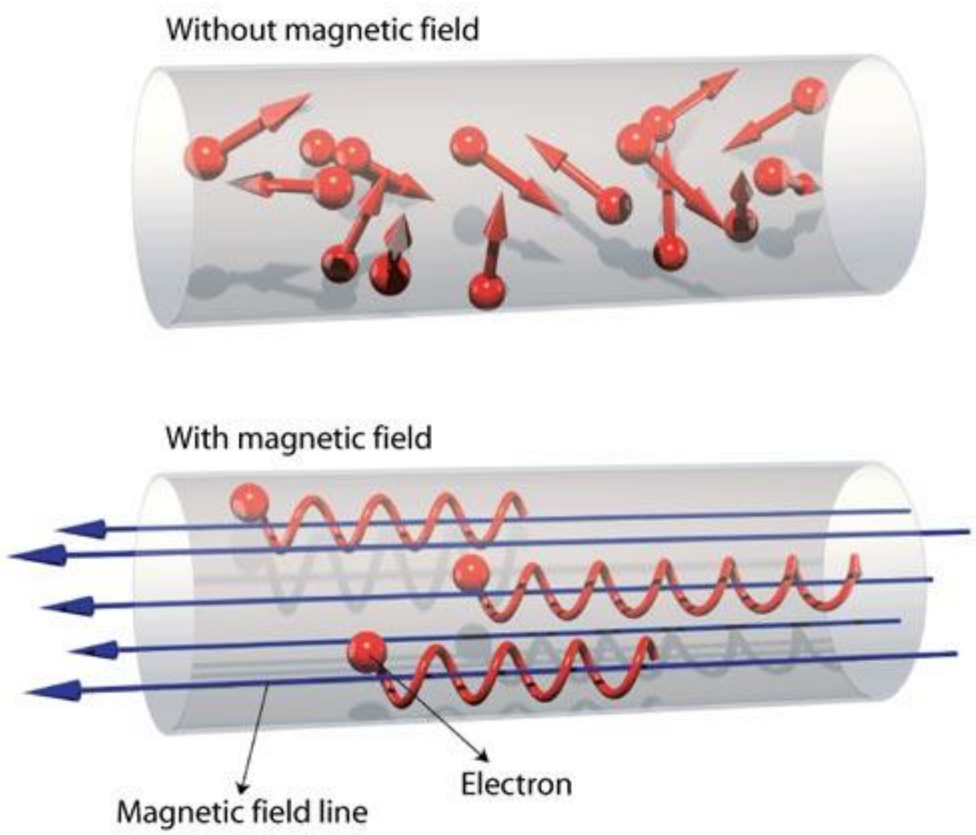
Introduction to Nuclear Fusion

Prof. Dr. Yong-Su Na

Plasma wall interaction (PWI)

Plasma Confinement



- Minimise contact to material walls by magnetic field

http://www.mi.infn.it/~alimonti/press/docs/Pres_DeMarco.pdf+&cd=12&hl=ko&ct=clnk&gl=kr

Fluxes to the Surface

- **Particle Fluxes**

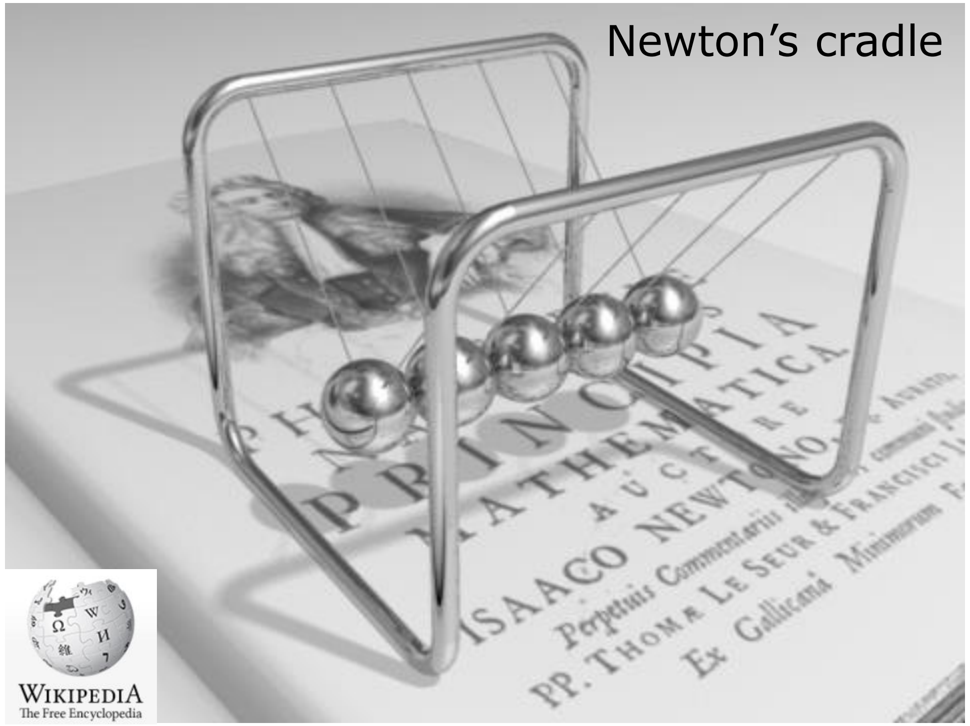
  - Ions: diffusing fuel ions (H, D, T)
    diffusing impurities (wall materials, residual gases in
    chamber adsorbed gases in surface)
    energetic ions from NBI, ICRH
    fusion alpha particles
  - Electrons: diffusing plasma electrons
    runaway electrons
  - Neutrals: recycling neutrals
    NBI neutrals i.e. shine-through
  - Fusion neutrons

Fluxes to the Surface

- **Energy Fluxes**
  - Particle energies
  - Radiation energies
  - Heat conduction

- **Photon Fluxes**
  - Bremsstrahlung radiation
  - Cyclotron radiation
  - Impurity line radiations

Difference between particle energy flux and heat conduction?

