The Abdus Salam
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Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

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Plasma-Wall Interaction in Magentic Fusion

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Thomas Schwarz-Selinger

Plasma-Wall Interaction in Magnetic Fusion

the three lectures will cover:

- introduction: principles and status
- erosion mechanisms
- implantation and diffusion
- snapshots of my own work

Thomas Schwarz-Selinger

introductory talk to Plasma-Wall Interaction in Magnetic Fusion

- Principles and status of magnetic fusion
- Energy and particle fluxes to the vessel walls
- Selection criteria for wall materials
- Issues of plasma-wall interaction

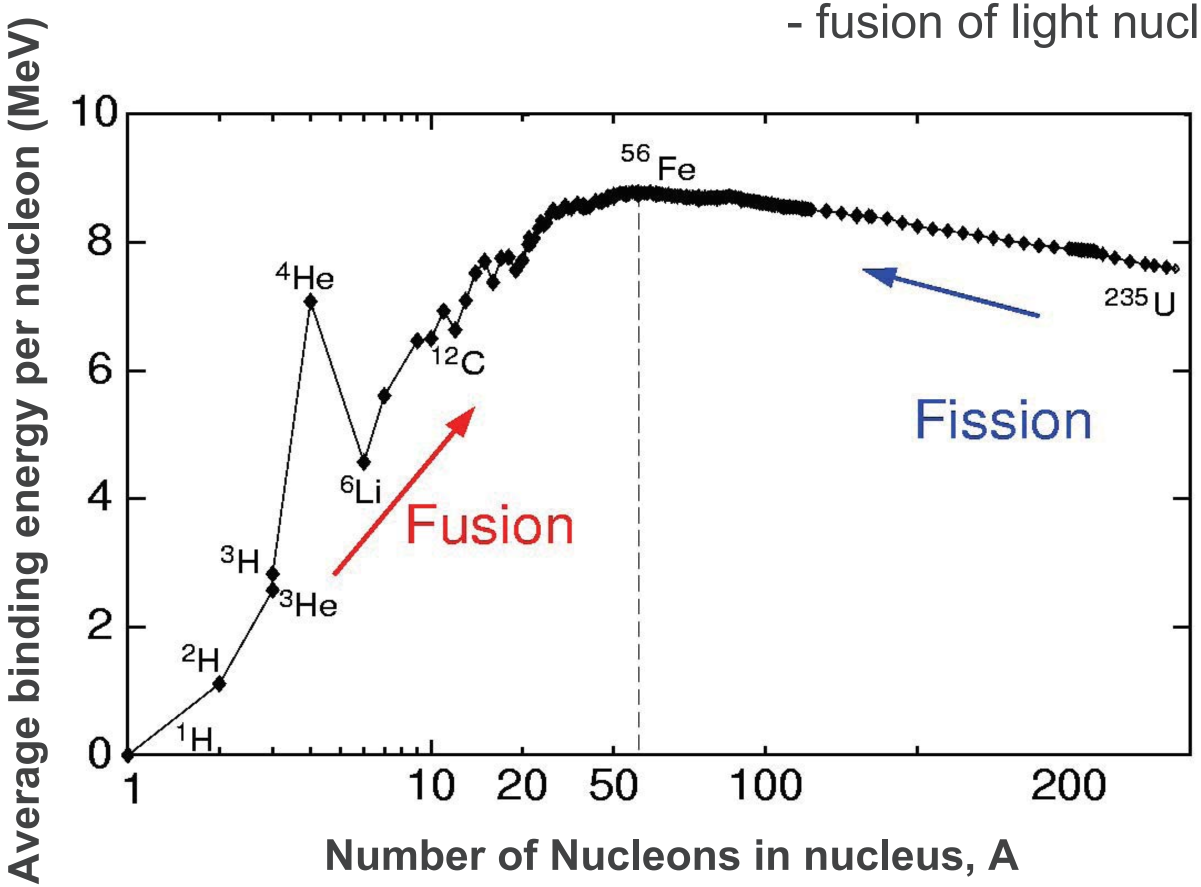
Thanks to the organizer for invitation

Thanks to Joachim Roth,
Karl Krieger, Hans Maier, Matej Mayer and Armin Manhard
for providing material for these talks

cuclear energy: fission/fusion

- Binding energy of nuclei: **MeV**, not eV as in chemistry (electrons binding molecules)

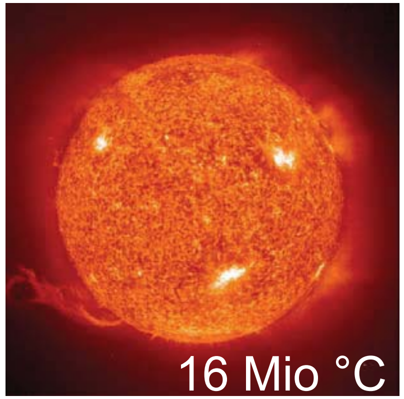
- Energy gain possible from - fission of heavy nuclei or
  - fusion of light nuclei.



- Advantages of fusion :
  - + fuel resources
  - + safety considerations
  - + waste production.

solar fusion reactions: the pp-chain

$$p + p \rightarrow d + e^+ + \nu_e$$
$$p + d \rightarrow {}^3He + \gamma$$



$${}^3He + {}^3He \rightarrow {}^4He + 2p$$

$${}^3He + {}^4He \rightarrow {}^7Be + \gamma$$

$$e^- + {}^7Be \rightarrow {}^7Li + \nu_e$$
$$p + {}^7Li \rightarrow {}^4He + {}^4He$$

$$p + {}^7Be \rightarrow {}^8B + \gamma$$
$${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$$
$${}^8Be^* \rightarrow {}^4He + {}^4He$$

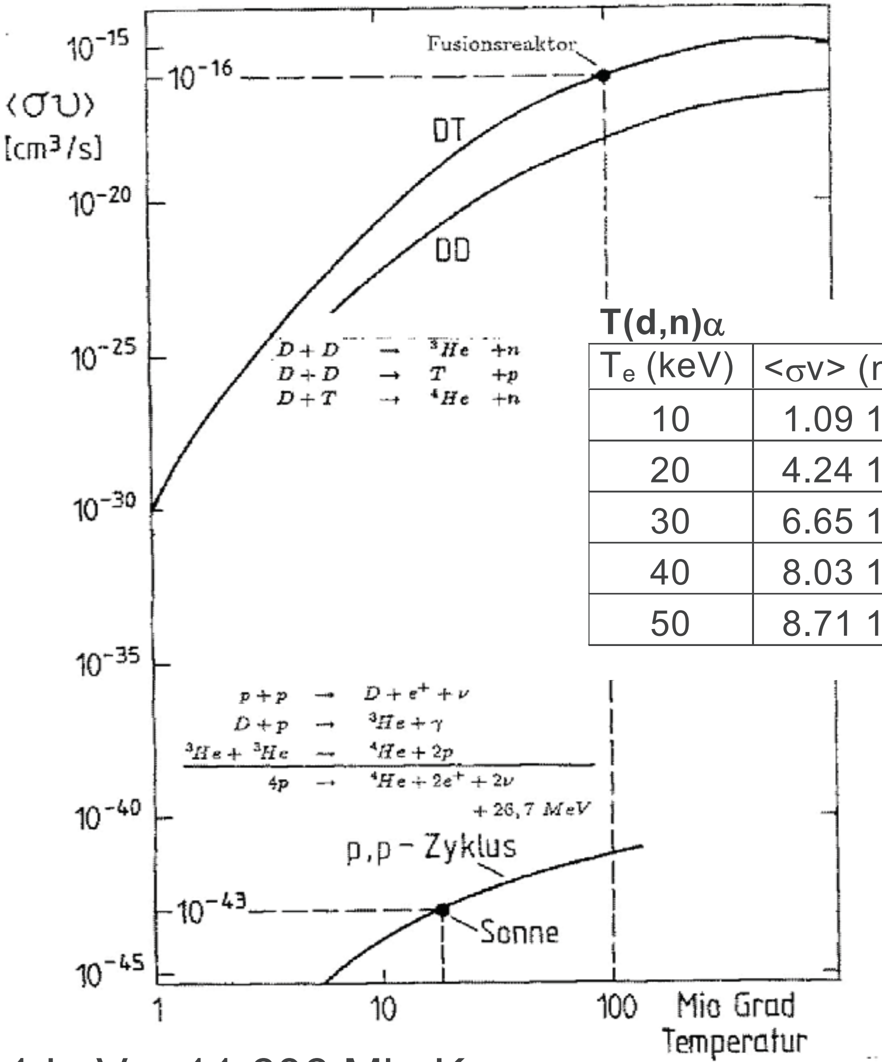
branch I (85 %)

branch II (15 %)

branch III (0.02 %)

- The first step involves the weak interaction, transforming a proton into a neutron, resulting in a very small reaction rate.
- This is the reason for the long life time of stars.

for a terrestrial energy source we need other fusion reactions!



T(d,n)α

T_e (keV)	<σv> (m³/s)
10	$1.09\ 10^{-22}$
20	$4.24\ 10^{-22}$
30	$6.65\ 10^{-22}$
40	$8.03\ 10^{-22}$
50	$8.71\ 10^{-22}$

1 keV = 11.606 Mio K

- fusion reaction rate
  $f_{fus} = n_1 n_2 \langle\sigma v\rangle$
- The weak interaction makes the pp-chain a rather slow reaction.
  => long lifetime of stars.
- The huge mass of the sun makes up for that easily, still resulting in a large power production.
- However, for power production in small volumes on earth, the weak interaction is not feasible.

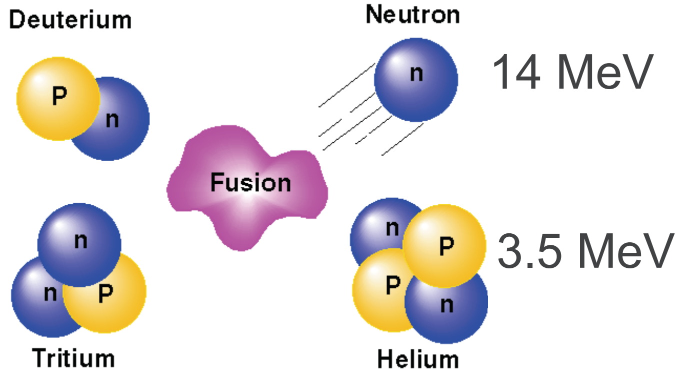
fusion on earth

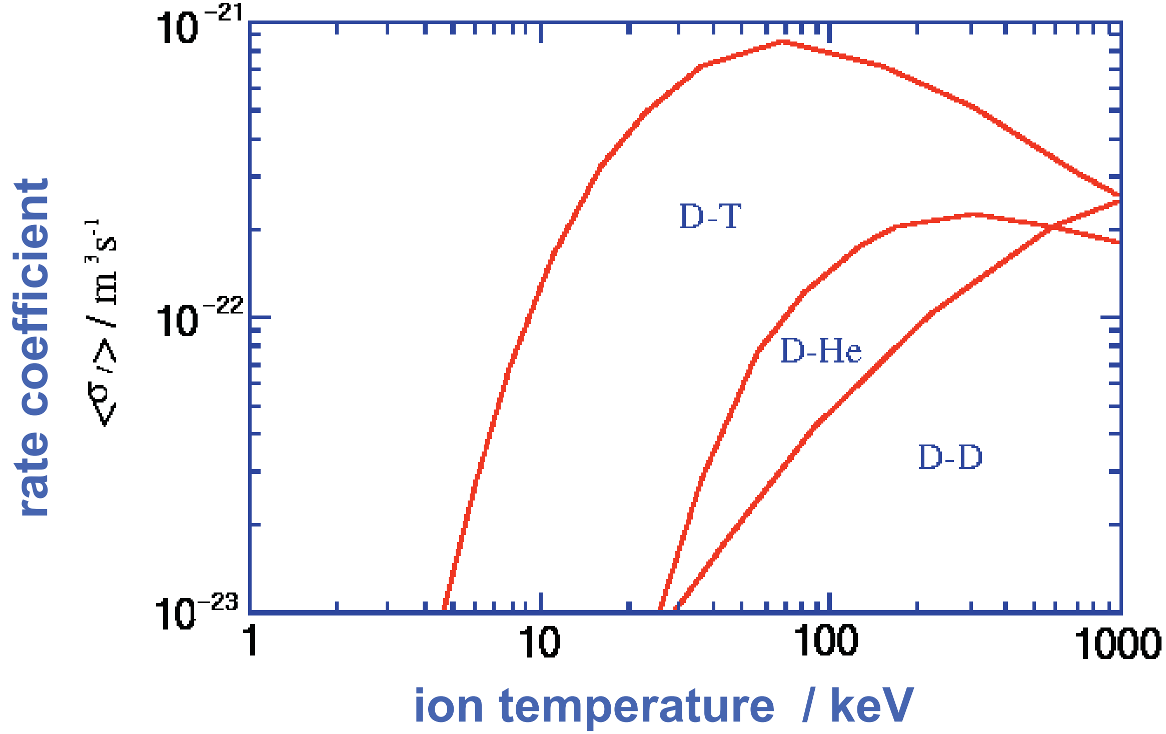
$D + T \Rightarrow {}^4He + n + 17.59\ MeV$

