Plasma wall interactions from a material perspective in fusion devices

Presented by H.T. Lee

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With material generously supplied by K. Krieger, Max Planck Institut fuer Plasmaphysik, Germany

第49回プラズマ若手夏の学校
六甲スカイヴィラ
2010年８月10日

Aim of this talk

Introduce how plasma-material interactions and plasma confinement are interlinked.

Introduce materials used in present and future Tokamaks (ITER).

Presentation overview

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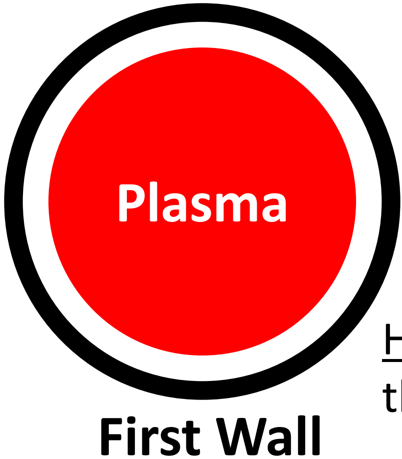

Set of Conditions for sustained or “burning” fusion reactions

Plasma operation

How does the *interaction* with the first wall affect these conditions?

Edge transport physics (Erosion/ Transport/ Re-deposition cycle).

Material operation

How does the *interaction* affect the first wall materials?

What materials can be used?
What are their properties?
(Carbon/ Beryllium/ Tungsten)

Edge Plasma

How do these conditions change for a reactor?

Power balance

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In 1957 Lawson introduced power balances:

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

Fusion power

Loss by radiation

Loss by transport (diffusion, convection, charge-exchange)

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

Simplifying assumptions: 1) $2n_D = 2n_T = n$ and $n_\alpha \ll n$

2) $T_i = T_e = T$

Fusion product:

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

Impurity effect

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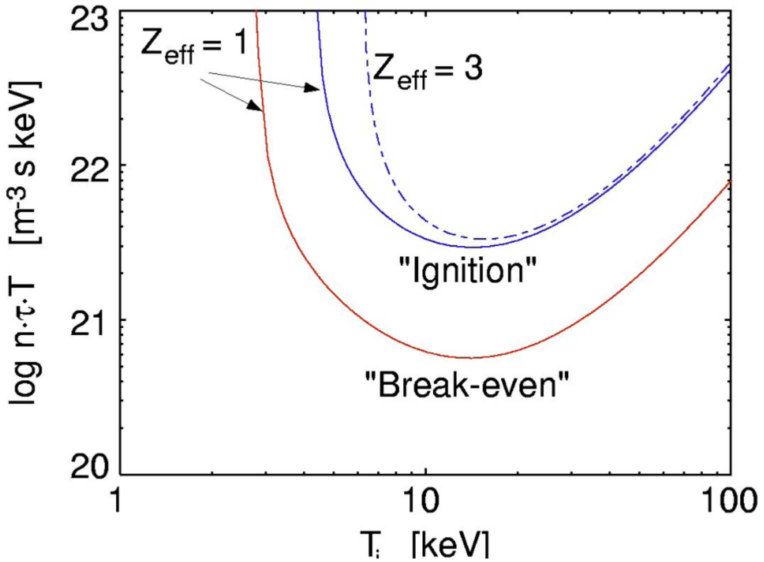
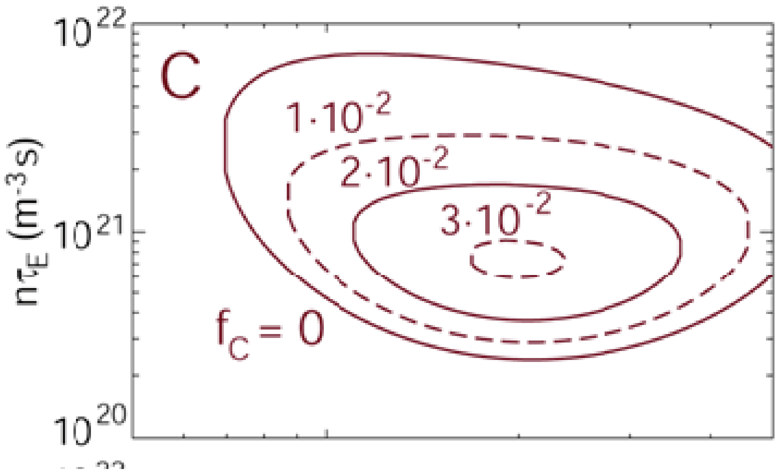
Break-even: the fusion power equals the loss by radiation, and by transport

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



Ignition condition



Impurity effect:

Fuel Dilution /Loss by line radiation

Result in closed curves and vanishing operation regime with increased impurity concentration

R. Neu & T. Puetterlich

Outline

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1. Plasma wall interactions

2. Physical concepts

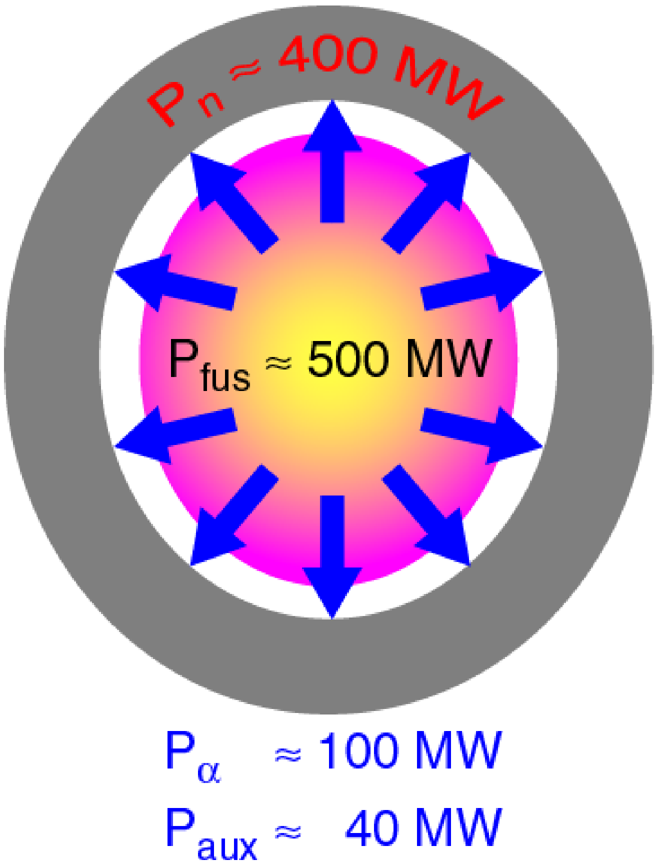
3. ITER materials

4. Mixed materials

5. Reactor conditions

PLASMA WALL INTERACTIONS

Role of material



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

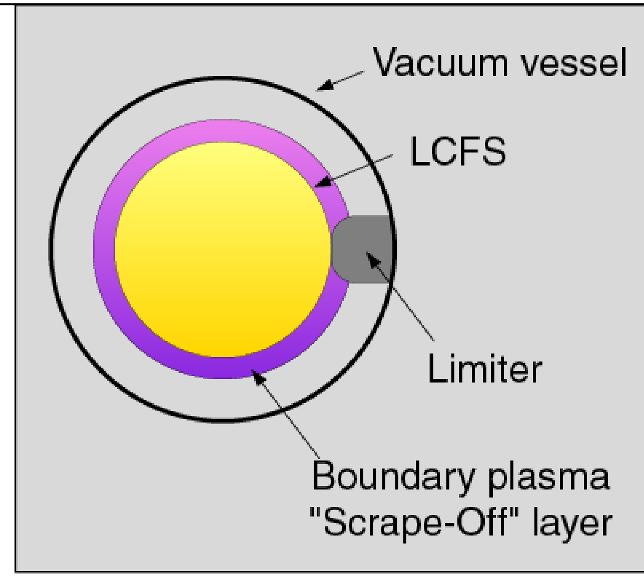
Slide by K. Krieger

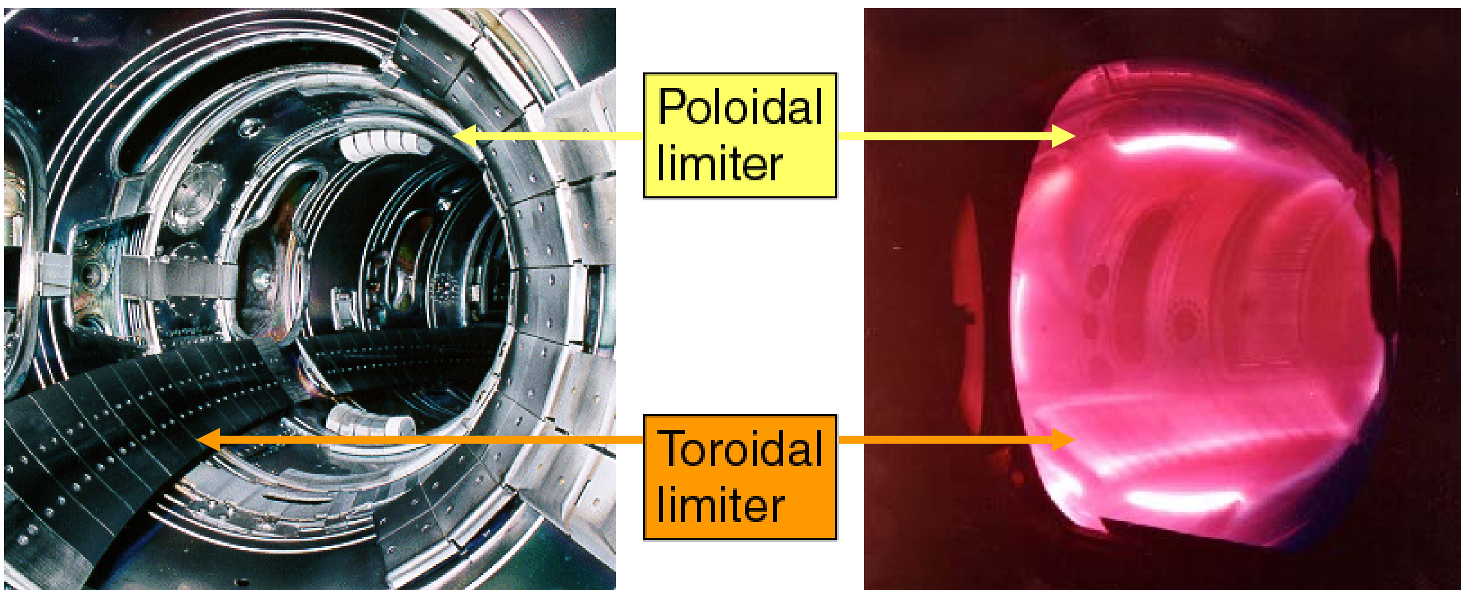
Plasma limiter

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.