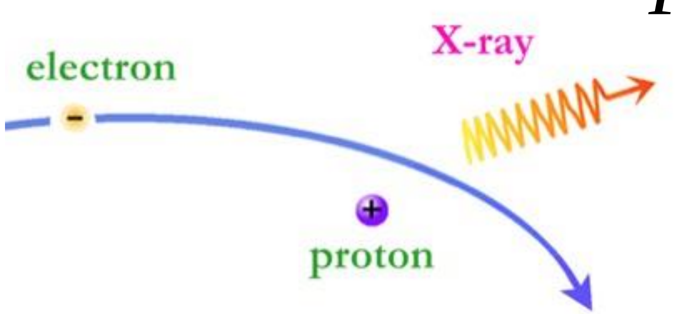


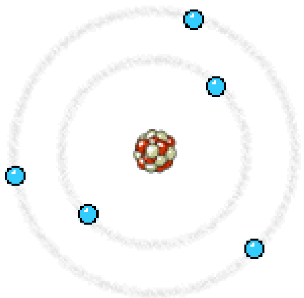
Plasma Radiation

- **Bremsstrahlung (Braking radiation)**

  - Process of radiation emission when a charged particle accelerates or decelerates
  - Contribution from ions can be neglected due to their heavier mass (m_p = 1836m_e) compared with that of electrons.
  - Mainly due to e-i collisions:
    in e-e or i-i collisions, radiation fields exactly cancel.
  - X-ray wavelength range (λ ~ 10^{-9} m): readily escaping from a plasma

$$P_{br} \approx 1.6\times10^{-38} n_i n_e Z^2 \sqrt{kT_e} \quad (\mathrm{W/m^{-3}})$$





http://www.profstelmark.com/Chapter_6.html
http://www.astro.wisc.edu/~bank/index.html

Plasma Radiation

- **Cyclotron Radiation**

  - Due to the centripetal acceleration of charged particles owing to the helical motion by magnetic field lines
  - contribution from ions can be neglected due to their heavier mass compared with that of electrons.
  - In the far infrared radiation spectrum (λ = 10^{-3}-10^{-4} m):
    partially re-absorbed in a plasma
  - The emitted radiation may be reflected from the surrounding wall in a magnetic confinement fusion device and thereby re-enter the plasma.

$$P_{cyc}^{net} \approx 6.23\times10^{-20} n_e B^2 k T_e \psi \quad (\mathrm{W/m^{-3}})$$

http://www.astro.wisc.edu/~bank/index.html

Ψ accounting for the complex processes of reflection and re-absorption of cyclotron radiation

Plasma Radiation

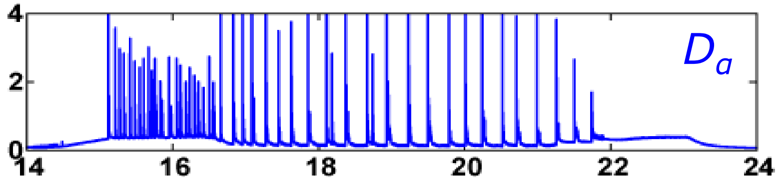
- **Line Radiation**
  - Due to radiative decay after electron collision excitation

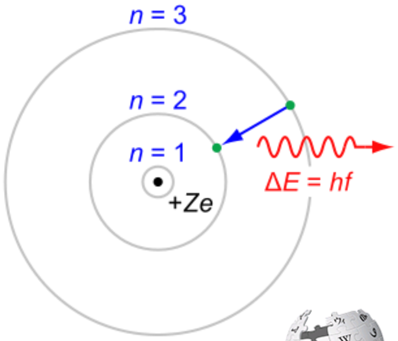
$$A_0^{+Z} + e \rightarrow \left(A_0^{+Z}\right)^* \rightarrow A_0^{+Z} + \gamma + E_{Zl}$$

$$P_L \approx 1.8\times 10^{-38} n_Z n_e Z^4 \sqrt{T_e} \quad (\mathrm{W/m^{-3}})$$

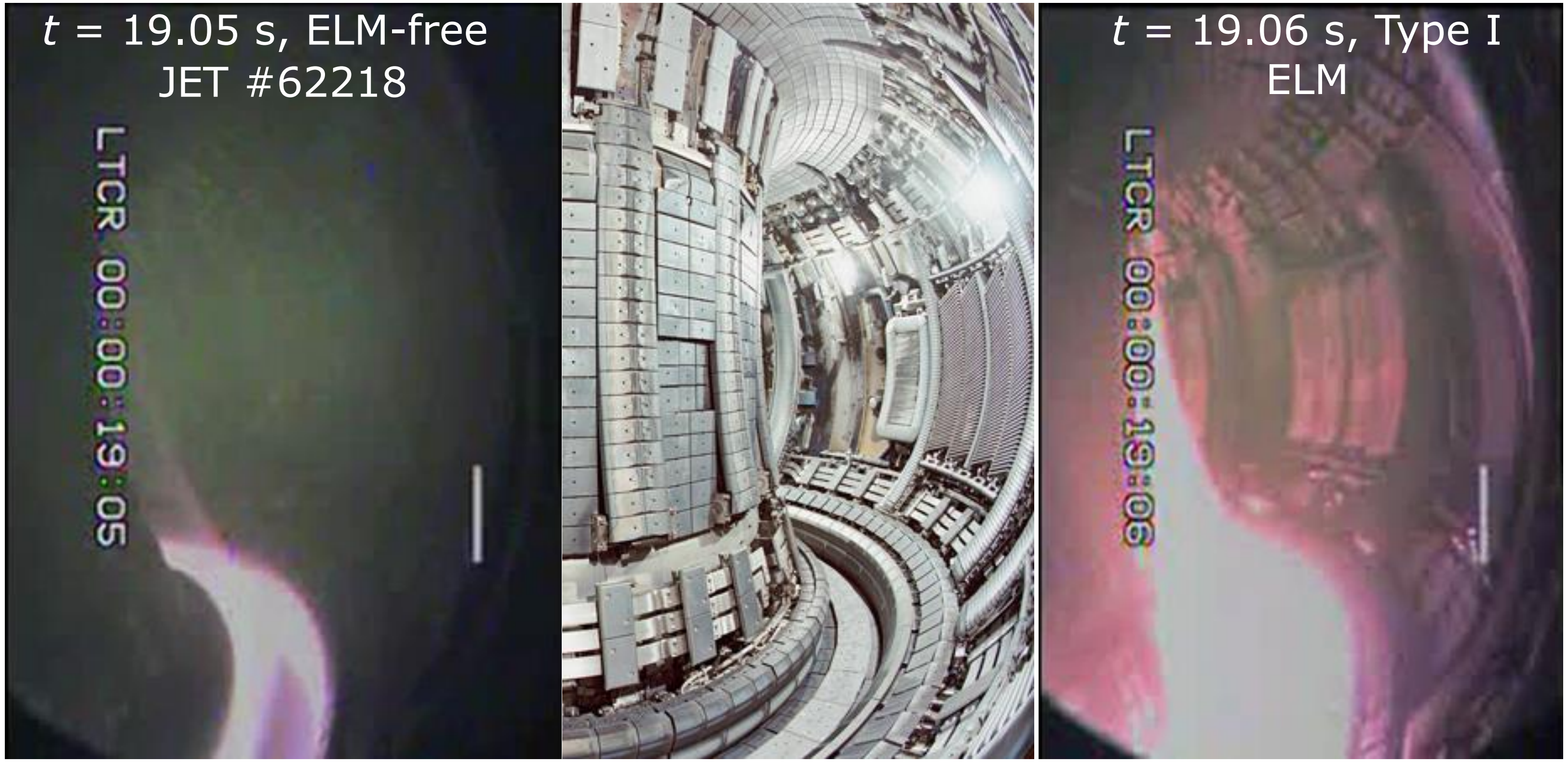
Flux Excursions

- **Transient Flux Excursions**
  - Plasma instabilities can lead to transient heat load excursions.





