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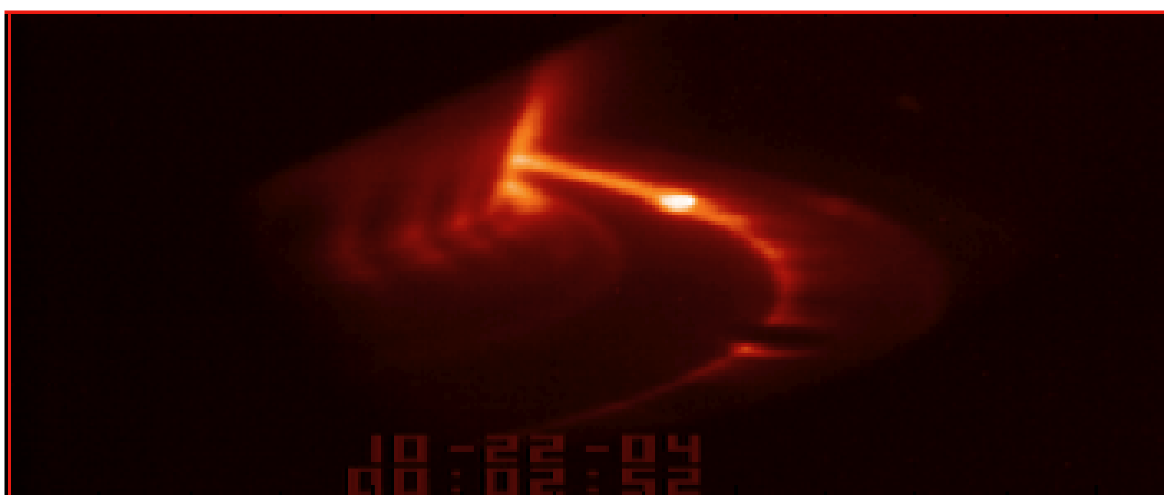
Plasma-Surface Interactions in Tokamaks

James Davis

University of Toronto Institute for Aerospace Studies



Outline

- Introduction
- Erosion and plasma contamination
- Redeposition of eroded material
- Tritium retention in wall materials
- ITER – Current Status

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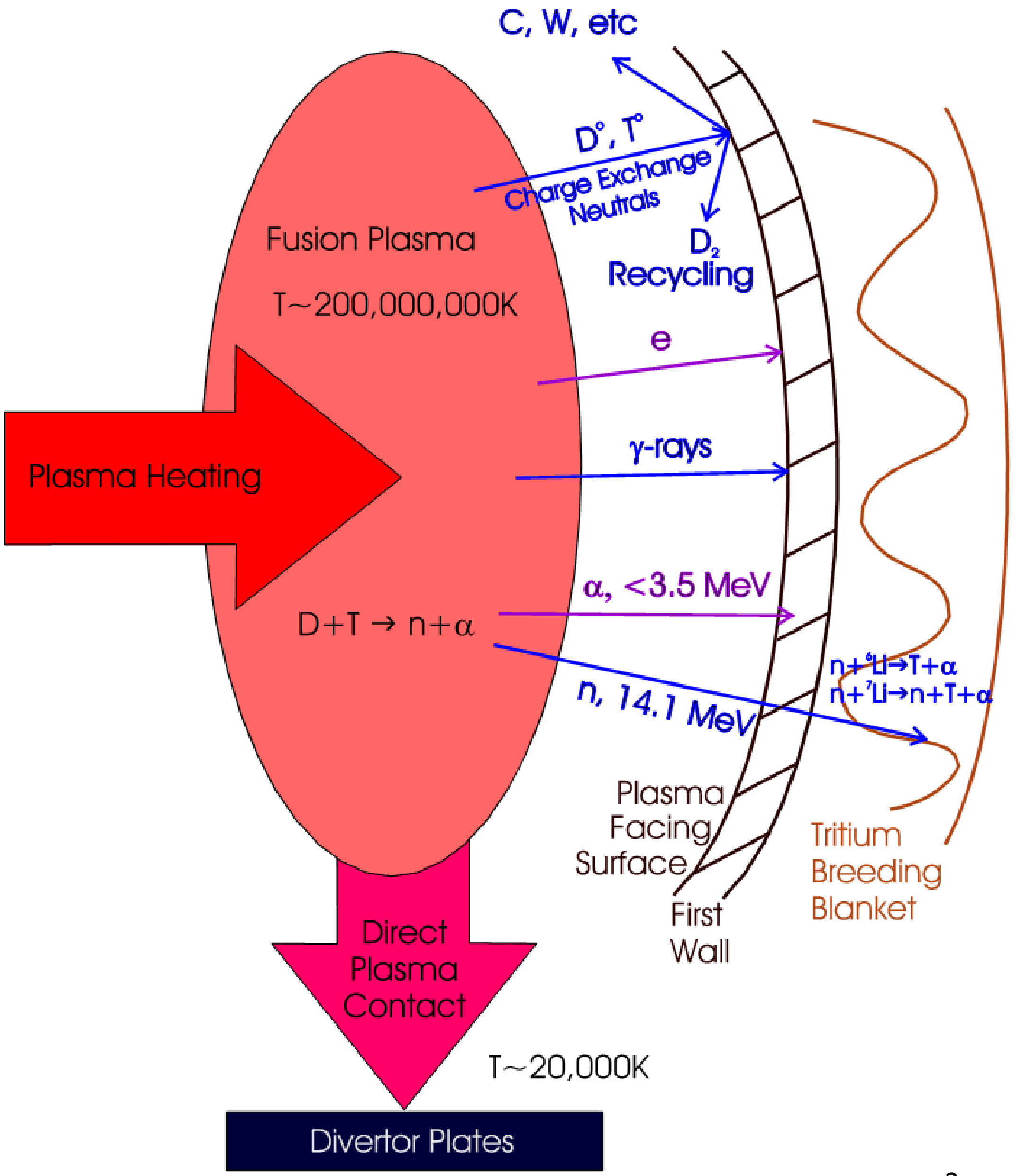
- Next to a fusion plasma is a very hostile environment
- All plasma-facing surfaces will be subject to a wide variety of particle interaction processes.