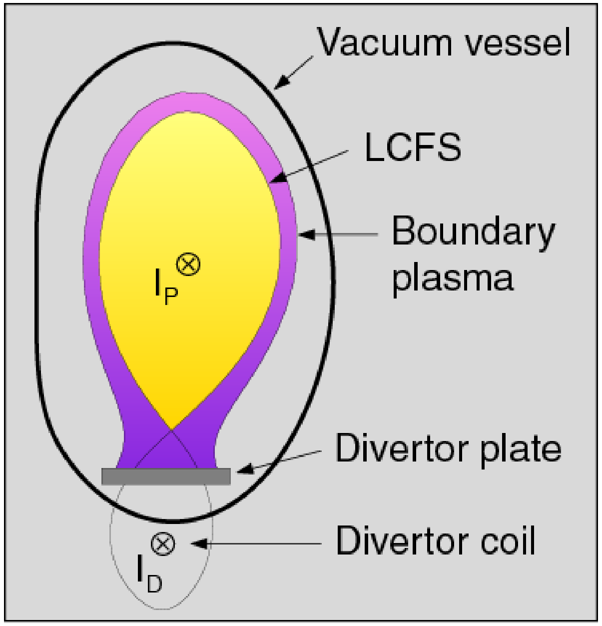


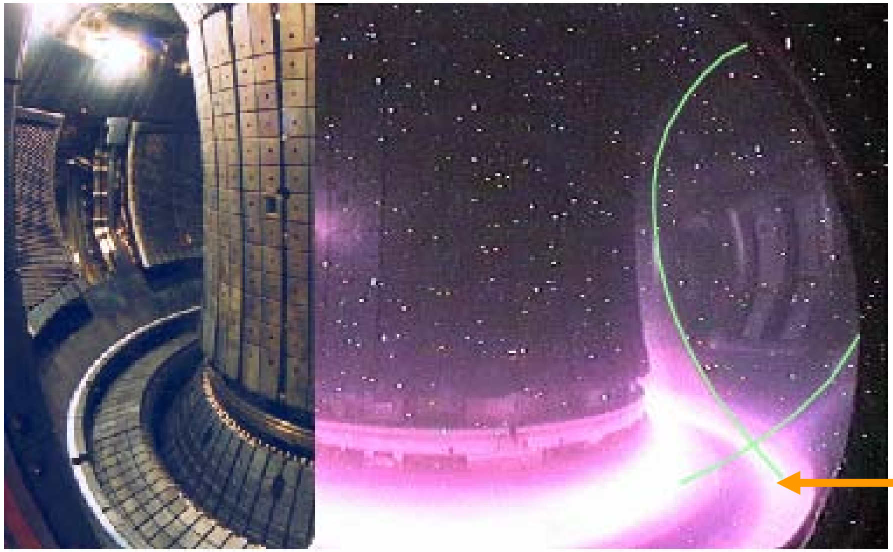
Slide by K. Krieger

Plasma divertor

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





Additionally, divertor exhausts He by increasing neutral pressure

The divertor in ASDEX Upgrade

Slide by K. Krieger

Key interactions/ implications I

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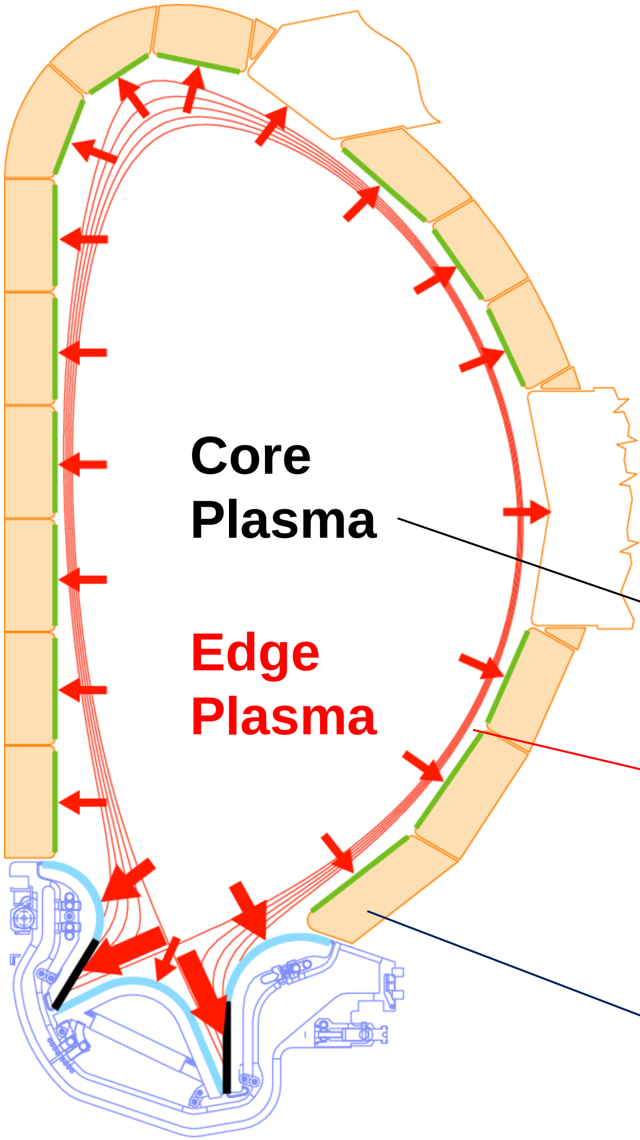

Interaction: Fuel ions + atoms (charge exchange) + impurity ions *bombard* the materials covering the wall

Implication: Hydrogen retention and recycling

- Fuelling efficiency
- Plasma density control
- Density of neutrals in edge plasma
  - ⮡ Particle and energy transport
- Tritium safety

Key interactions/ implications II

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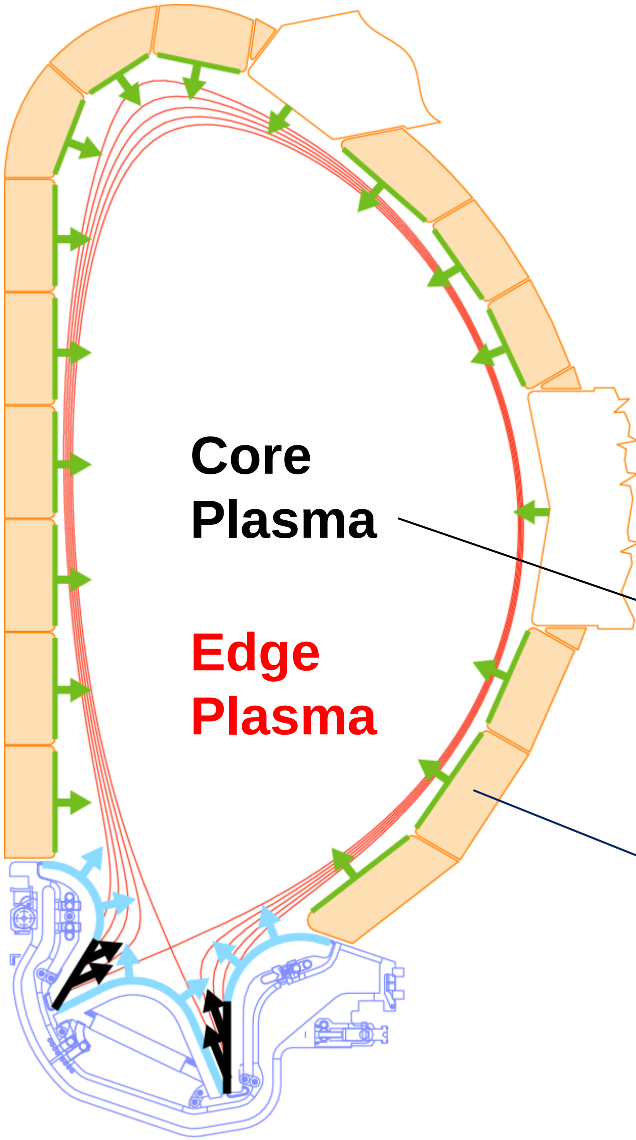

Interaction: Particle bombardment and power deposited causes *erosion* of the material.

Implication: Impurity generation

- Fuel dilution
- Cooling by radiation
- Component lifetime for net erosion

Key interactions/ implications III

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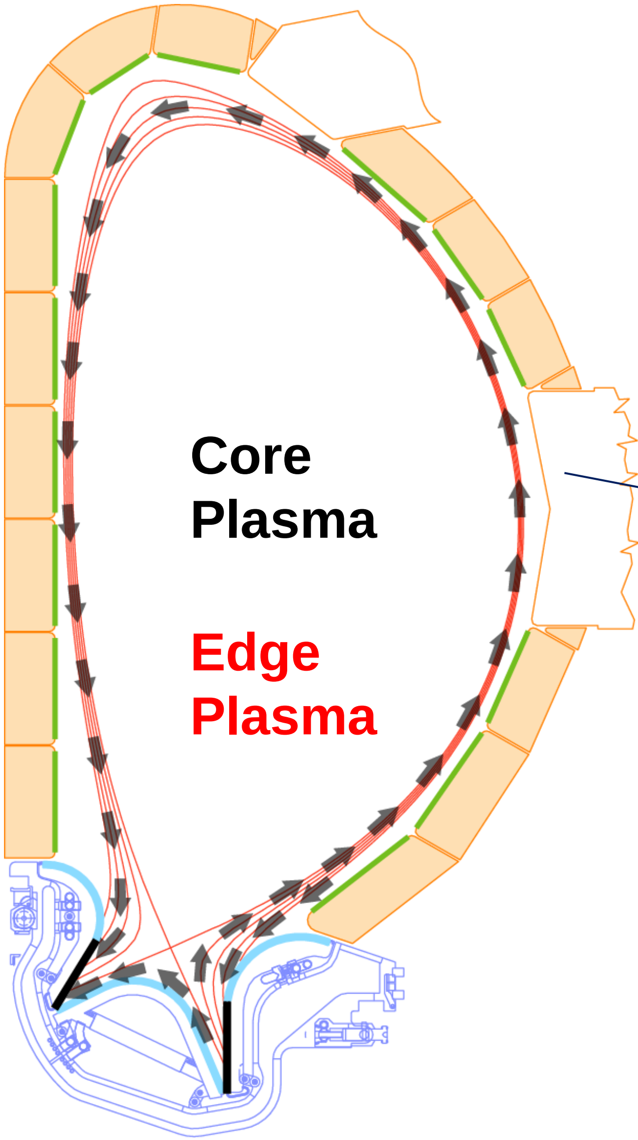
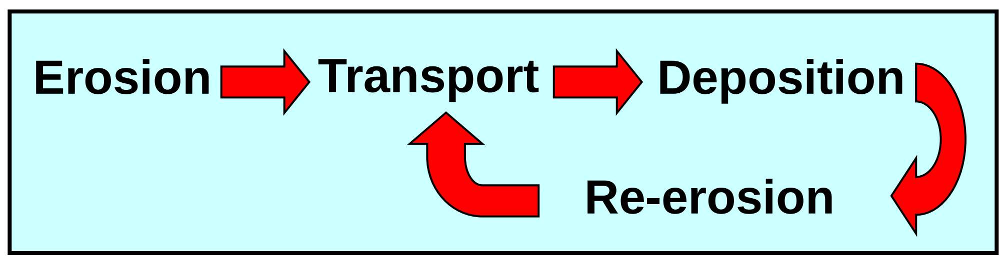


Interaction: Migration of impurities

Implication: Alters the surface of plasma facing materials/ dust issues

- Mixed material issues
- Layer deposition



Summary of key issues

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Plasma

A) Material migration/ Edge transport affecting core τ_E

1. Increase in density results in Greenwald limit: *implication* - disruptions and subsequent termination of plasma.
2. L/H mode confinement: function of external heating power + plasma material interaction.
3. Edge localized modes (ELMs)

B) Plasma startup – wall conditioning

C) Fuel dilution/ Impurities

Material

A) Erosion (Component lifetime issue)

1) Net vs. Gross erosion
2) Heat load effects

B) Tritium Retention (Safety issue)

1) Helium effects
2) Neutron effects
3) Mixed material effects
4) Co-deposition

PHYSICAL CONCEPTS

Erosion process I

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A) Physical sputtering

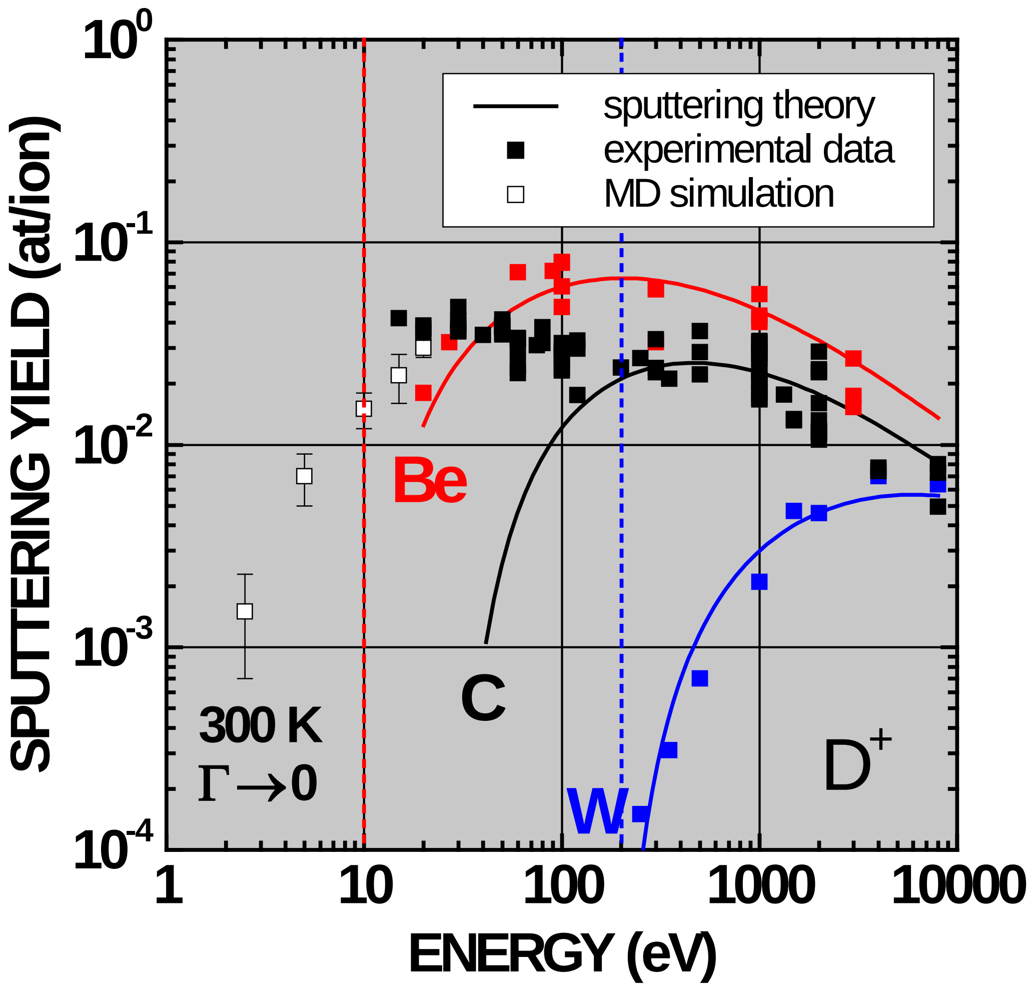
Momentum Transfer
(Energy threshold)

Collision cascades.

