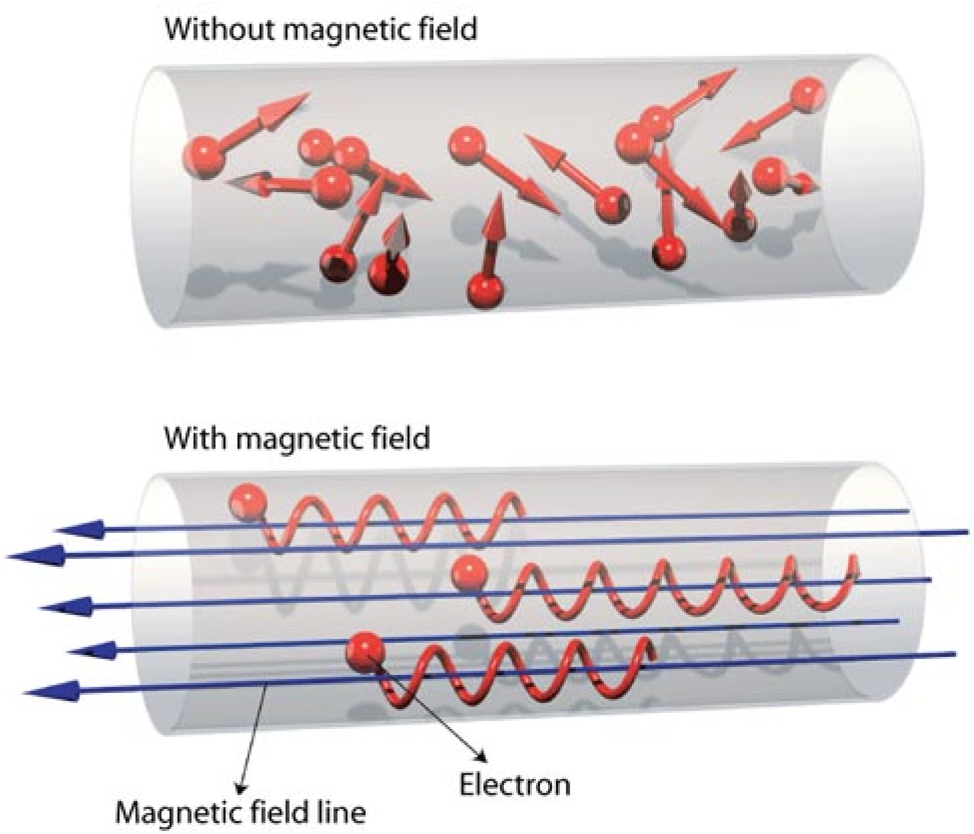
Fusion Reactor Technology 2
(459.761, 3 Credits)

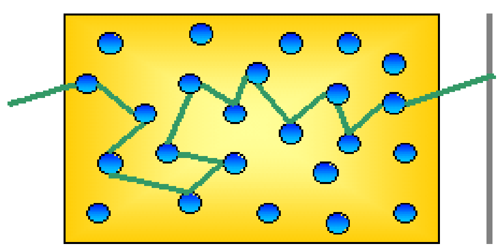
Prof. Dr. Yong-Su Na

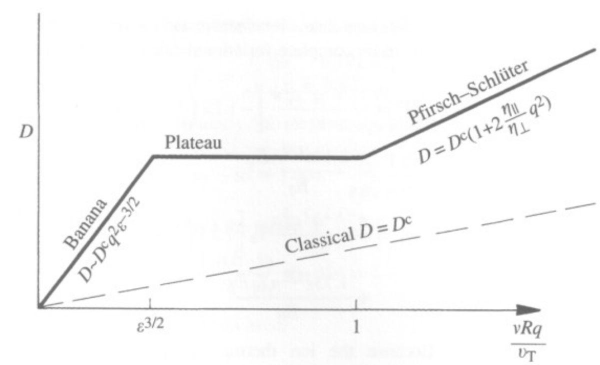
(32-206, Tel. 880-7204)

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

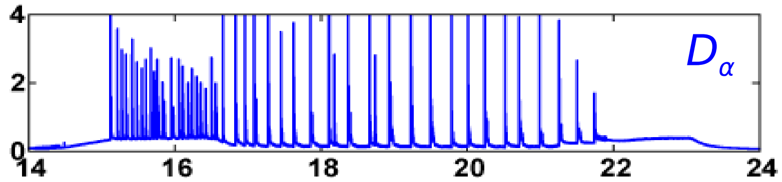
Fluxes to the Surface

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

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

Flux Excursions

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



Flux Excursions

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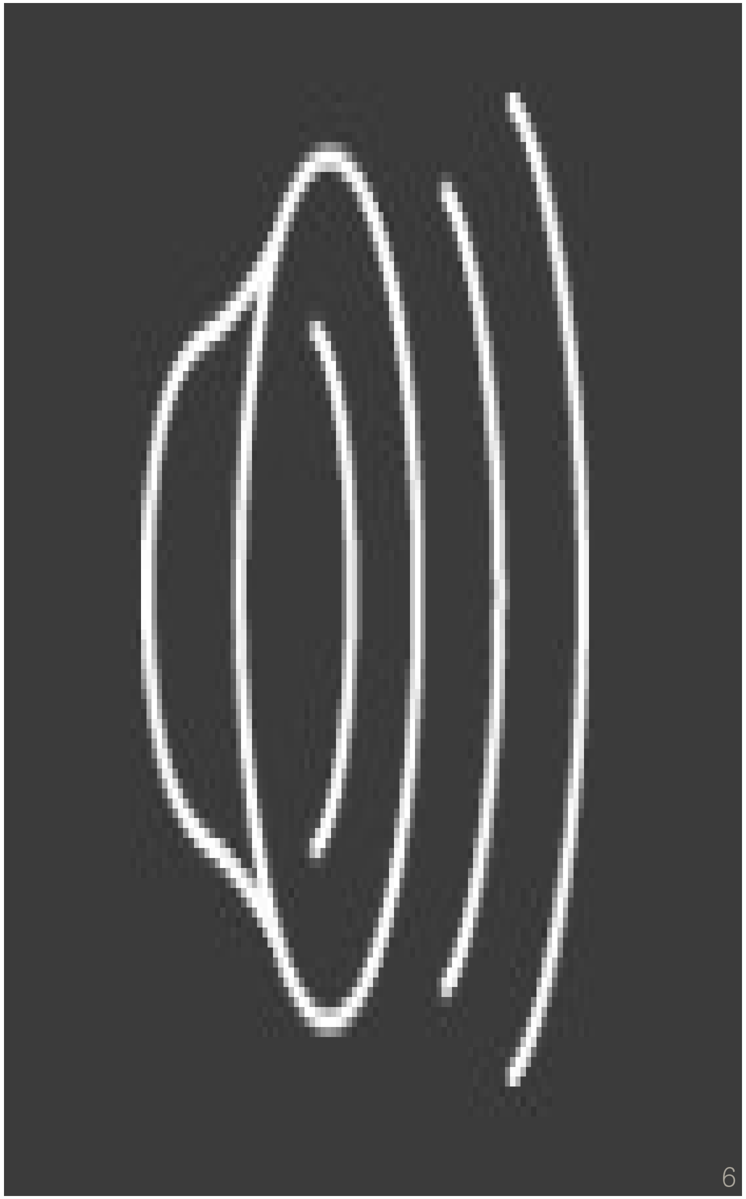
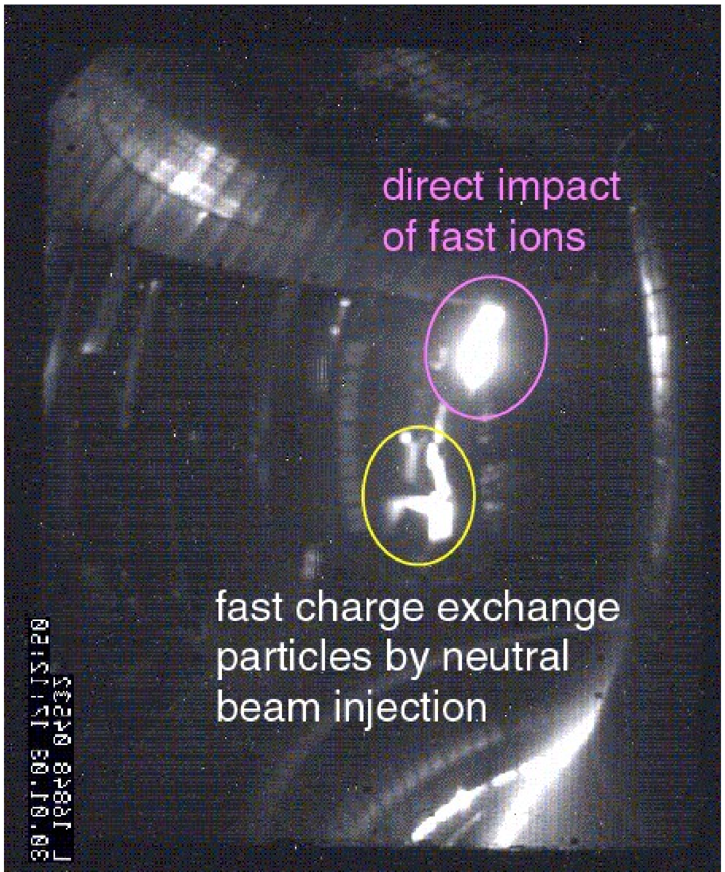
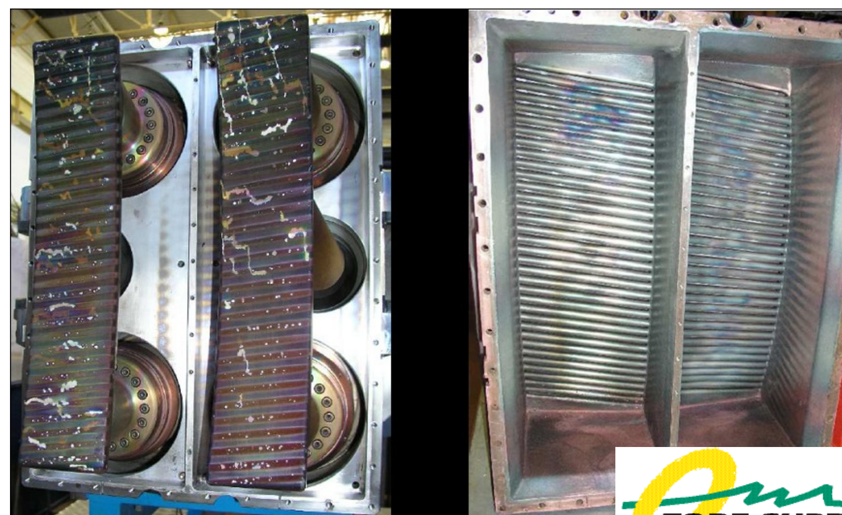


