Fusion Reactor Technology I

(459.760, 3 Credits)

Prof. Dr. Yong-Su Na

(32-206, Tel. 880-7204)

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Plasma Instabilities (Kadomtsev 6, 7, Wood 6)

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Week 13-14. How to Build a Tokamak (Dendy 17 by T. N. Todd)

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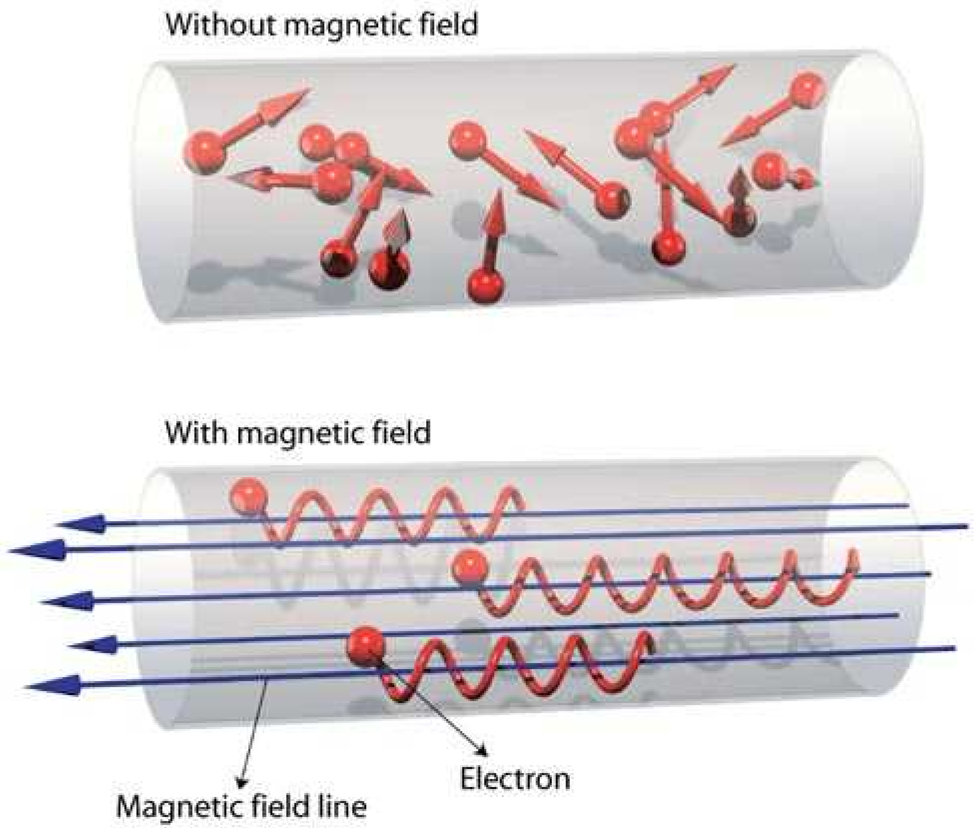
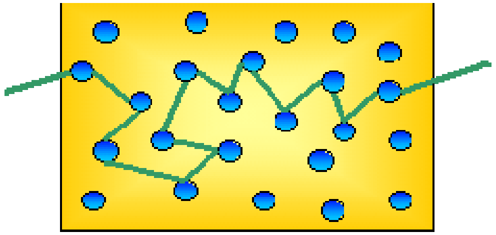
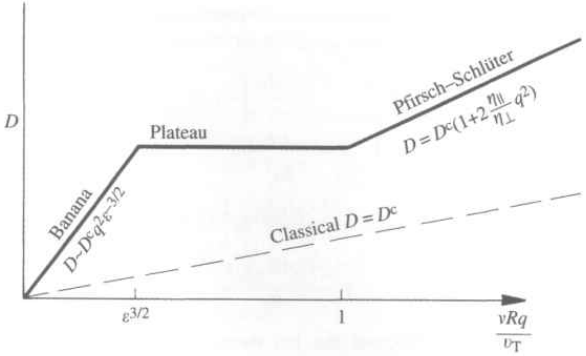
Plasma Confinement



- Minimise contact to material walls by magnetic field





J. Wesson, Tokamaks

Fluxes to the Surface

- **Particle Fluxes**

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

Fluxes to the Surface

- **Photon Fluxes**

- Bremsstrahlung radiation
- Cyclotron radiation
- Impurity line radiations

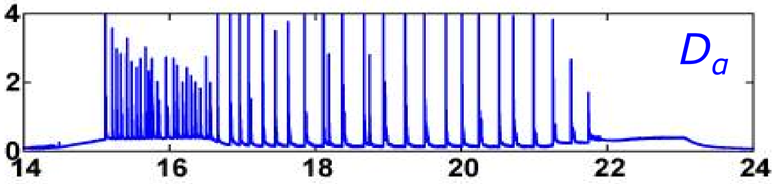
- **Energy Fluxes**

- Particle energies
- Radiation energies
- Heat conduction

Flux Excursions

- **Transient Flux Excursions**

  - Plasma instabilities can lead to transient heat load excursions.



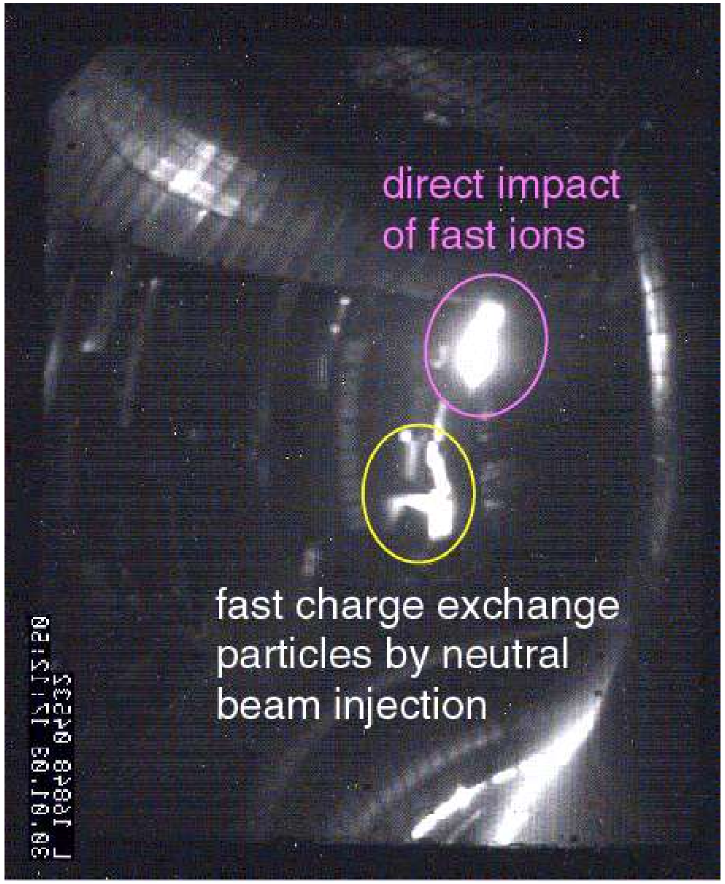
Flux Excursions

- **Transient Flux Excursions**

- Plasma instabilities can lead to transient heat load excursions.