$D + {}^3He \Rightarrow {}^4He + p + 18.35\ MeV$

$D + D \Rightarrow {}^3He + n + 3.27\ MeV$ (50%)

or $T + p + 4.03\ MeV$ (50%)





- $D = {}^2H$, $T = {}^3H$,
- The reaction energy is distributed to the reaction products inversely to their mass ratio (energy and momentum conservation).
- Best choice: the DT-reaction

fusion fuels

- **Deuterium** exists with a weight fraction of $3.3 \cdot 10^{-5}$ in water
  $\Rightarrow$ static range of billions of years. (33 g in $1 m^3$ water equiv. of 300 000 l oil)

- **Tritium** is a radioactive isotope and decays with a half life of 12.33 years:

$$T \rightarrow He + e^- + \nu_e$$

  $\Rightarrow$ no natural tritium available, but breeding with fusion produced neutrons is possible:

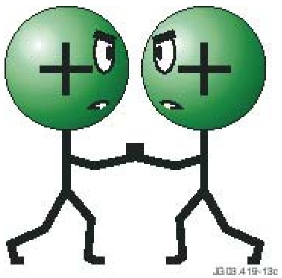
$$n + {}^6Li \rightarrow {}^4He + T \quad + 4.8\ MeV$$

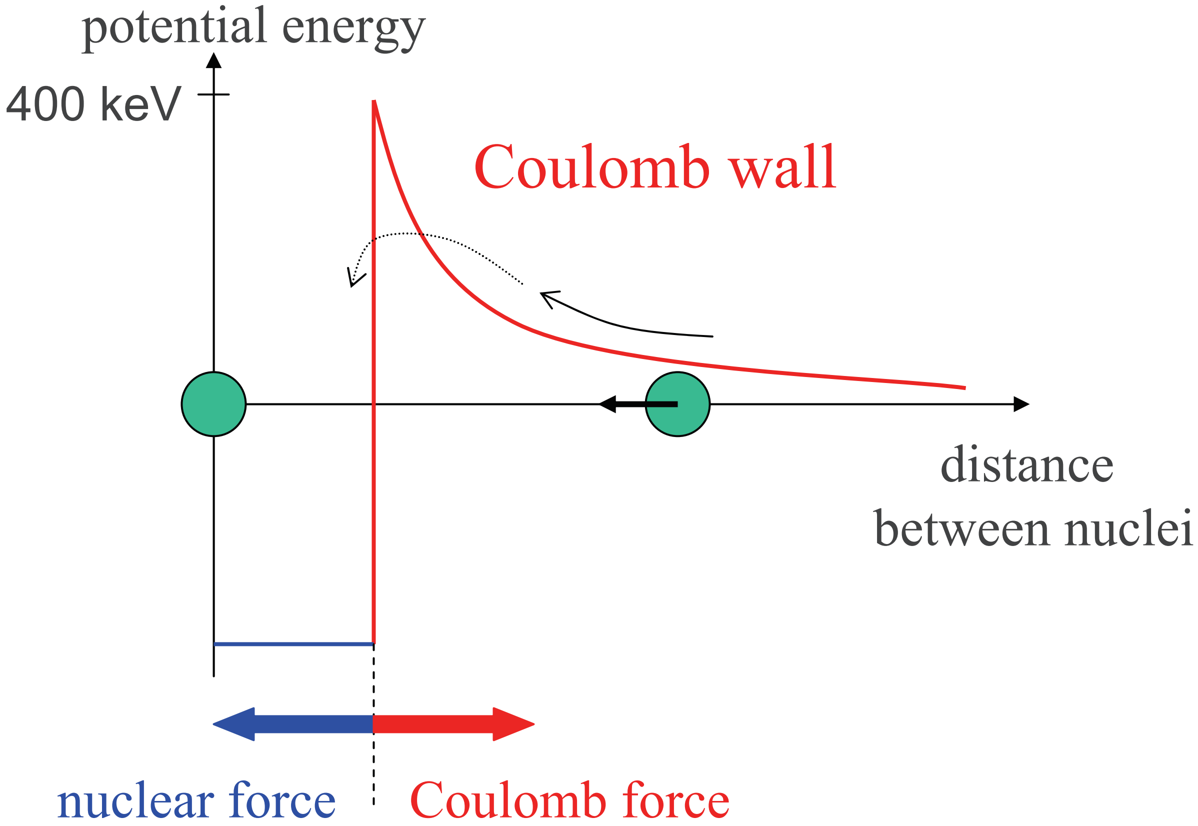
$$n + {}^7Li \rightarrow {}^4He + T + n' \ - 2.5\ MeV$$

  The latter reaction allows self-sufficient tritium breeding.

- **Lithium** is very abundant and widespread (in the earth's crust and 0.15 ppm in the ocean water), sufficient for at least 30 000 years.

the need for high temperatures





$$P_{\text{tunneling}} \propto \exp\left(-\frac{2\pi Z_1 Z_2 e^2}{\hbar v}\right)$$

thermonuclear fusion

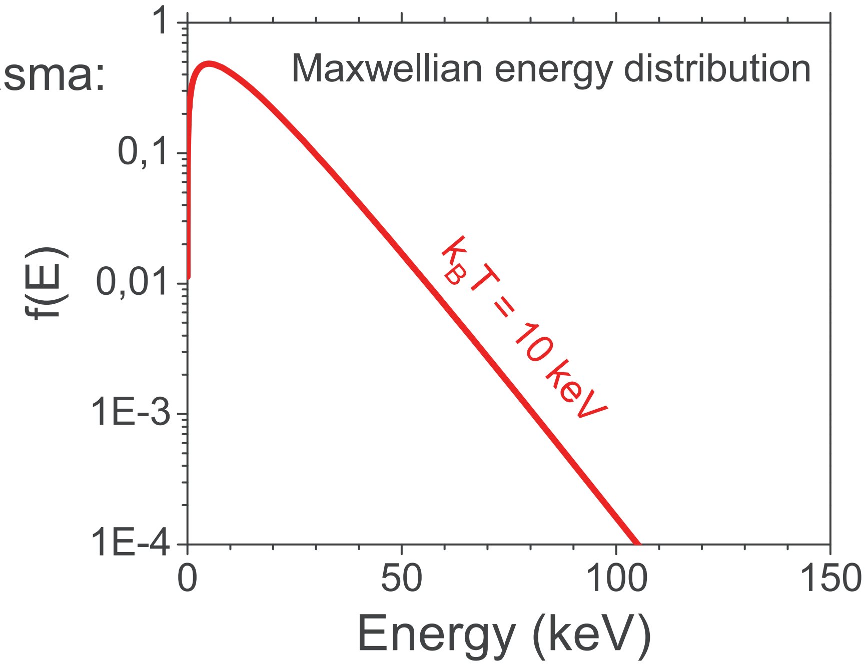
High relative velocity of the nuclei is necessary ⇒ accelerator?
No! Coulomb scattering makes the beams diverge ⇒ not efficient

Thermalised mixture of deuterium and tritium at temperatures of some 10 keV is needed ⇒ thermonuclear plasma.

Energy distribution of particles in a thermal plasma:
Maxwell distribution

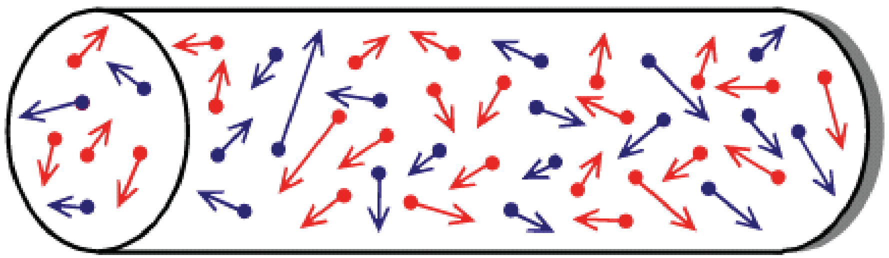
$$f(\mathrm{v})d\mathrm{v} = \left(\frac{m}{2\pi k_B T}\right)^{3/2} 4\pi \mathrm{v}^2 \exp\left(-\frac{m\mathrm{v}^2}{2k_B T}\right)d\mathrm{v}$$

where $f(\mathrm{v}) = f(|\vec{\mathrm{v}}|)$ defines the probability in the velocity interval [v, v+dv].

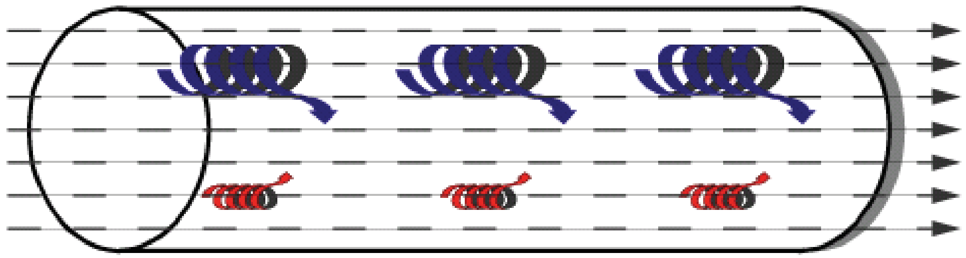


plasma confinement by a magnetic field

without B-field



with B-field



Mobility || B >> Mobility ⊥ B

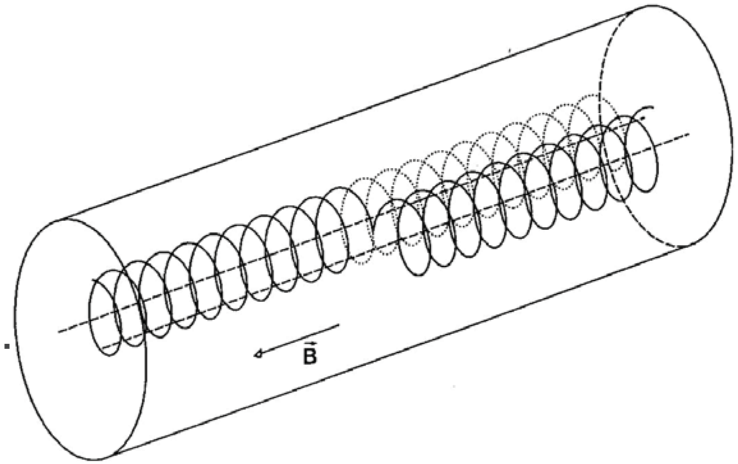
⇒ Strongly decreased plasma-wall contact

magnetic confinement

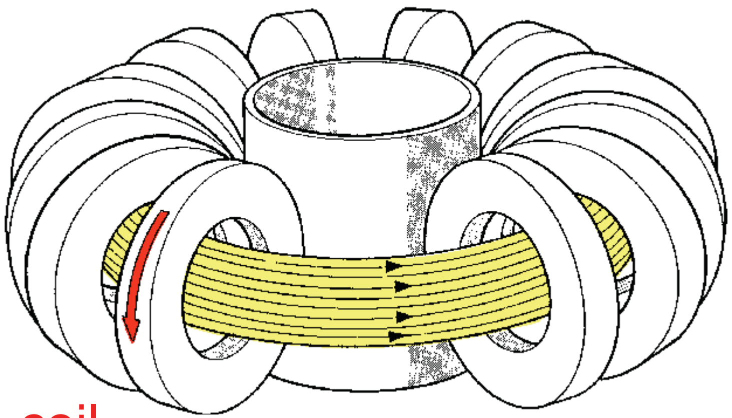
Charged particles are confined by magnetic fields

Transport perpendicular to $\vec{B}$ only by collisions.

Particles escape only parallel to $\vec{B}$, i.e. at the ends.