Flux Excursions

- **Localised Flux Excursions**

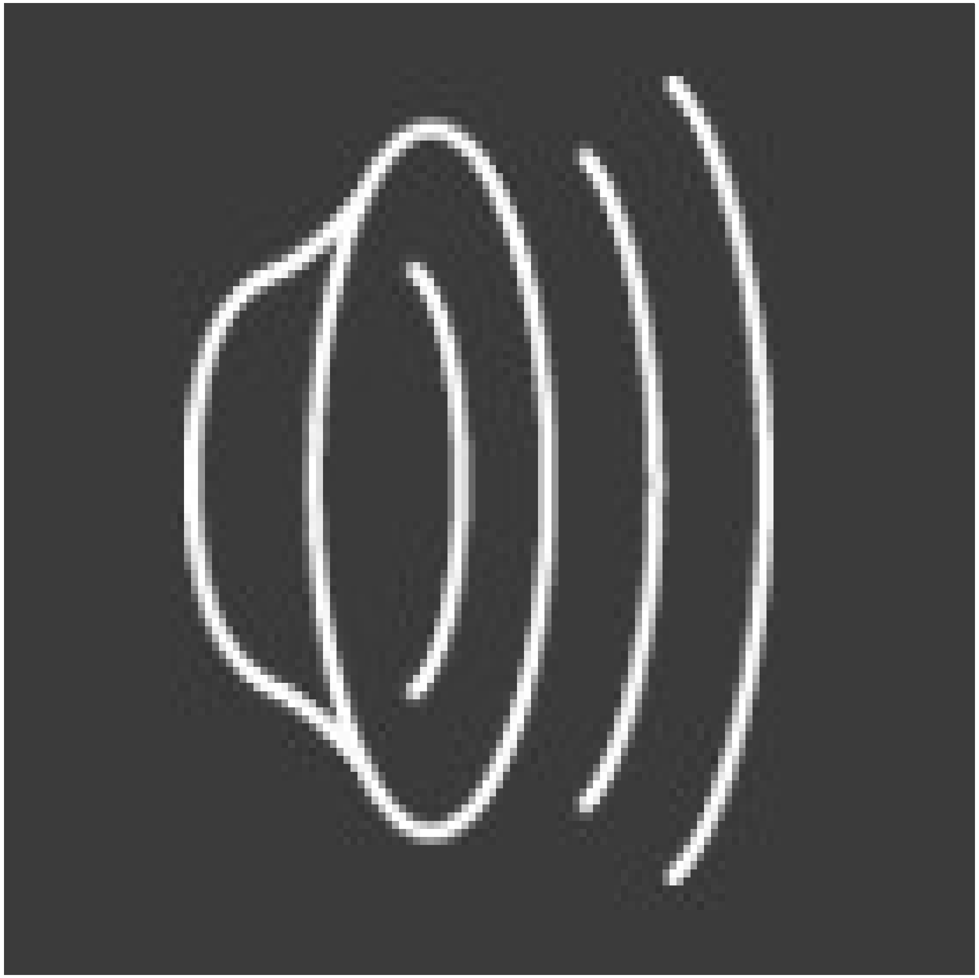


- Loss of fast particles can lead to excessive local heat loads.
  - charge exchange neutrals by heating with NBI
  - orbit losses of fast ions
  - runaway electrons



Flux Excursions

- **Importance of Plasma-Wall Interaction**

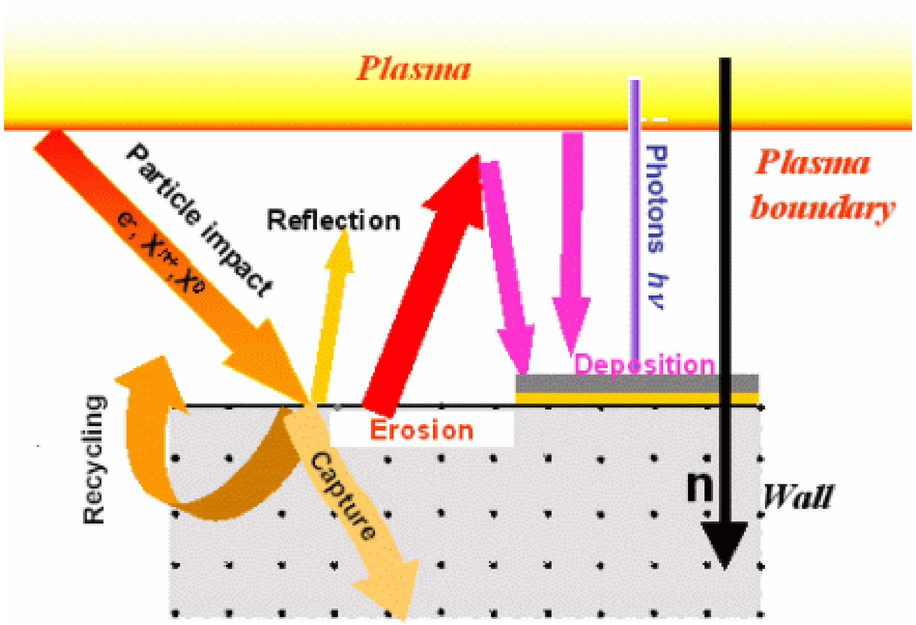


KSTAR
first H-mode plasma with good shape control (#4202)

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

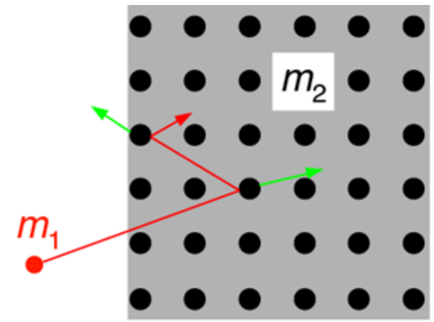


http://www-rcp.ijs.si/mic/our_work/applications/fusion/fusion.php

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:



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

$$Y(E) \approx \frac{20}{U_0}(Z_1 Z_2)^2 \frac{m_1}{m_2} \frac{E}{(E+50 Z_1 Z_2)^2}$$ semi-theoretical value

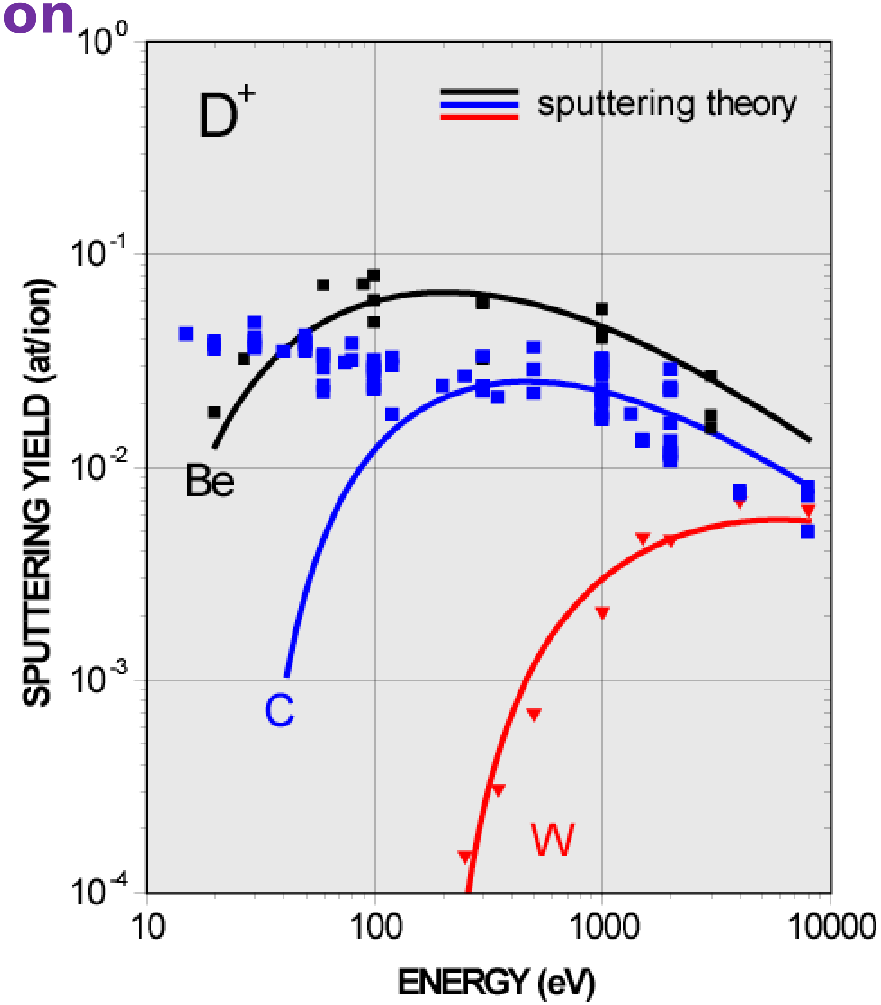
- Threshold incident energy to produce sputtering $E = \frac{(m_1+m_2)^2}{4 m_1 m_2} U_0$

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**



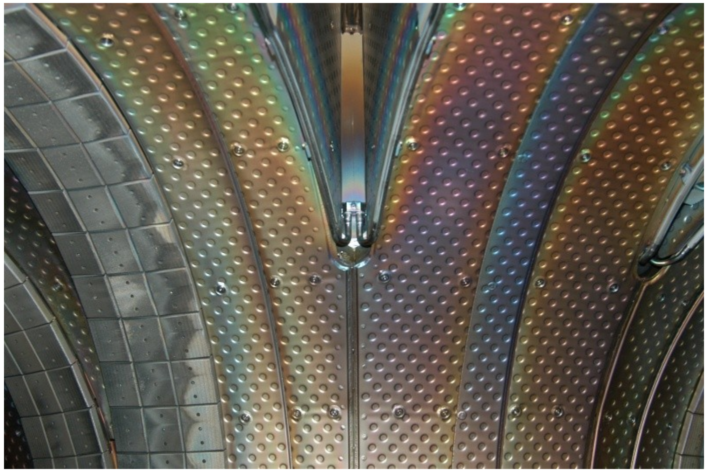
Surface Interaction Phenomena

- **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:

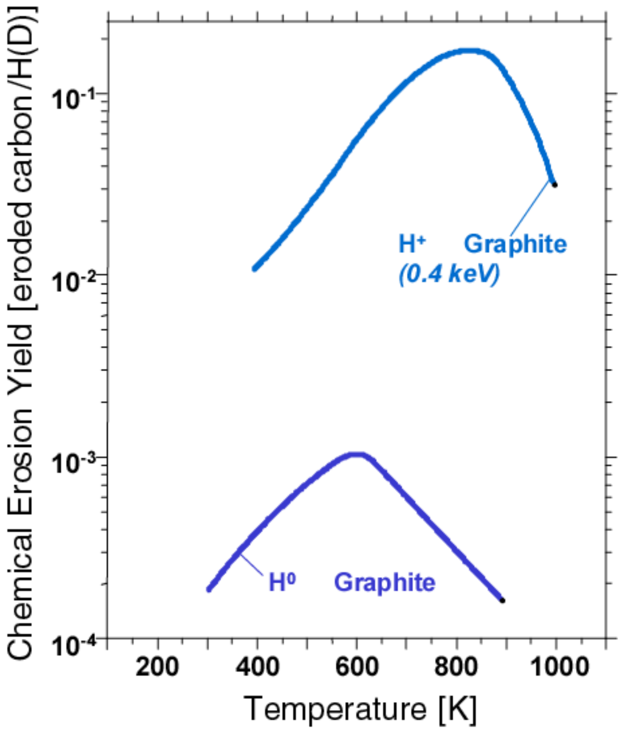
    $O + Metal \rightarrow Metal(O)$

    (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

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  - 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