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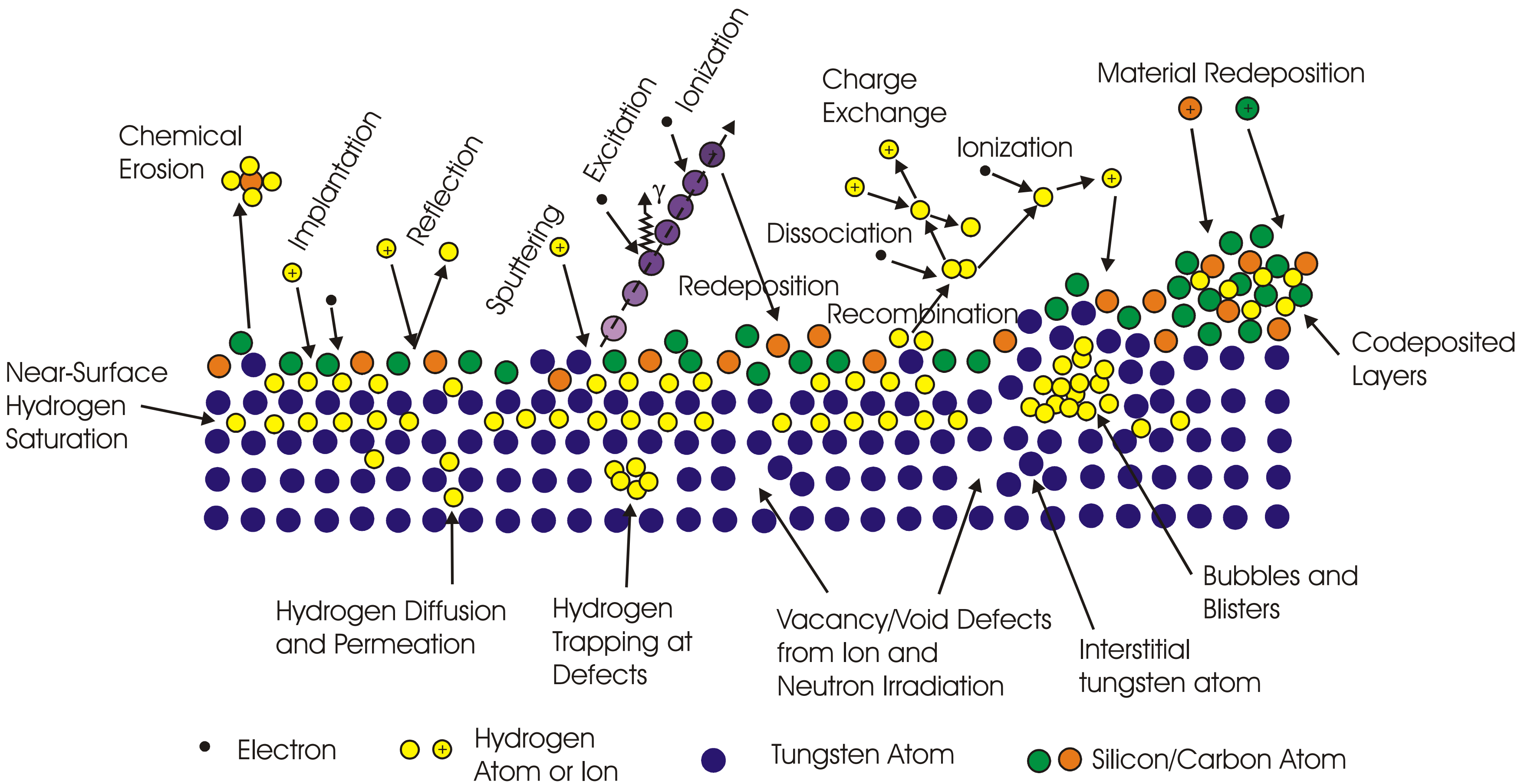
Details of the surface



Adapted from B.D. Wirth et al., MRS Bulletin 36 (2011) 216

Outline

- Introduction
- Erosion and plasma contamination
  - Erosion processes
  - Impurity transport
  - Radiation losses
  - Which material?
- Redeposition of eroded material
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Erosion Mechanisms

- Physical sputtering
  - Billiard ball collisions
- Chemical erosion
  - Chemical reactions between hydrogen and wall atoms
- Radiation-enhanced sublimation
  - Surface binding energy is reduced at high temperature
- Melting

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INCREASING TEMPERATURE

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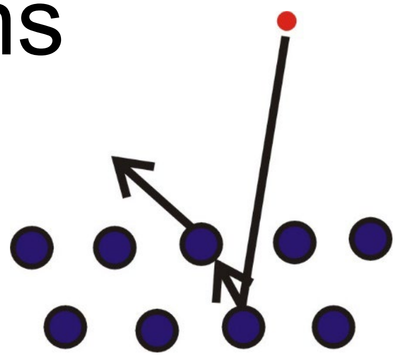
Erosion Mechanisms



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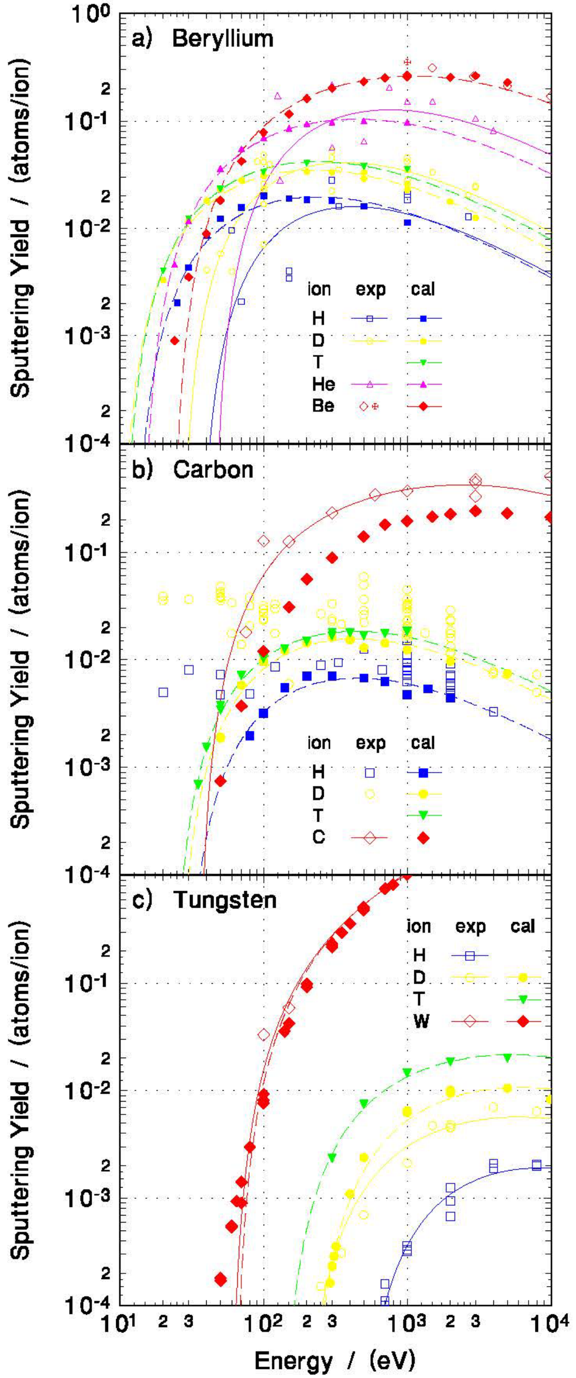
Physical sputtering

- D^+/T^+ sputtering yields all fall about 1 - 2%
- Differences lie in the threshold energy