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

Flux Excursions

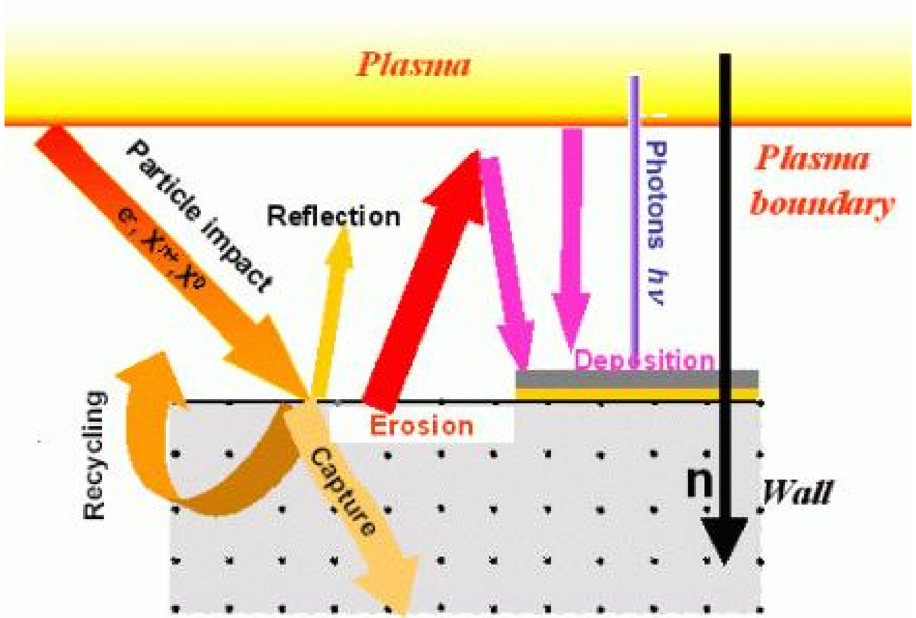
- **Importance of Plasma-Wall Interaction**

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

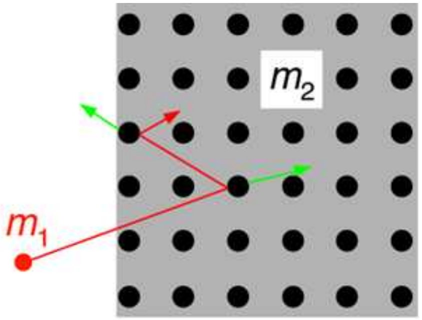
- **Reflection by Backscattering**
- **Adsorption and Desorption**

- 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

- Sputtering yield:



$$Y \equiv \frac{ejected\ atoms}{incident\ particles} \quad (atoms/particles)$$

$$Y(E) \approx \frac{20}{U_0}(Z_1Z_2)^2 \frac{m_1}{m_2} \frac{E}{(E+50Z_1Z_2)^2}$$ semi-theoretical value

- Threshold incident energy to produce sputtering $E = \frac{(m_1+m_2)^2}{4m_1m_2}U_0$

굴러들어온 돌이 박힌 돌 빼낸다.

Bad money drives out good.