- **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

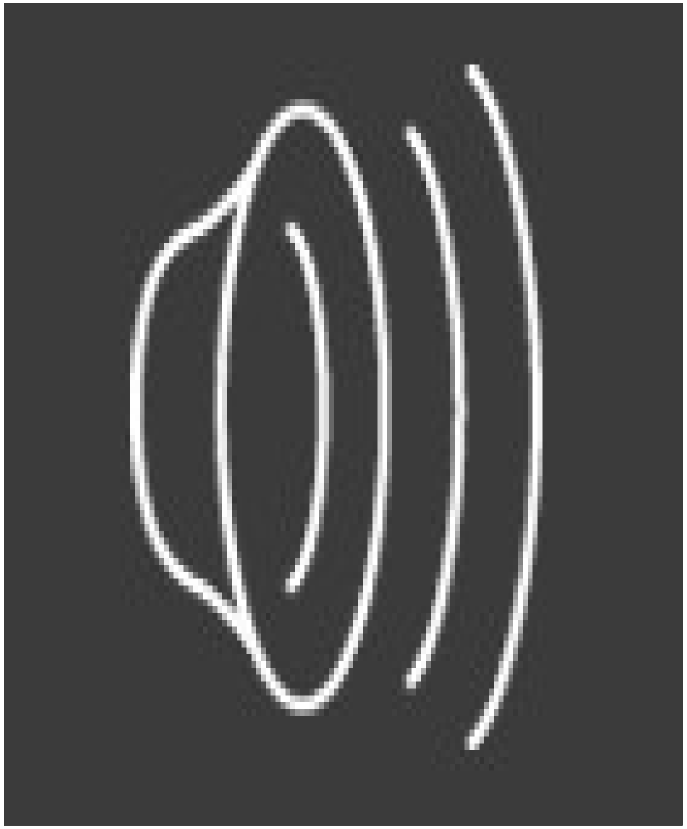
Surface Interaction Phenomena

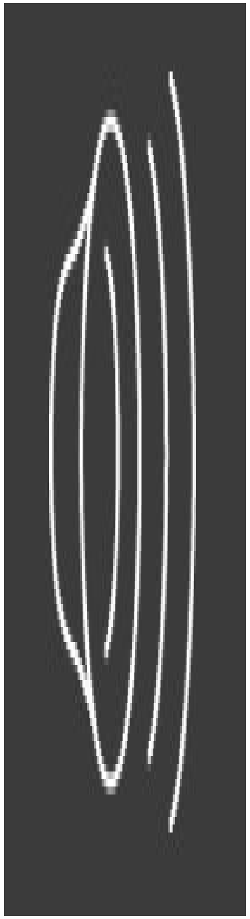
- **Dust Formation**

  - 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

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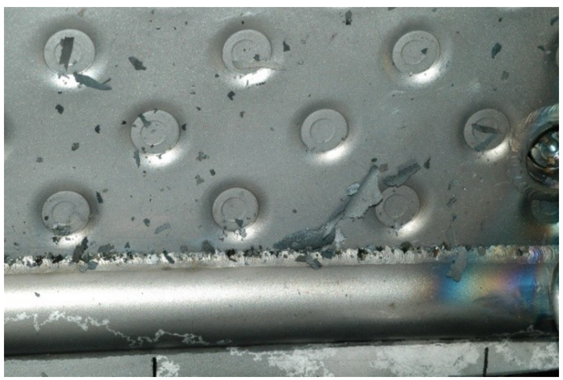
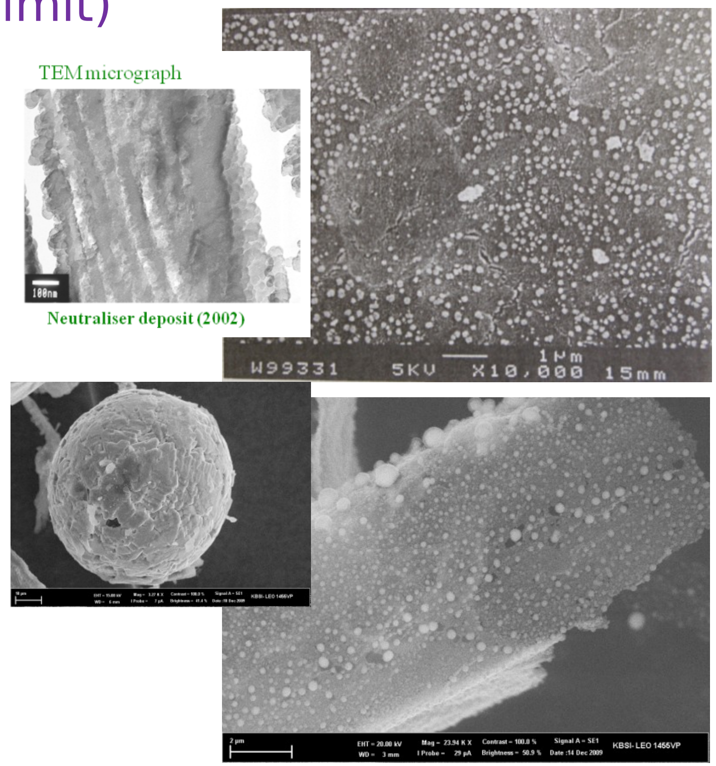


Mobilised „dusts“
(Tore Supra)



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

Impurity Radiation

- **Bremsstrahlung (Braking radiation)**

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

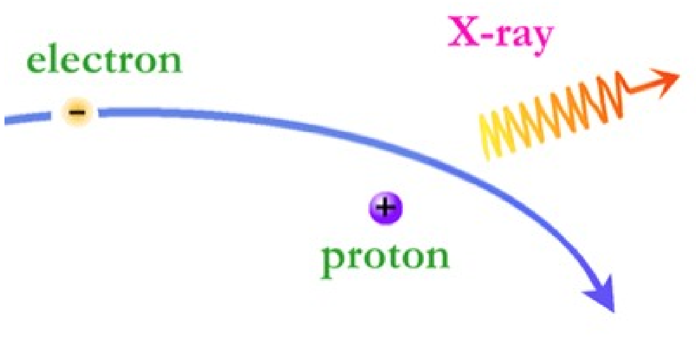
  - Contribution from ions can be neglected due to their heavier mass (m_p=1836m_e) compared with that of electrons.

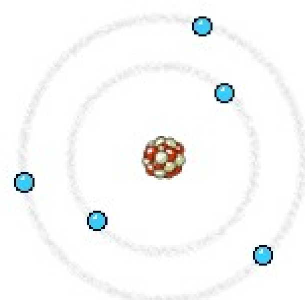
  - Mainly due to e-i collisions:

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

  - X-ray wavelength range (λ ~ 10^{-9} m): readily escaping from a plasma

$$P_{br} \approx 1.6 \times 10^{-38} n_i n_e Z^2 \sqrt{kT_e} \quad (\mathrm{W/m^{-3}})$$





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

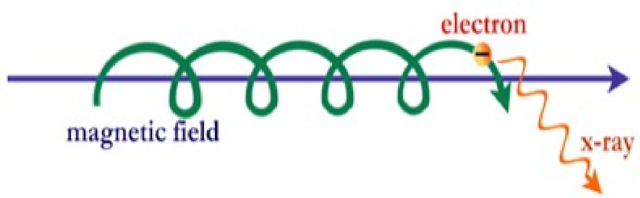
  - contribution from ions can be neglected due to their heavier mass compared with that of electrons.

  - In the far infrared radiation spectrum (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

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

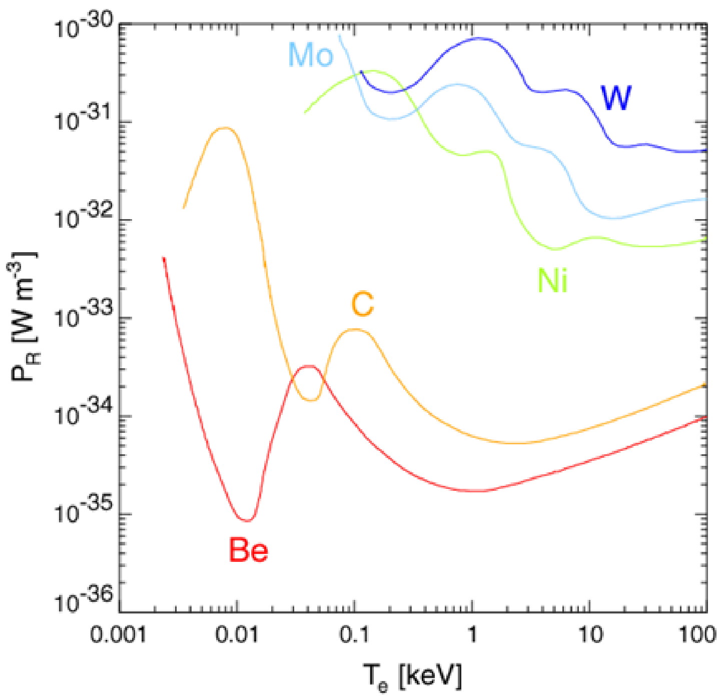


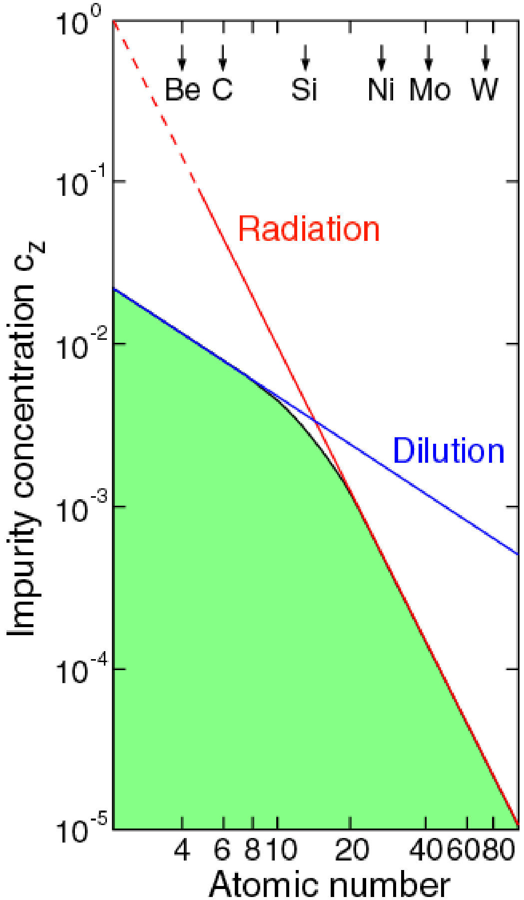
Ψ accounting for the complex processes of reflection and reabsorption of cyclotron radiation

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 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, swelling by neutrons

  - Li: evaporation easily

  - Be: toxic

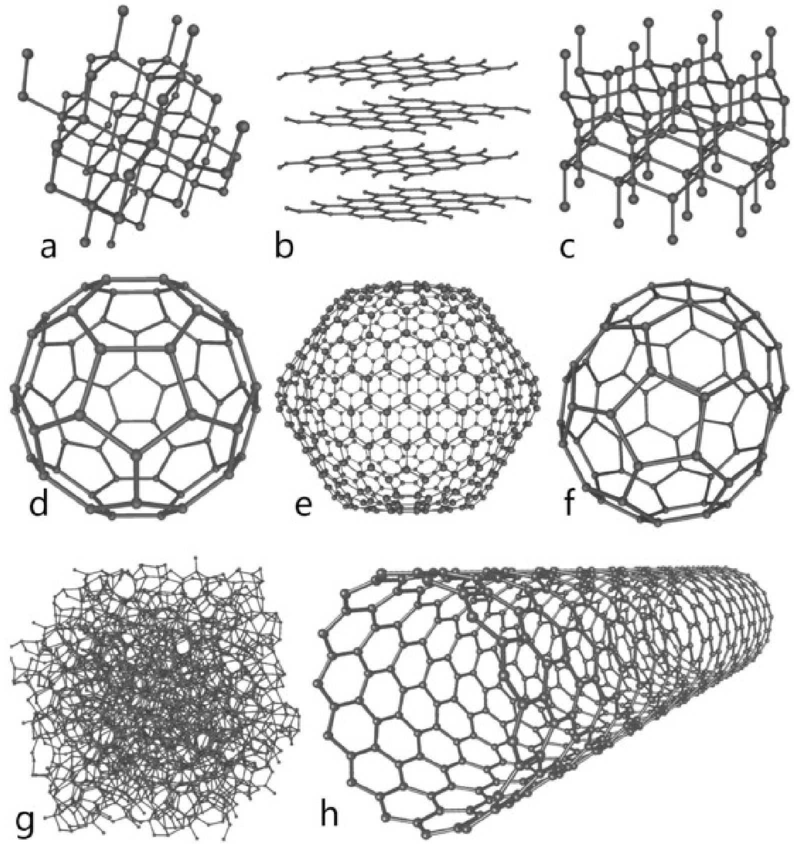
  - B: He, H production by neutrons ((n,α), (n,p))

Impurity Radiation

- **Maximal Permissible Impurity Concentration**

Carbon:
Why no more interested in fusion reactors?