Sputtering when the surface binding energy (SBE) can be overcome.

$$Y = \frac{\text{atoms removed}}{\text{incident particle}}$$

Function of incident energy.



Erosion process II

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B) Chemical effects

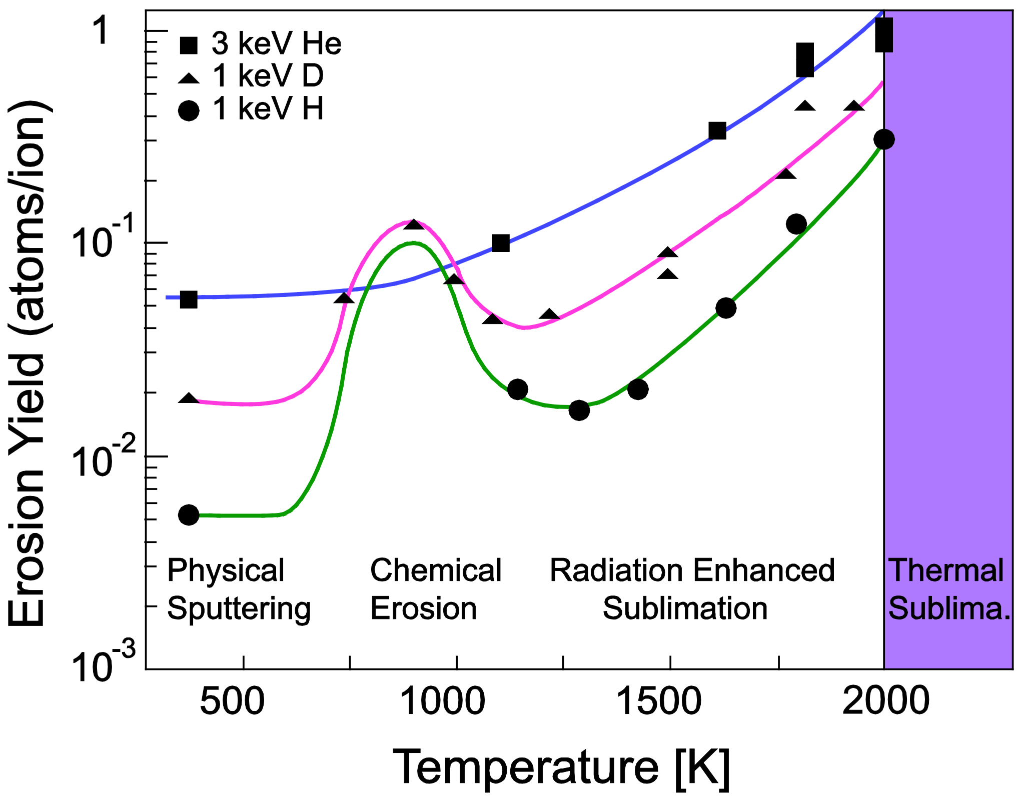
<u>Formation of volatile species</u>
(No energy threshold)

Chemical Erosion
reaction between incident species with target atom.

Chemical Sputtering
production of volatile species induced by incident species.

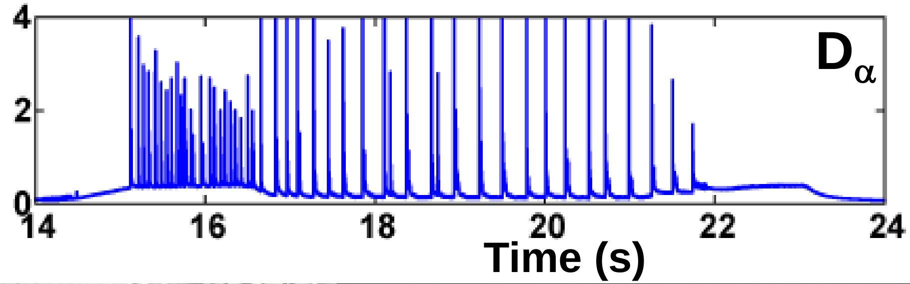
Function of temperature and energy.

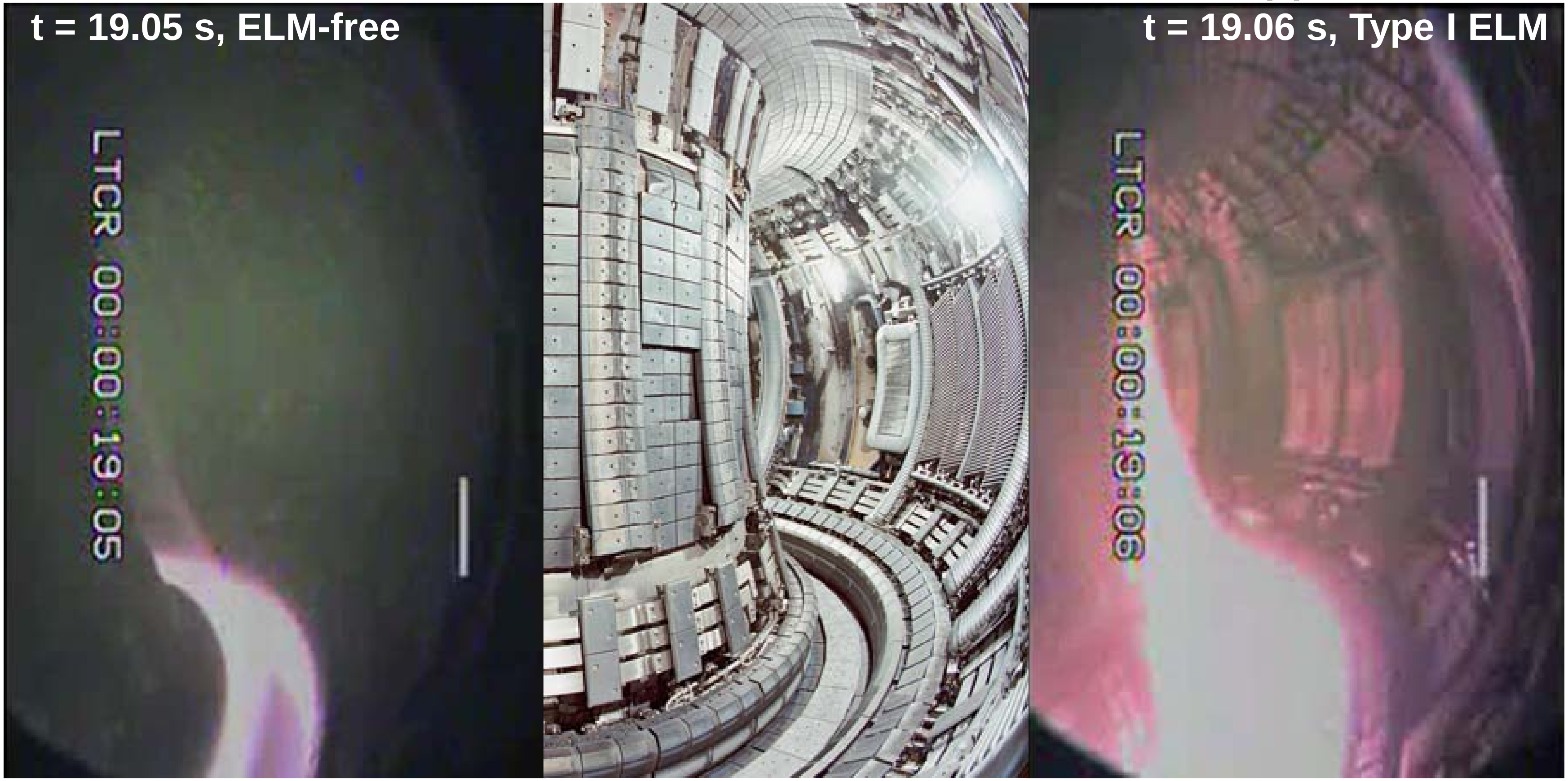
Volatile species are hydrocarbons



Transient heat loads (ELMs)

Plasma instabilities can lead to transient heat load excursions





JET #62218

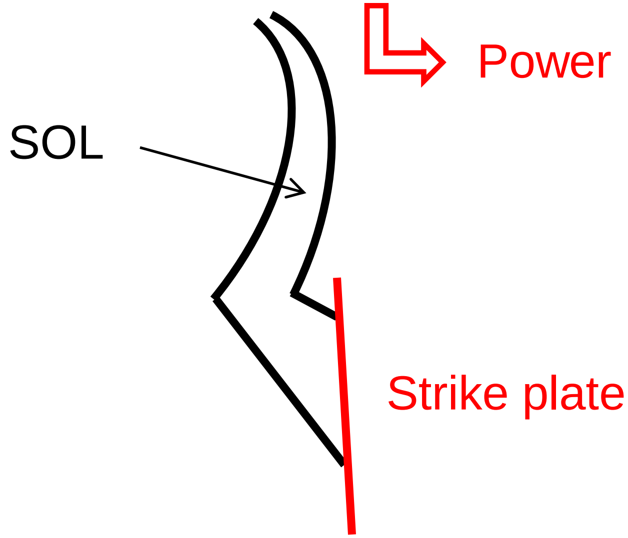
Slide by K. Krieger

Erosion by ELMs

λ_Q ~ O(1 cm) : power concentrated in the near SOL.

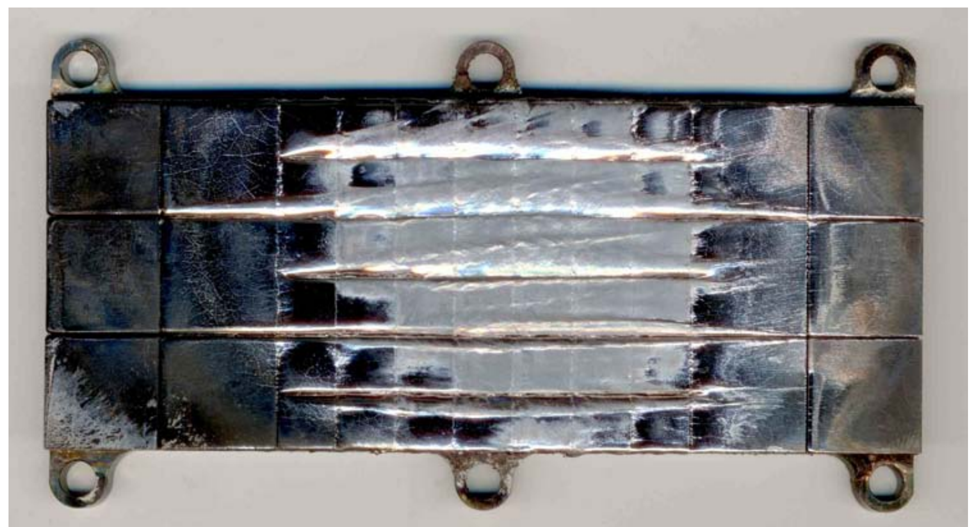
Power limited to very small areas in short pulses. O(GW/m^2)

Most of the parallel power flux must be prevented from reaching the plates by divertor detachment and high radiative loss



Plasma gun

W exposed to 100 pulses of 1.5 MJ/m^2



M. Merola, ITPA (2009)

Material requirements

Low erosion rates:
→ low power loss by dilution /radiation originating from impurities
→ long lifetime of PFCs
→ low dust production
→ low T co-deposition

Low atomic number
→ low radiation loss parameter

Low tritium retention
→ safety operation

Low hydrogen/helium embrittlement and nuclear activation
→ component lifetime

High thermal conductivity and resistance to thermal fatigue
→ reduce cracking and failure