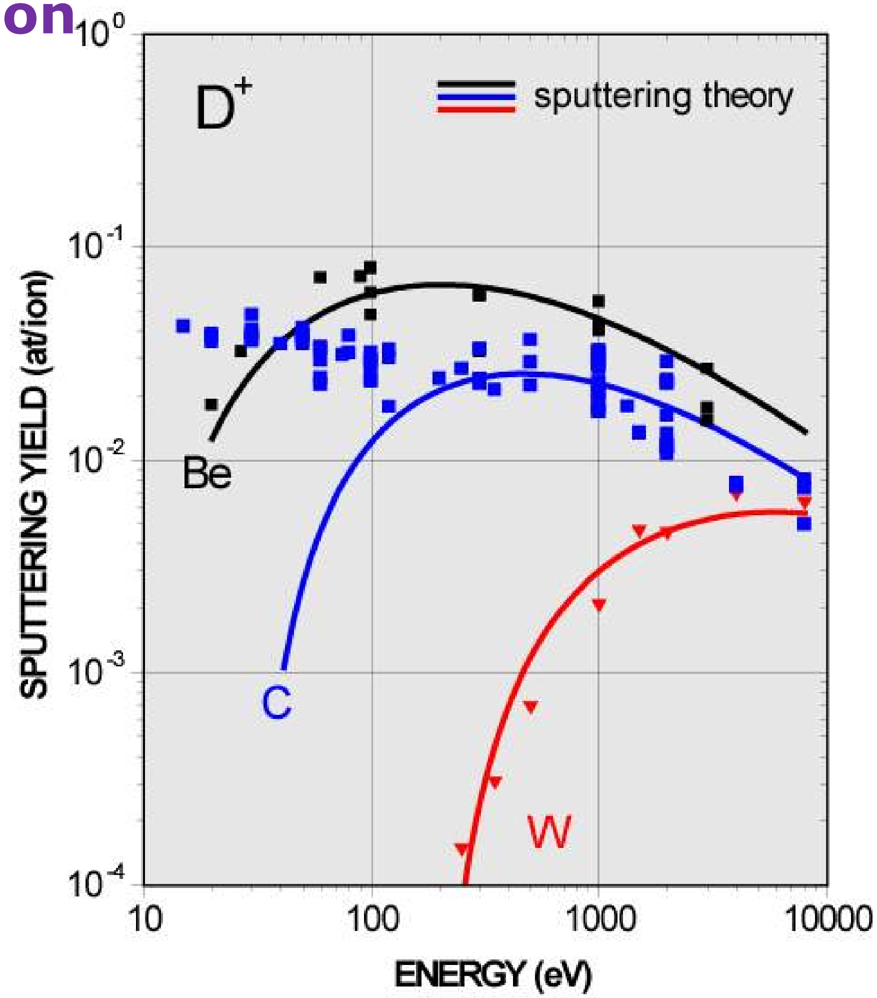
Surface Interaction Phenomena

- **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

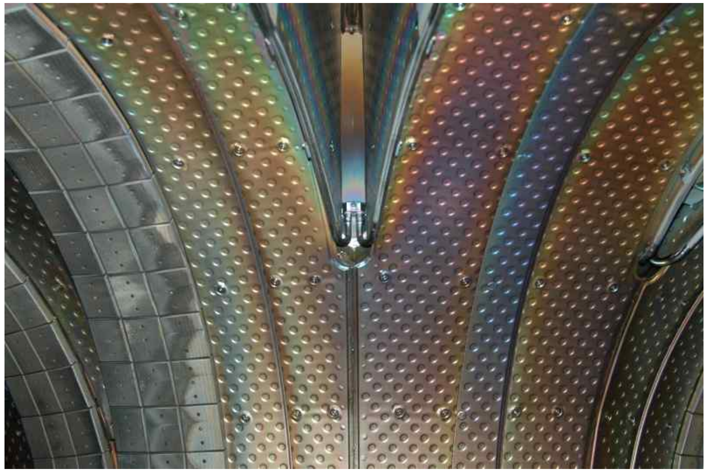
- **Chemical Sputtering**

- Chemical reaction of incident projectiles with target atoms

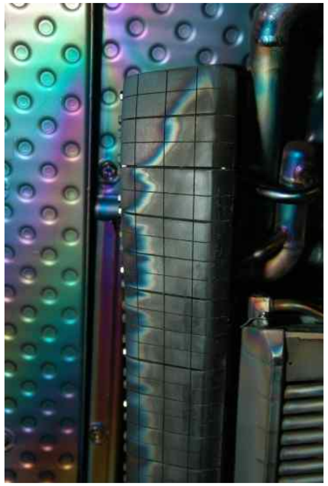
- Formation of a volatile chemical compound leaving the solid:

  occurs only for certain target-projectile combinations

- incident particle + surface atom → chemical compound + reduced U_0



HFS inner wall



antenna protection/outer wall

Surface Interaction Phenomena

- **Chemical Sputtering**

- Chemical erosion in fusion devices:

formation of hydrocarbons:

$H + C \rightarrow CH_4$ $(+C_xH_y)$

formation of carbon oxides:

$O + C \rightarrow CO+CO_2$

reaction with some metals:

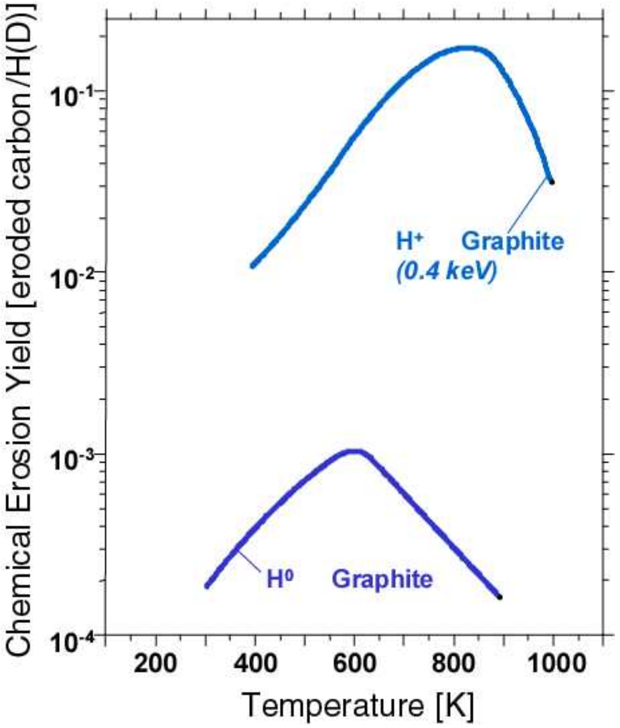
$O + Metal \rightarrow Metal(O)$

(W above 1000°C)

$H + Metal(O) \rightarrow Metal(OH)$

$H + Metal(OH) \rightarrow Metal+H_2O$

- Chemical erosion vanishes at high surface temp.



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

Surface Interaction Phenomena

- **Vaporisation and Melting**

- disruptive instabilities → thermal shock on the wall
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- **Blistering and Flaking**

- Blistering: gas bubble in ~*μ*-thick surface layer (insoluble, He)
- Flaking: blister rupture by lateral stress and surface layer breaking

- **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 polymerization in edge plasma
- Safety and operational issue (limit)

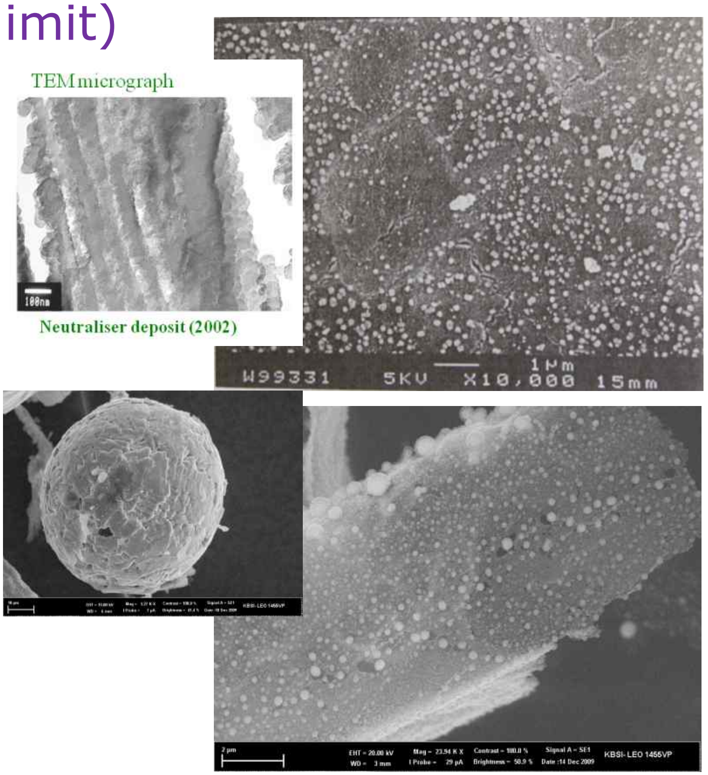
JET IR camera observation
after a major disruption