- Chemical reactions
- Retention
- Swelling by neutrons



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

WIKIPEDIA
The Free Encyclopedia

Impurity Control

- **Wall Surface Control**

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

  2) Wall modification

  - Bake-out (baking)

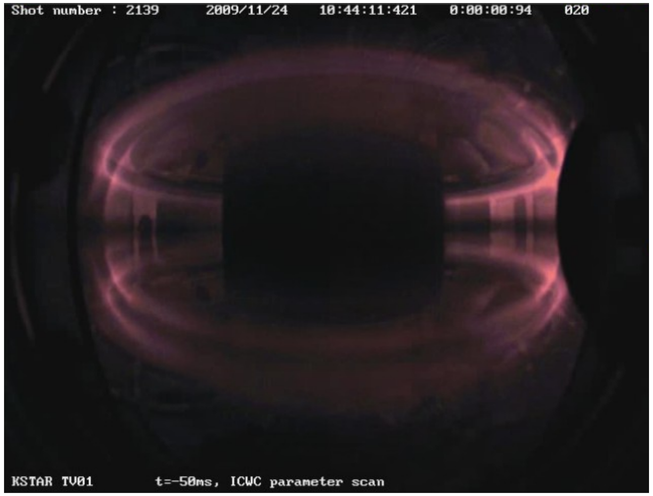
  - Discharge cleaning

- ICRH, ECRH, LH, BNI conditioning

- Boronisation, Siliconisation

- Gettering

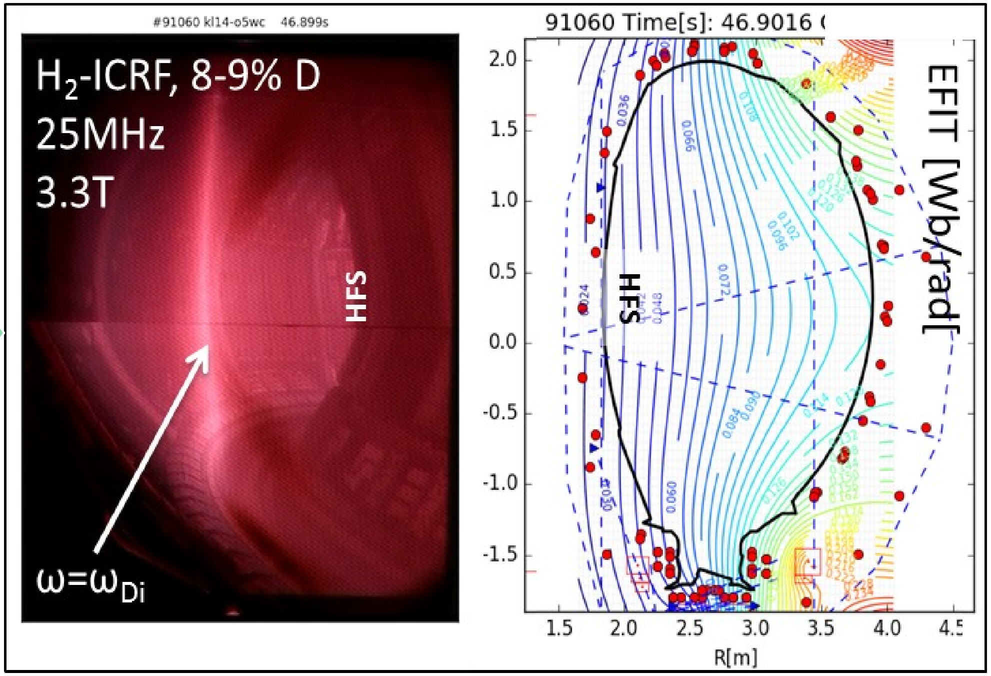
- Honey comb surface



Ion Cyclotron Wall Conditioning (ICWC) in KSTAR

ICWC may provide an effective means for removal of fuel buried in co-deposited layers

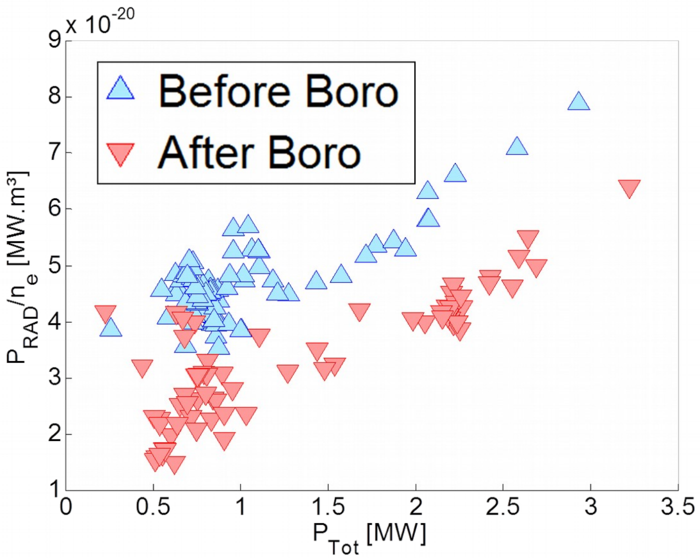
JET ICRF conditioning at 25 MHz at 3.3 T and 1.65 T mimicked the ITER situation at full and half field using 40 MHz RF and central resonance



- **ICWC procedure developed at JET could remove 52% of the permanent retention, which would correspond to the full expected fuel retention in the main vessel including the divertor apron**
- ***ICWC between or after a series of D-T pulses may offer a potentially a very promising strategy for T inventory control on ITER***

Impurity Control

- **Boronisation**



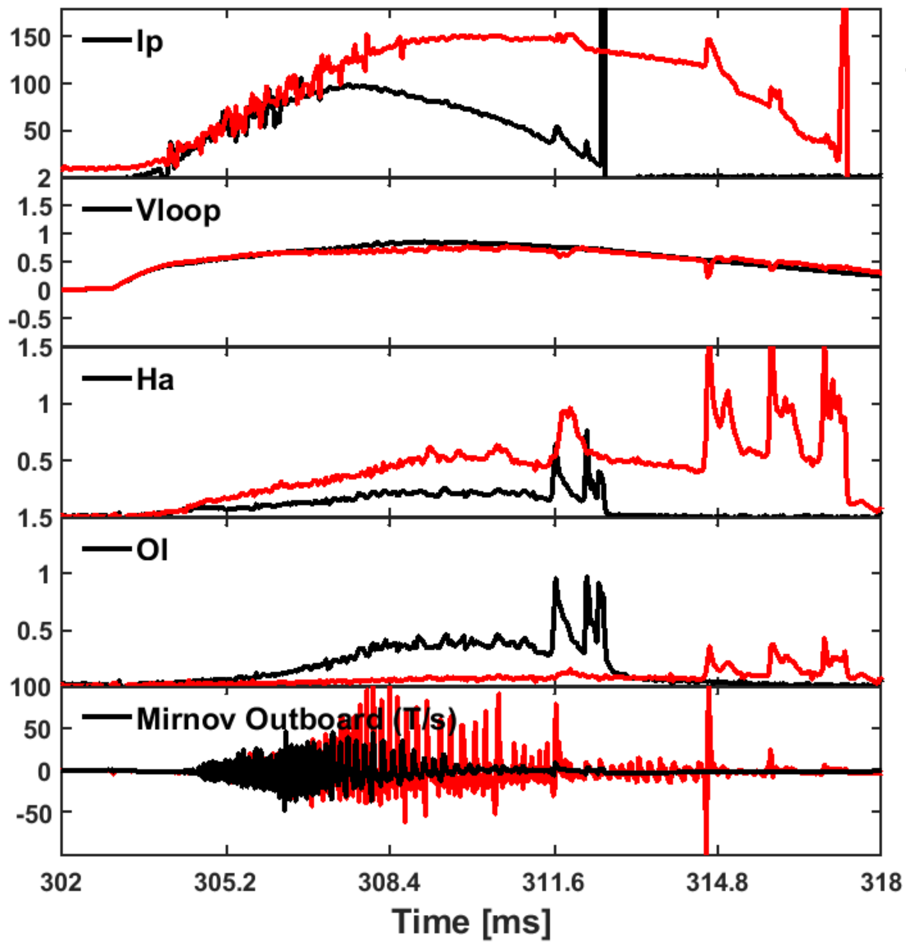
VEST?