$\Rightarrow$ bend it to a torus.



coils

coil current

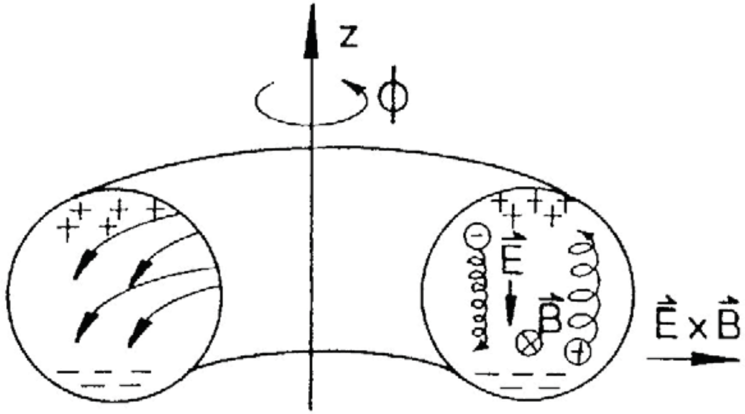
magnetic field lines

magnetic confinement II

However, a purely toroidal field has a radial gradient because $B \propto \frac{1}{R}$

$$\vec{v}_{\nabla B} = \frac{m v_\perp^2}{2qB^3} \cdot (\vec{\nabla}\vec{B} \times \vec{B})$$

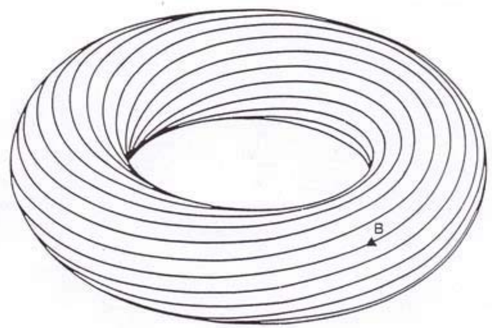
⇒ gradient drift separate electrons and ions:



⇒ charge separation creates electric field, which in turn results in an ExB-drift

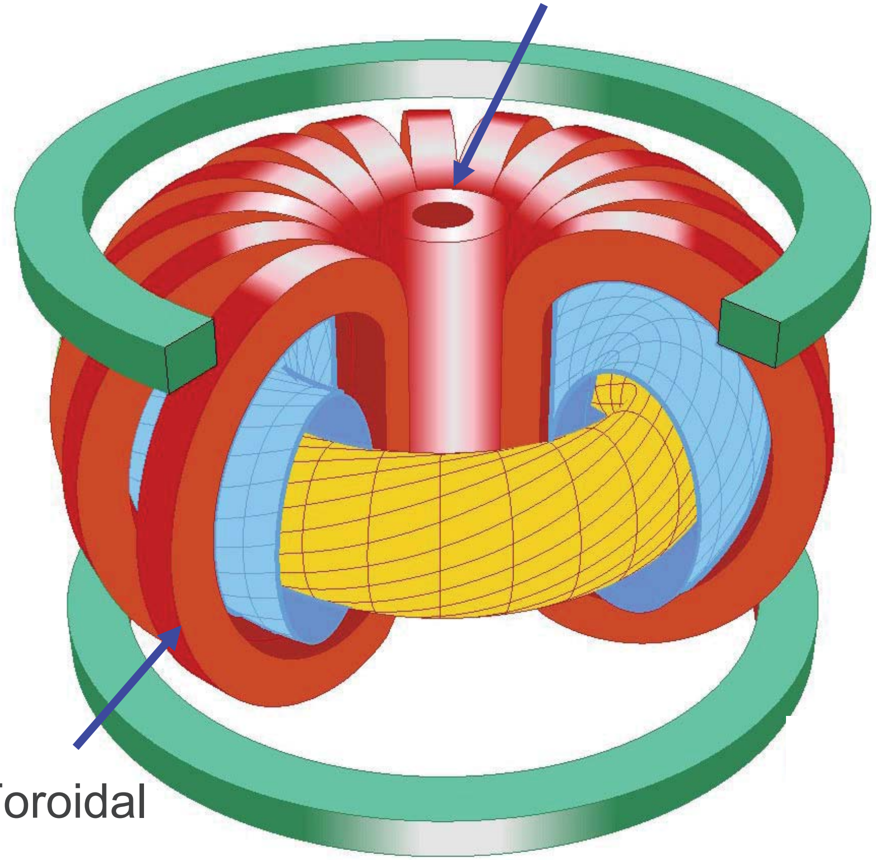
$$\vec{v}_E = \frac{\vec{E} \times \vec{B}}{B^2}$$ (independent on charge sign)

Consequence: plasma drifts outward!



⇒ The magnetic field lines have to be twisted, so that they „average“ over regions with strong and weak field.

Tokamak



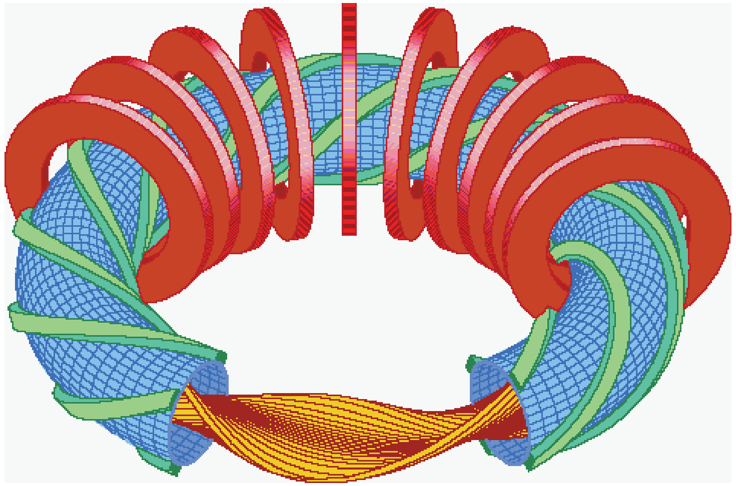
A current in the plasma is induced, using the plasma as secondary winding of a transformer.

Only confining when plasma is ignited.

Invented in the 50‘s in Moscow, by L. Artsimovich and Sacharov.

+ intrinsic heating,
- due to the transformer instationary ⇒ current drive
- possibility of current disruptions
+ most advanced fusion concept

Stellarator

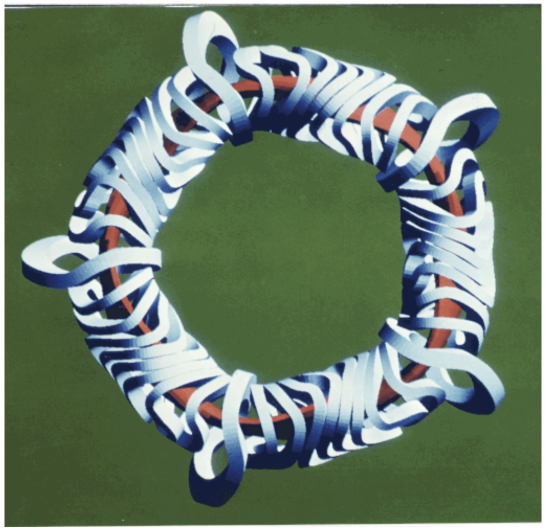


vacuum B flied already confining

no net current in the plasma

+ stationary
- less advanced fusion concept
-complex geometry

advanced stellarator W7-X



Lawson criterion

In 1957 Lawson introduced power balances:

Break-even: The fusion power equals the loss by radiation, and by transport (diffusion, convection, charge-exchange):

$$P_{fus} = n_D \cdot n_T \cdot \langle\sigma \cdot v\rangle \cdot E_{fus} \geq P_{bremsstrahlung} = c_1 \cdot n_e^2 \cdot Z_{eff} \cdot (kT)^{1/2} + P_{loss} = 3\, n\, kT / \tau_E$$

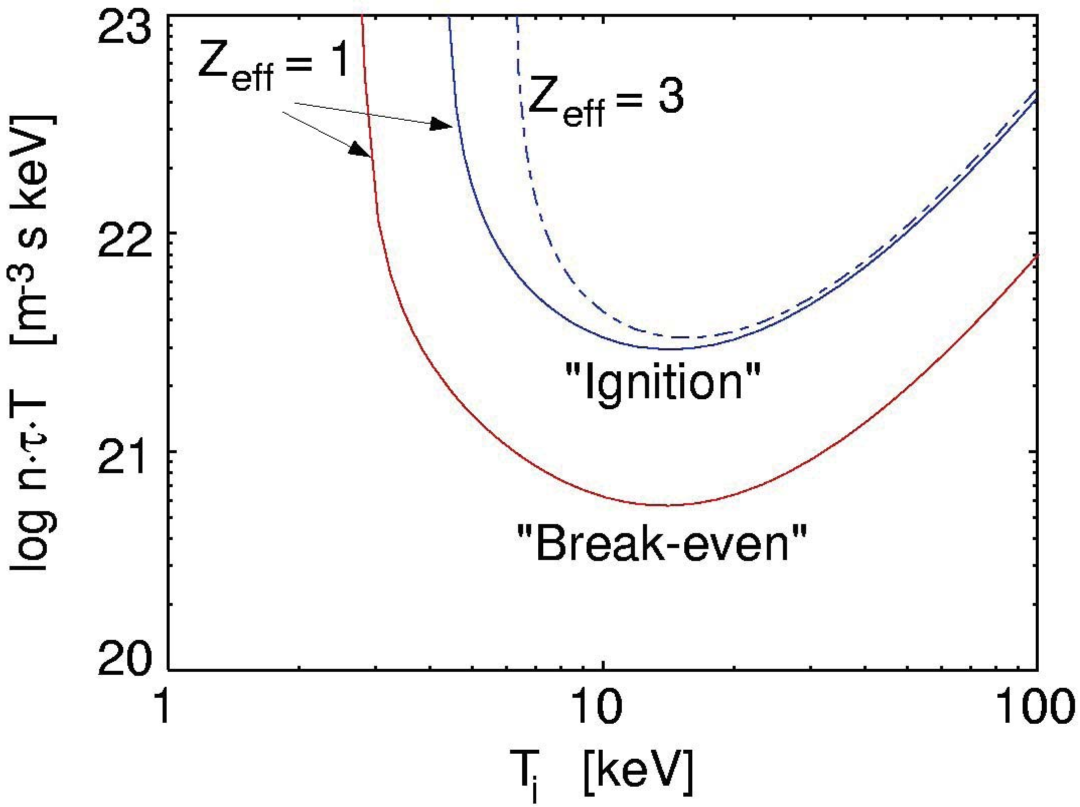
(where E_{fus} is the α particle heating, $c_1 = 5.4 \cdot 10^{-37}$ $Wm^3keV^{-1/2}$, and $Z_{eff} = \Sigma f_i Z_i^2$ is the effective plasma charge)

With $n_D = n_T = n/2$, and $T_i = T_e = T$ we find a condition for the fusion product $n\tau T$:

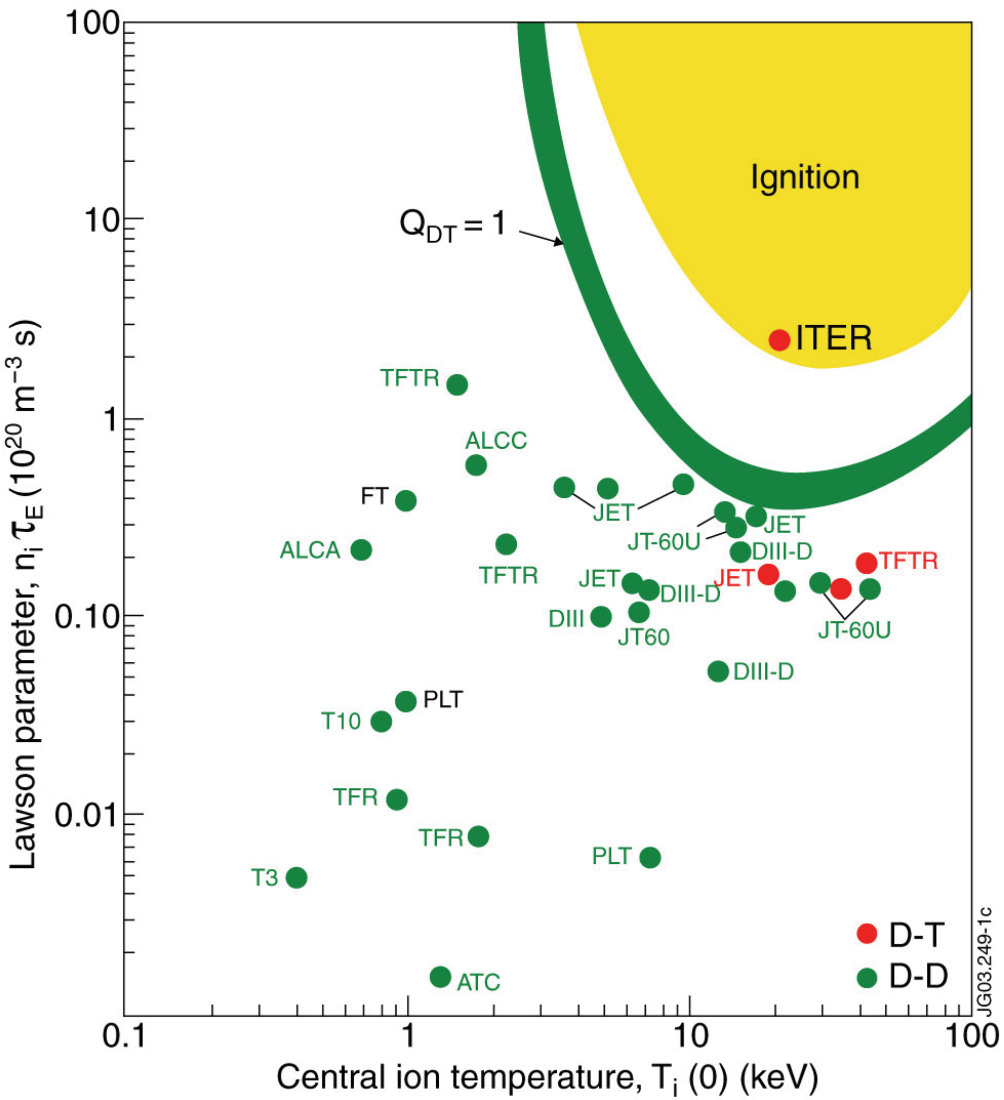
$$n\,\tau\,T = \frac{12\,(kT)^2}{\langle\sigma \cdot v\rangle \cdot E_{fus} - 4\, c_1\, Z_{eff}\, (kT)^{1/2}}$$