Surface Interaction Phenomena

Dust Formation

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

Mobilised „dusts"
(Tore Supra)



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

Impurity Radiation

- **Bremsstrahlung (Braking radiation)**

- Process of radiation emission when a charged particle accelerates or decelerates

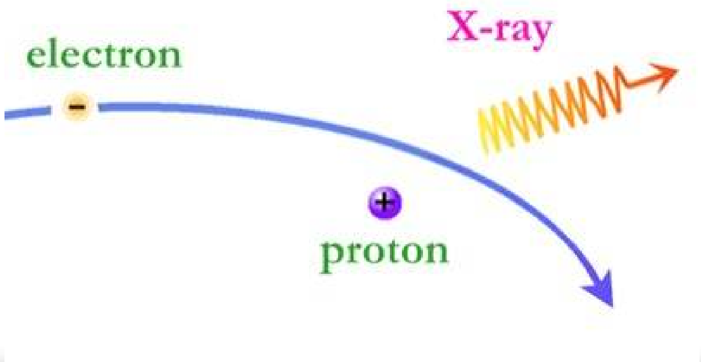
- Contribution from ions can be neglected due to their heavier mass (m_p=1836m_e) compared with that of electrons.

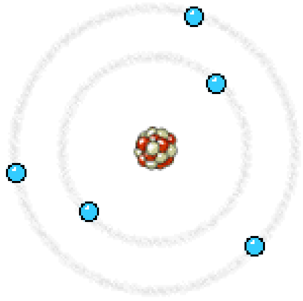
- Mainly due to e-i collisions:

in e-e or i-i collisions, radiation fields exactly cancel.

- X-ray wavelength range ($\lambda \sim 10^{-9}$ 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

Impurity Radiation

- **Line Radiation**

- Due to radiative decay after electron collision excitation

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

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

Impurity Radiation

- **Cyclotron Radiation**

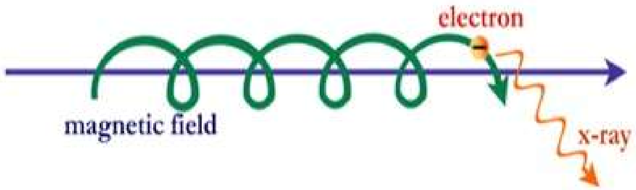
- Due to the centripetal acceleration of charged particles owing to the helical motion by magnetic field lines

- contribution from ions can be neglected due to their heavier mass compared with that of electrons.

- In the far infrared radiation spectrum ($\lambda = 10^{-3}$-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

$$P_{cyc}^{net} \approx 6.23 \times 10^{-20} n_e B^2 k T_e \psi \quad (\mathrm{W/m^{-3}})$$

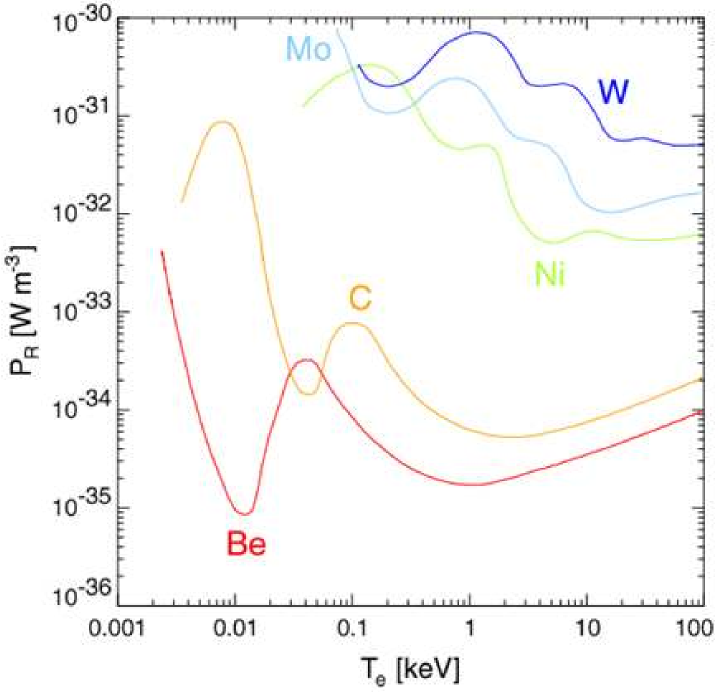


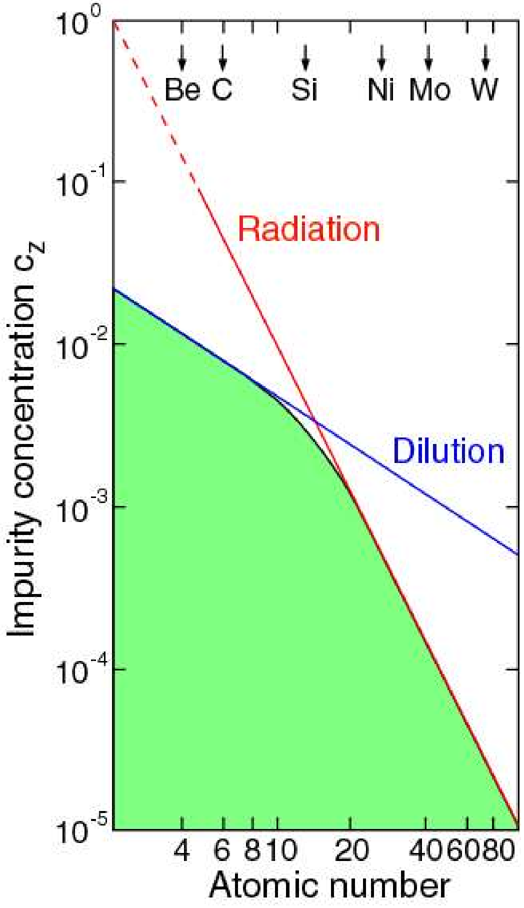
Ψ accounting for the complex processes of reflection and reabsorption of cyclotron radiation