Impurity Control

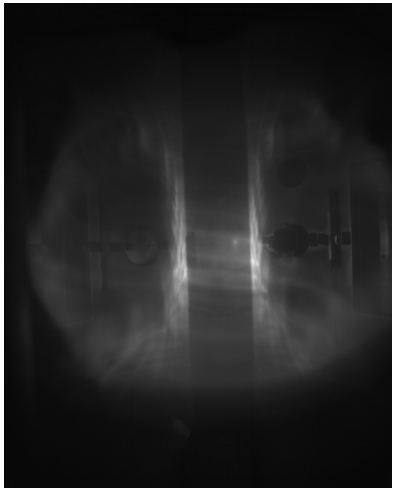
- **Boronisation**

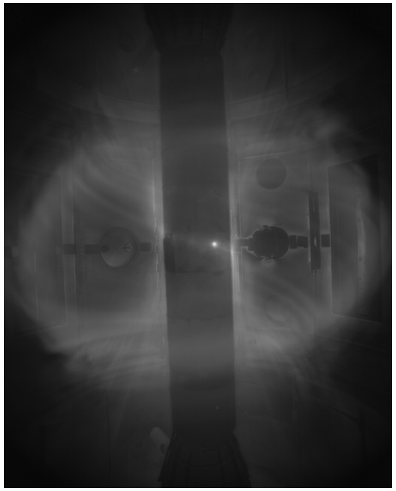
#25229 (No Boronization)

#25234 (Boronization)



#25229 (No Boronization)

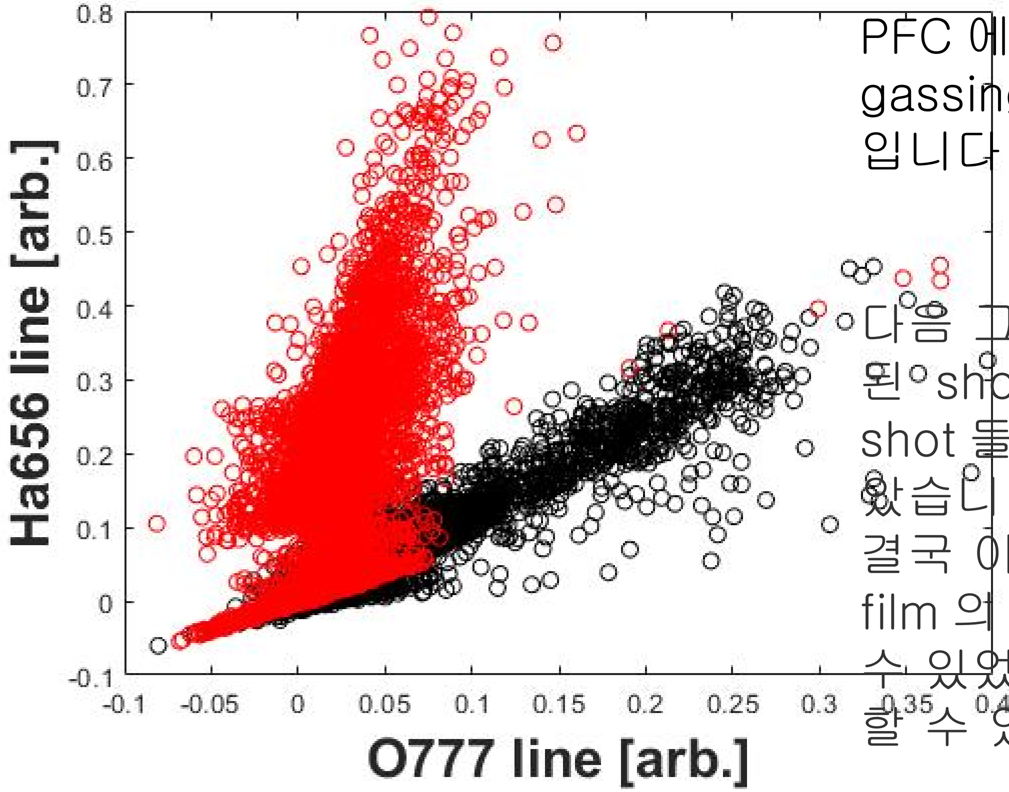




#25234 (Boronization)

Impurity Control

- **Boronisation**



Boronization 은 BxOy 의 thin film 을 PFC 에 형성하여 벽으로부터 나오는 Out gassing 을 막는 wall conditioning 방법 입니다 .

다음 그림은 VEST 에서 boronization(빨 된 shot 들과 GDC(검) 처리 후 방전된 shot 들의 emission line 들을 plot 해 보았습니다 .
결국 이 plot 을 통하여 boronization 의 film 의 Oxygen getter 의 역할을 확인 할 수 있었고 , O line 의 감소가 극명함을 확 할 수 있습니다 .

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

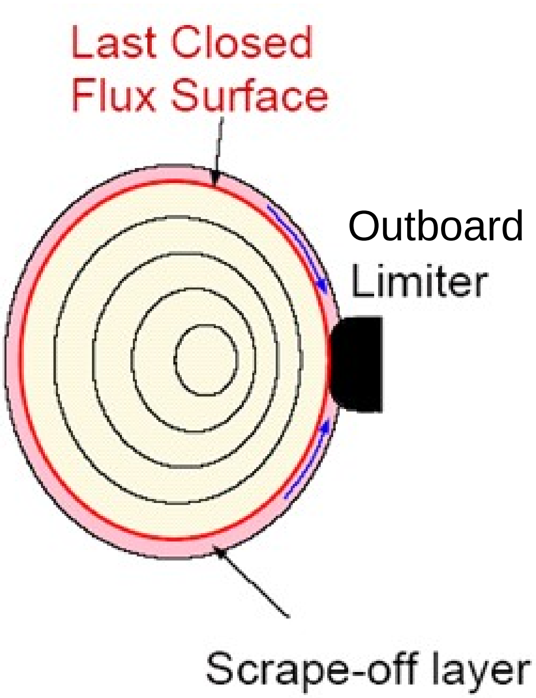
- **Plasma Boundary Region Control**
  - Limiter: a material structure protruding from the main wall used to intercept particles at the plasma edge particularly to stop runaway electrons from damaging the vacuum vessel, to protect the vessel from NBI shine-through, and to shadow in-vessel components 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

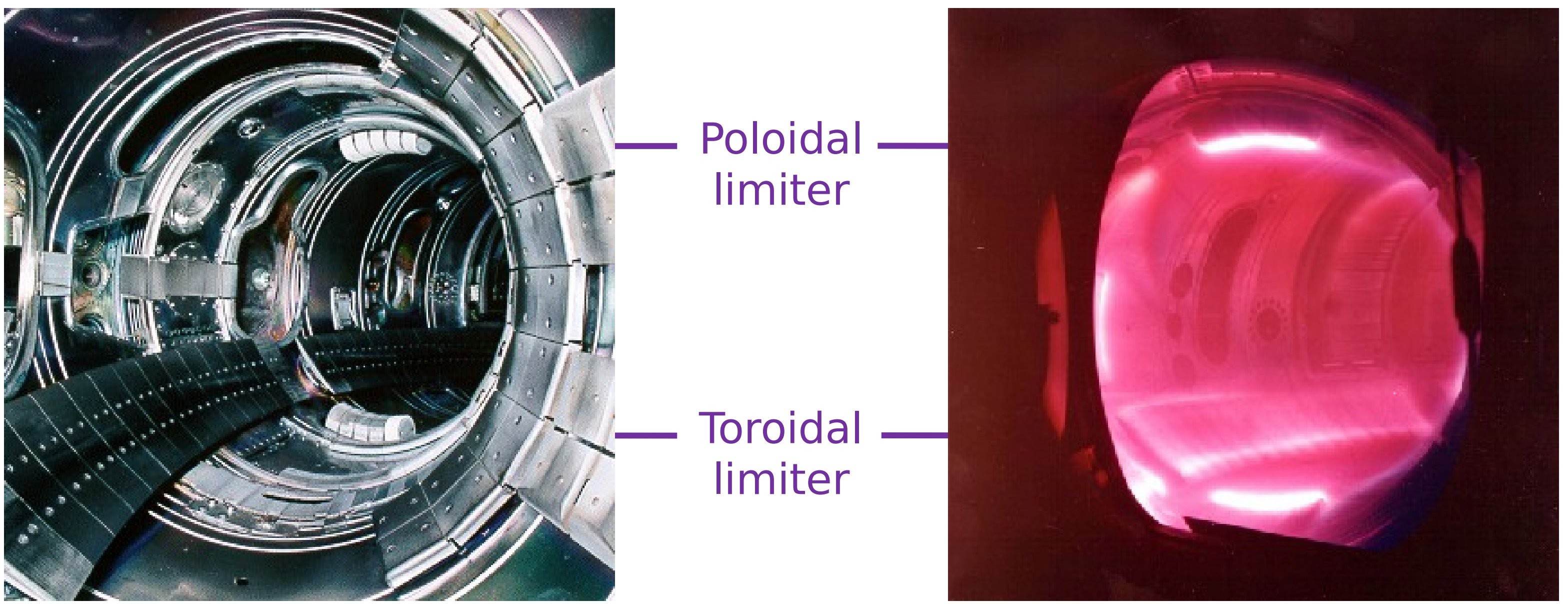
Scrape-off Layer (SOL):
The plasma region located in the limiter shadow
i.e. between the LCFS and the vessel wall

Impurity Control

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

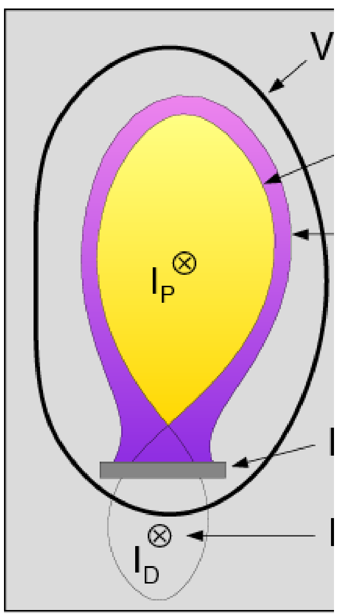
    High heat load and sputtering rate on limiter

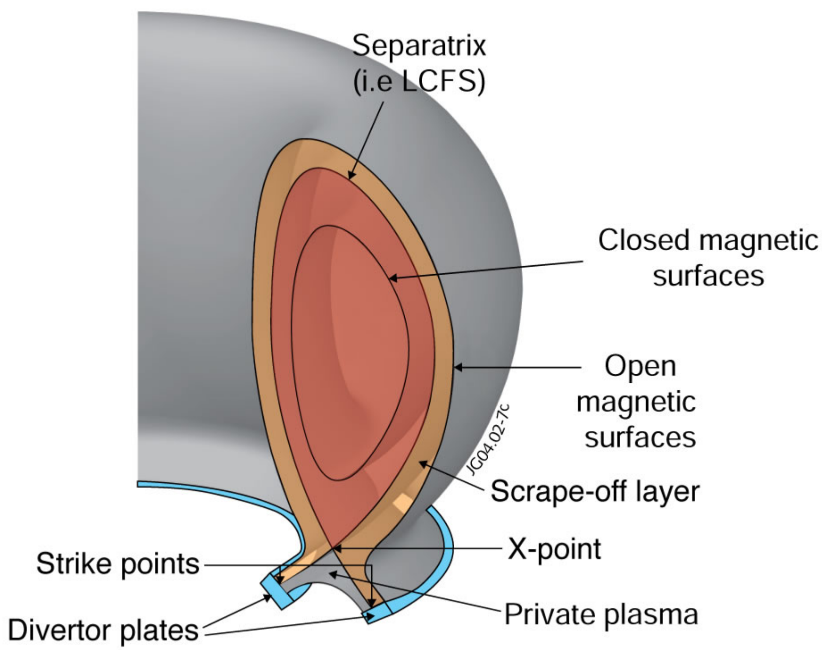
    → Impurities → Low-Z coating of limiters (C or Be on W)