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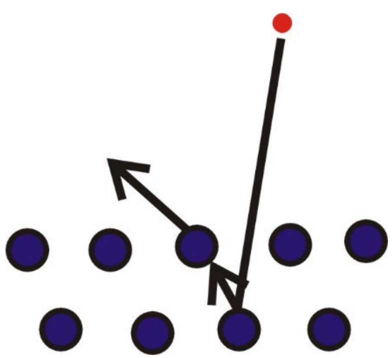

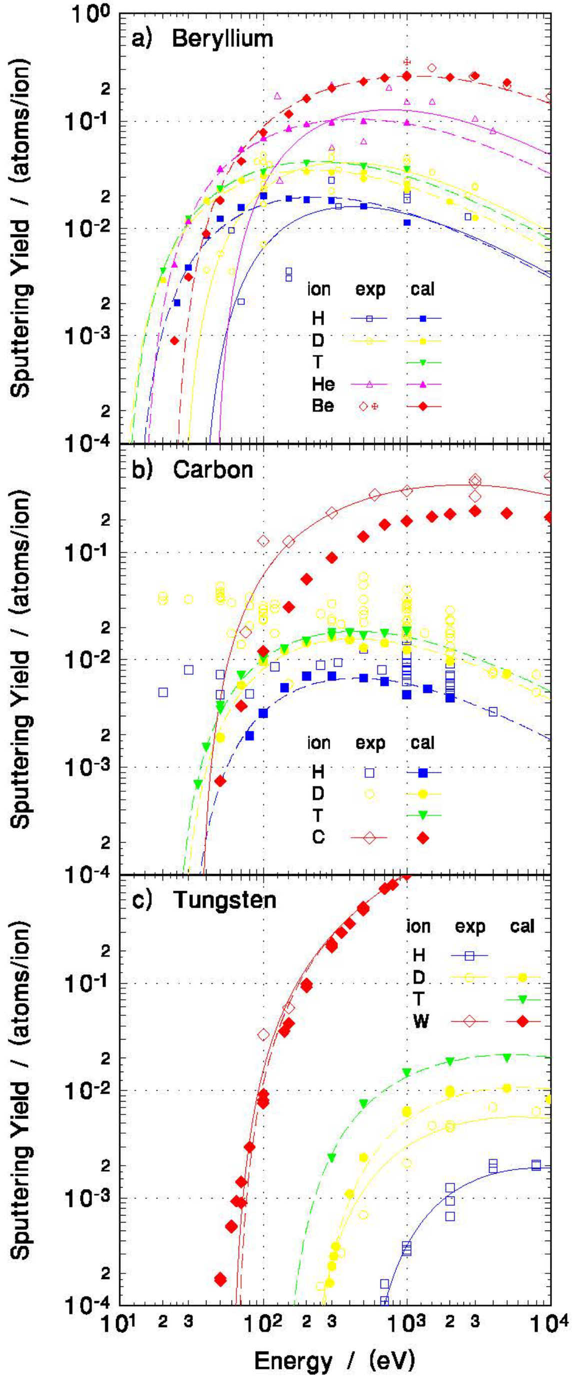

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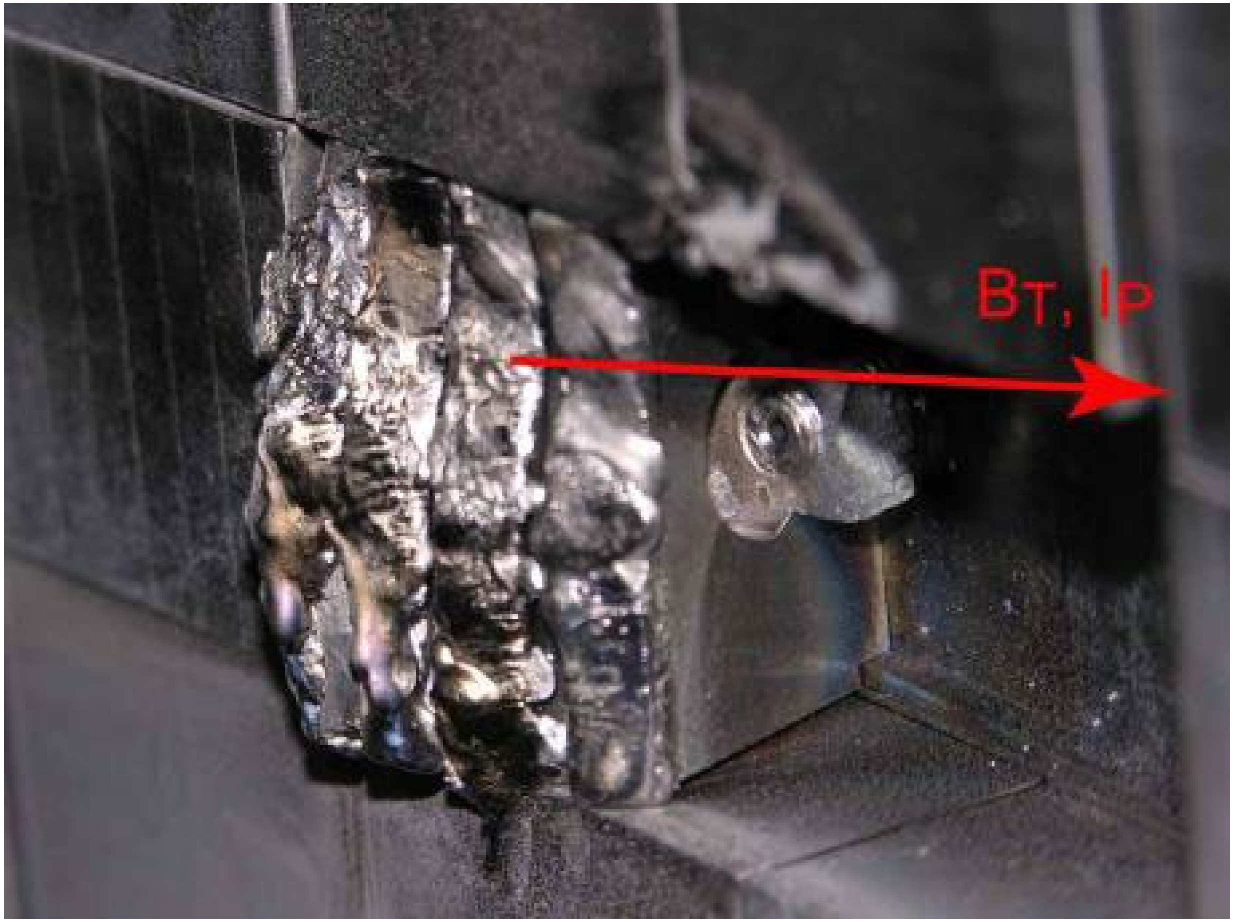

- Once melting starts, things can only get worse
- Large scale loss of material

Lipschultz NF 2012

Plasma transport of impurities

Atoms released from the wall have three options:

- Prompt redeposition
  - Atoms are ionized within one Larmor radius of the surface
- Carried by the scrap-off plasma to the divertor
- Transport into the core plasma

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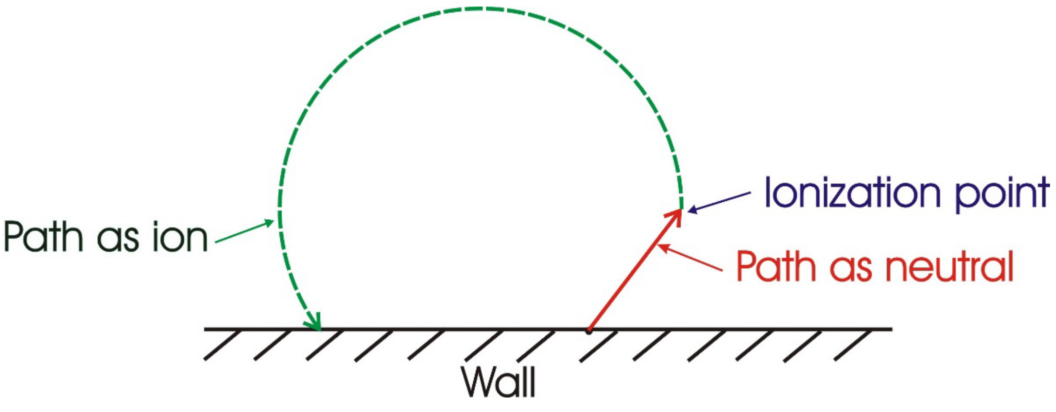

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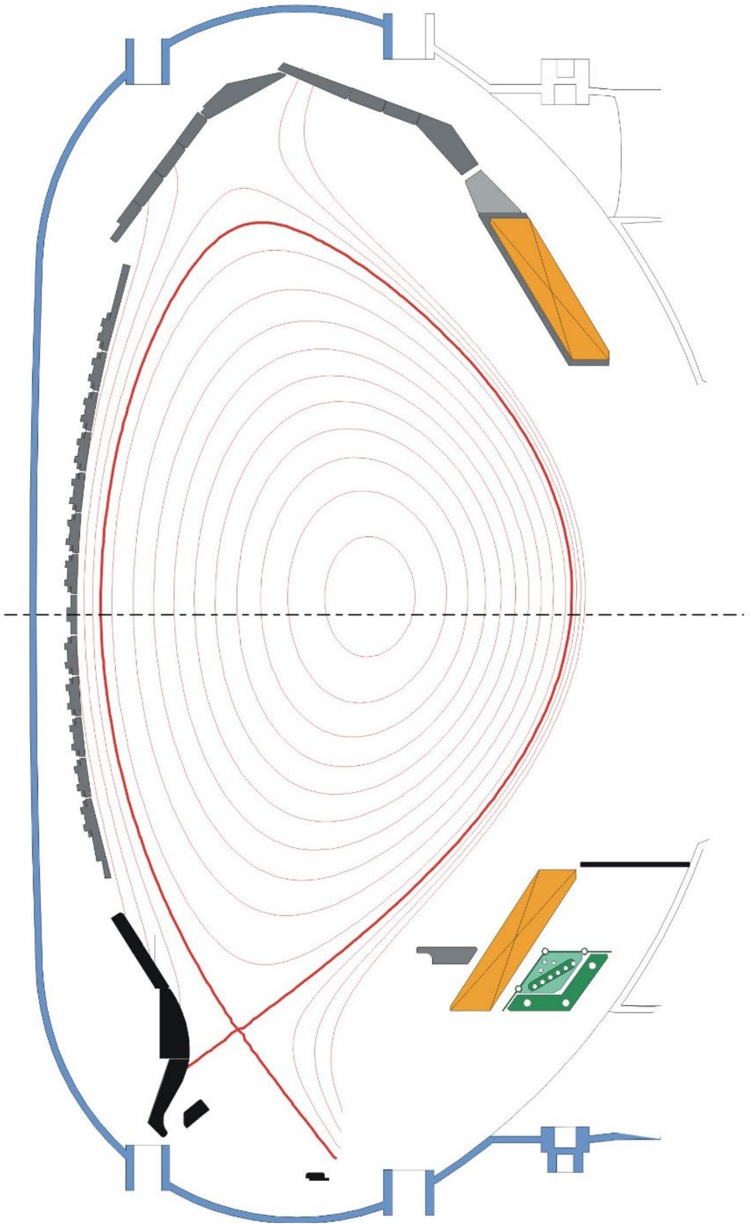
ASDEX-Upgrade



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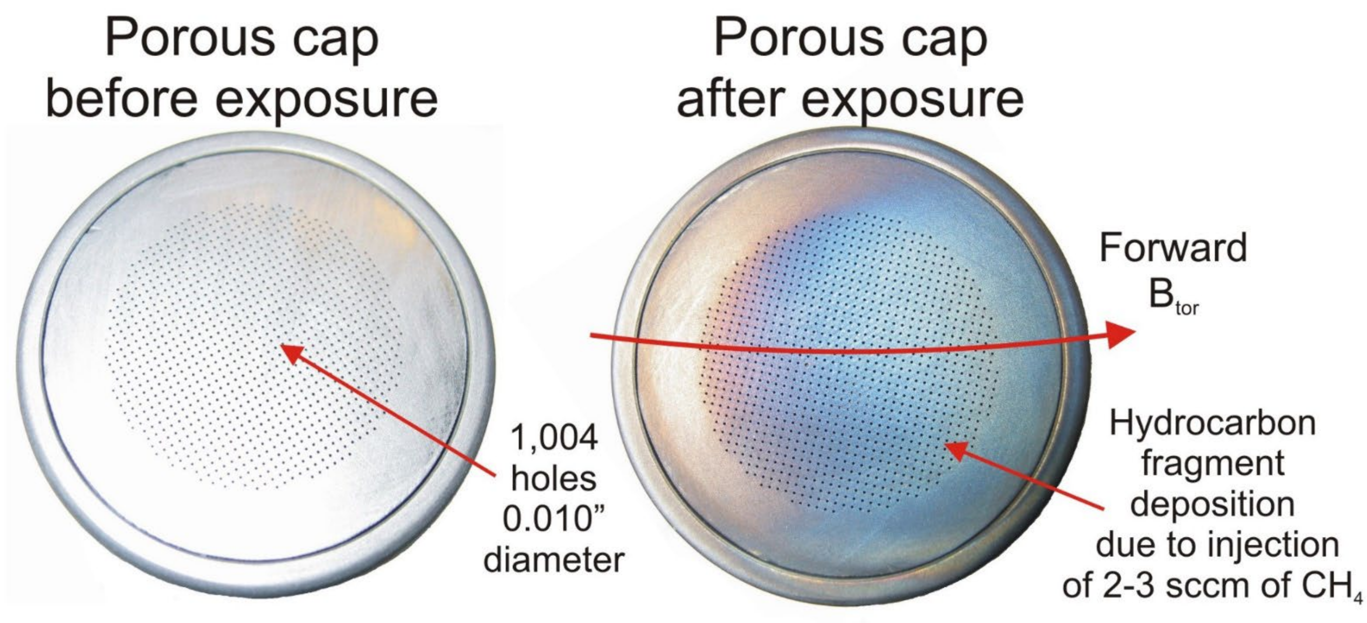
Porous plug gas injection system