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

Impurity Radiation

- **Maximal Permissible Impurity Concentration**





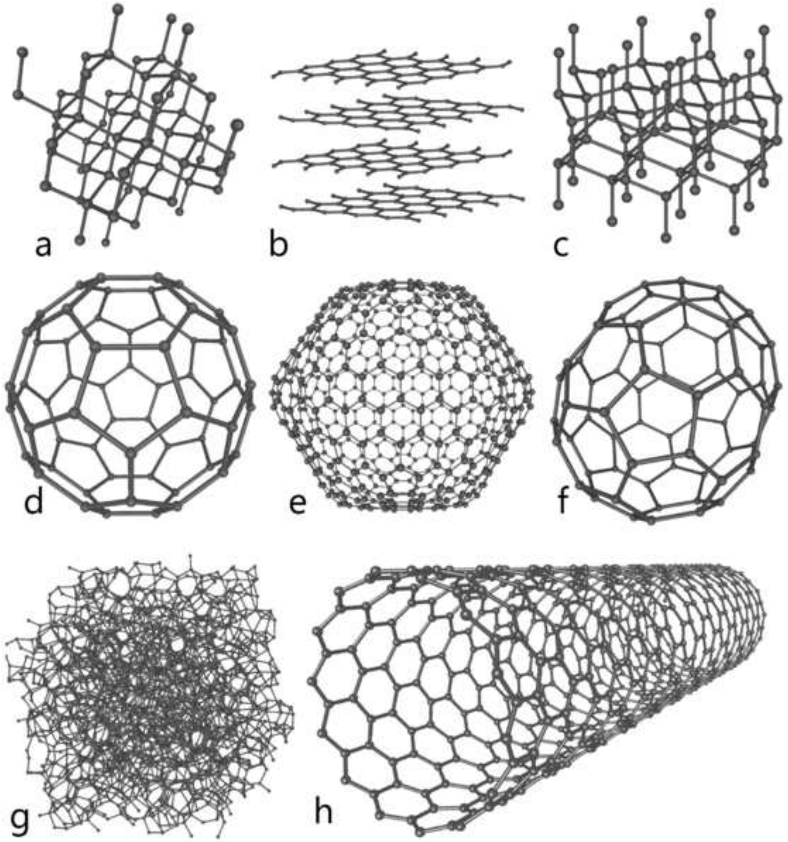
At 10 keV
- Low Z (~10): $(n_Z/n_{DT})_{max}$~10% (Ne)
- Medium Z (~26): $(n_Z/n_{DT})_{max}$~0.5% (Fe)
- High Z (~74): $(n_Z/n_{DT})_{max}$~0.01% (W)

Maximal concentrations for sustained ignited plasma

Impurity Radiation

- **Maximal Permissible Impurity Concentration**

Carbon:
Why no more love in
fusion reactors?



Some allotropes of carbon: a) diamond; b) graphite; c) lonsdaleite; d–f) fullerenes (C60, C540, C70); g) amorphous carbon; h) carbon nanotube.

Impurity Control

- **Maintain**

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

Impurity Control

- **Wall Surface Control**

- Suppression of high-Z impurity formation or impurity formation itself

1) Low-Z wall surface

- ~μm coating, < 1 cm curtain or shingle
- C: high chemical sputtering, tritium retention
- Li: evaporation easily
- Be: toxic
- B: (n,α), (n,p) → He, H production

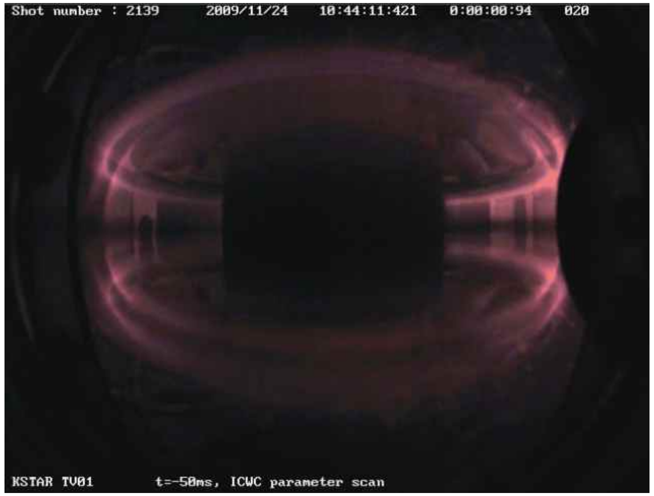
Impurity Control

Wall Surface Control

- Suppression of high-*Z* impurity formation or impurity formation itself

2) Wall modification

- Bake-out (baking)
- Discharge cleaning
- ICRH, ECRH, LH, BNI conditioning
- Boronisation, Siliconisation
- Gettering
- Honey comb surface



Ion Cyclotron Wall Conditioning (ICWC)
in KSTAR

Impurity Control

- **Plasma Boundary Region Control**

\- Gas blanket model

High density cold neutral gas refreshed continuously in boundary region

→ particle and energy flux reduced with low energies

→ wall erosion reduced

Expected thickness ~ 1 m and high pressure drives instabilities

→ impractical!

Impurity Control

- **Plasma Boundary Region Control**

- Vacuum model

Low particle densities in SOL by limiter and/or divertor

→ reducing particle, energy, impurity fluxes

Impurity Control

- **Plasma Boundary Region Control**

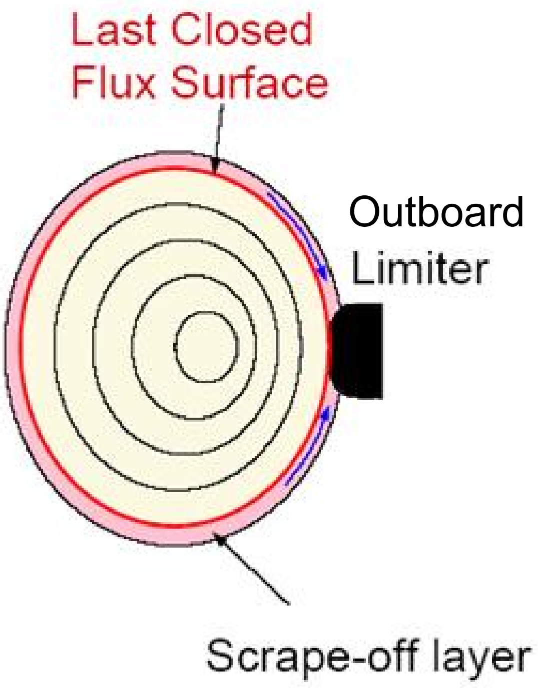
- Limiter: a material structure protruding from the main wall used to intercept particles at the plasma edge particularly to stop runaway electrons from damaging the vacuum vessel, to protect the vessel from NBI shine-through, and to shadow in-vessel components from the plasma edge (limiting/defining 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