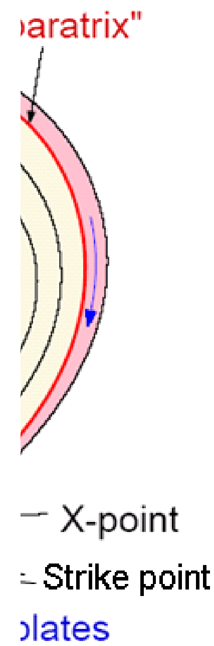


Impurity Control

- **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



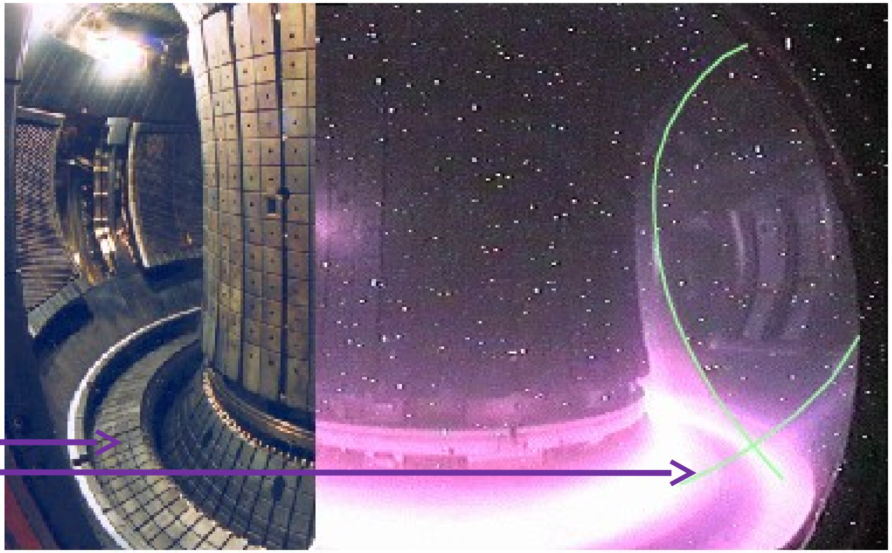




The magnetic boundary between confined plasma and edge/divertor plasma is called **separatrix ≡ LCFS**

Impurity Control

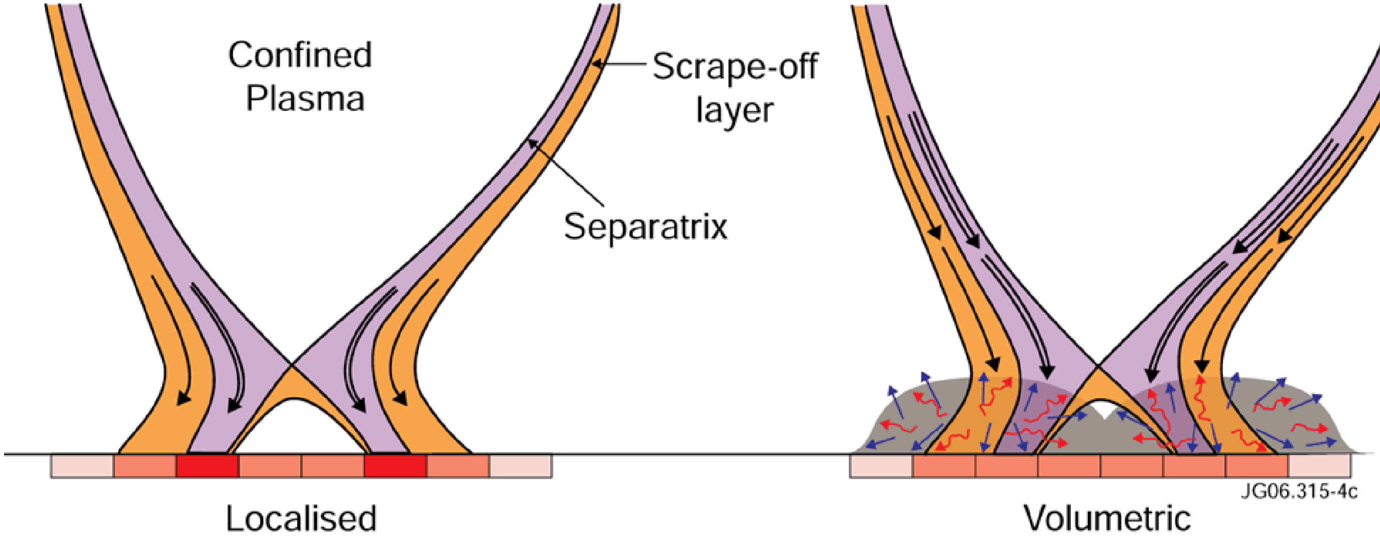
- **Plasma Boundary Region Control**
  - Divertor functions
    - Reduction of 1st wall bombardment (unloading):
      First contact with material surface at a distance from plasma boundary
    - Reduction of impurity flow into plasma (shielding for impurity control):
      Reducing the influx of ionized impurities into the interior of the plasma by diverting them into an outer SOL
    - 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

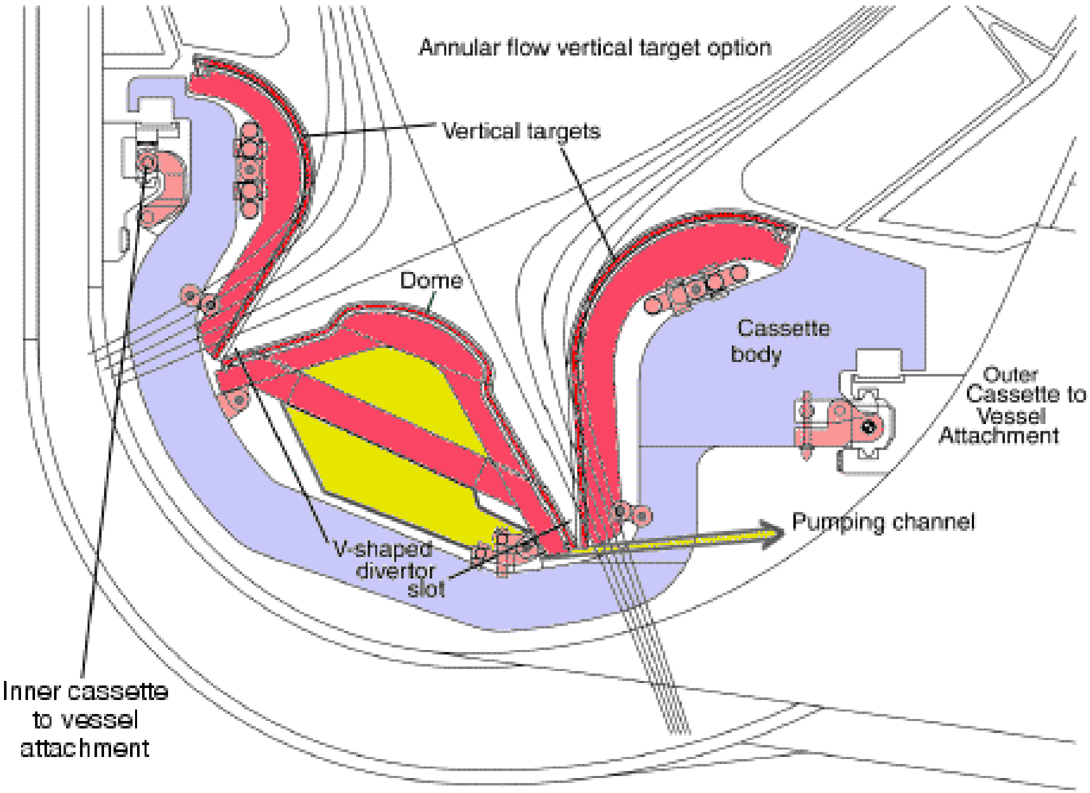


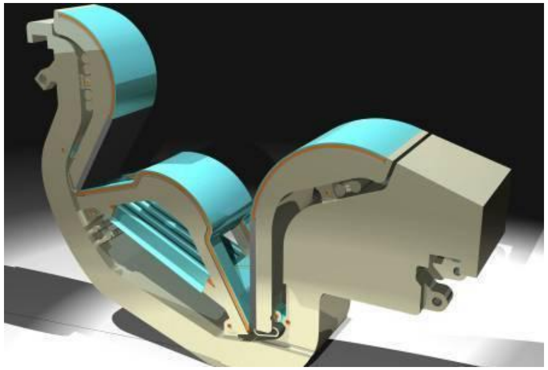
Proposed by L. Spitzer for stellarators

Impurity Control

- **Plasma Boundary Region Control**
  - Divertor

- Sun surface: 50 MW/m²
- Divertor: 10~20 MW/m²
- W^{ITER}_{ELM}~20 MJ
  If W_{ELM} > 1 MJ: W melting

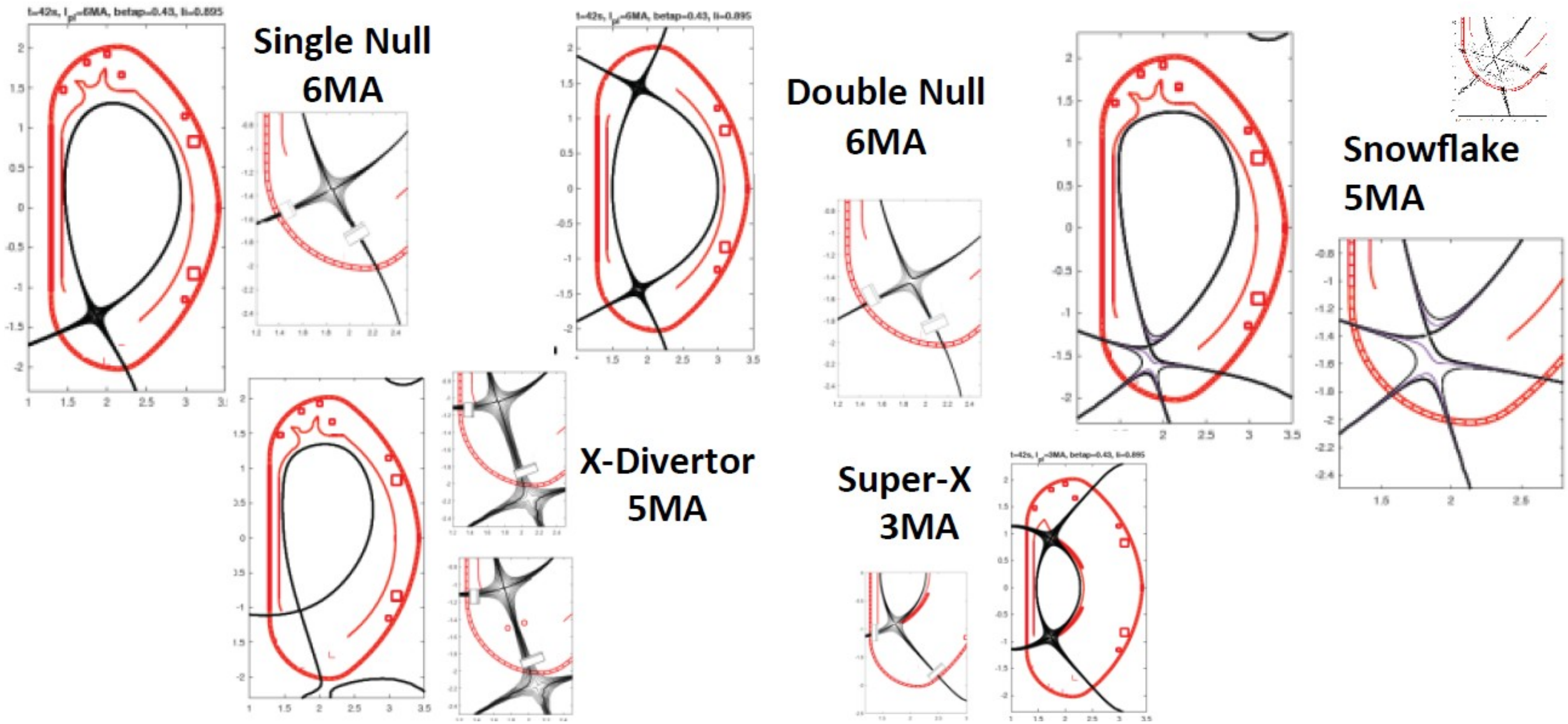




ITER divertor material?