WIKIPEDIA
The Free Encyclopedia



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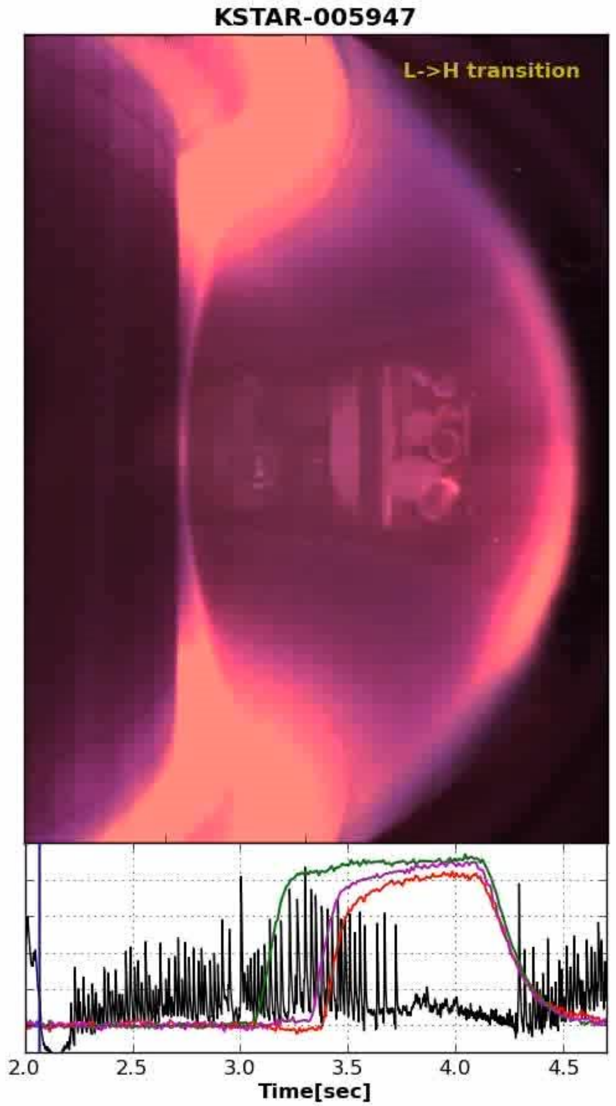
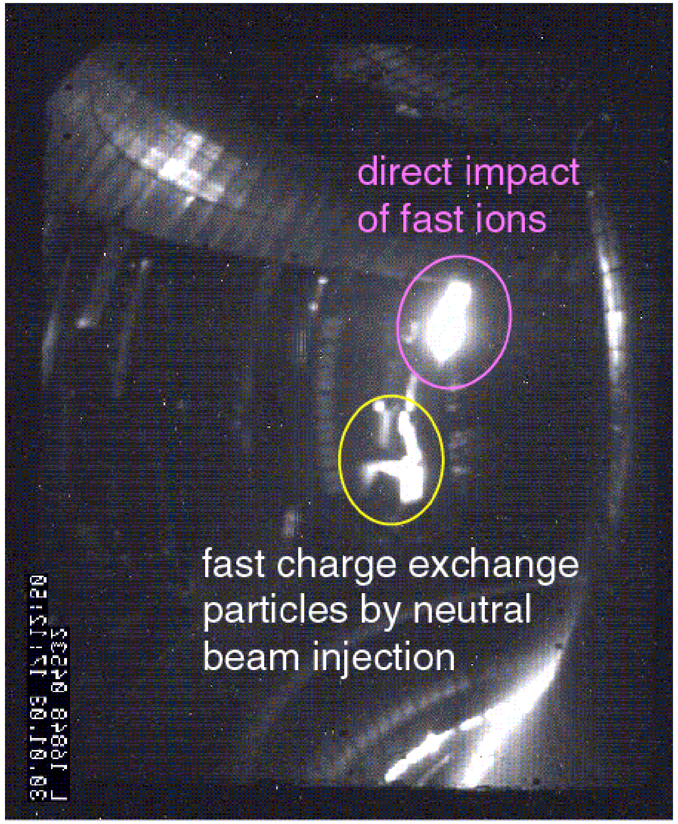


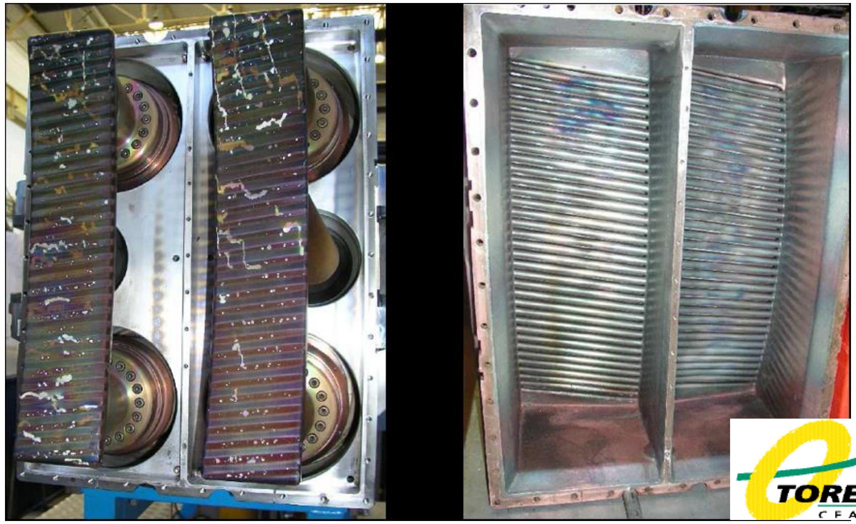
Flux Excursions

- **Localised Flux Excursions**



- Loss of fast particles can lead to excessive local heat loads
  - charge exchange neutrals by heating with NBI
  - orbit losses of fast ions
  - runaway electrons