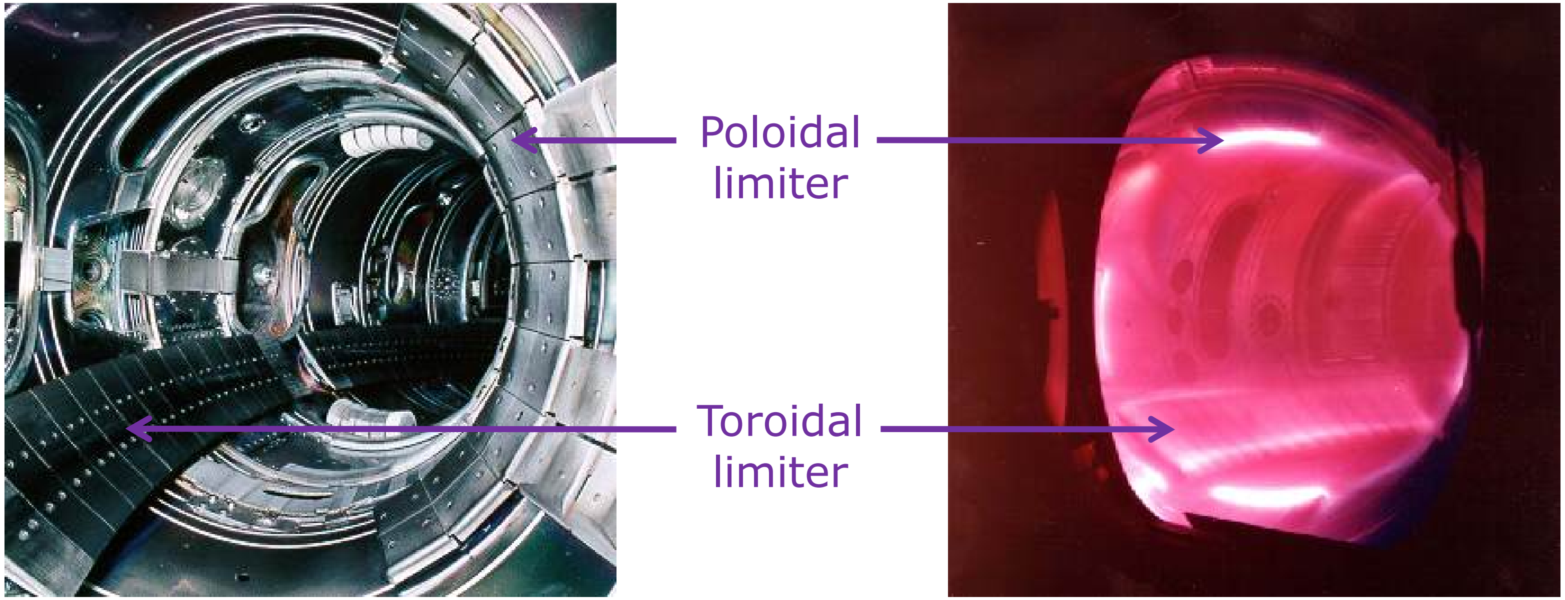
Impurity Control

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)