- Gas can be injected into the tokamak edge plasma without significant disruption to the local plasma properties



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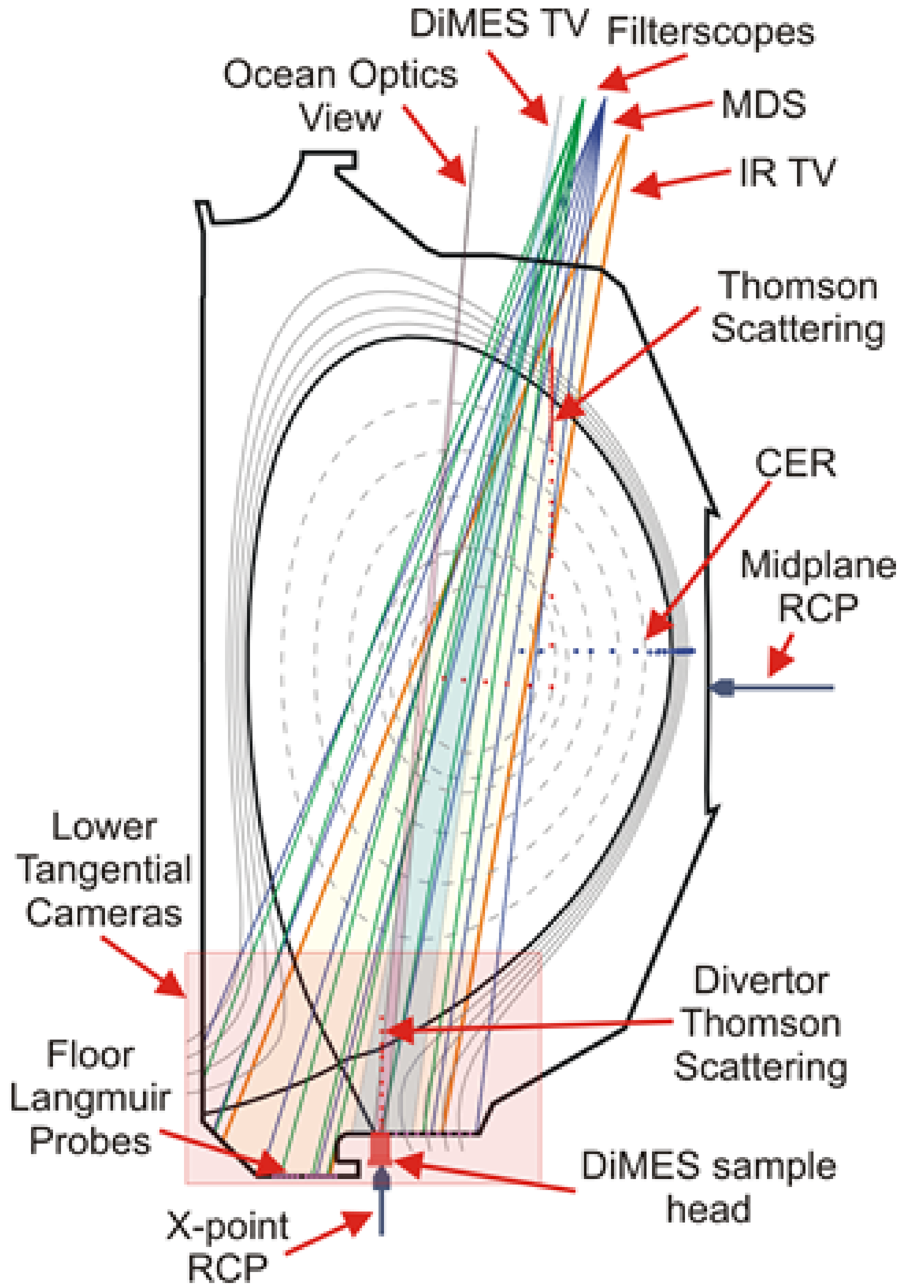
DIII-D tokamak



McLean RSI 2009

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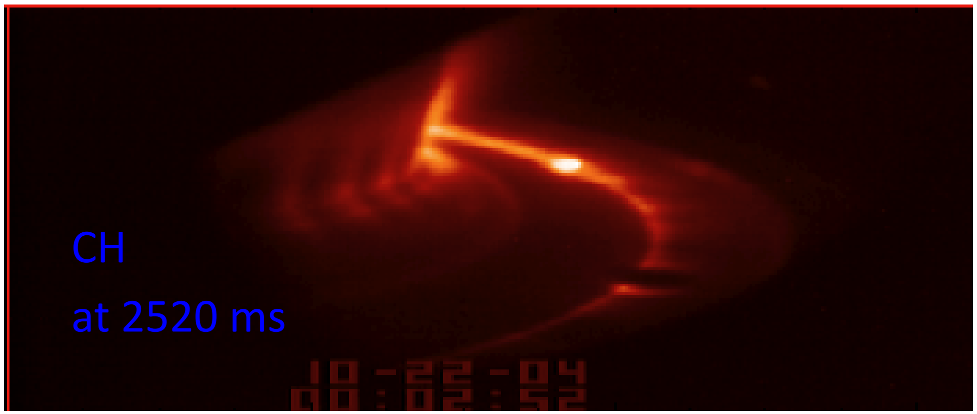
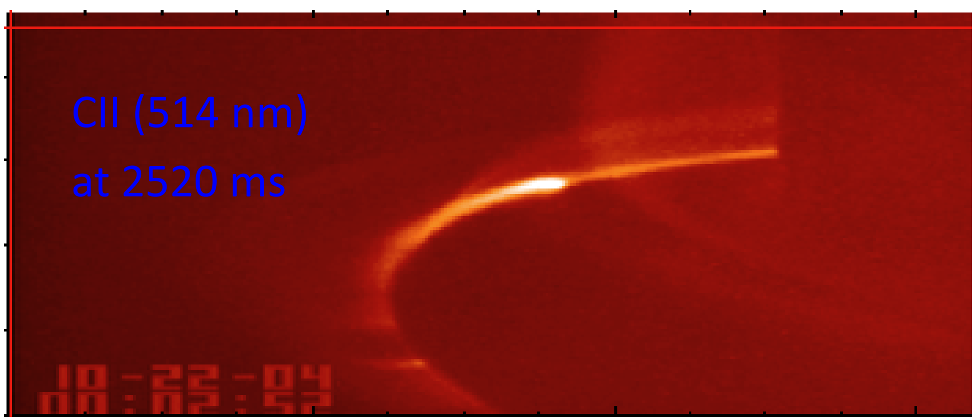