Impurity Control

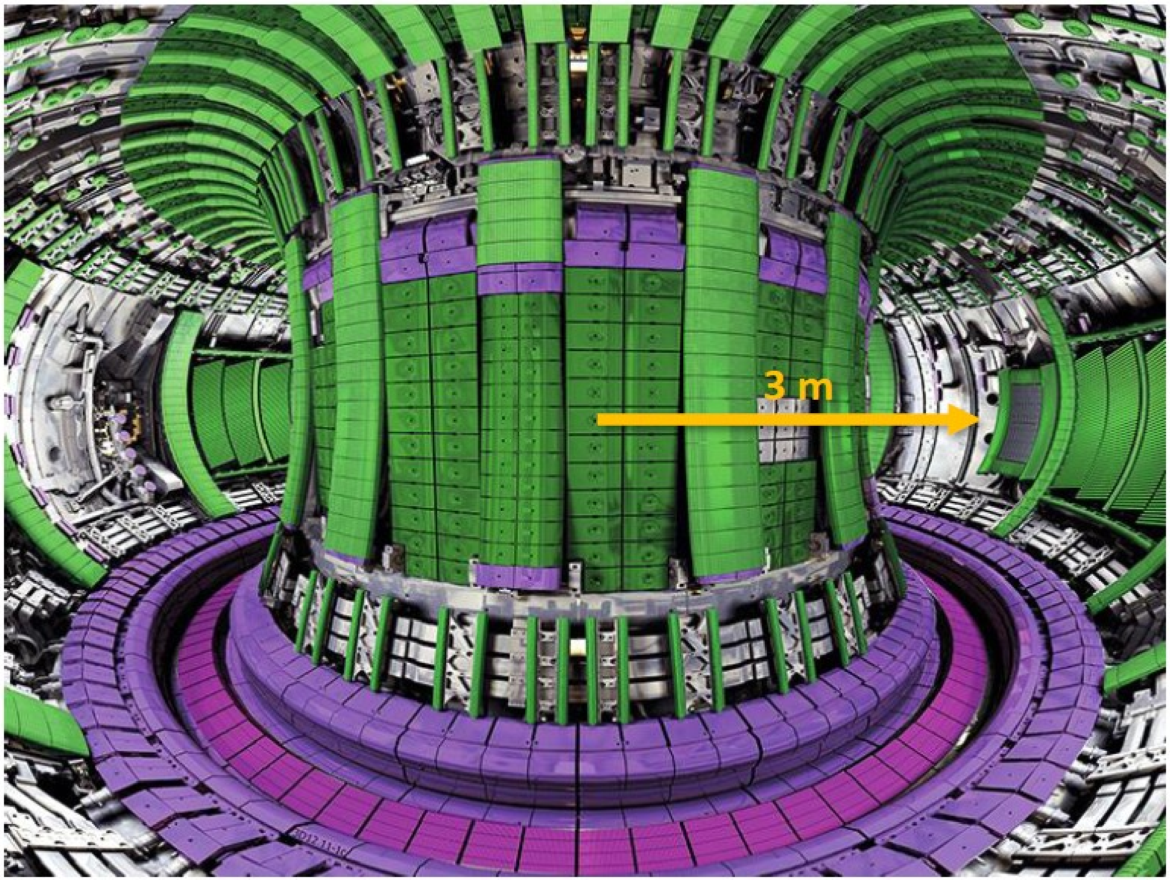
- **Plasma Boundary Region Control**
  - Divertor



I-DTT (Italian Divertor Test Tokamak facility)

Impurity Control

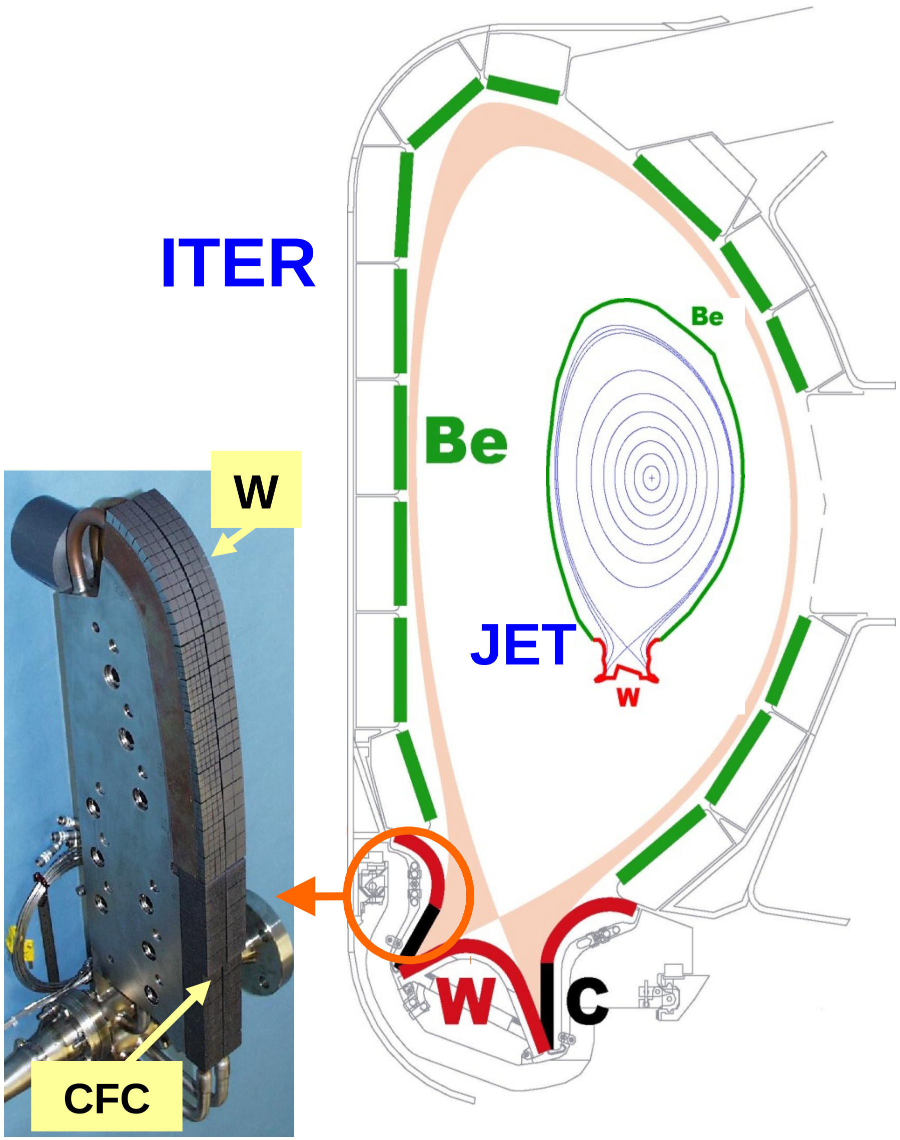
Carbon wall refurbished with W divertor+ Be main chamber in 2011



CPS15.139-2c

Bulk Be PFCs
Be−coated inconel PFCs
Bulk W
W−coated CFC PFCs

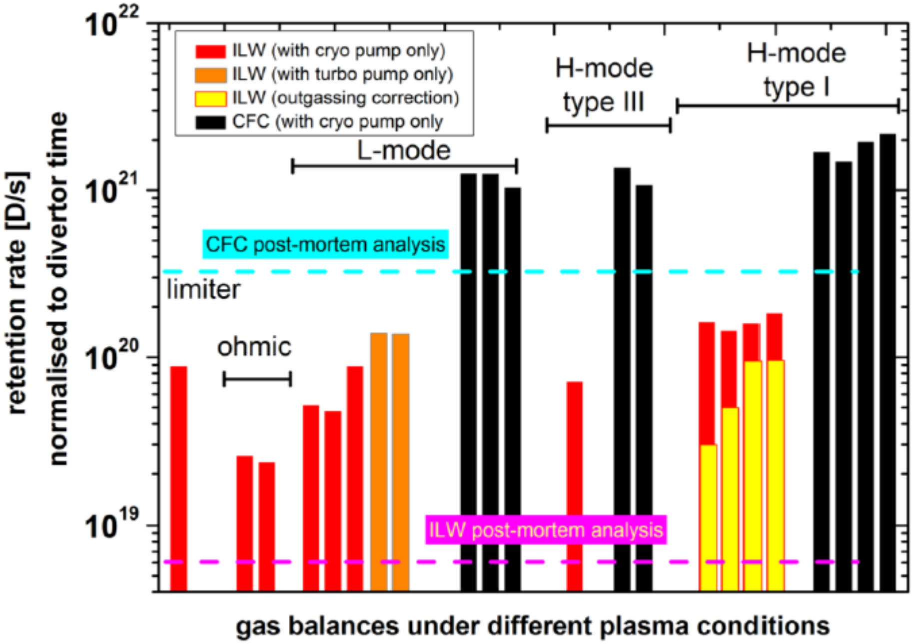
ITER-like-wall

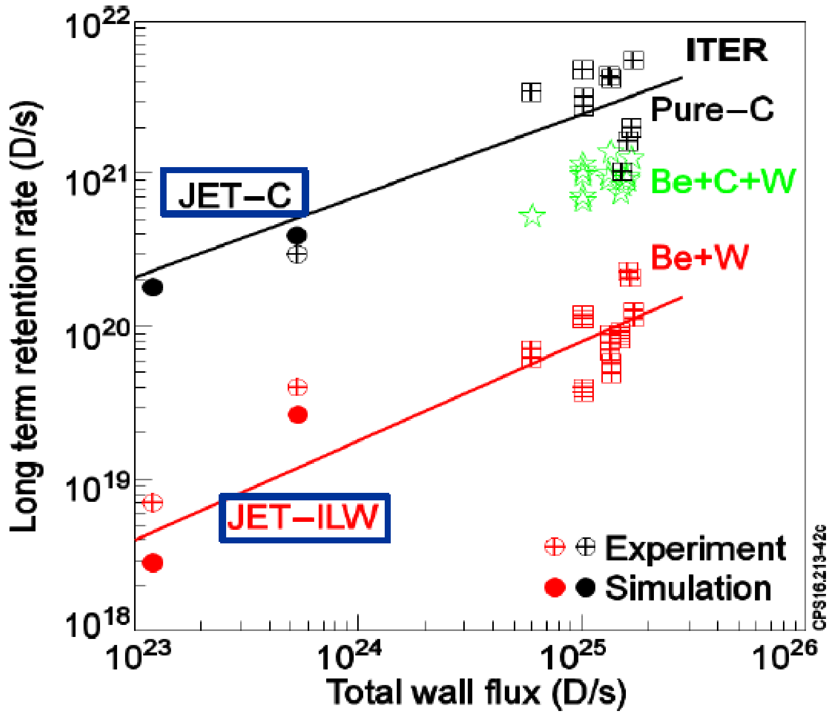


- ITER plans to install a Beryllium first wall and Tungsten divertor for the Tritium phase
  - This material mix has not been tested so far
- **JET is the only machine that can use Beryllium and that can fully characterize plasma scenarios with ITER plasma facing materials**.