ITER MATERIALS

ITER Materials

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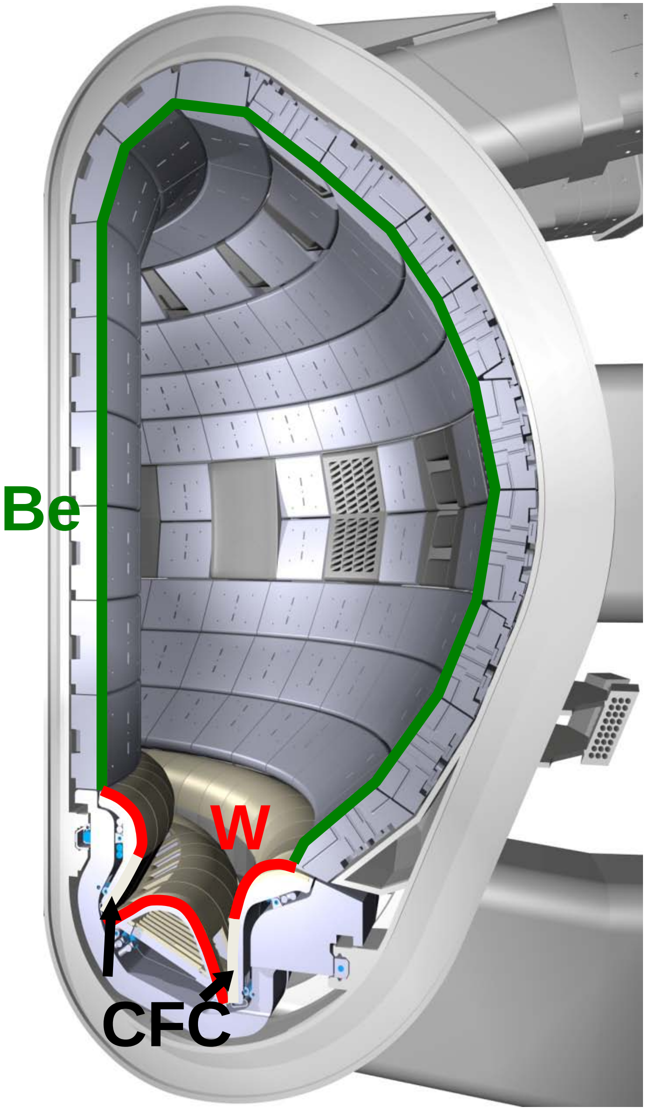
Wall materials in ITER

- **690 m^2 Be**: first wall and start-up limiter modules
- **140 m^2 W**: divertor dome / baffle region
- **55 m^2 CFC**: divertor strike point areas

1) Properties: Advantages/Disadvantages

2) Material mixture: Implications



ITER Material Properties

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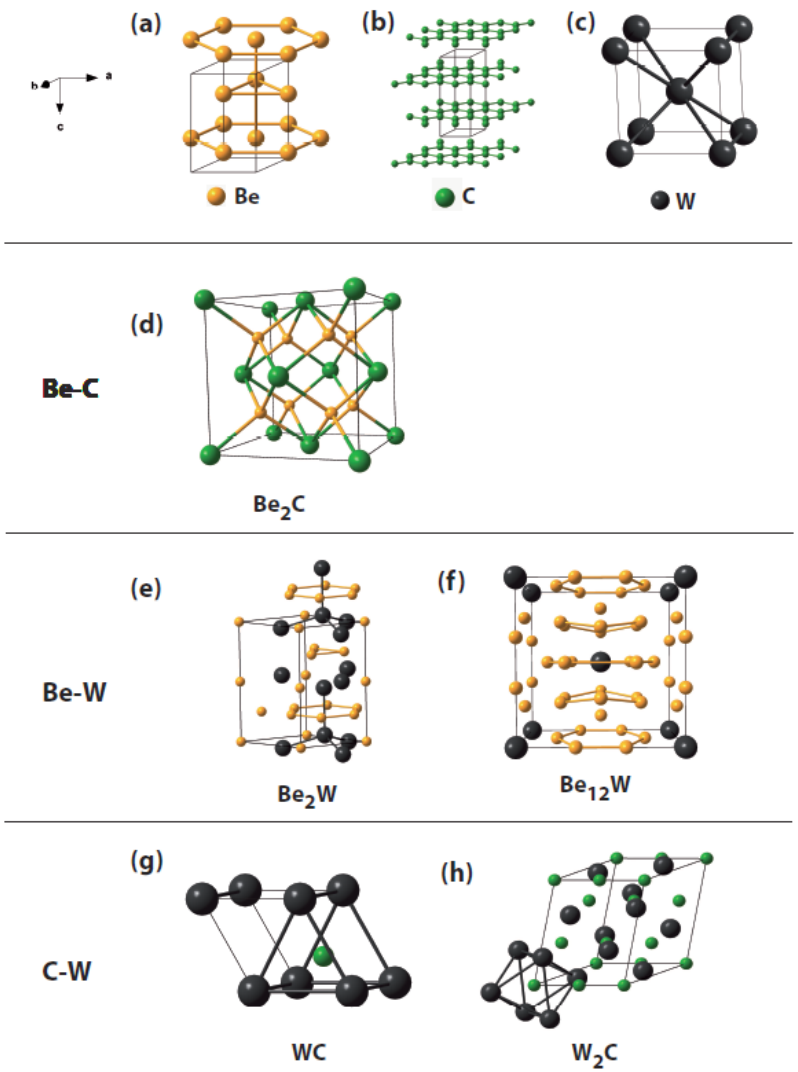

A) Beryllium

- Low atomic number
- Oxygen gettering capability
- No chemical sputtering
- High thermal conductivity

B) Carbon

- Low atomic number
- No melting
- Excellent thermal shock resistance
- High thermal conductivity

C) Tungsten

- Lowest sputtering
- Highest melting point
- High thermal conductivity
- Limited tritium inventory

Tritium retention

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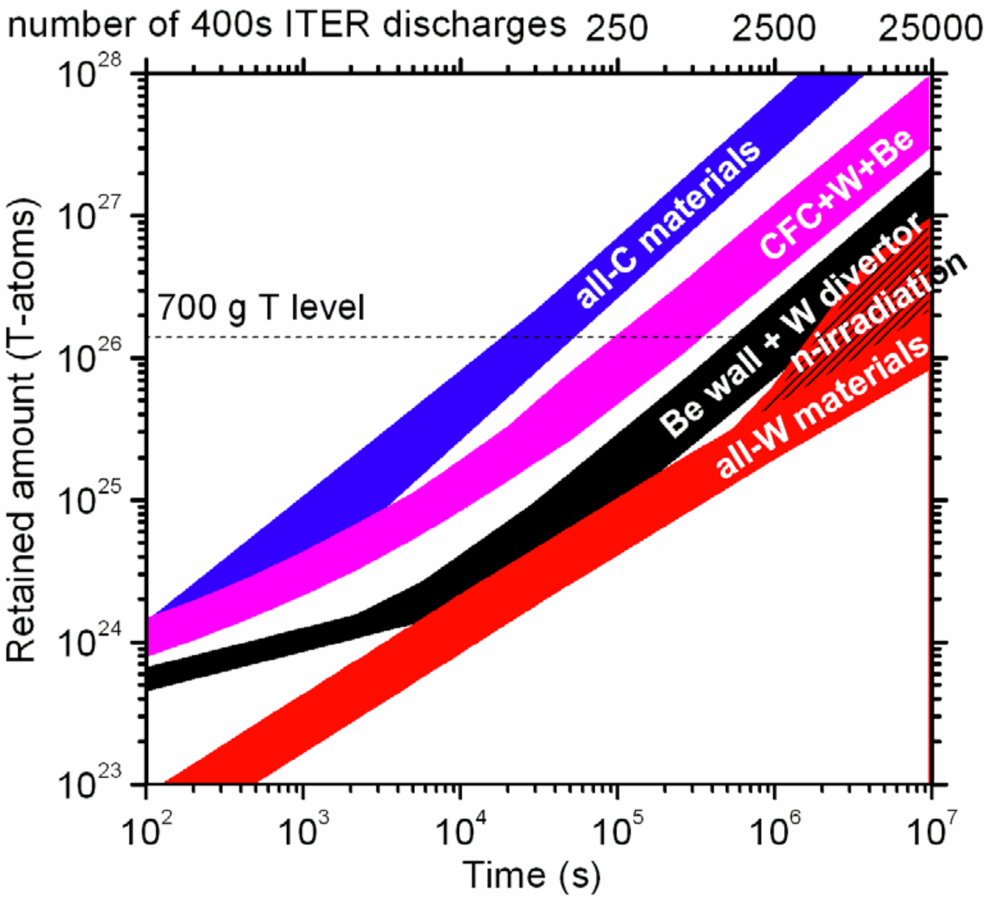


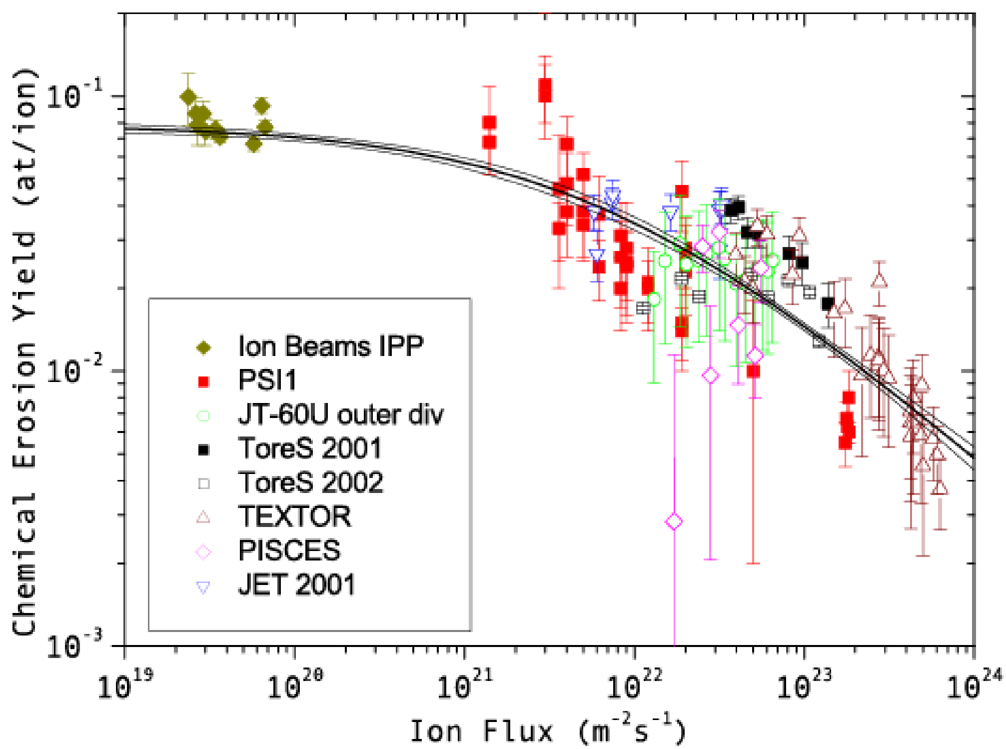
The use of Carbon is foreseen to be limited by its large impact on Tritium retention.

ITER is planning to use a full W divertor for the D-T campaign.

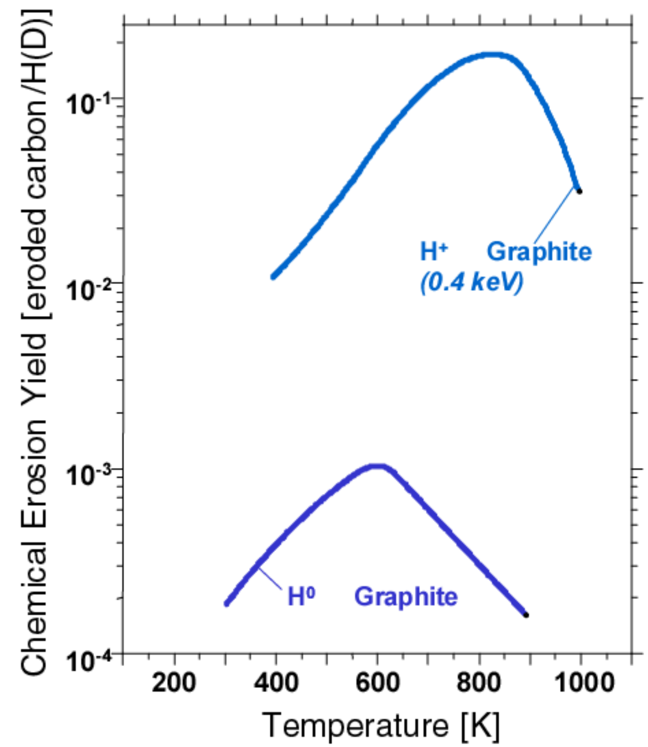
J. Roth, PPCF (2008)

Carbon

chemical erosion decreases for high Γ_D



chemical erosion vanishes at high T_{surf}



good for divertor strike point conditions!