Ignition criterion

Ignition: The neutrons leave the plasma, the α-particles are confined and heat it. Only their energy should enter the balance! $E_{fus} \rightarrow E_{\alpha}$

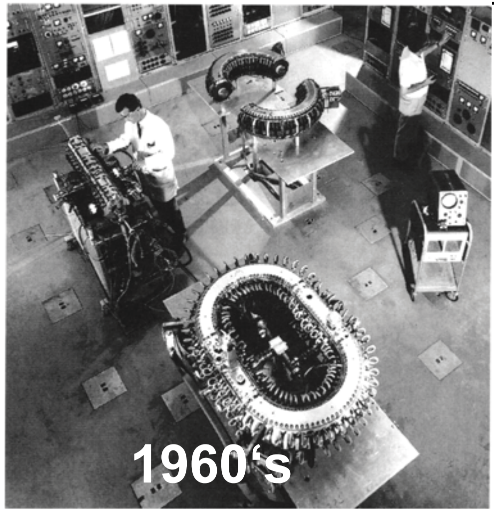


Lawson criterion status of fusion research



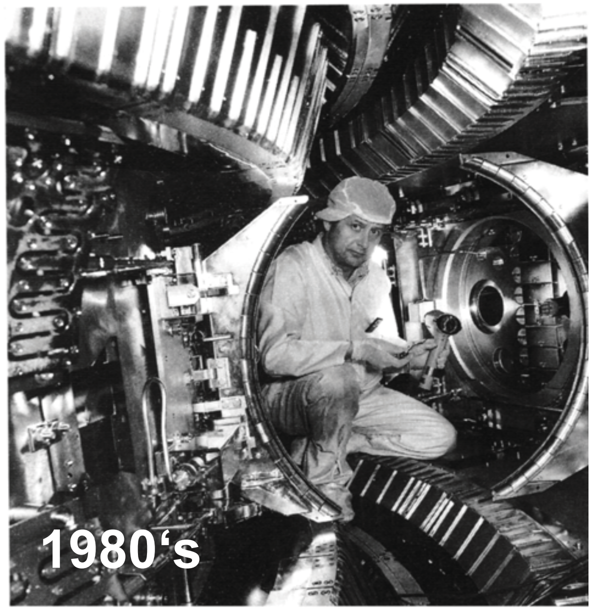
- Todays tokamak plasmas are close to breakeven,
- The next step (ITER) will ignite or at least operate at high Q (≈10),
- and thereby prove the scientific and technological feasibility of fusion energy.