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



Plasma wall interaction

Plasma-wall Interactions

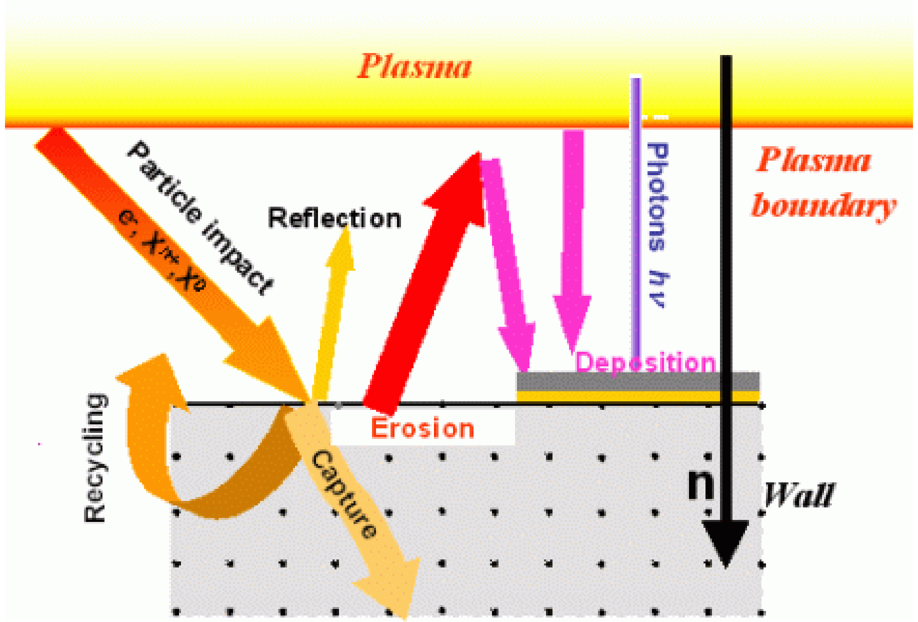
- **Importance of Plasma-Wall Interaction**

KSTAR
first H-mode plasma
with good shape
control (#4202)

Plasma-wall Interactions

- **Physical/chemical interaction between plasma and (surrounding) surface**

  - Reflection by backscattering
  - Adsorption and desorption
  - Physical sputtering: Erosion
  - Chemical sputtering
  - Vaporisation and melting
  - Blistering and flaking
  - Electron emission
  - Radiation damage and transmutation by 14.1-MeV Neutron
  - Dust formation



http://www-rcp.ijs.si/mic/our_work/applications/fusion/fusion.php

Alteration of surface (wall erosion) and production of particle and photon fluxes → Impurities

Surface Interaction Phenomena

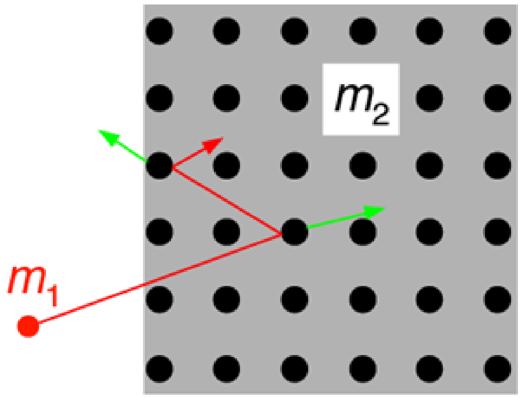
- **Reflection by Backscattering**
- **Adsorption and Desorption**

  - Residual cooler gases implanted inside wall → release of gases
- **Physical Sputtering – Erosion**

  - Ejection of surface atom from (low-temperature) wall as a result of collision cascade in the lattice atoms by particles when acquired energy > surface binding energy
  - Threshold exists in incident energy to produce sputtering

굴러들어온 돌이 박힌 돌 빼낸다.

Bad money drives out good.

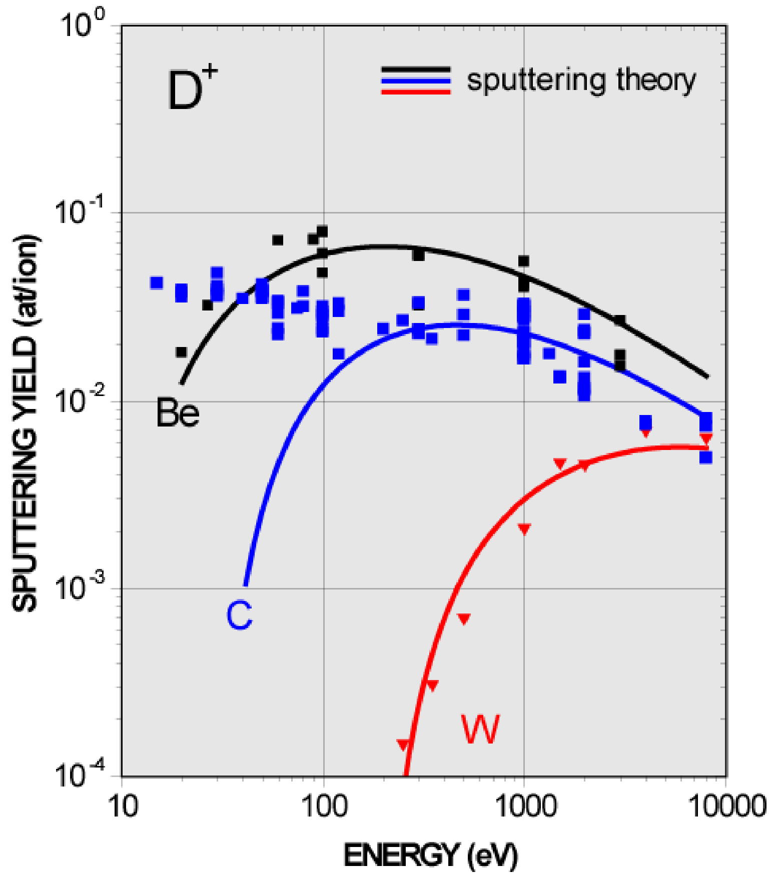


Surface Interaction Phenomena

- **Physical Sputtering – Erosion**

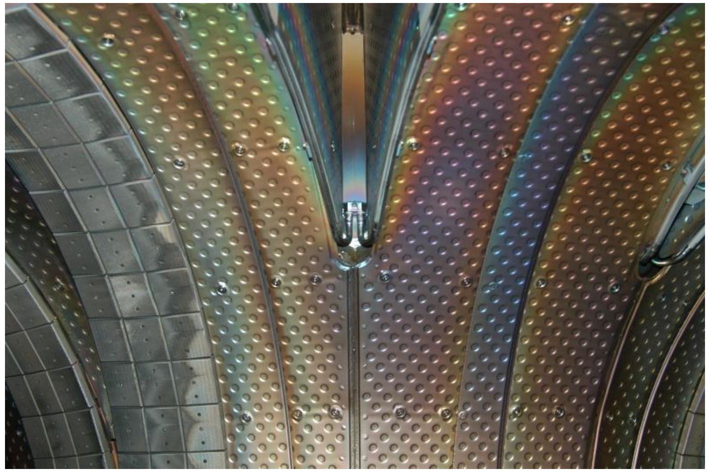
  - For **beryllium** and **tungsten**, theoretical and experimental yields agree very well.
  - **Carbon** shows additional erosion with only weak dependency on impact energy