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Carbon fibre composites

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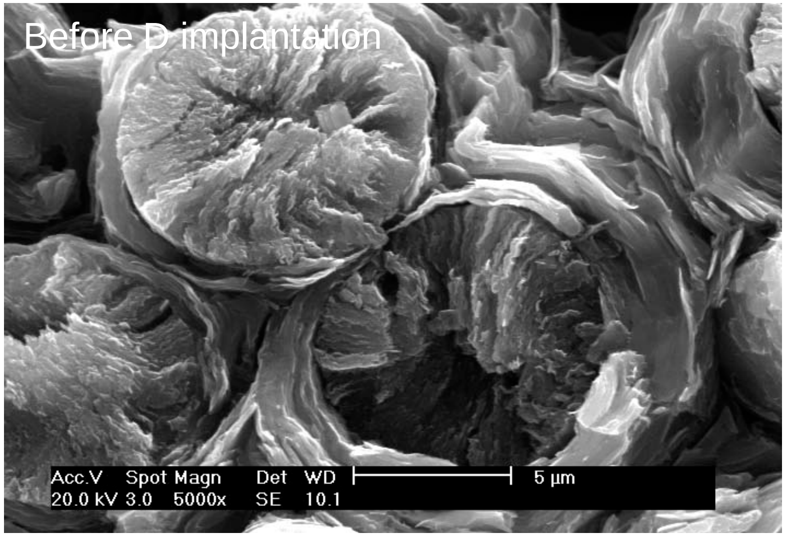

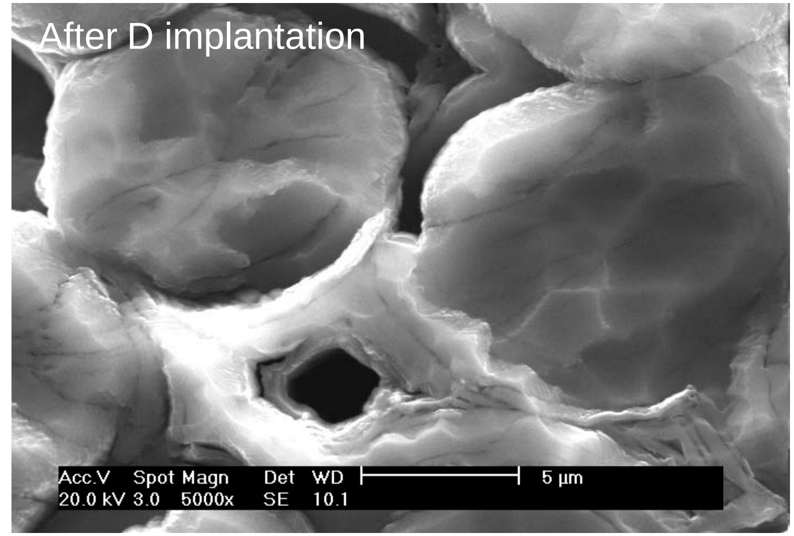

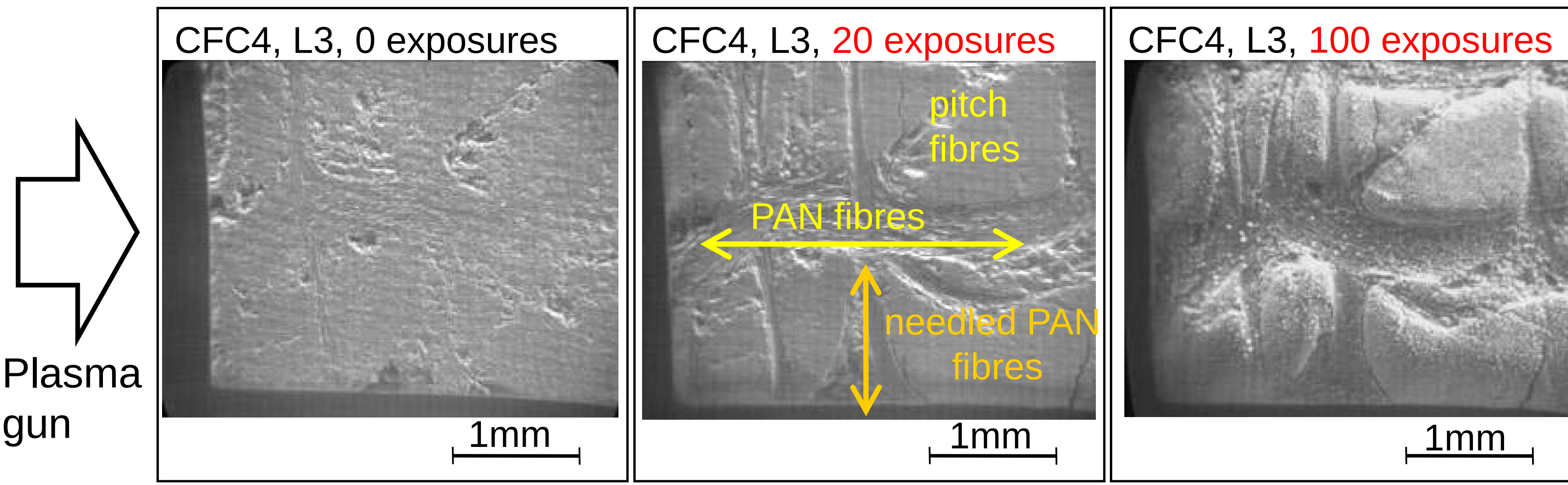

M. Merola, ITPA (2009)

Tungsten

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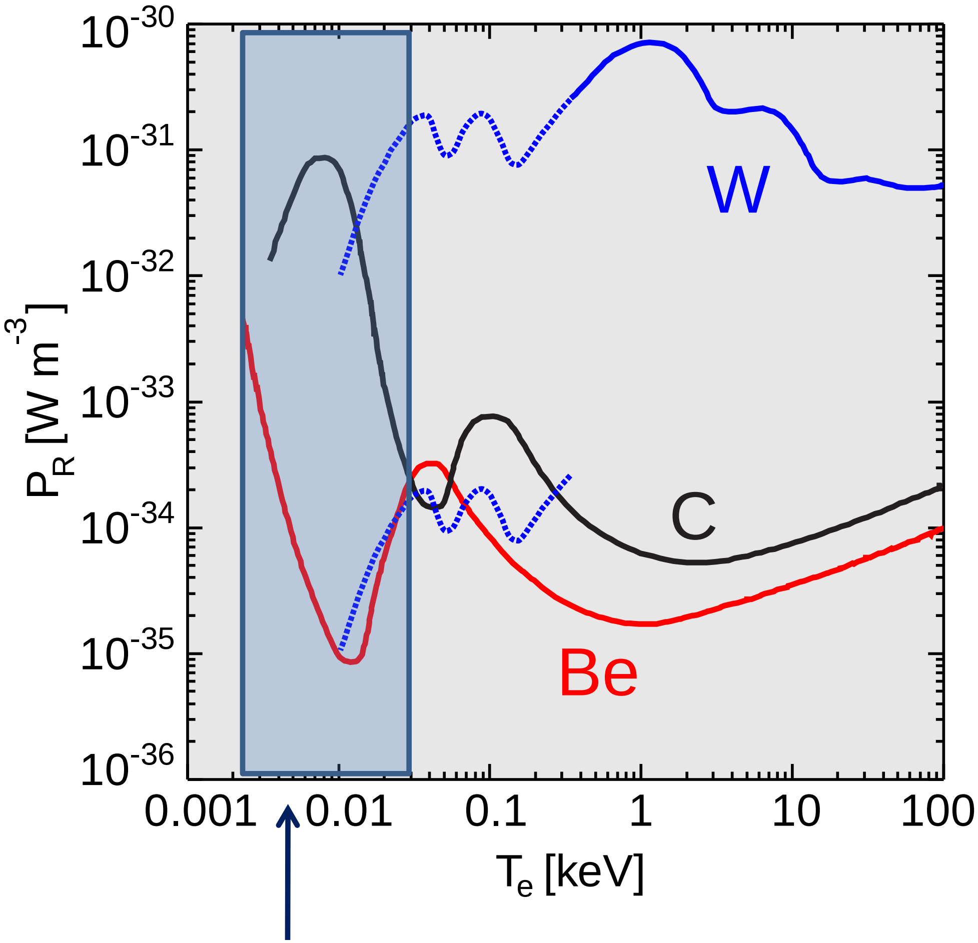
Radiated power density per atom



Tungsten qualification is mainly dependent on erosion under heat Loads due to the restricted W concentration allowed in the core:

No ignition for core W conc. > 10^{-4}

Divertor region: Elimination of C results in intrinsic radiation loss.
Seeded impurities (Ar/Ne) are required.

Tungsten melting

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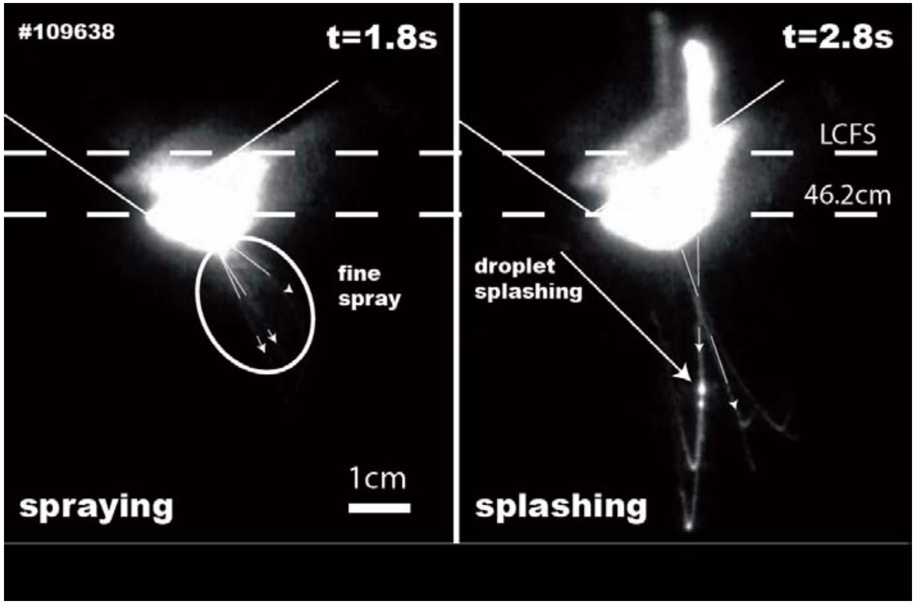

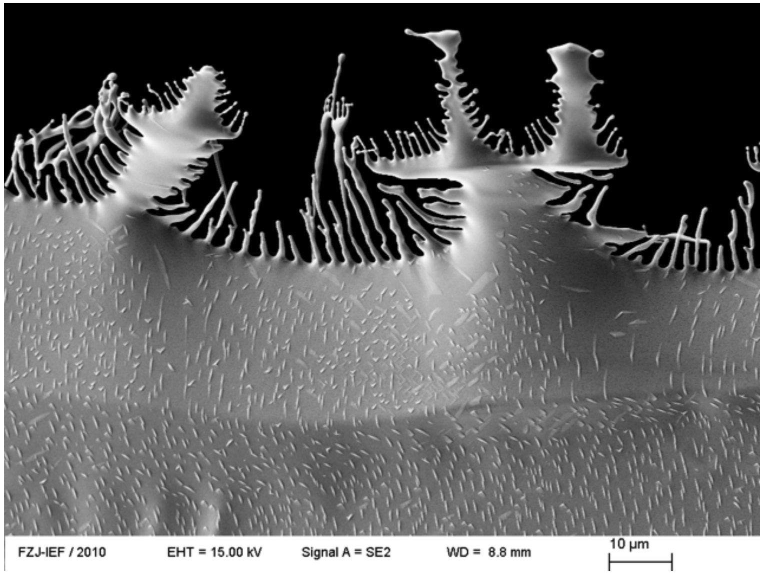

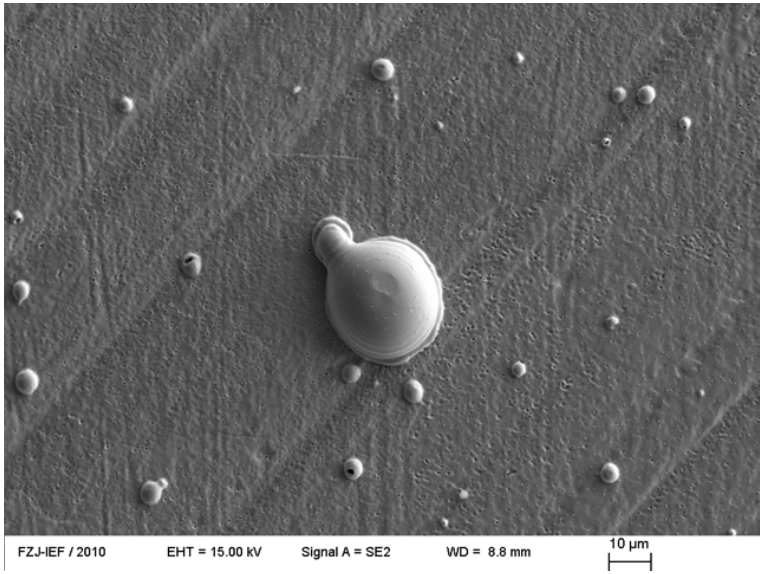

Tungsten exposed to TEXTOR limitor plasma results in spraying and splashing of the molten tungsten.