development of fusion experiments: size

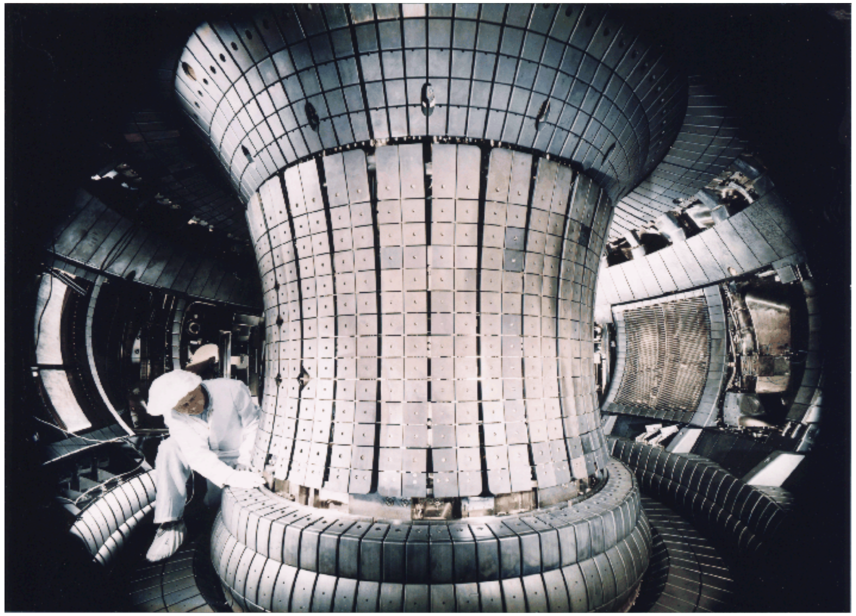


W1a, W1b

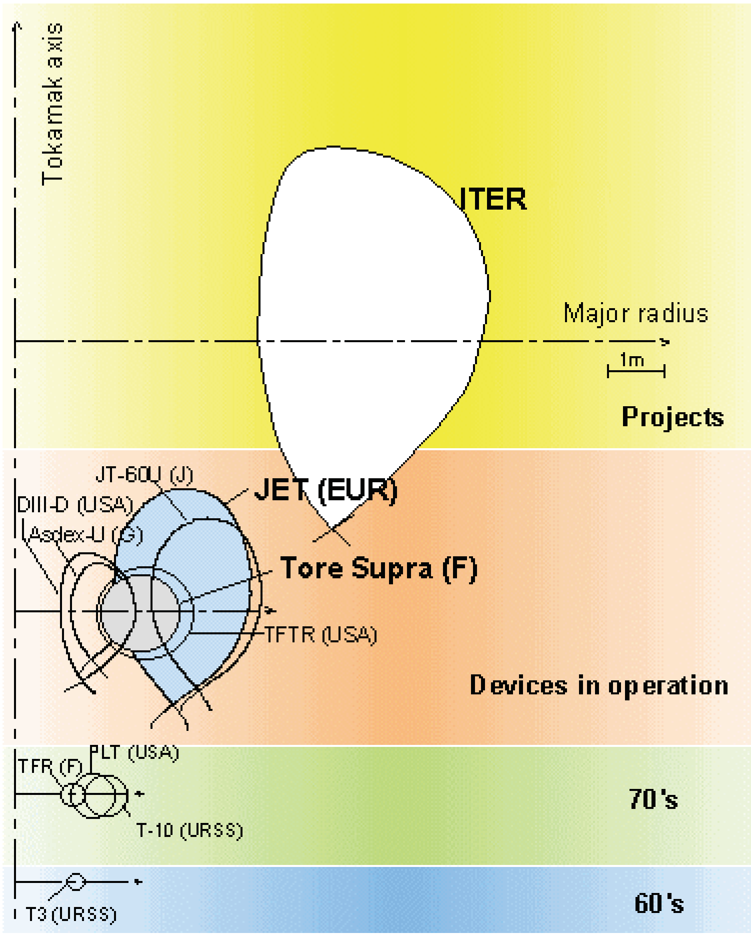
ASEDX

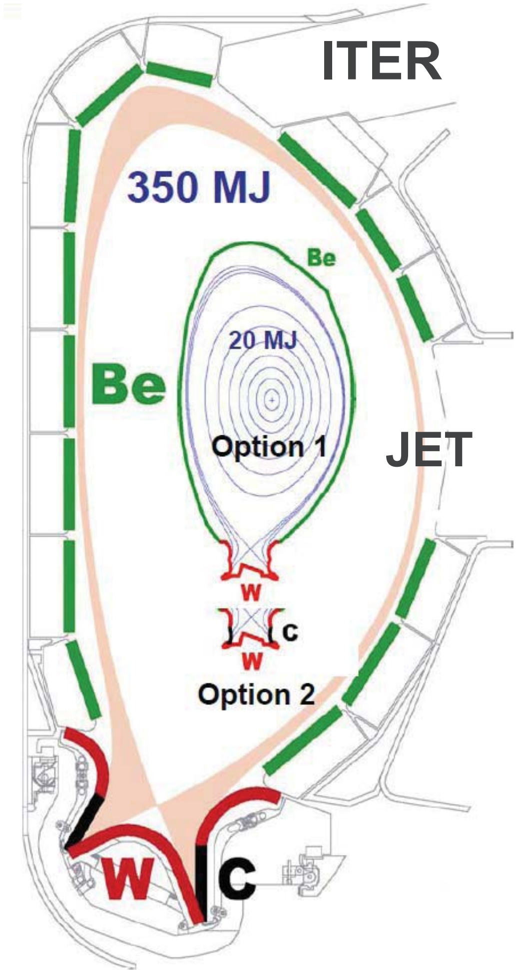


ASEDX Upgrade

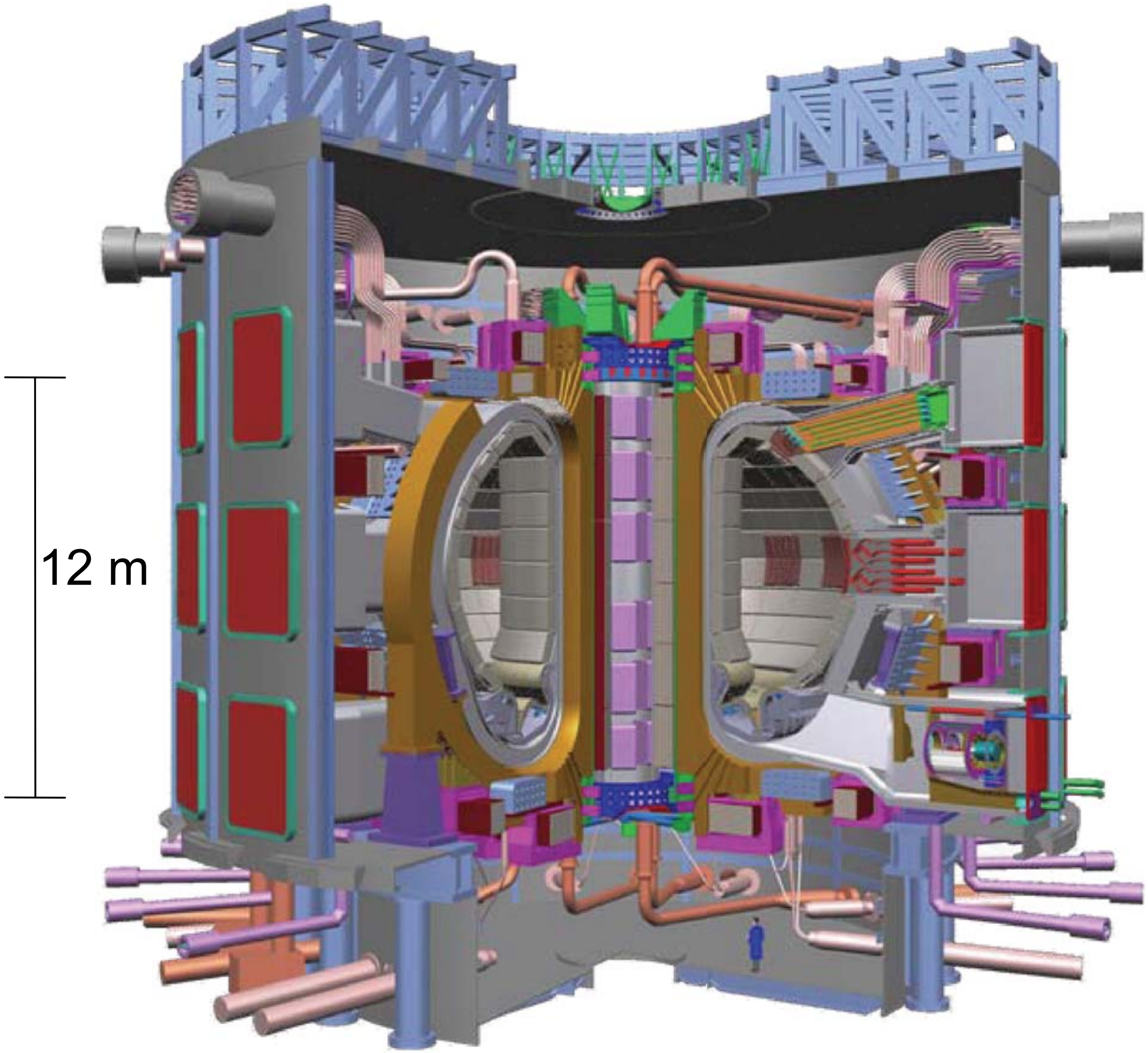


development of fusion experiments: size





International Thermonuclear Experimental Reactor ITER

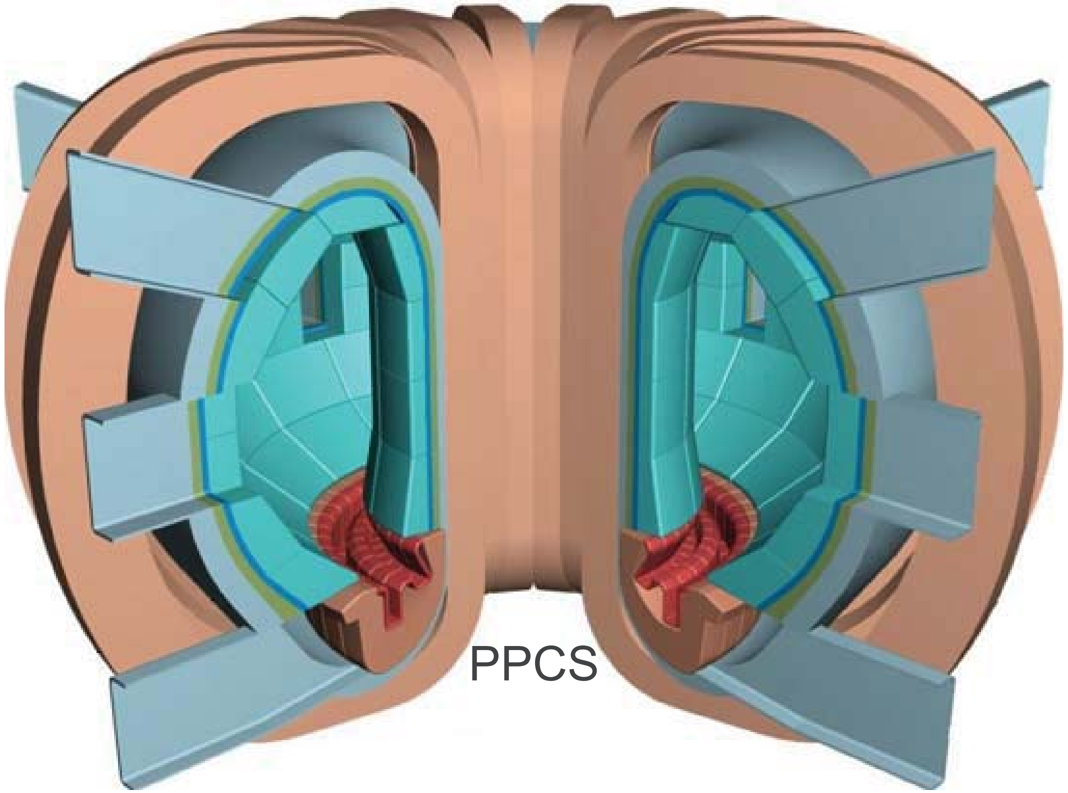


- International project: Europe, Japan, Russia, USA, China and Korea
- Outline Design in 1999, Design Review 2008, construction ahead.
- First plasma 2018
- DT Phase 2022

R [m]	6.2
a [m]	2.0
I_p [MA]	15.1
B [T]	5.3
T_{puls} [s]	400
P_{fusion} [MW]	400

from ITER to a Fusion Reactor

European **P**ower **P**lant **C**oncept **S**tudies



Component lifetime considerations

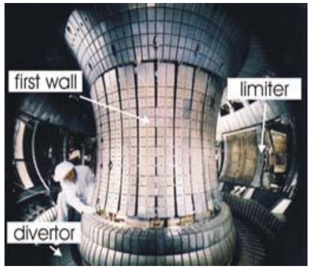
Flexibility not needed here
Main Chamber First Wall:

Tungsten
Very low erosion yield, high threshold energy

Compatible with low tolerable concentration?

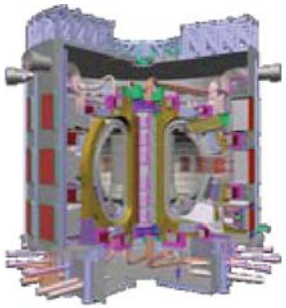
ASDEX Upgrade tungsten experiment!

present and future fusion devices



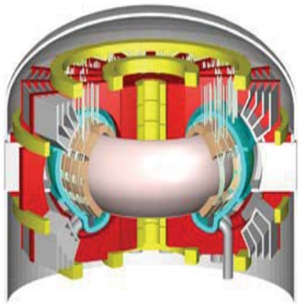
Present tokamaks

PF surface:	< 150 m^2
heating power:	< 40 MW
discharge duration:	<60 s



ITER

PF surface:	800 m^2
fusion power:	400 MW
alpha power:	100 MW
heating power:	<73 MW
discharge duration:	400 s



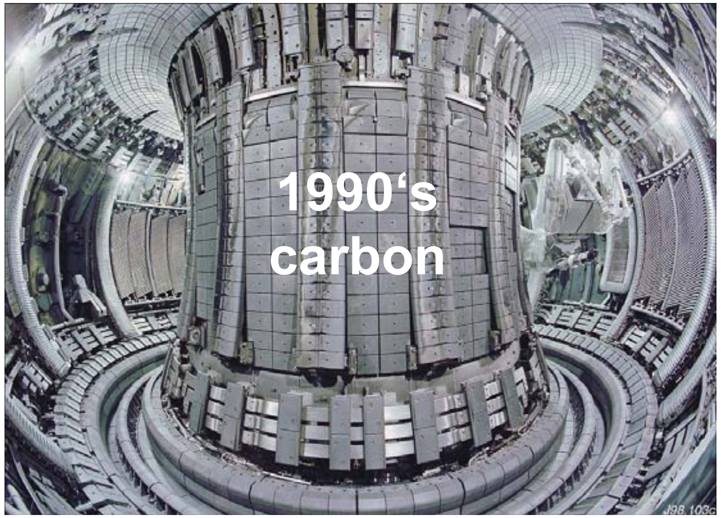
Reactor (DEMO)*

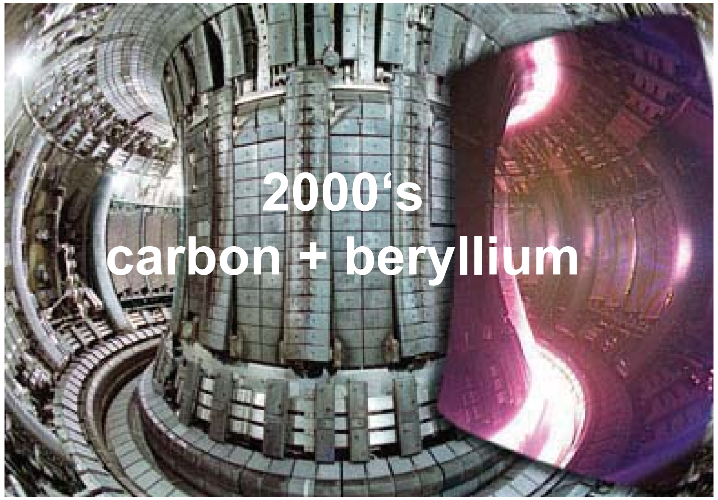
PF surface:	1000 m^2
fusion power:	2000 MW
alpha power:	400 MW
heating power:	80 MW
stationary operation	

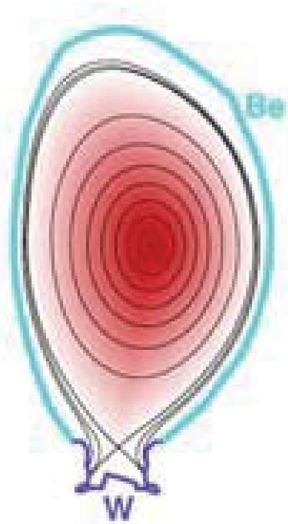
Size, power load, and duration increase

*** ITER sized reactor (Toschi et al., SOFT 2000)**

development of fusion experiments: first wall materials at JET







**> 2010
beryllium +
tungsten
(ITER like
wall project)**

history of first wall materials (high Z vs low Z)

stainless steel

↓

carbonization

↓

carbon → tungsten (molybdenum)

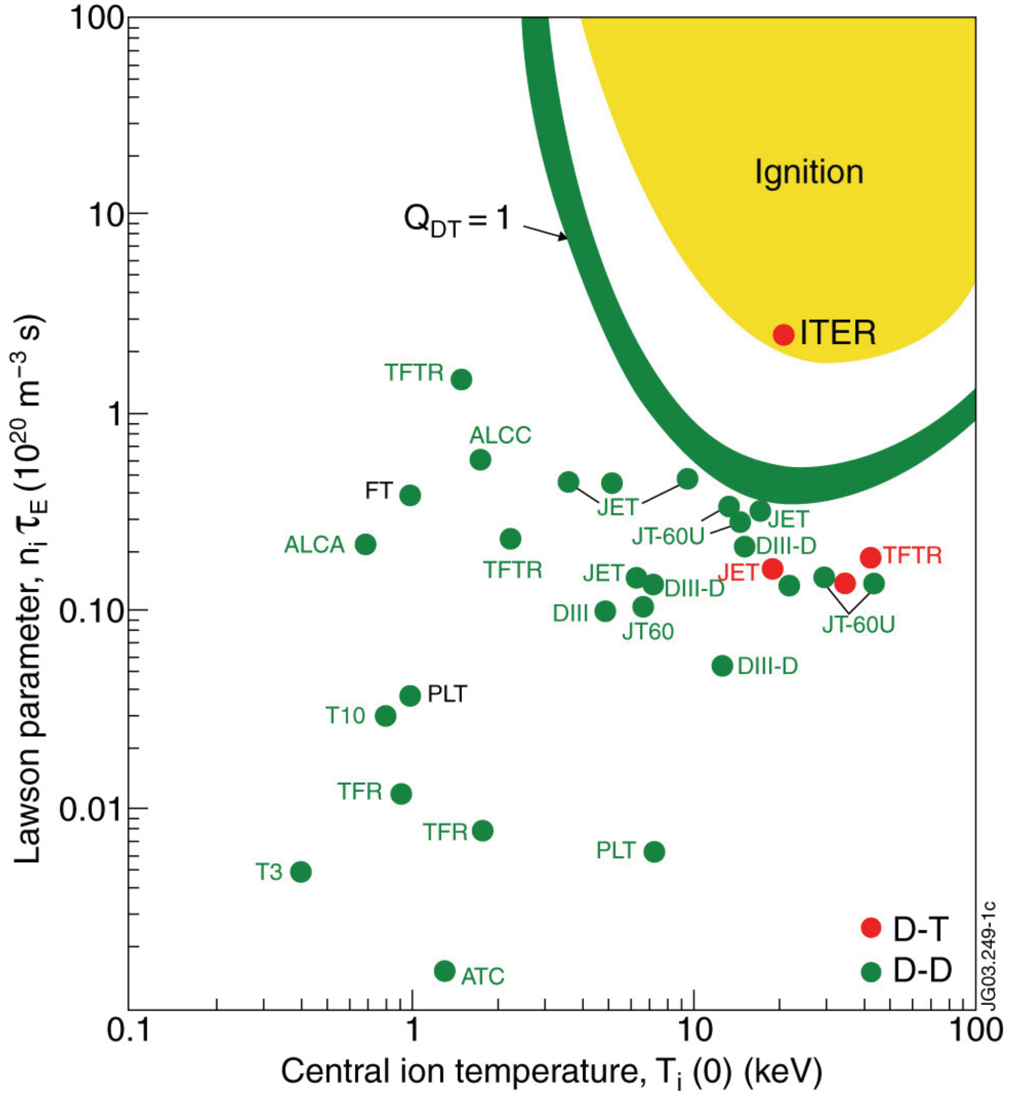
↓

boronization (siliconization)

ITER:
tungsten, beryllium, carbon

DEMO:
tungsten

Why plasma wall interaction at all?



Why bother?