CH band emissions in the DIII-D tokamak



C^+ line emissions in the DIII-D tokamak

- Modelling of the emissions allows us to evaluate plasma transport parameters
- A key result was a calibration of spectrometer measurements for hydrocarbon influx

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Impurities in the core plasma

Impurities in the core plasma have two detrimental effects on fusion power:

1. Increased radiation – bremsstrahlung
   – line radiation

2. Plasma dilution – additional electrons increase pressure

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$P = nkT$

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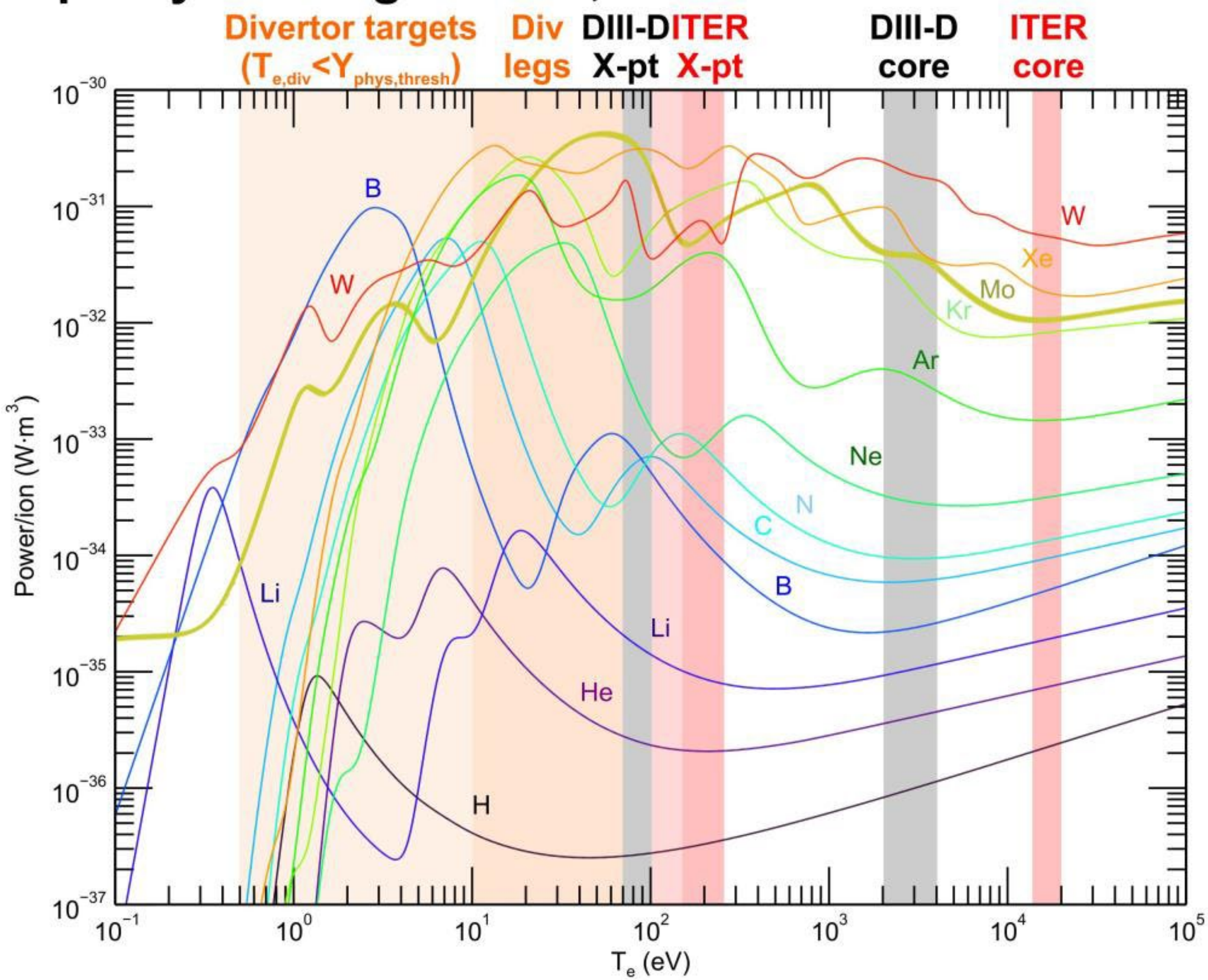
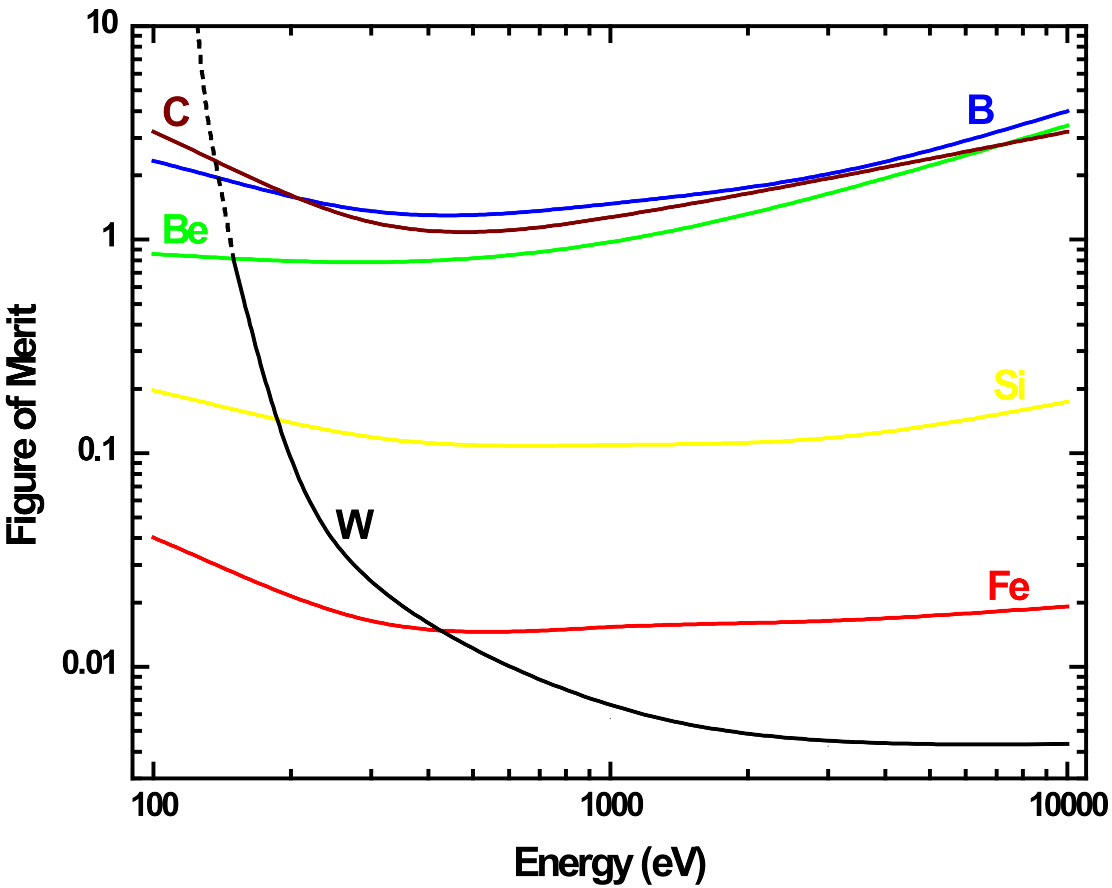
Impurity Cooling Curves, Coronal Radiative Model



Adam McLean, PPPL, private communication

Which material is best?