J. Coenen, PSI 19 (2010)
Forschungszentrum Juelich

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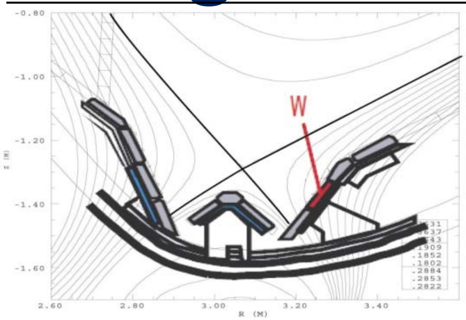
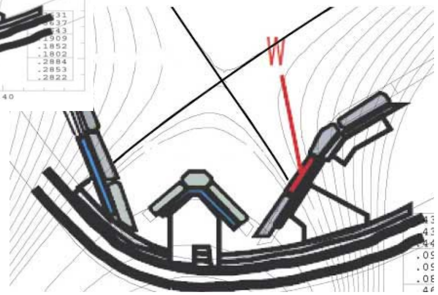
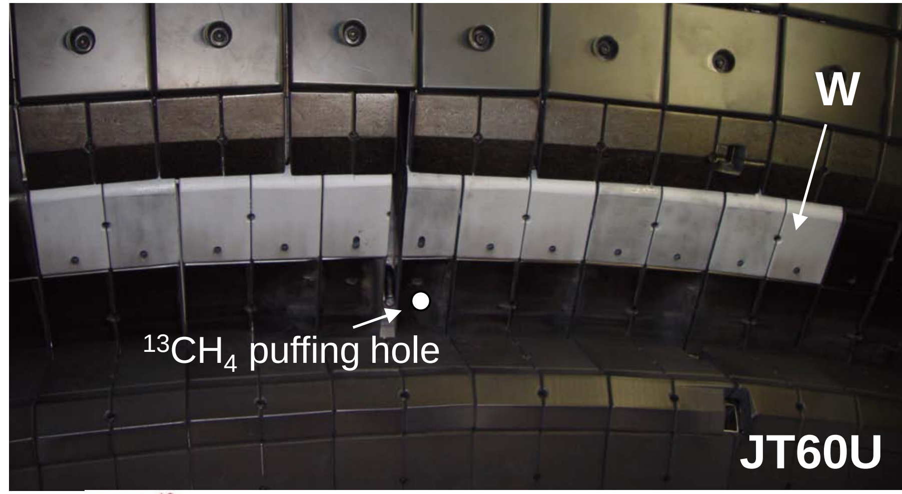
Tungsten transport

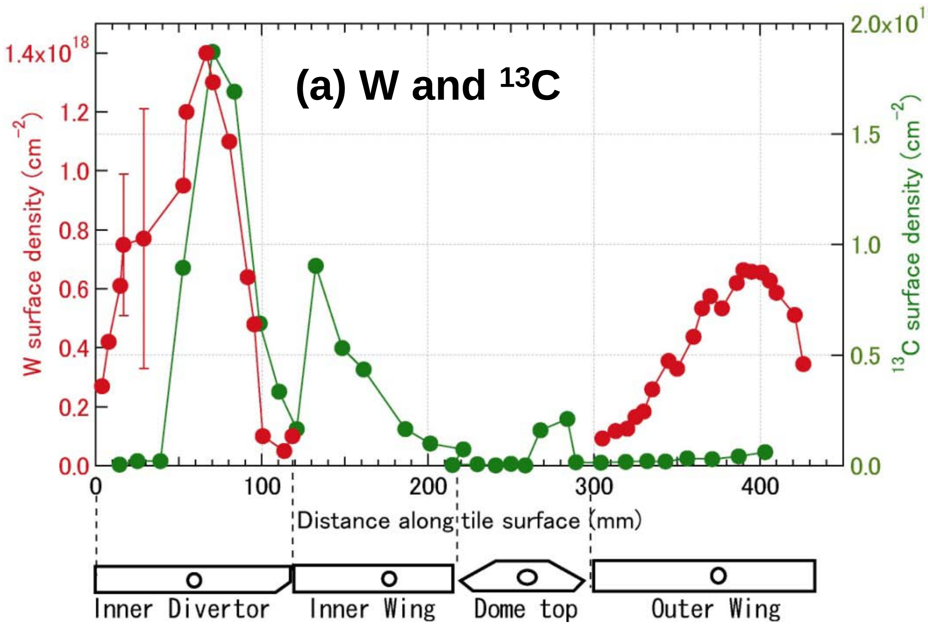


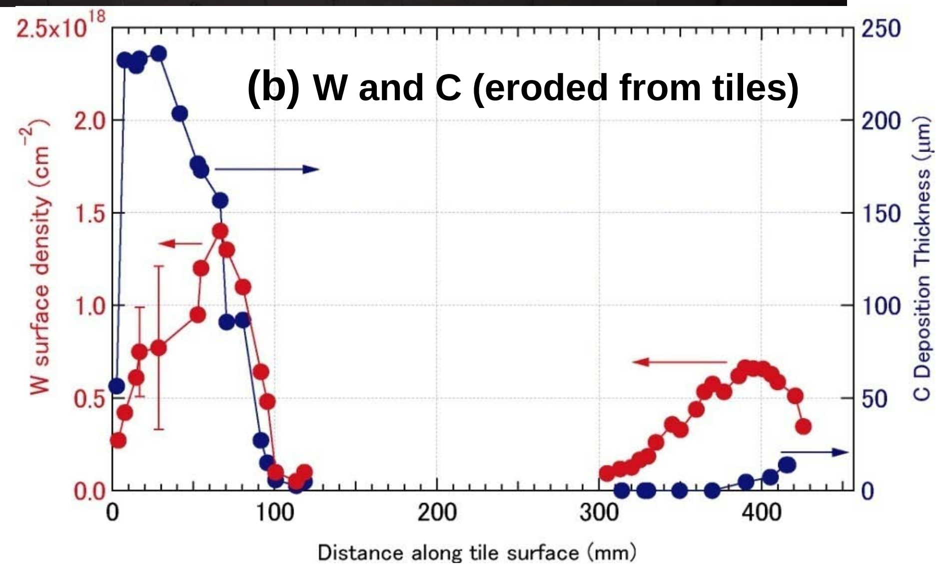
Flux surface
Normal exp.



Flux surface
W div. exp.







Y. Ueda, PSI 17 (2006)

MIXED MATERIALS

Alloy formation

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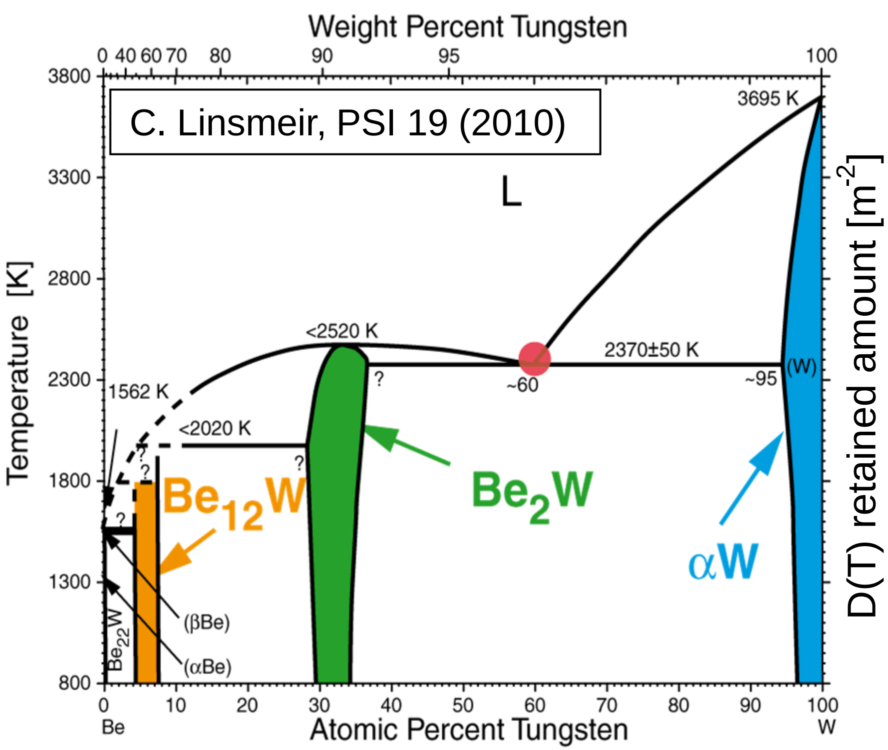
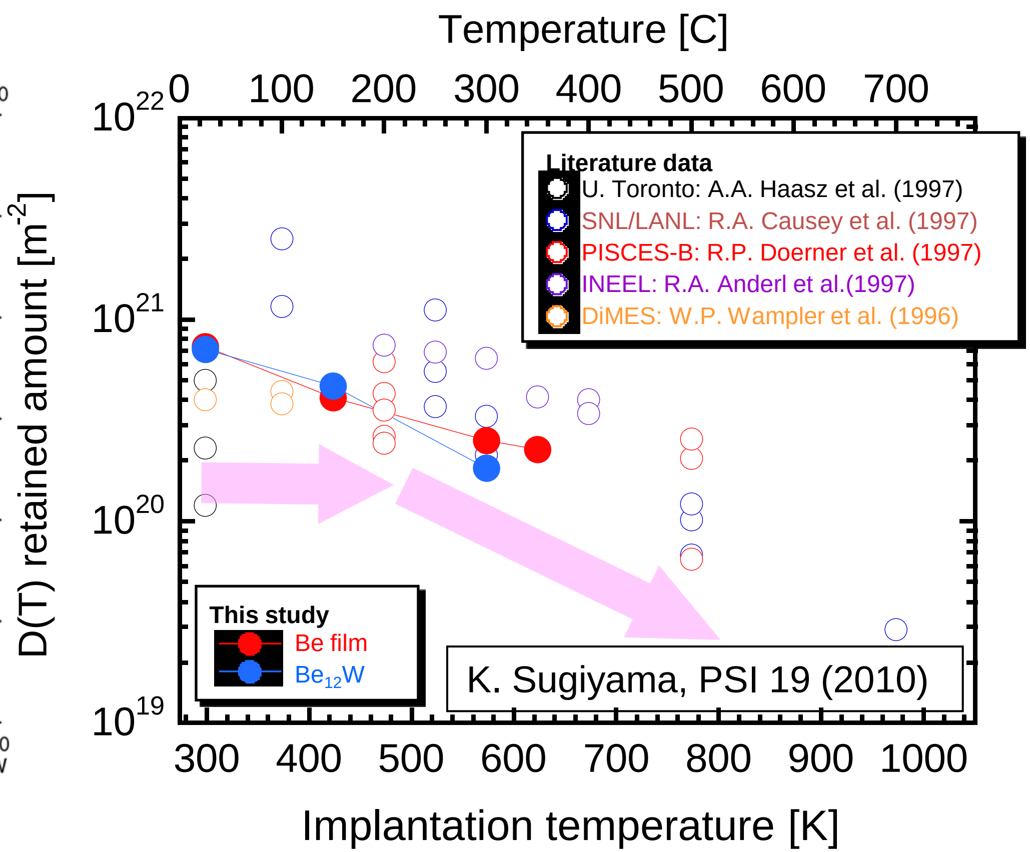
A) Erosion properties



B) Retention properties



Reduction of melting temperature (but…)