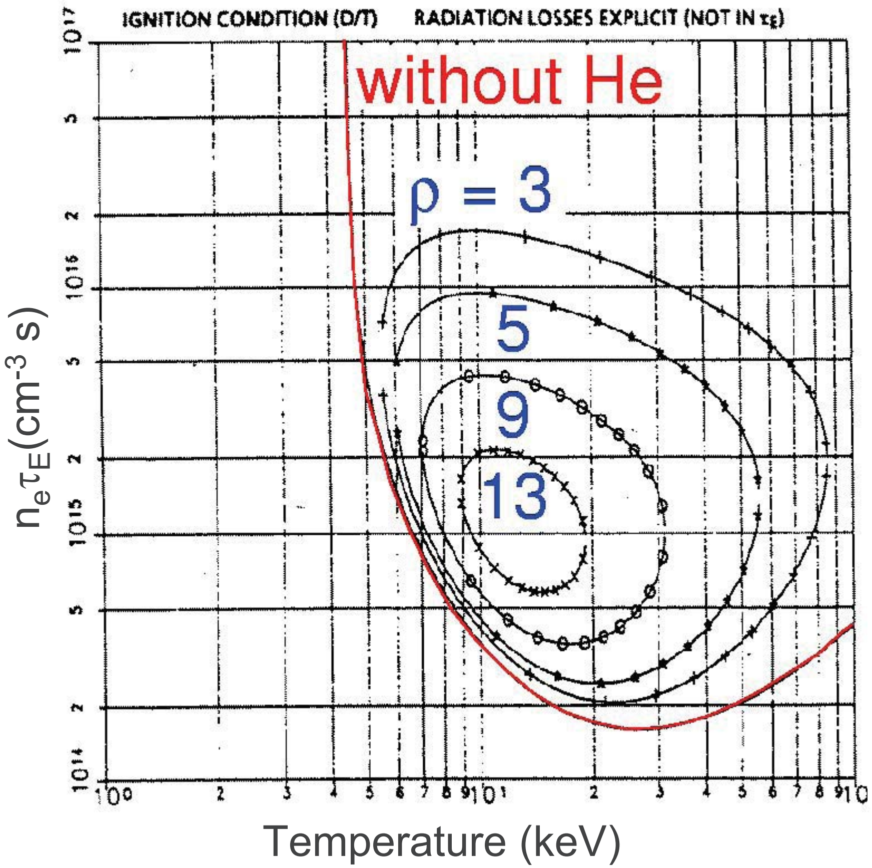
- confine the plasma with a perfect magnetic field
- heat it up

and you are fine, isn't it?

ignition criterion

The α-particles also dilute the plasma, as they are intrinsically coupled to fusion power ($3.53 \cdot 10^{11}$ atoms/s/W).

$\Rightarrow$ Upper limit for particle confinement time



$\rho_{He} = \tau^*_{He} / \tau_E$

τ^*_{He} global a particle confinement time

τ_E energy confinement time

here: $Z_{eff} = 1$

$\Rightarrow$ gain in τ_E must be accompanied by gain in τ^*_{He}

D. Reiter et al.
Nuclear Fusion 30 (10), 2141 (1990).

PWW issues in fusion

wall

sink for energy and particles from the plasma

source of wall atoms and previously implanted fuel atoms

challenges

- plasma contamination (radiation losses, dilution)
- density control (wall loading – reemission: recycling)
- altering material properties (heat conductivity, integrity)
- component lifetime (erosion)

power exhaust and limitation of the plasma

Heating power leaves the plasma in form of:

- ❑ radiation
- ❑ kinetic energy of escaping particles.

⇩

Direct contact of the plasma with the vessel walls must be avoided.

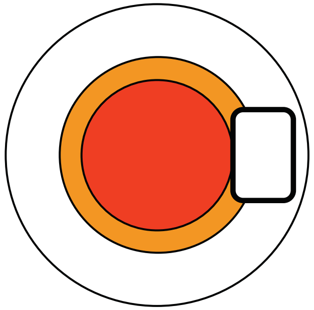
Imperfections in the magnetic configuration or displacement of the plasma might lead to concentrated heat deposition on areas that are difficult to control and cool.

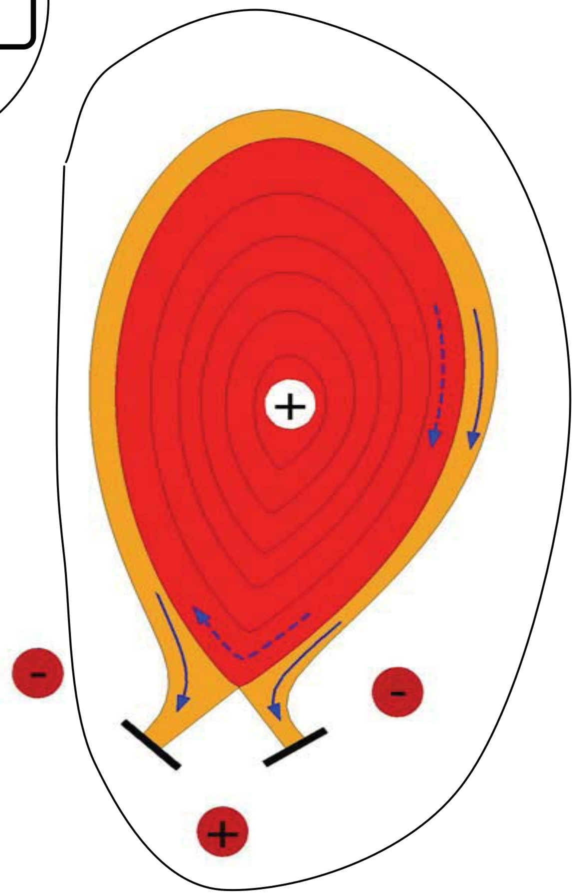
⇩

The plasma edge must be controlled (limited).

limiter / divertor for controlled plasma-wall interaction

- plasma confinement with nested, closed magnetic surfaces, but
- plasma edge has to be defined either
  - physically by a material limiter, or
  - magnetically by additional poloidal fields, defining a last closed flux surface, the separatrix.



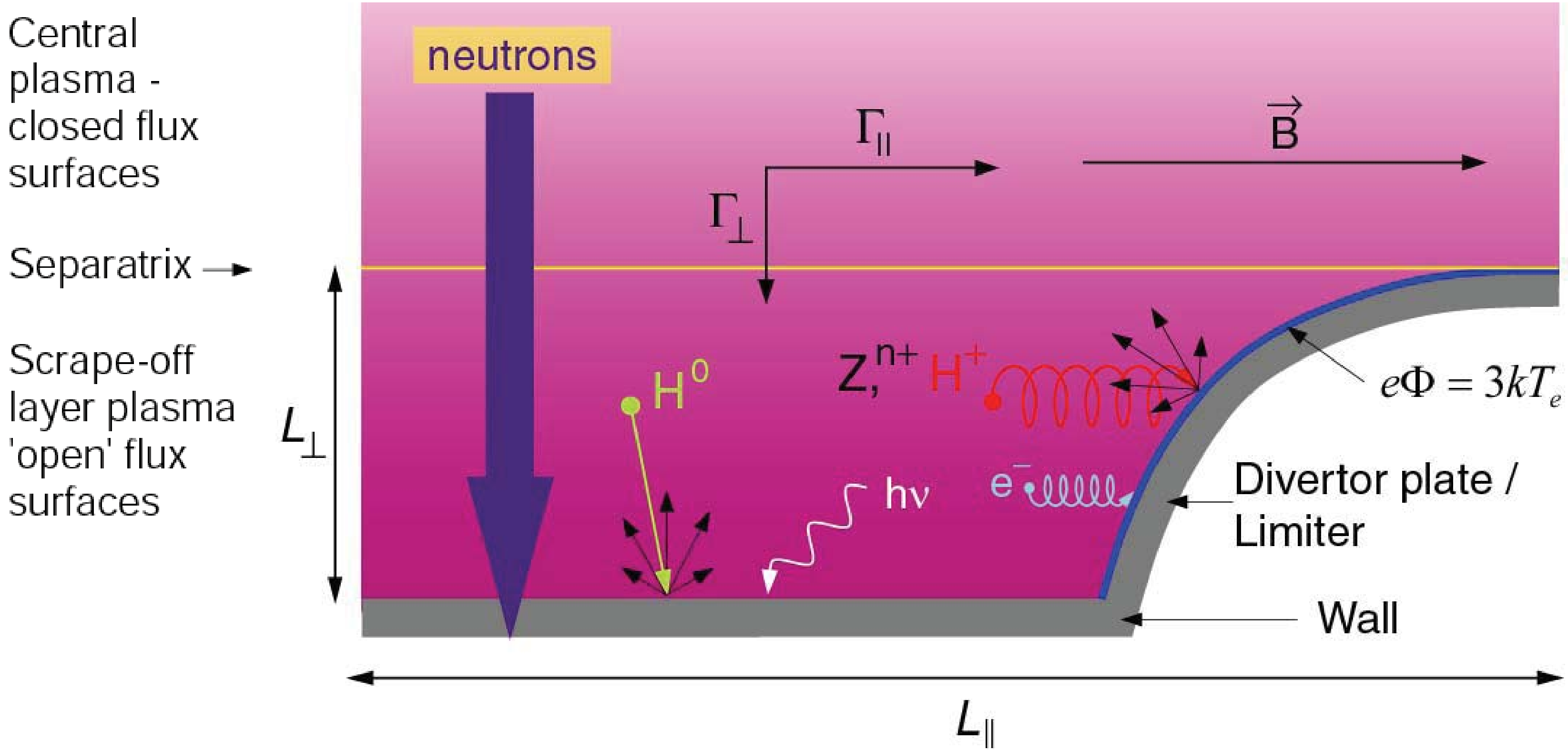


- First successful experiments in ASDEX in the 80's:
  - cleaner plasmas
  - steep edge gradients
  - $\Rightarrow$ H-mode with improved confinement

- Meanwhile all major tokamaks use a divertor for power and particle exhaust.

- Stellarators have an intrinsic separatrix

plasma wall interaction processes



<u>Hydrogen isotope processes</u>

- Reflection
- Implantation, diffusion, trapping
- Reemission

<u>Plasma facing material (impurity) processes</u>

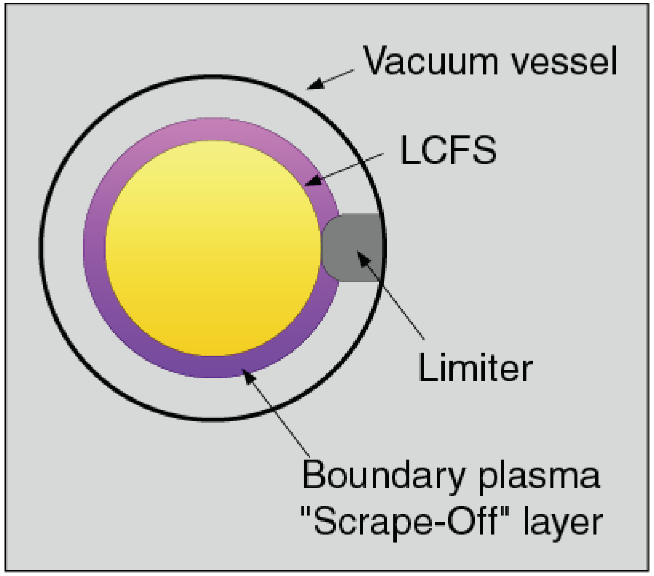
- erosion by particle impact
- evaporation, sublimation
- arc erosion
- migration and redeposition

plasma limiters

Limiter:
A material structure protruding from the main wall used to intercept particles at the plasma edge.

Last Closed Flux Surface (LCFS):
The magnetic surface that touches the innermost part of the limiter.

Scrape-off Layer (SOL):
The plasma region located in the limiter shadow i.e. between the LCFS and the vessel wall.