Max concentration

Erosion rate

Stangeby et al., PPCF, 2022

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Outline

- Introduction
- Erosion and plasma contamination
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    - Deposited layers
    - Slag removal
- Tritium retention in wall materials
- ITER – Current Status

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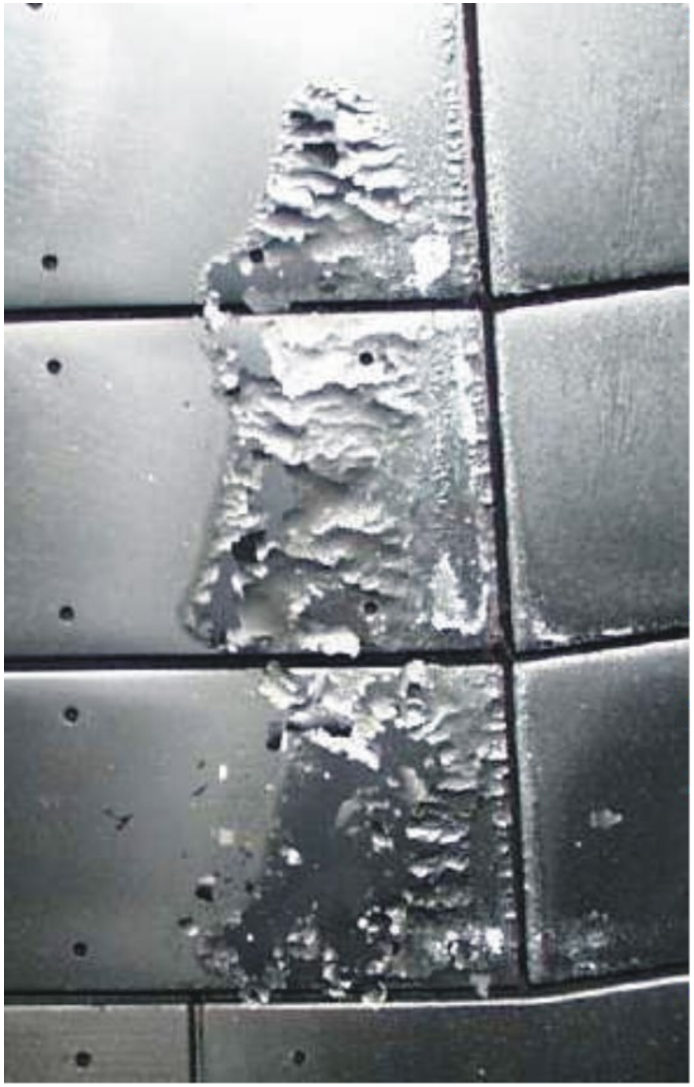

- All eroded atoms, whether they make it to the core plasma or not, will eventually be deposited somewhere.
- In current tokamaks, regions of net deposition tend to be near the divertor, and fairly small in area.
- Even small erosion rates may lead to large deposit thicknesses.

Photo is from TFTR (Federici, 2001)

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Annual slag amounts

Device	P_{SOL} [MW]	τ_{annual} run time [s/year]	E_{load}^{year} [TJ/yr]	Beryllium net wall erosion rate [kg/yr]	boron net wall erosion rate [kg/yr]	carbon net wall erosion rate [kg/yr]	silicon net wall erosion rate [kg/yr]	iron net wall erosion rate [kg/yr]	tungsten net wall erosion rate [kg/yr]
DIII-D	20	10^4	0.2	0.13	0.11	0.08	0.39	1.0	0.16
JT-60SA	34	10^4	0.34	0.22	0.19	0.15	0.66	1.7	0.27
EAST	24	10^5	2.4	1.6	1.2	0.82	4.7	12	1.8
ITER	100	10^6	100	77, 60[1], 29[2]	64	44, 54[1], 53[2]	196	500, 187[1]	80, 40[1], 41[2]
CFETR[4]	1000	$1.2x10^7$	12000	7800	6400	4400	23,500	60,000	9,500
ST Pilot P[5]	50	10^7 est.	500	330	270	190	1,000	2500	400
ARC Pilot P[6]	100	10^7 est.	1000	650	530	370	1,960	5,000	790
Comp. Pilot P[5]	260	10^7 est.	2600	1700	3200	1000	5100	13,000	2000
Reactor	400	$2.5x10^7$	10000	6500, 21000[3] *4.3[a]* *3.5[b]*	5300 *2.9[a]* *2.1[b]*	3700 *1.8[a]* *1.6[b]*	19,600 *4.2[a]* *8.5[b]*	50,000 *5.4[a]* *6.4[b]*	7900, 5000[3] *0.26[a], 0.16[a]* *0.42[b], 0.26[b]*

Stangeby et al., PPCF, 2022

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Stangeby et al., PPCF, 2022

Outline

- Introduction
- Erosion and plasma contamination
- Redeposition of eroded material
- Tritium retention in wall materials
  - Implantation and permeation
  - Neutron damage
  - Codeposited layers
- ITER – Current Status

Tritium cycle

- Tritium does not occur naturally ($T_{1/2}$ ~ 12 yrs) – any reactor will need to be self-sufficient
- Produced from lithium: e.g., n + $^{6}Li \rightarrow T + {}^{4}He$
- Using the neutron from the $D + T \rightarrow {}^{4}He + n$ reaction
- With tritium breeding ratios ~ 1.1 T/n, there will only be room for small losses of tritium through the entire fuel cycle