Impurity Control

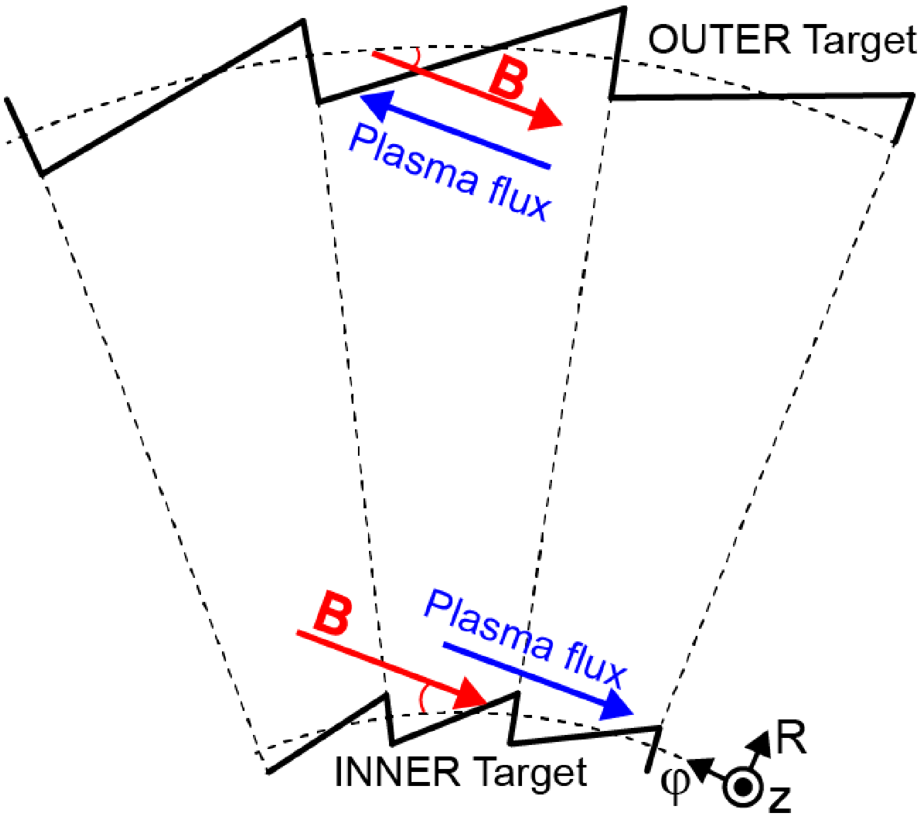
- **Fuel retention with the ILW**

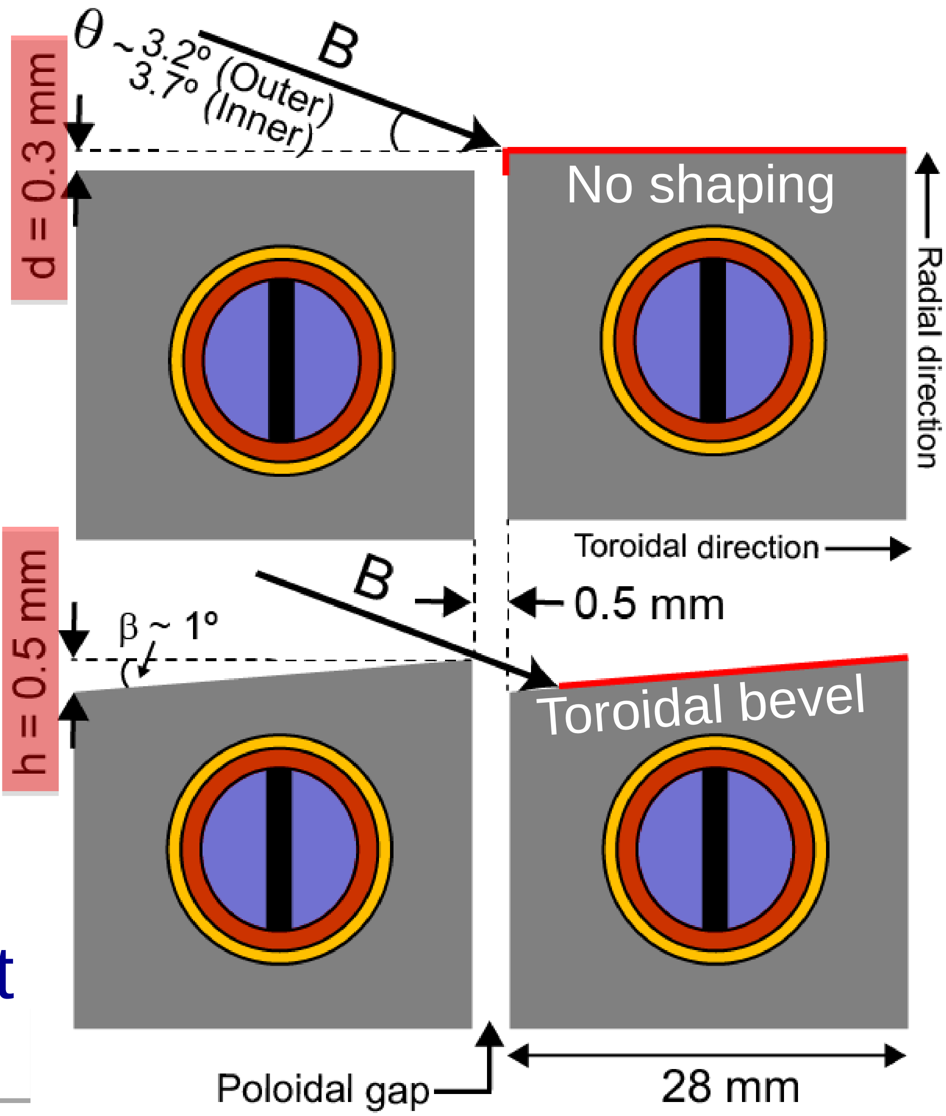




- T retention at carbon wall is unacceptably high for ITER.
- Fuel retention reduced by more than one order of magnitude in ILW.
- Simulations extrapolated to ITER predict that 3000-20000 of 400 s discharges would be feasible for Tritium experiments in ITER.

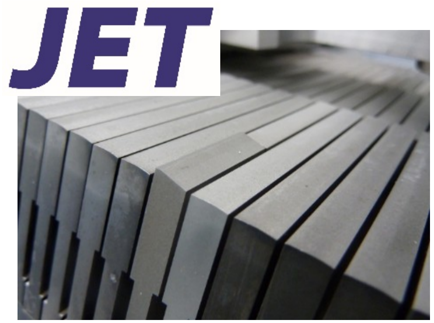
Shaping in HHF(High Heat Flux) areas

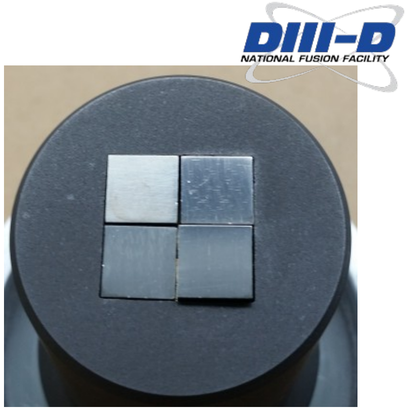


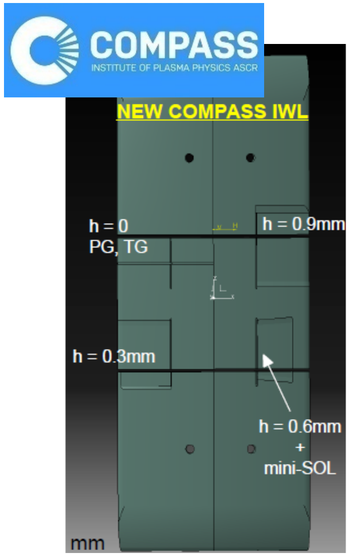


- Global target tilt of ~0.5º at inner and outer targets

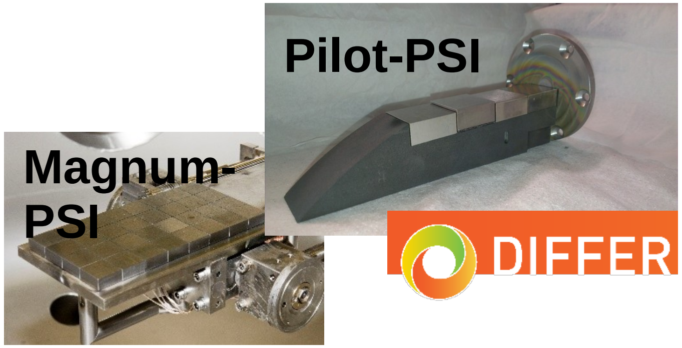
Multi-machine experiments







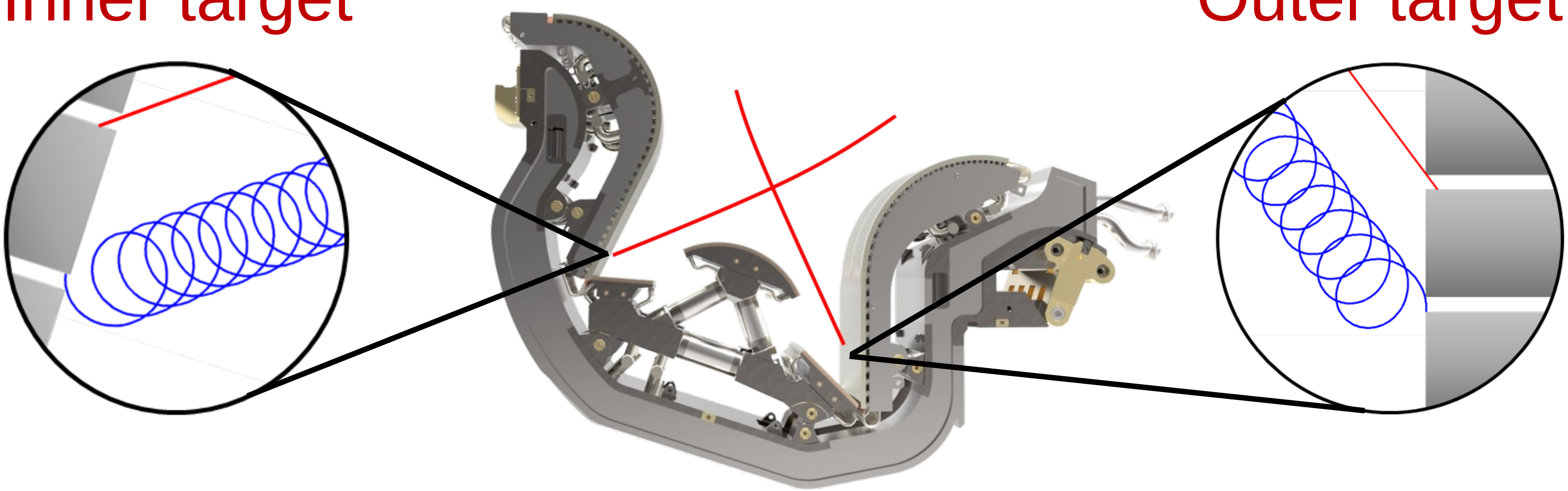
R. A. Pitts et al., PSI 2016, submitted to Nuclear Materials and Energy



TG (Toroidal Gap) loading

- TGs are accessible, even with toroidal bevelling
- Helicity of ion orbits introduces asymmetry between inner and outer target toroidal gaps

J. P. Gunn., Nucl. Mater. and Energy (2016)



Ions strike lower toroidal edge
Electrons the upper edge
 both TG edges loaded

Electrons and ions strike upper toroidal edge

Heat Flux Control

- **Snowflake**
  -

Heat Flux Control

- **Super-X divertor**
  -

Heat Flux Control

- **Super-X divertor**

  - Negative triangularity

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*