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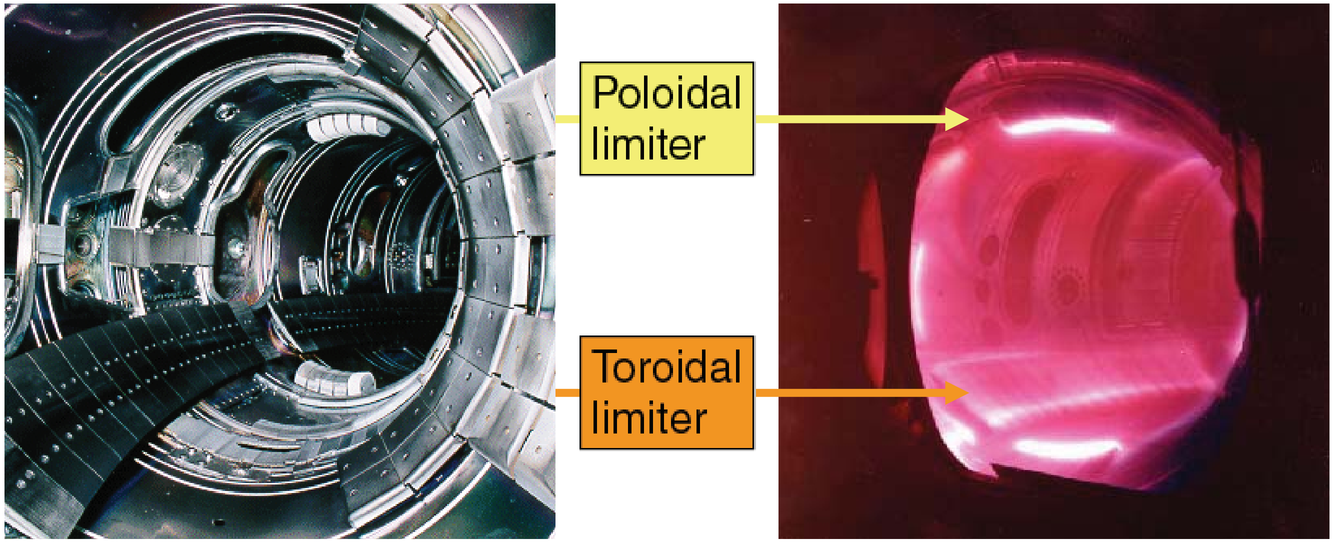
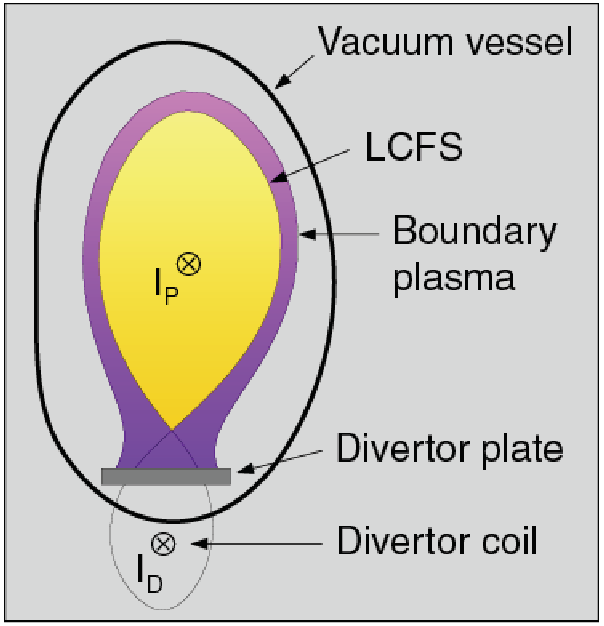
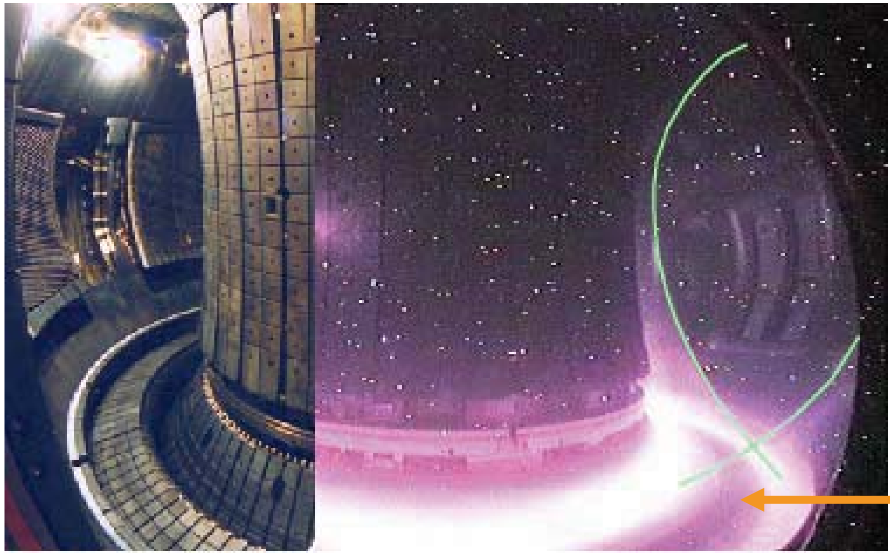


plasma divertors

Divertor:
A separate region in the vacuum vessel to which escaping ions are exhausted || B by means of auxiliary magnetic coils.

The magnetic boundary between confined plasma and edge/divertor plasma is called **separatrix** ≡ LCFS





The divertor in ASDEX Upgrade

limiter vs. divertor operation

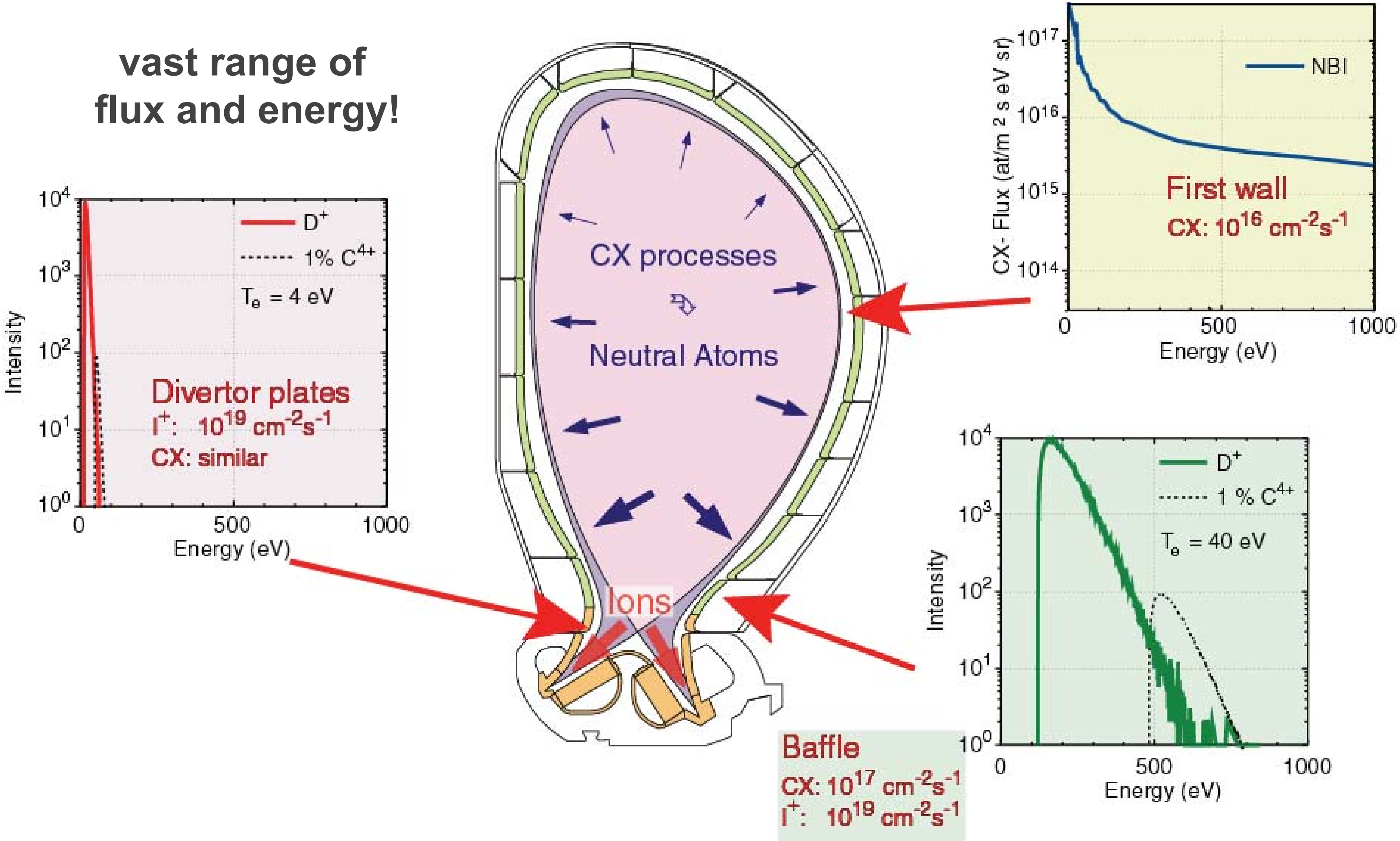
Divertor tokamaks need limiters for discharge ramp-up and shutdown

Example: JET

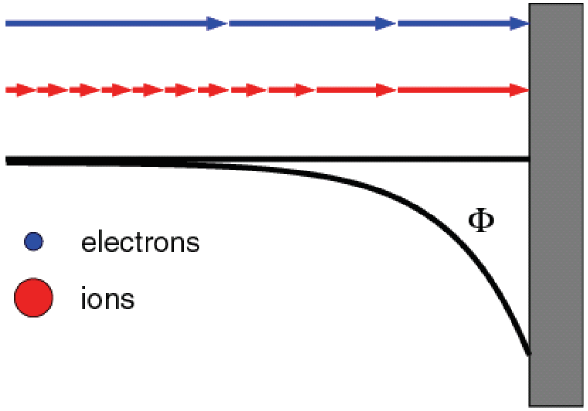
#62218: plasma visible light emission

Limited R.A. Pitts, EPS 2005 **Diverted**

stationary particle fluxes



formation of a sheath potential



consider ignition:

$$\text{v}_e >> \text{v}_i$$

build up of a potential Φ

⇨ to repel electrons

⇨ to accelerate ions ⇨ $\Gamma_W^e = \frac{1}{4} n_W \bar{\text{v}}_e = \frac{1}{4} n_e \cdot \exp(-e\Phi / kT_e)\, \bar{\text{v}}_e$

$$\Gamma_W^i = n_i c_s = n_i \sqrt{\frac{k(T_e + T_i)}{m_i}}$$

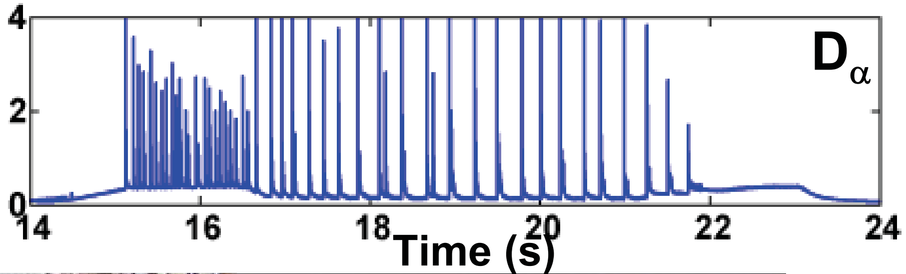
steady state: $\Gamma_W^e = \Gamma_W^i$

(net current must be zero)

⇨ $$\frac{e\Phi}{kT_e} = \frac{1}{2} \ln\left[\left(2\pi \frac{m_e}{m_i}\right)\left(1 + \frac{T_i}{T_e}\right)\right] \approx 3$$

transient flux excursions

plasma instabilities can lead to
transient heat load excursions
e.g. Edge Localized Modes (ELMs)



JET #62218

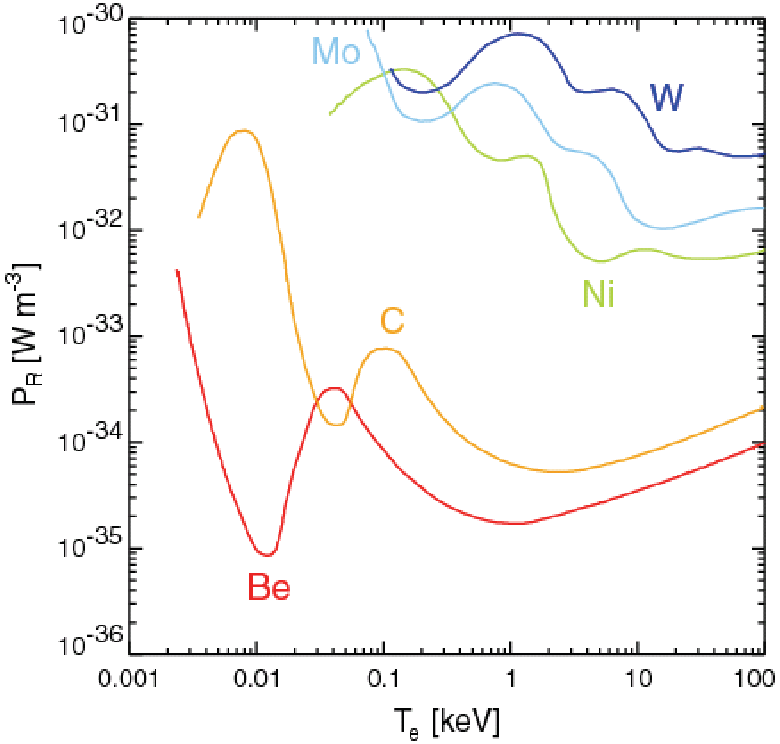
impurities: selection criteria for wall materials