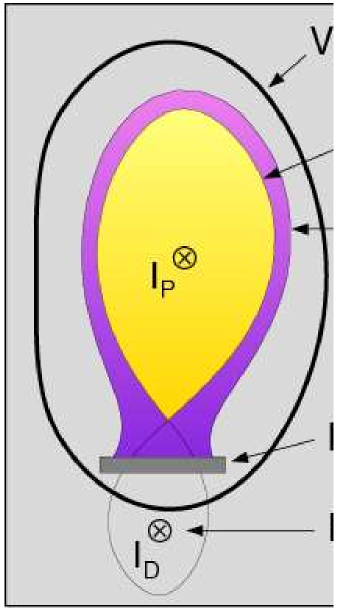
Poloidal limiter

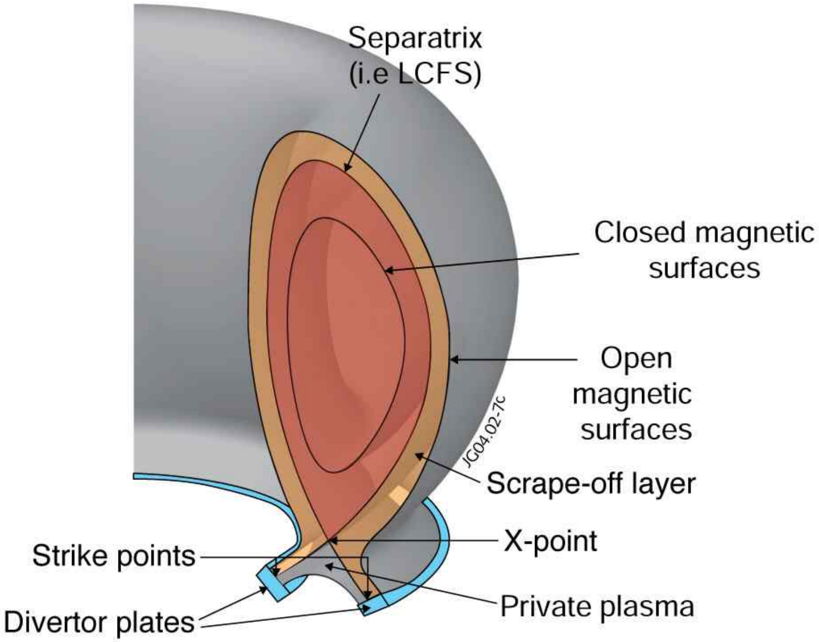
Toroidal limiter

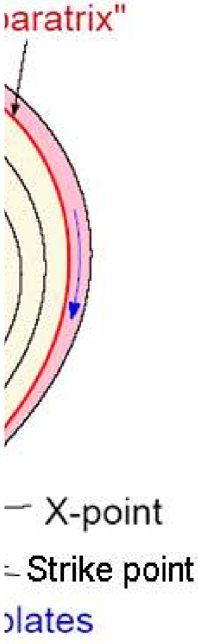
Impurity Control

● Plasma Boundary Region Control

- 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





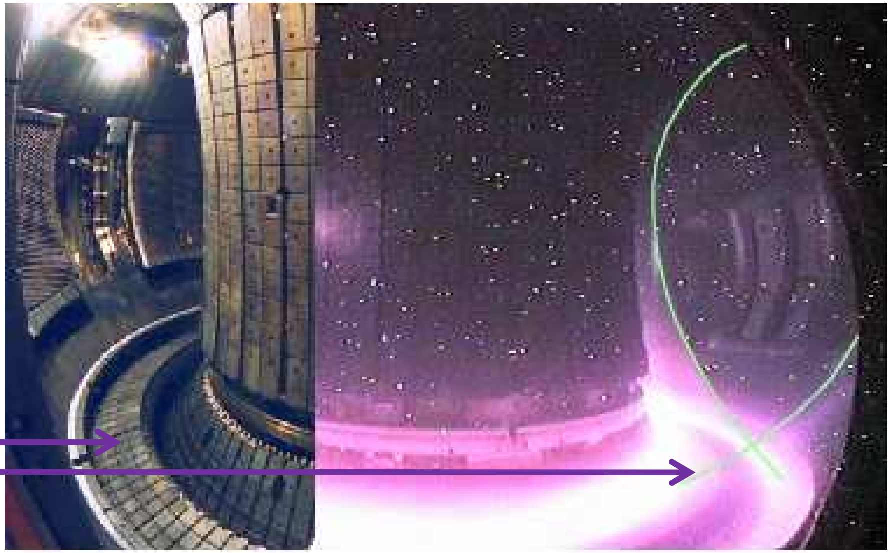


The magnetic boundary between confined plasma and edge/divertor plasma is called **separatrix ≡ LCFS**

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



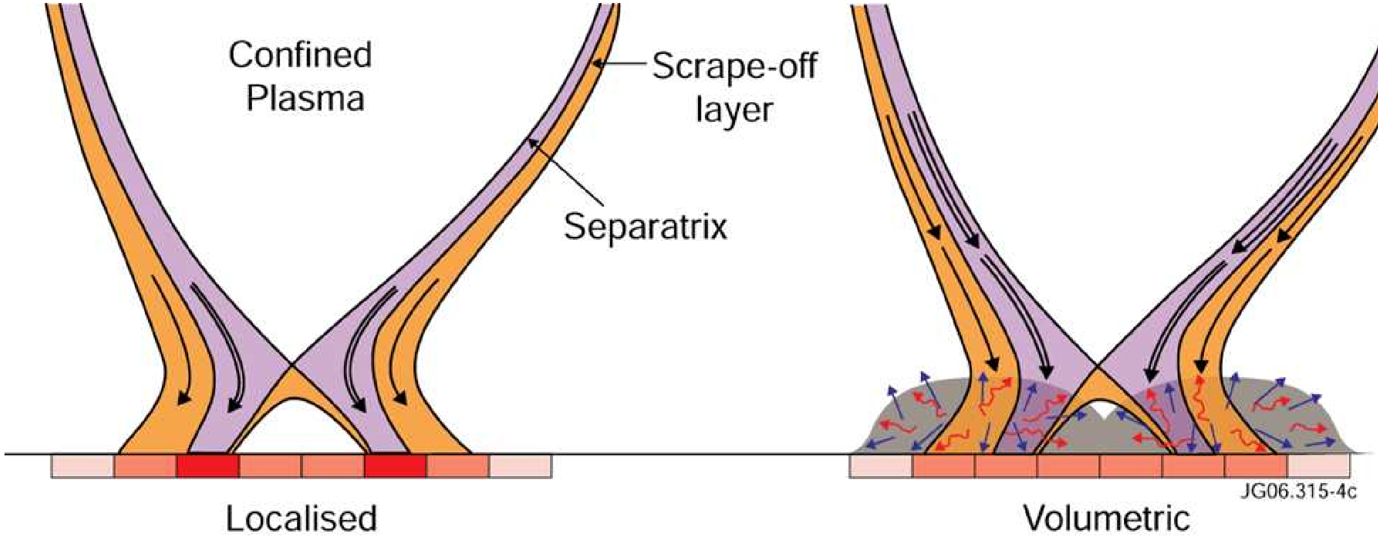
The divertor in
ASDEX Upgrade

Impurity Control

• Plasma Boundary Region Control

- Divertor

Proposed by L. Spitzer for stellarators



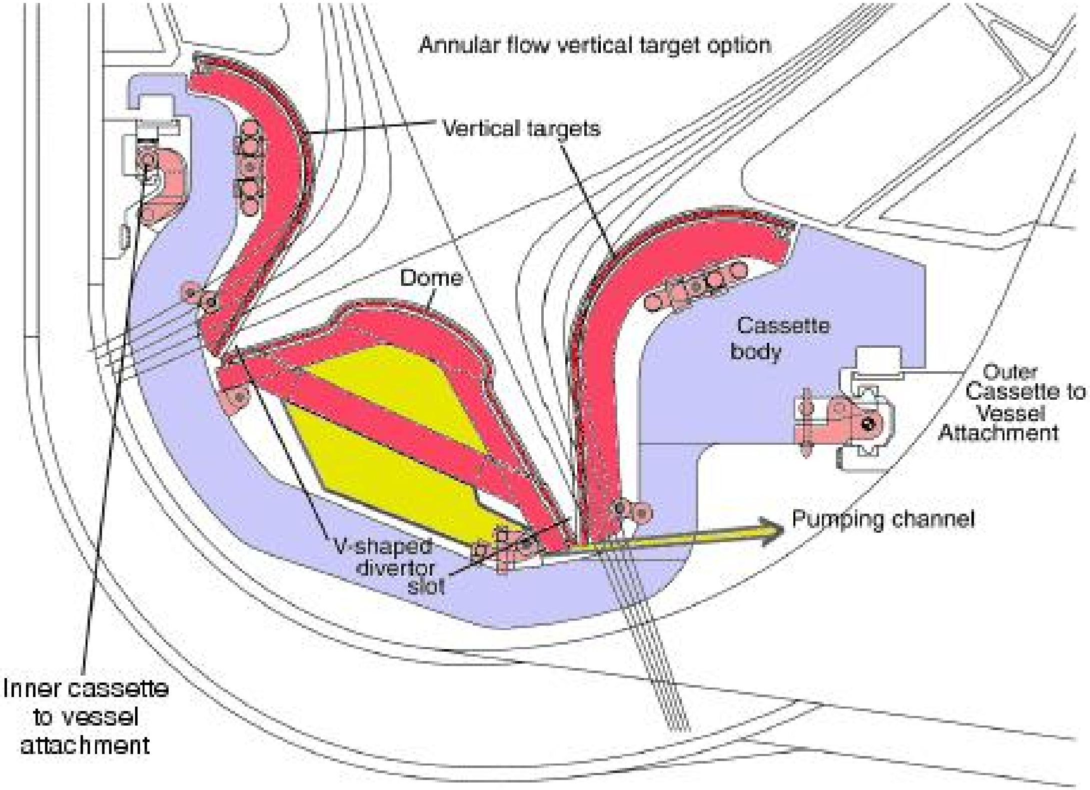
- Advantage of the divertor configuration