  → **Chemical erosion**

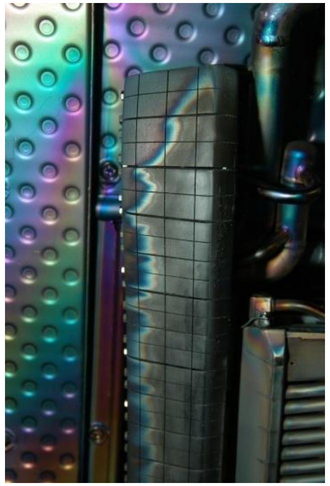


Surface Interaction Phenomena

- **Chemical Sputtering**
  - Chemical reaction of incident projectiles with target atoms
  - Formation of a volatile chemical compound leaving the solid:
    occurs only for certain target-projectile combinations



High Field Side (HFS) inner wall



antenna protection/outer wall

TORE SUPRA
CEA - EURATOM

Surface Interaction Phenomena

- **Vaporisation and Melting**
  - disruptive instabilities → thermal shock on the wall
  → spalling, cracking, melting, evaporation
- **Blistering and Flaking**
  - Blistering: gas bubble in ~μ-thick surface layer (insoluble, He)
  - Flaking: blister rupture by lateral stress and surface layer breaking

flaking

TORE SUPRA
CEA - EURATOM

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- **Electron Emission**

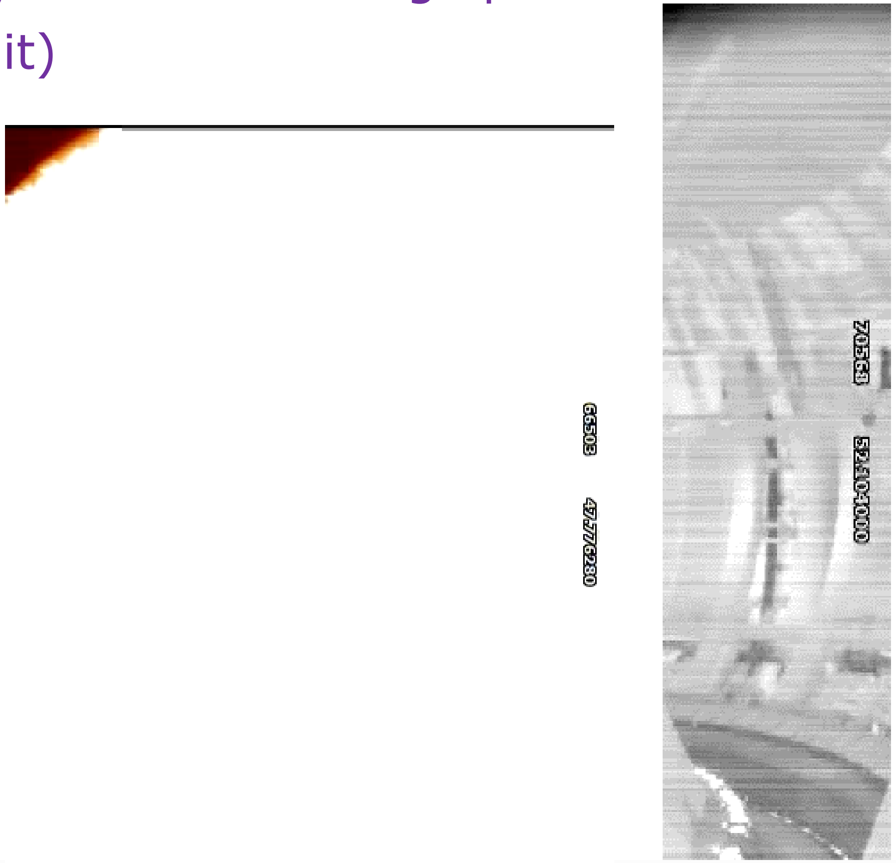
  - Photoelectric, thermionic, X-ray, secondary

- **Radiation Damage and Transmutation by 14.1-MeV Neutron**

  - Knock-on collision → interstitial, spikes, voids, displacements, …
  - Neutron capture reactions: (n,p), (n,α) → production of p, α in the first wall → swelling, radiation damage of wall, diffusing back to plasma

Surface Interaction Phenomena

- **Dust Formation**
  - ITER definition: solid particles/debris of size about 10 nm-100 μm
  - Consequence of PWI/volume polymerisation in edge plasma
  - Safety and operational issue (limit)



JET IR camera observation
after a major disruption

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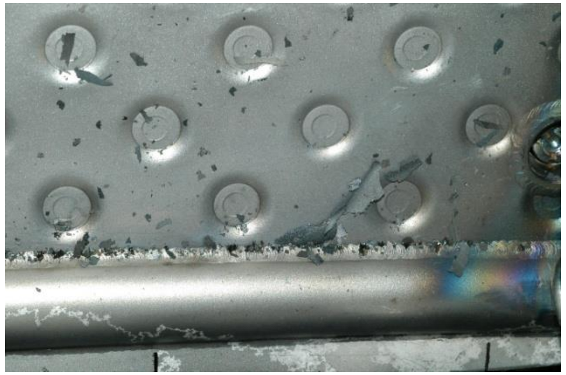
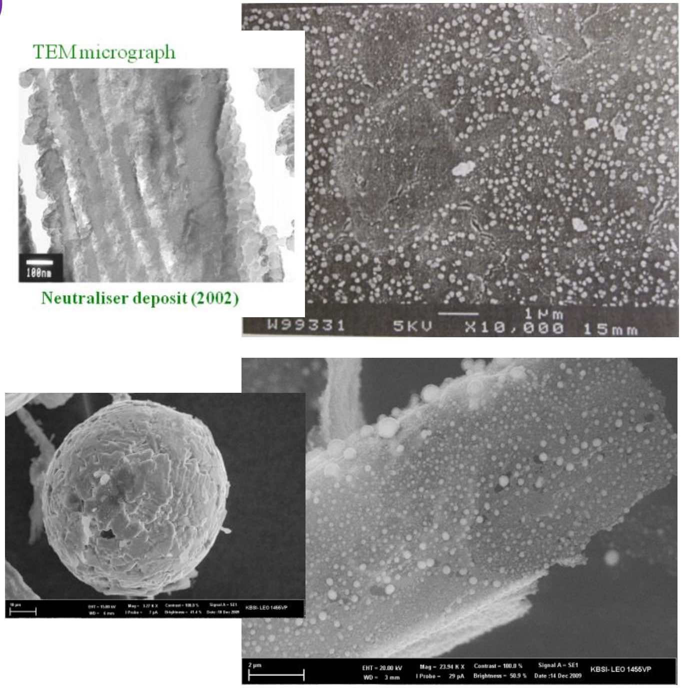