- Dilution of fuel ions

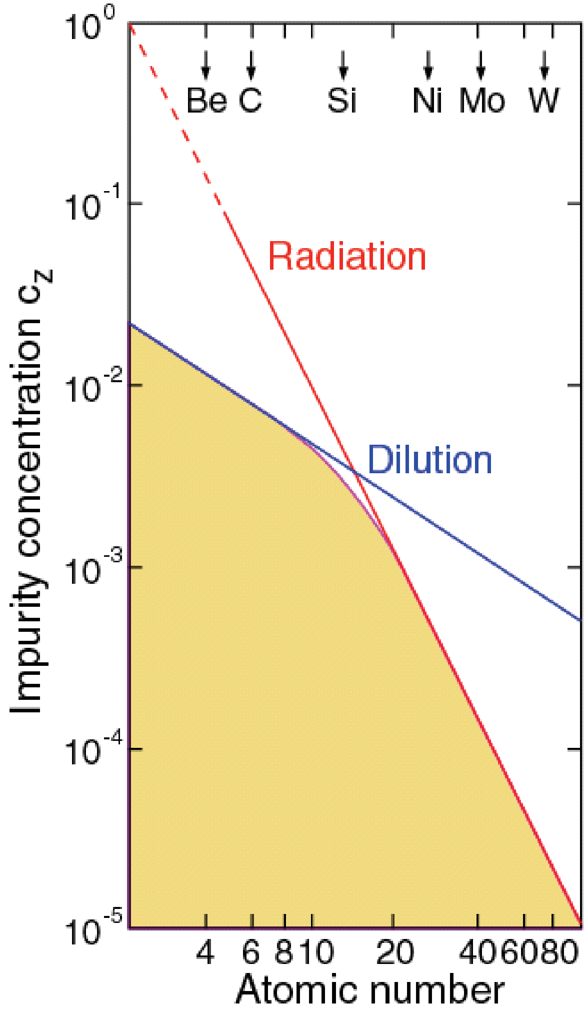
  $n_i = n_e - Z\,n_z = n_e\,(1 - Z\,c_z)$

- Energy loss by line radiation

  $P_{rad} = n_e\,n_{imp}\,P_R$



Concentration limits



impurities: selection criteria for wall materials

- physical sputtering:
  - low energy: better Wo, M than C or Be
  - high energy: better Li or Be than W or Mo
- dilution: Better C or Be than W, or Mo
- radiation cooling: better Li or Be than W or Mo
- diffusion: better C than metals
- thermal load:
  - transient: C (no melting)
  - long term: Cu or W ()
- n-Damage: W? (not Cu)

material selection for ITER

- Main chamber first wall
  - Inevitably erosion by CX-neutral impact
  - Low particle flux and power load
  - Minimize radiation losses

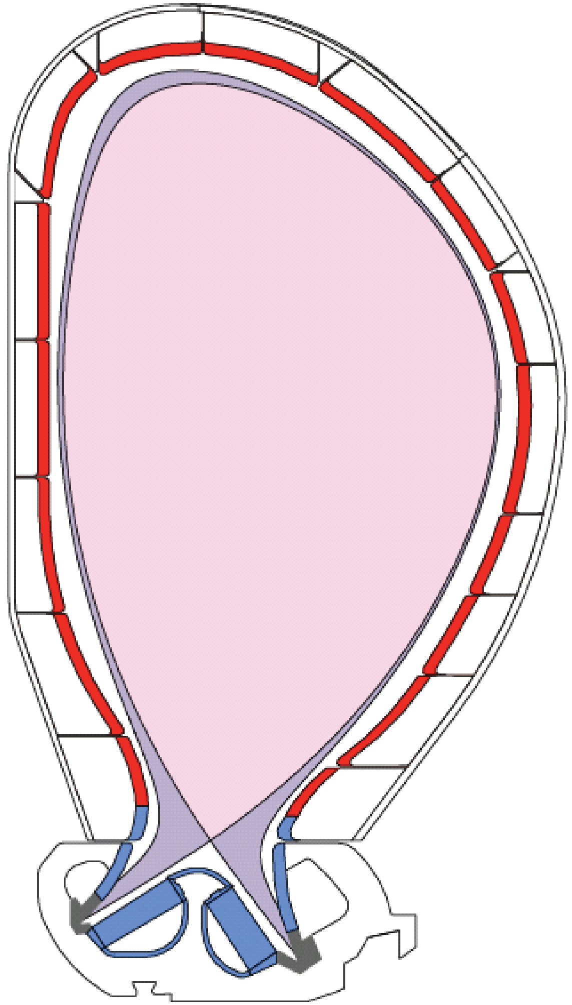
⇨ Beryllium

- Divertor wall
  - Particle energy < 200 eV
  - Medium particle flux and power load
  - Use high sputtering threshold

⇨ Tungsten

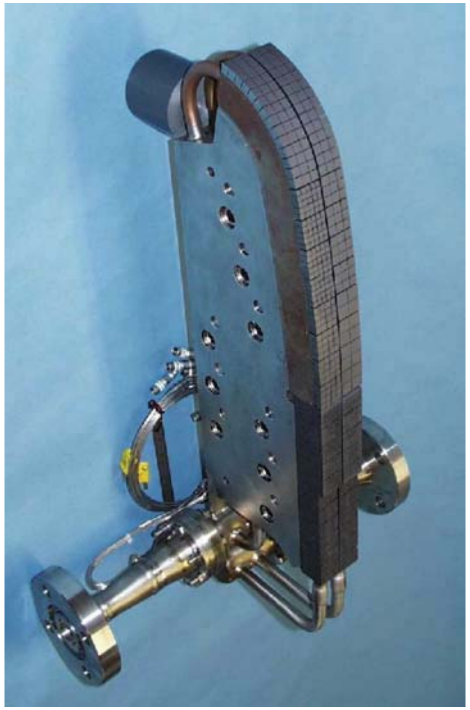
- Target plates
  - Particle energy < 100 eV
  - High particle flux and power load
  - Extremely high transient power load
  - No surface melting

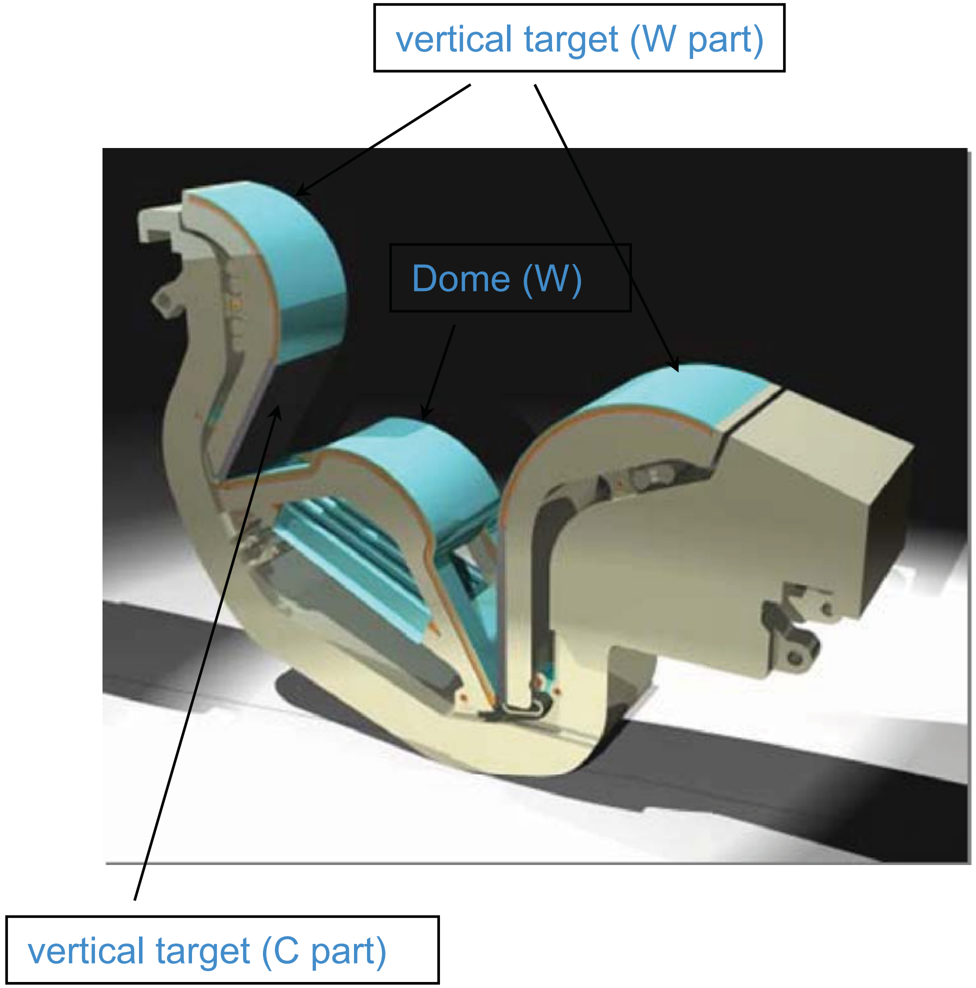
⇨ Carbon - CFC



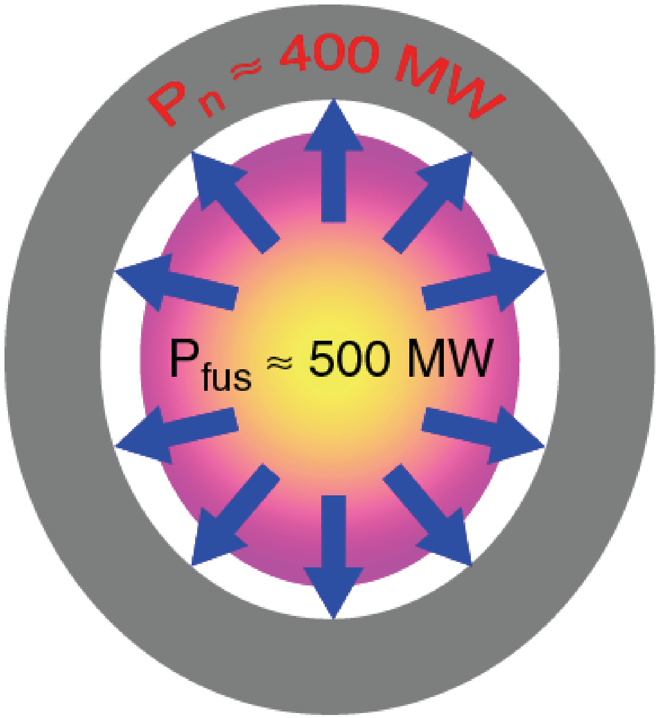
ITER divertor

EU prototype of inner vertical target with CfC & W armour





summary: the role of the wall



$P_\alpha \approx$ 100 MW

$P_{aux} \approx$ 40 MW

1. VACUUM CONDITIONS

Unlike the sun, a fusion plasma can only be maintained under ultra high vacuum conditions -

base pressure ≈ O(10^{-8} mbar)

2. EXTRACTION OF POWER

The α-particle power and auxiliary injected power used to heat the plasma must be finally extracted through the plasma facing wall

Power carried by neutrons is converted to heat in blanket wall

neutrons also breed tritium in blanket

3. HELIUM REMOVAL

The removal of the helium ash requires thermalisation and neutralisation of plasma ions

preview

Erosion Processes (erosion of carbon by hydrogen)

- Chemical erosion
- Physical sputtering
- Chemical sputtering

Implantation, diffusion and release

Heat Load issues

exercise 1

- Estimate the possible DT fusion energy gain of these ingredients:

- Calculate the neutron emission rate from a DT plasma
  with $T=30$ keV and $n=10^{20} m^{-3}$
  (ignoring secondary reactions of fusion products)

- Assume an uniform ITER edge plasma with $T_e=T_i=100$ eV and $n_e=5\ 10^{19} m^{-3}$ of thickness $\Delta r=30$cm having an impurity concentration of 2 % C or $2 \cdot 10^{-5}$ W. Calculate Z_{eff} and the radiation power losses.

- Give a simple estimate of the maximum possible concentration of Fe ($Z=26$) for ignition of a 40 keV DT plasma, assuming bremsstrahlung radiation is dominant and using the Lawson power balance.