Similar to retention in pure Be

Carbide formation

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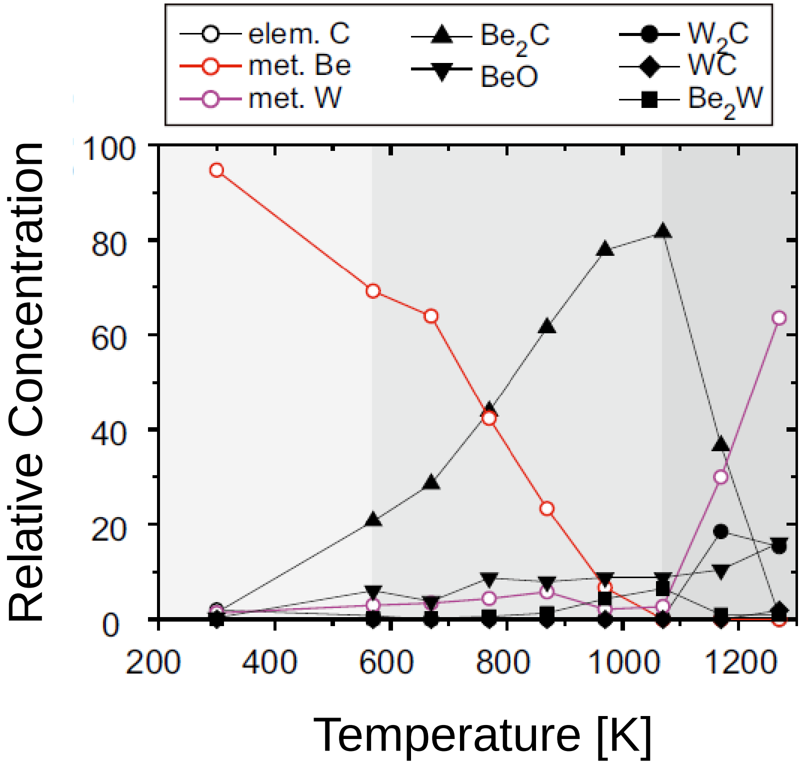
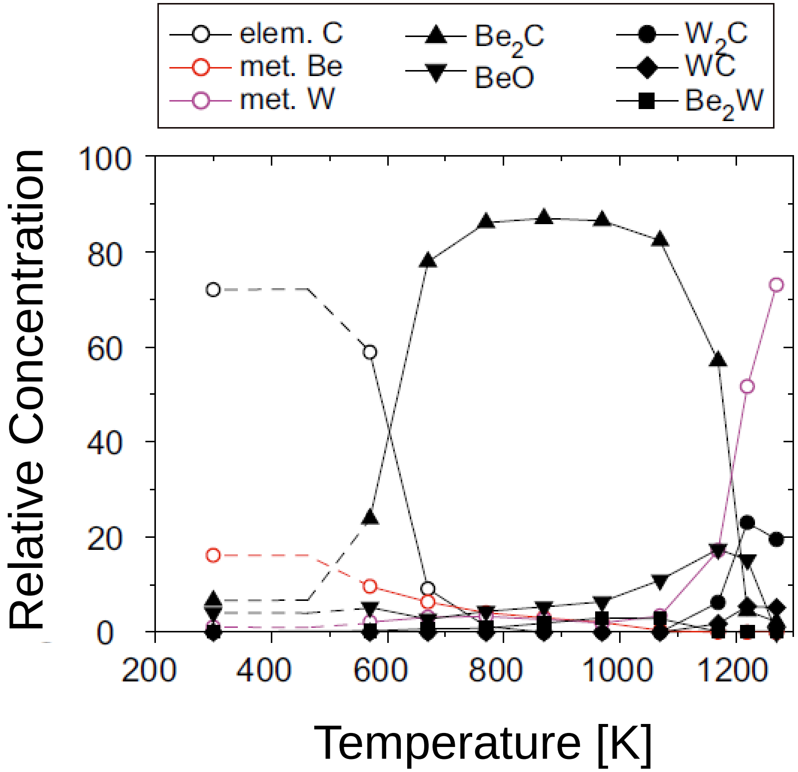
Which carbide dominates in Be/ C/ W system?

1) Be on C on W substrate



2) C on Be on W substrate



In both cases, Be2C dominates at T<1170K. At T>1170 K tungsten carbides dominate.

F. Kost, PhD thesis, IPP (2009)

Be_2C formation - implication

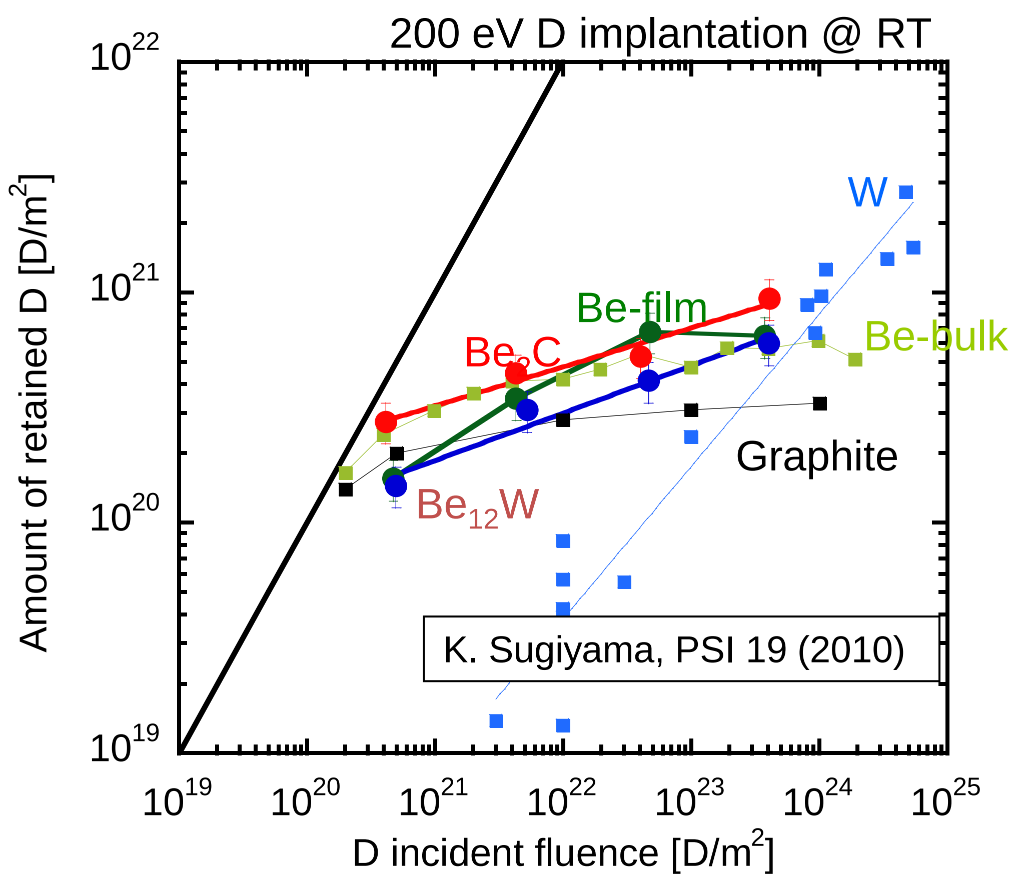
A) Erosion properties

• No chemical sputtering/erosion.

• In the strike points, Be_2C will not survive due to the high temperature. There is no gain in the reduction of erosion.

• In other areas, the formation of Be_2C may be beneficial in trapping carbon thus negating effects of co-deposition. Carbon in Be_2C-state cannot trap hydrogen.

B) Retention properties



W_2C / WC formation - implication

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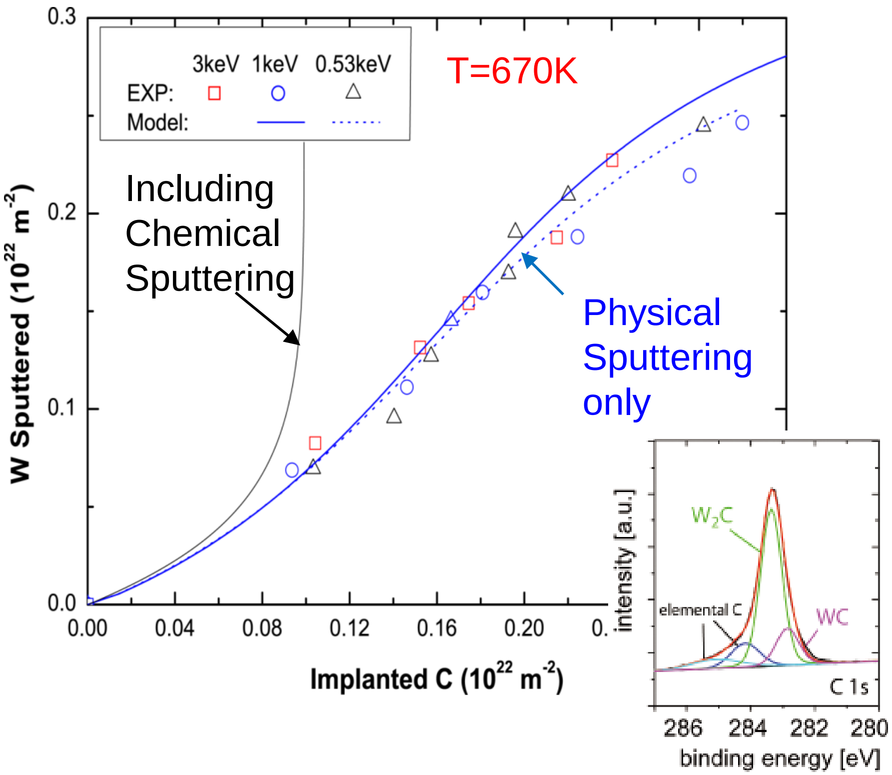
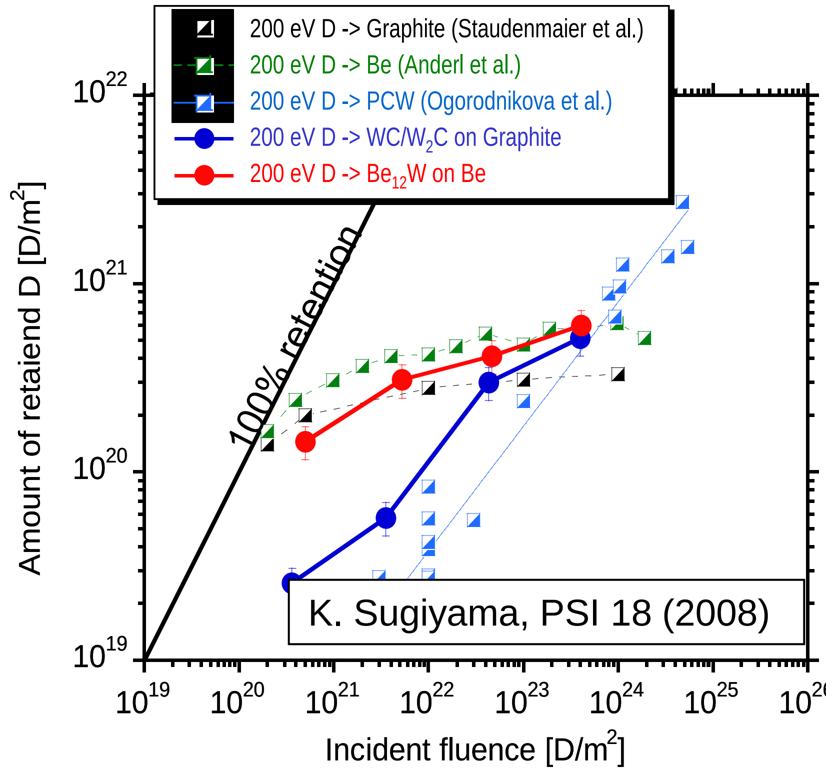
A) Erosion properties



B) Retention properties



- No chemical sputtering of C-W mixed material at elevated temperature.
- Tungsten sputter yield will be reduced due to carbon coverage of surface.

- Factor of two increase in retention compared to pure W.
- Follows hydrogen trapping in W with increasing temperature (not Carbon).