Mobilised „dusts“
(Tore Supra)

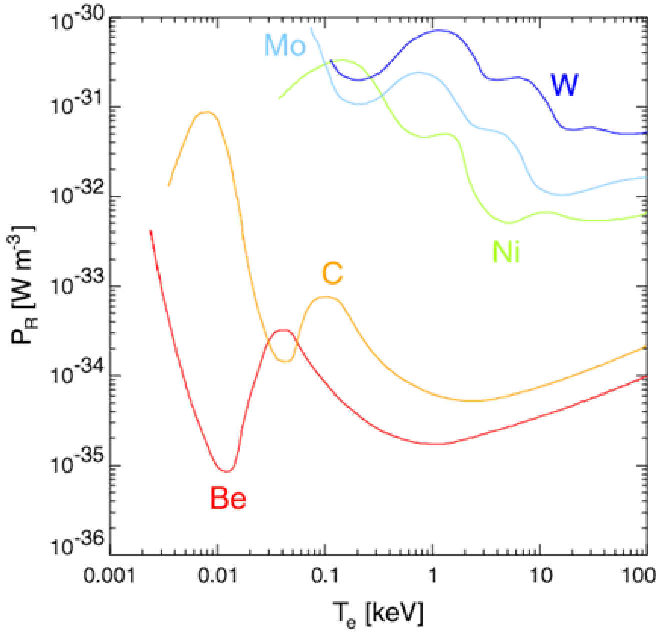


Nanoparticles/metal droplet
(Tore Supra/JET/KSTAR)

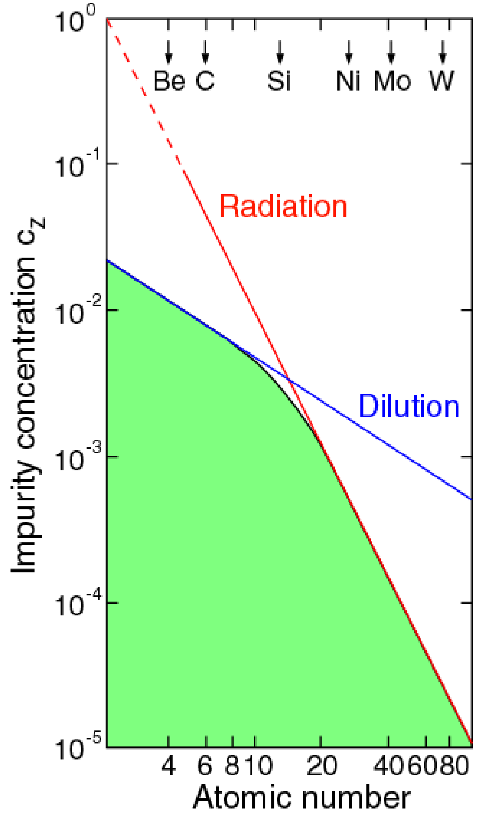
How to control impurity influx?

Impurity Control

- **Maximal Permissible Impurity Concentration**



At 10 keV
- Low Z (~10): $(n_Z/n_{DT})_{max}$~10% (Ne)
- Medium Z (~26): $(n_Z/n_{DT})_{max}$~0.5% (Fe)
- High Z (~74): $(n_Z/n_{DT})_{max}$~0.01% (W)



Maximal concentrations for sustained ignited plasma

https://www.ipp.mpg.de/16535/einfuehrung

Impurity Control

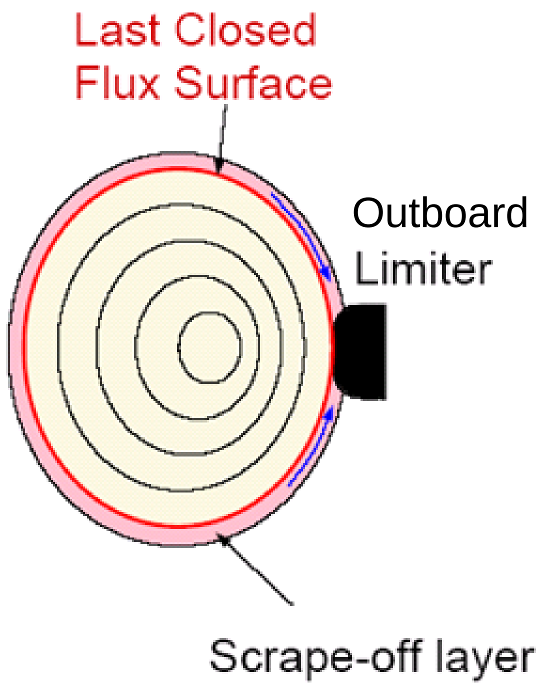
- **Maintain**

$$\frac{n_Z}{n_{DT}} < \left(\frac{n_Z}{n_{DT}}\right)_{\max}$$

Impurity Control

- **Plasma Boundary Region Control**

  - Limiter



a material structure protruding from the main wall used to intercept particles at the plasma edge particularly to stop runaway electrons from damaging the vacuum vessel and to shadow in-vessel components from the plasma edge (limiting/defining the plasma size)

