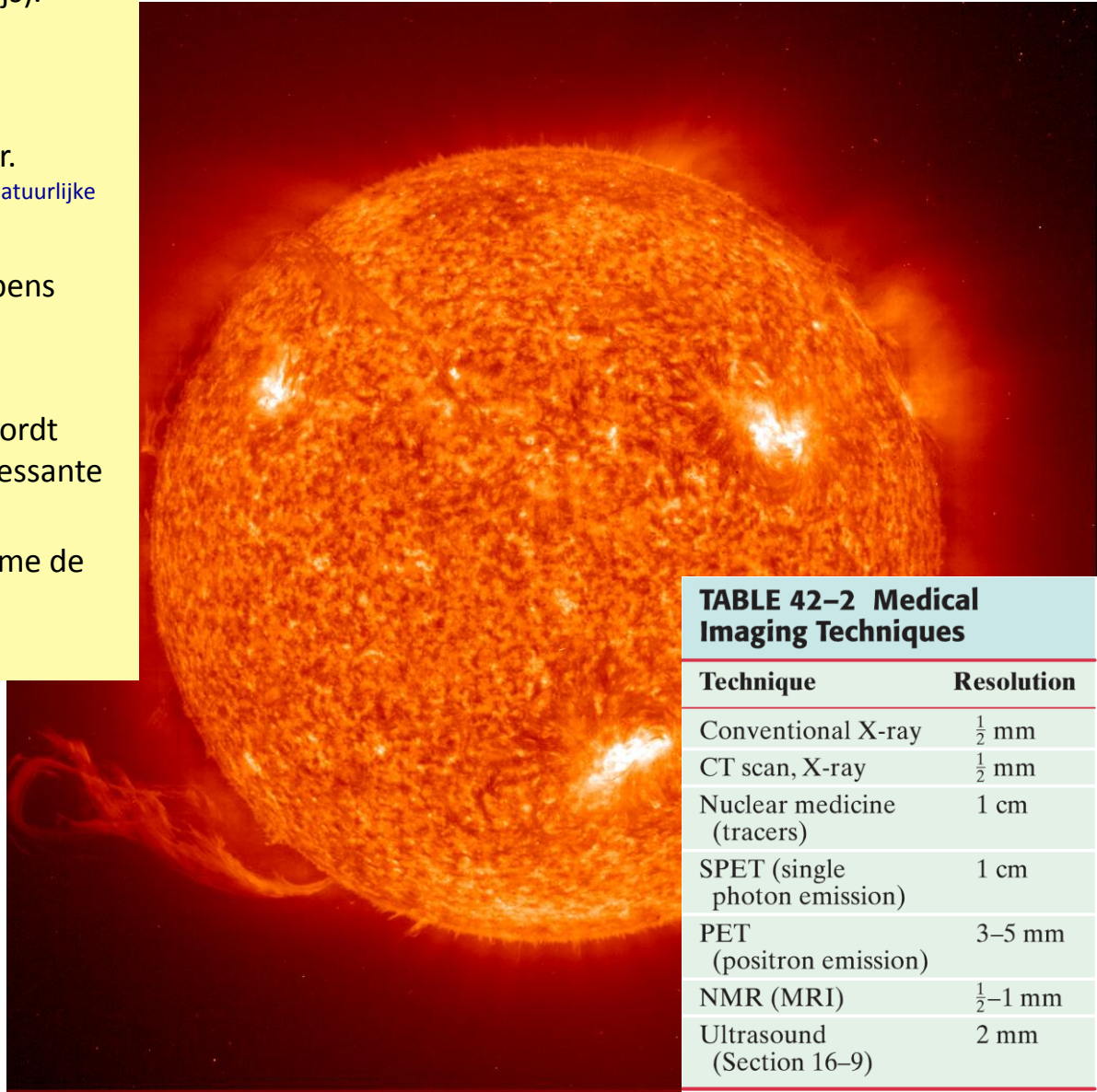


TABLE 42-2 Medical Imaging Techniques

Technique	Resolution
Conventional X-ray	$\frac{1}{2}$ mm
CT scan, X-ray	$\frac{1}{2}$ mm
Nuclear medicine (tracers)	1 cm
SPET (single photon emission)	1 cm
PET (positron emission)	3–5 mm
NMR (MRI)	$\frac{1}{2}$ –1 mm
Ultrasound (Section 16–9)	2 mm