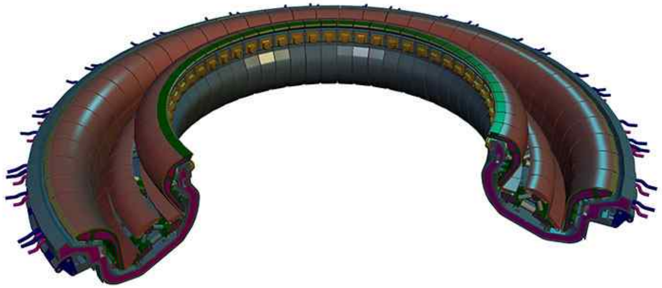
- First contact with material surface at a distance from plasma boundary
- Reducing the influx of ionized impurities into the interior of the plasma by diverting them into an outer scrape-off layer (SOL)

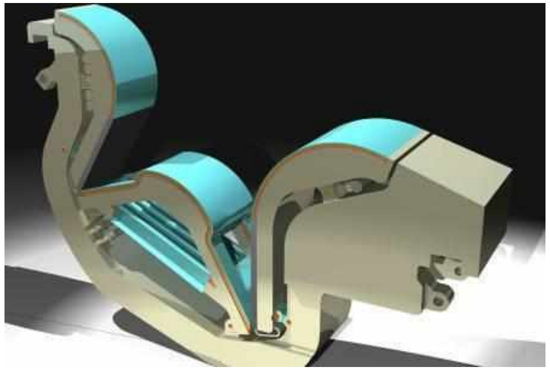
Impurity Control

- **Plasma Boundary Region Control**

- Divertor

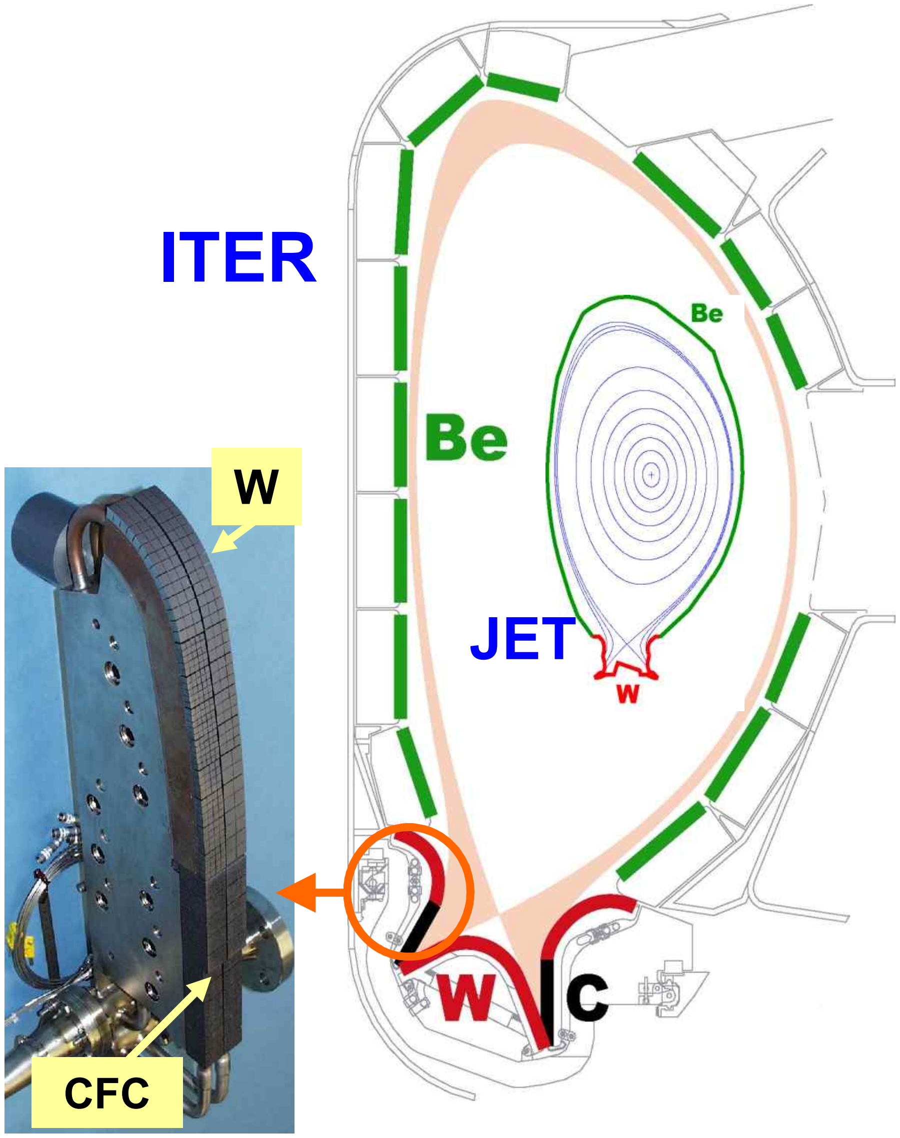






ITER divertor material?

ITER-like-wall



- ITER plans to install a Beryllium first wall and Tungsten divertor for the Tritium phase
  - This material mix has not been tested so far
- **JET is the only machine that can use Beryllium and that can fully characterize plasma scenarios with ITER plasma facing materials**.
- Can we install in ITER a W divertor from the beginning? ITER needs an answer by 2013.
- An ITER-like wall is being inserted in JET in 2010
- In addition
  - Increase NB heating power from 20MW short pulse to 30MW long pulse (routine)
  - Improve control capability
  - Improve diagnostics

References

- Karl Krieger, "Plasma Wall Interaction and First Wall", IPP Summer School, IPP Garching, September, 2009
- Suk-Ho Hong, "Current plasma-wall interaction activities in KSTAR", SNU Seminar, Seoul, 5 February, 2010