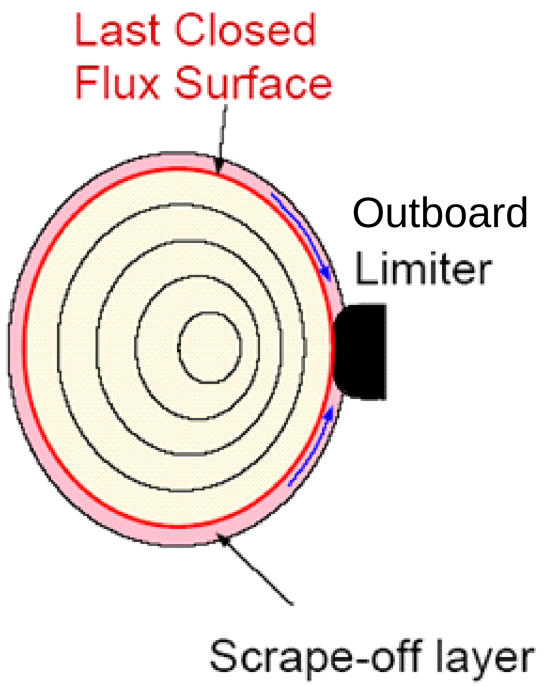
→ Reflecting neutrals

→ Pumping out

Impurity Control

- **Plasma Boundary Region Control**

  - Limiter



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

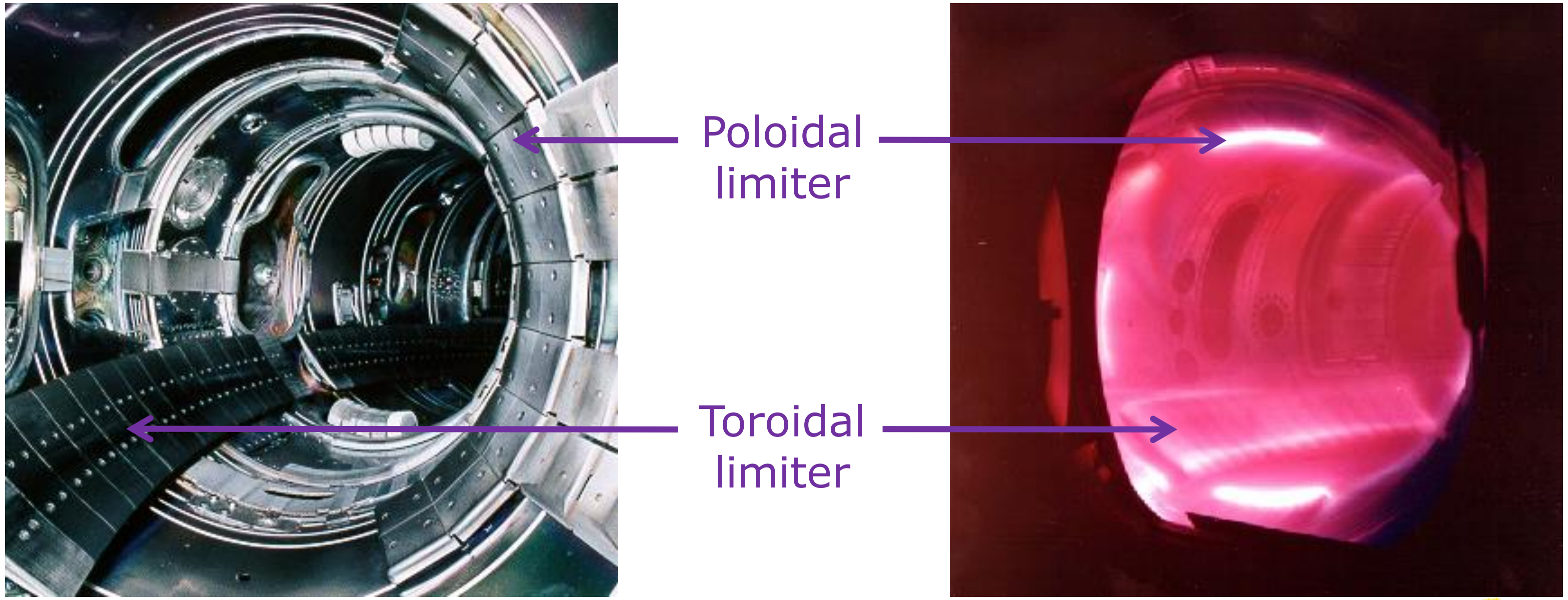
Scrape-off Layer (SOL):
The plasma region located in the limiter shadow
i.e. between the LCFS and the vessel wall

Impurity Control

- **Plasma Boundary Region Control**
  - Limiter problems

    High heat load and sputtering rate on limiter

    → Impurities → Low-Z coating of limiters (C or Be on W)



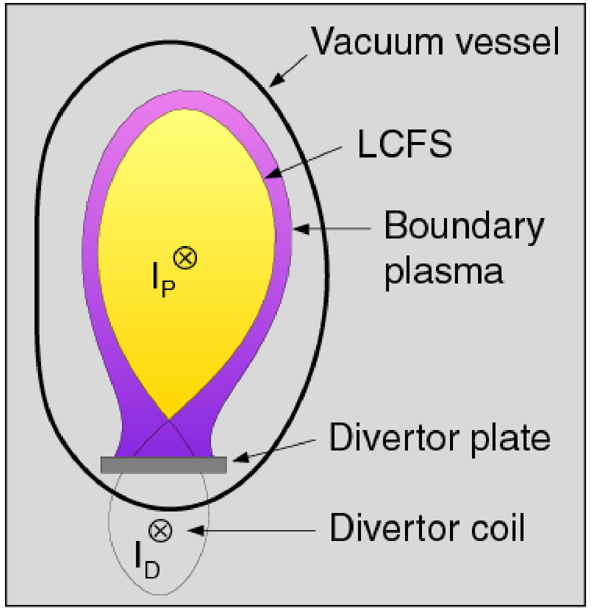
www.ipp.mpg.de/1533235/Tutorial_Schmid.pdf+&cd=1&hl

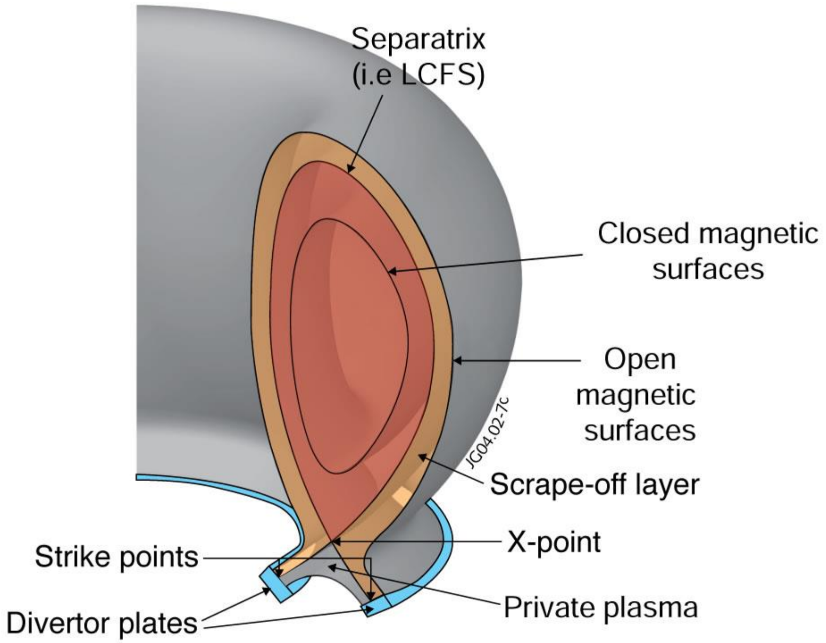
Impurity Control

- **Plasma Boundary Region Control**

Proposed by L. Spitzer, Jr. for stellarators

  - Divertor: Bending outer magnetic fields away from plasma by means of auxiliary magnetic coils → Removing outer layer of plasma to external chamber → Cooling → Neutralising → Pumping away