H.T. Lee, PhD thesis, IPP (2009)

Mixed materials - summary

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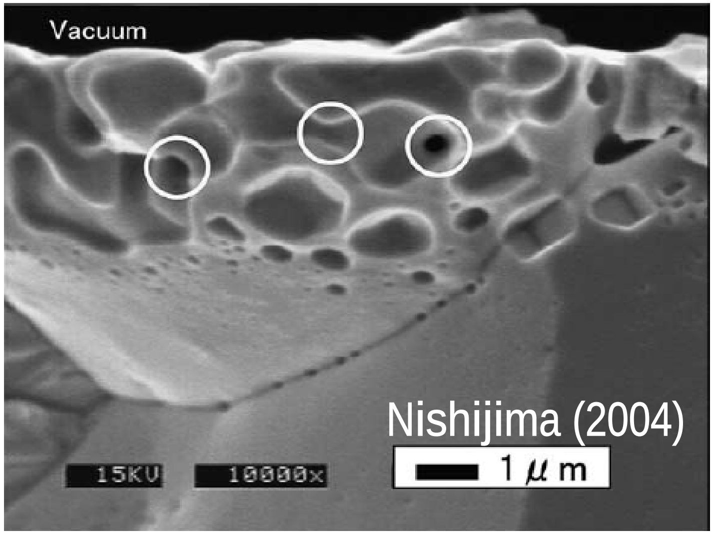
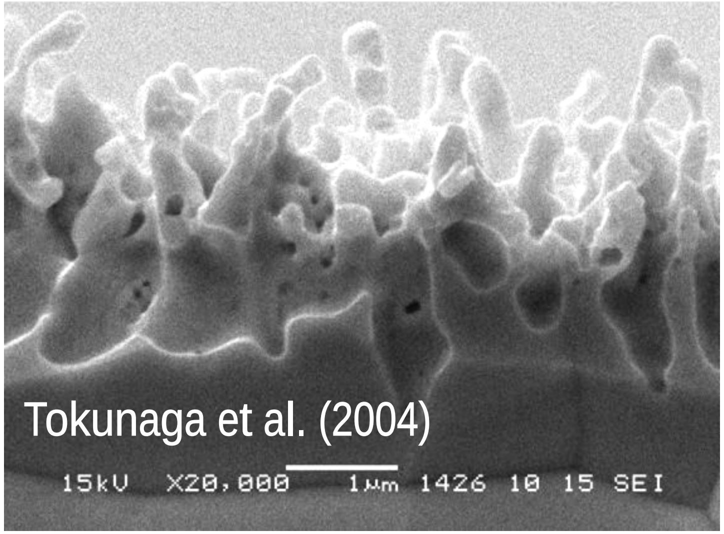
Tentatively, laboratory data indicates that the formation of mixed materials will not significantly alter the favorable properties of each material.

But we have no data regarding mixed material formation coupled with transient heat loads. Possible synergistic effects maybe present.

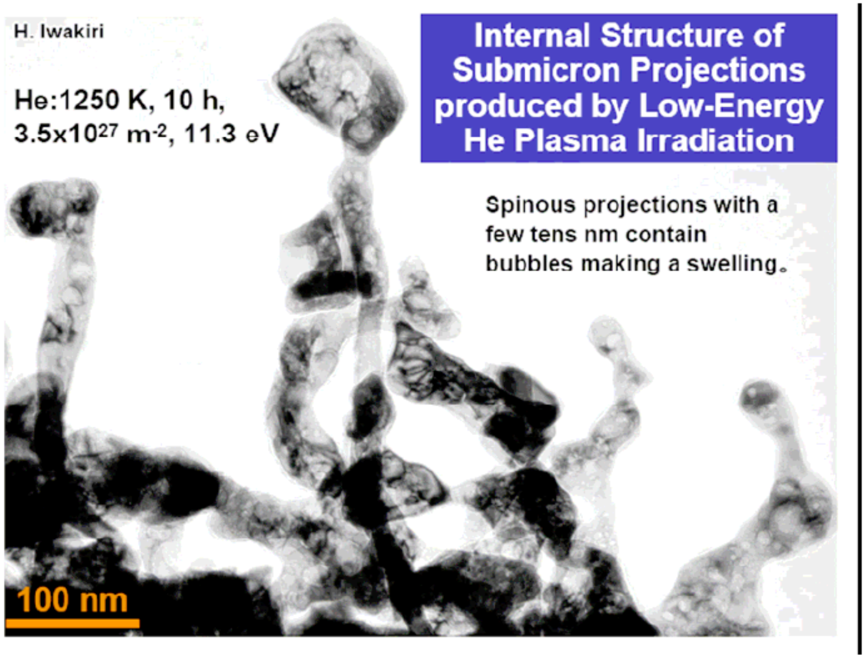
Helium effects - tungsten



Nishijima (2004)



Tokunaga et al. (2004)



From Prof. Takamura presentation at ITPA sol./div meeting, Toronto, Nov. 2006.

Helium effects - permeation

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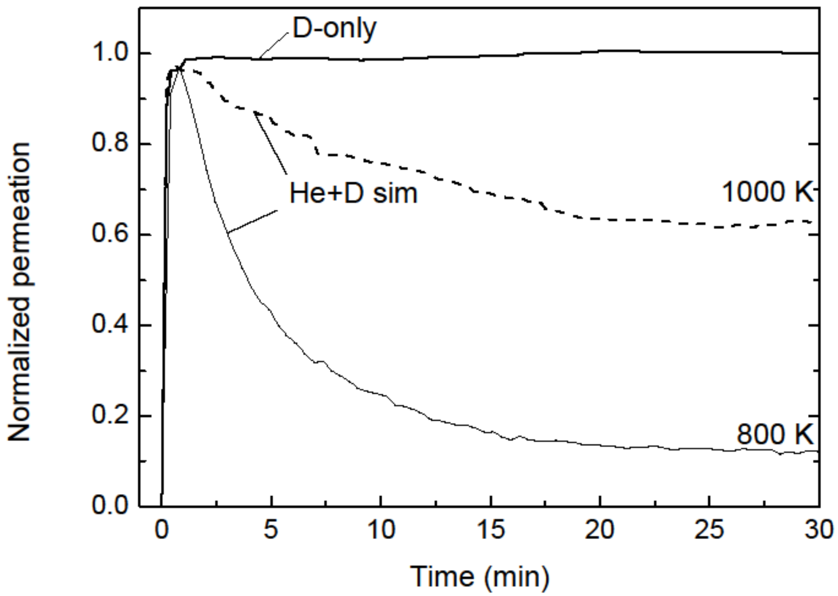
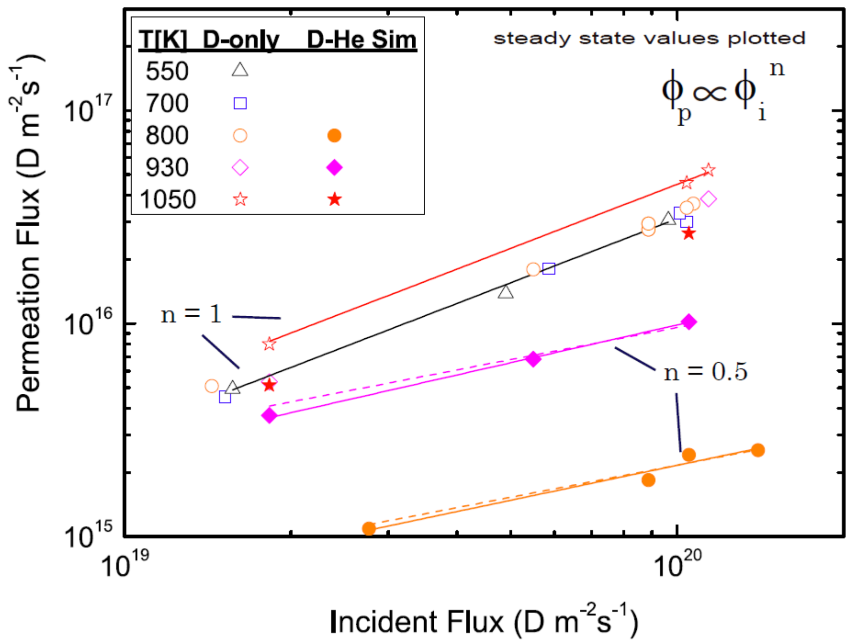
Helium reduces hydrogen permeation





- The effect is greater with decreasing temperature

- Flux dependence shifts from linear to square root
- Interpreted as increased diffusion at the front surface

H.T. Lee, PSI 19 (2010)

REACTOR CONDITIONS

Expected neutron load

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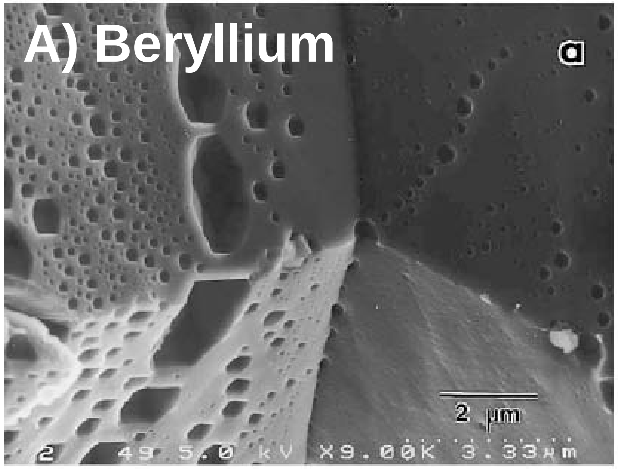
	ITER	DEMO	*Reactor*
Fusion Power	0.5 GW	2-2.5 GW	*3-4 GW*
Heat Flux (First Wall)	0.1-0.3 MW/m^2	0.5 MW/m^2	*0.5 MW/m^2*
Neutron Wall Load (First Wall)	0.78 MW/m^2	< 2 MW/m^2	*~2 MW/m^2*
Integrated wall load (First Wall)	0.07 MW/m^2 (3 yrs inductive operation)	5-8 MW.year/m^2	*10-15 MW.year/m^2*
Displacement per atom	<3 dpa	50-80 dpa	*100-150 dpa*
Transmutation product rates (First Wall)	~10 appm He/dpa ~45 appm H/dpa	~10 appm He/dpa ~45 appm H/dpa	

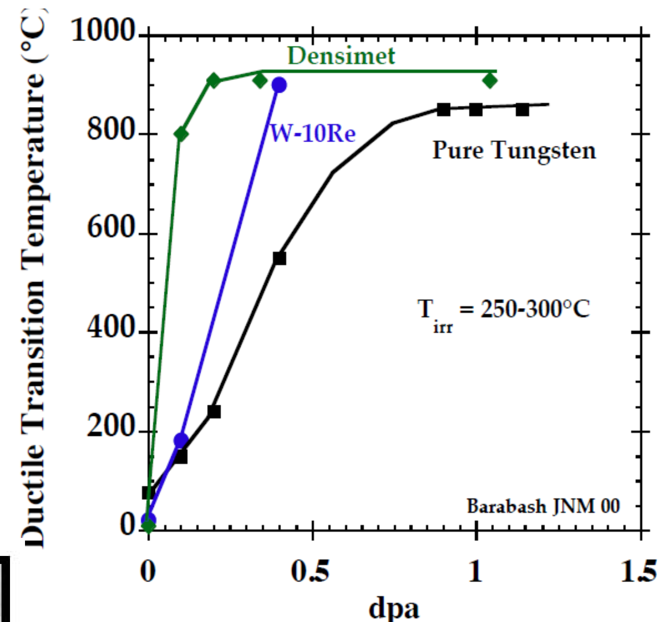
J. Boutard, EFDA (2008)

Neutron effects

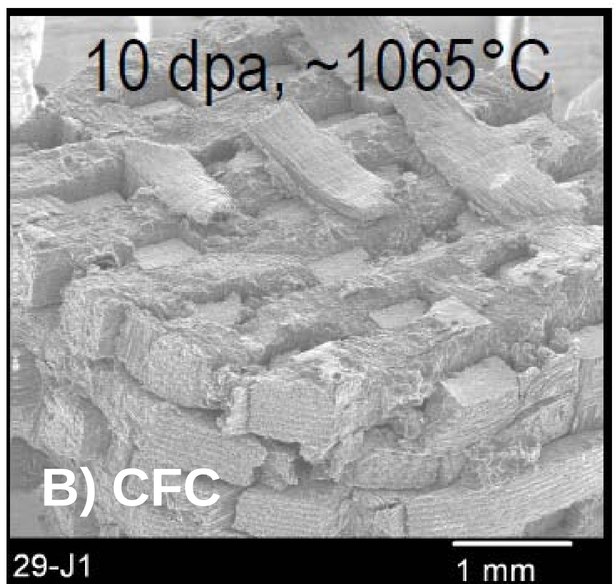
Osaka University



Embrittlement/ Swelling



Changes in dimension due to swelling perpendicular to basal plane and shrinkage within planes



C) Tungsten

Ductile to Brittle temperature increases

No material developed today fully meets the engineering criteria for reactor operations.

L. Snead, PSI 19 (2010)