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

https://www.euro-fusion.org/glossary/divertor/
http://www.ipp.mpg.de/1533235/Tutorial_Schmid

Impurity Control

- **Plasma Boundary Region Control**

  - Divertor functions

    Reduction of 1st wall bombardment (unloading)

    Reduction of impurity flow into plasma (shielding for impurity control)

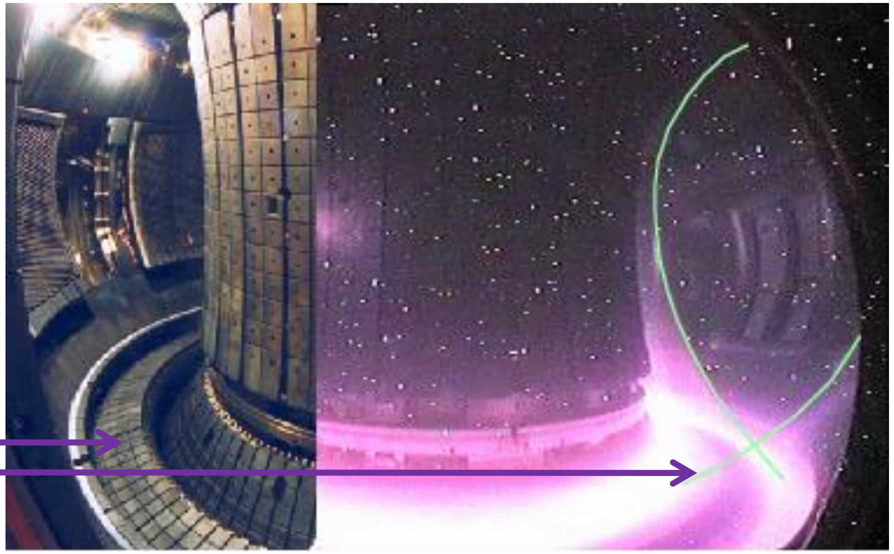
    Exhaust plasma particles and power and removal of He ash

  - Divertor problems

    Complex coil systems

    High cost

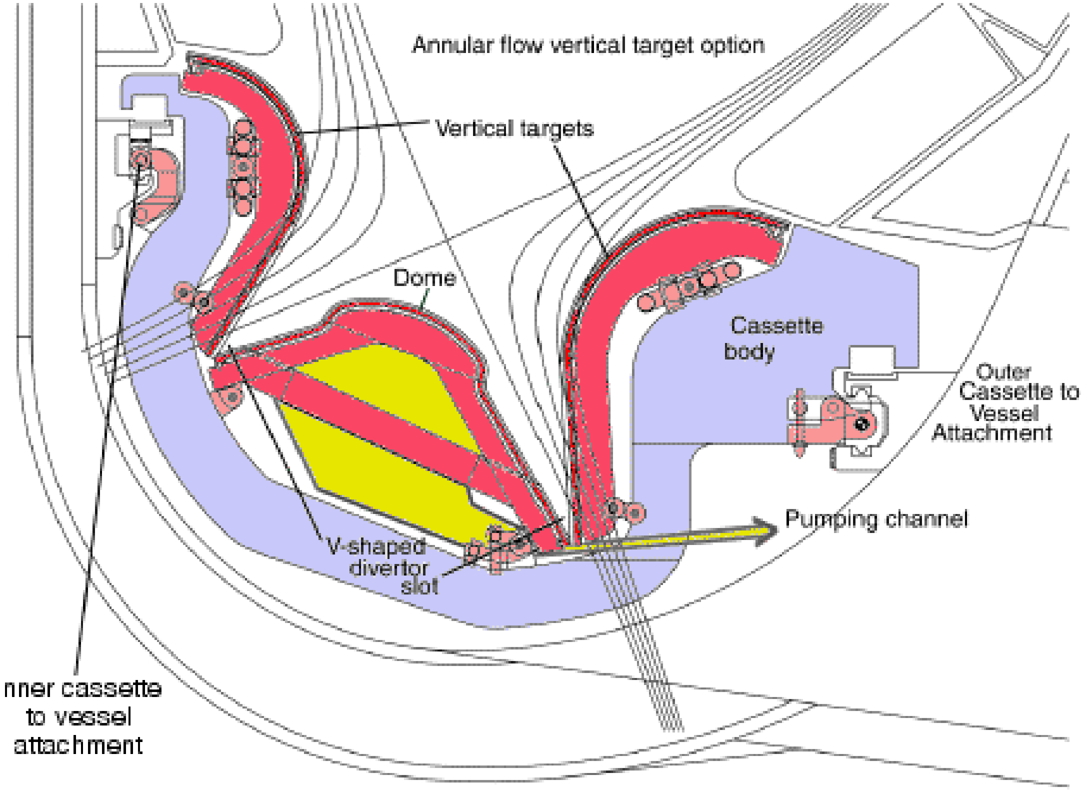
    Difficult maintenance

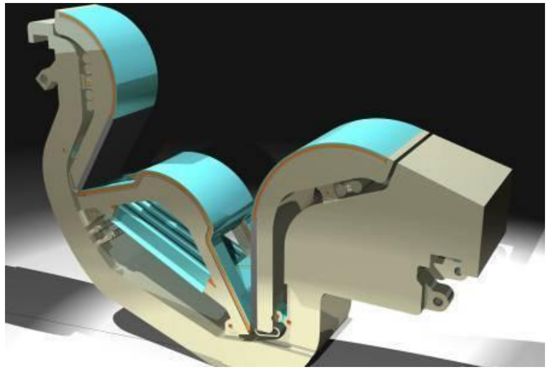


The divertor in ASDEX Upgrade

Impurity Control

- **Plasma Boundary Region Control**
  - Divertor





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