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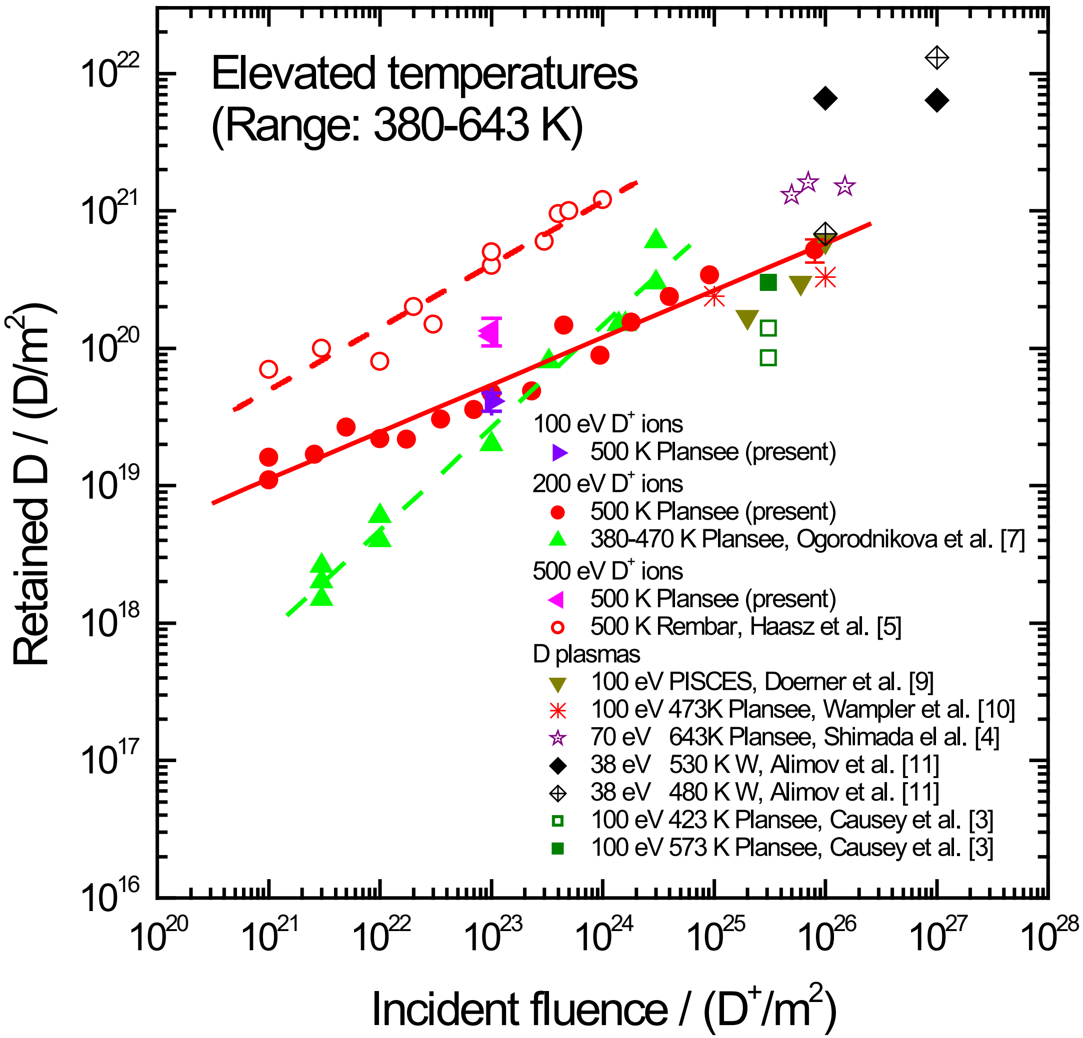
D retention in tungsten due to D^+ implantation



Tian, JNM 2010

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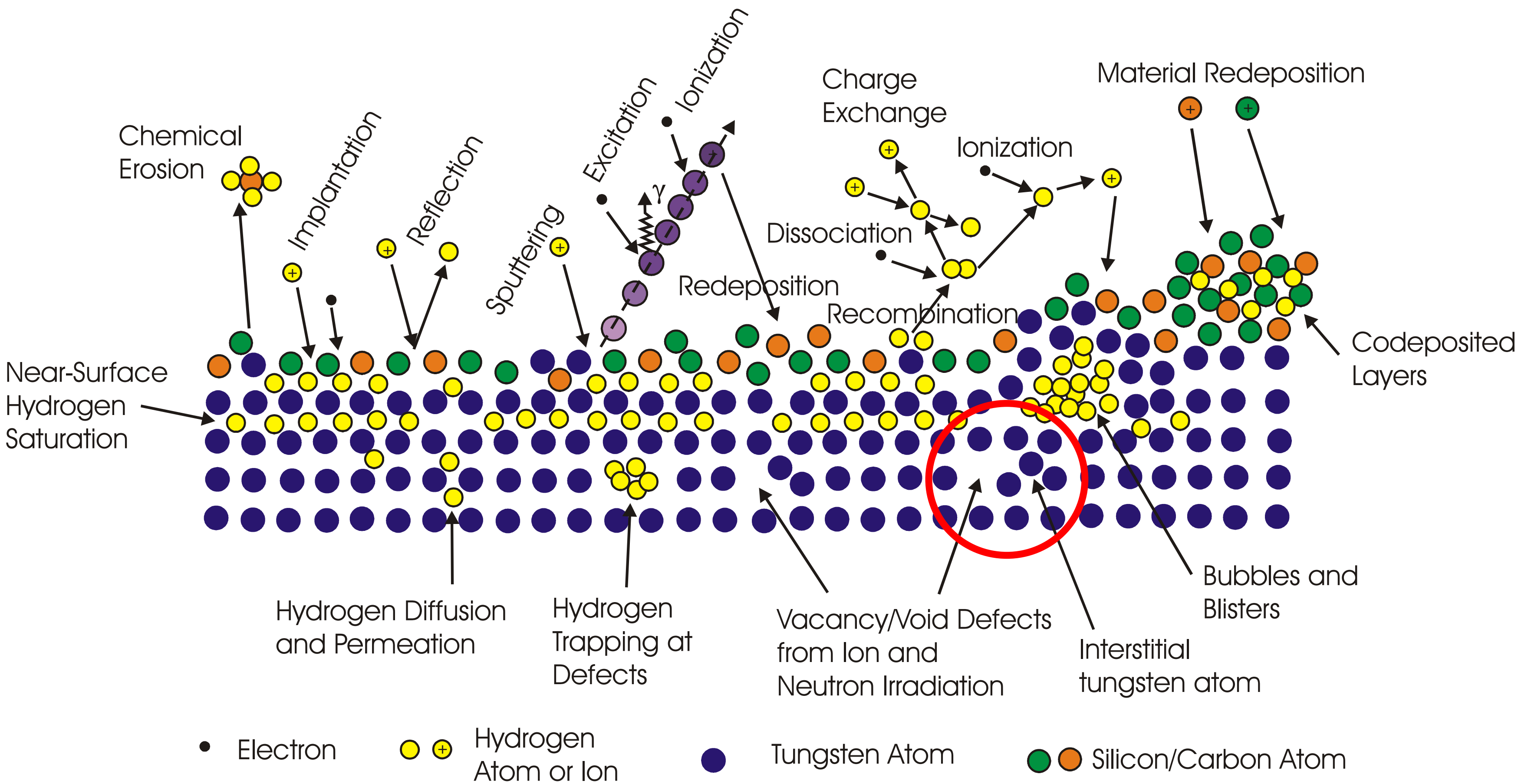
Details of the surface



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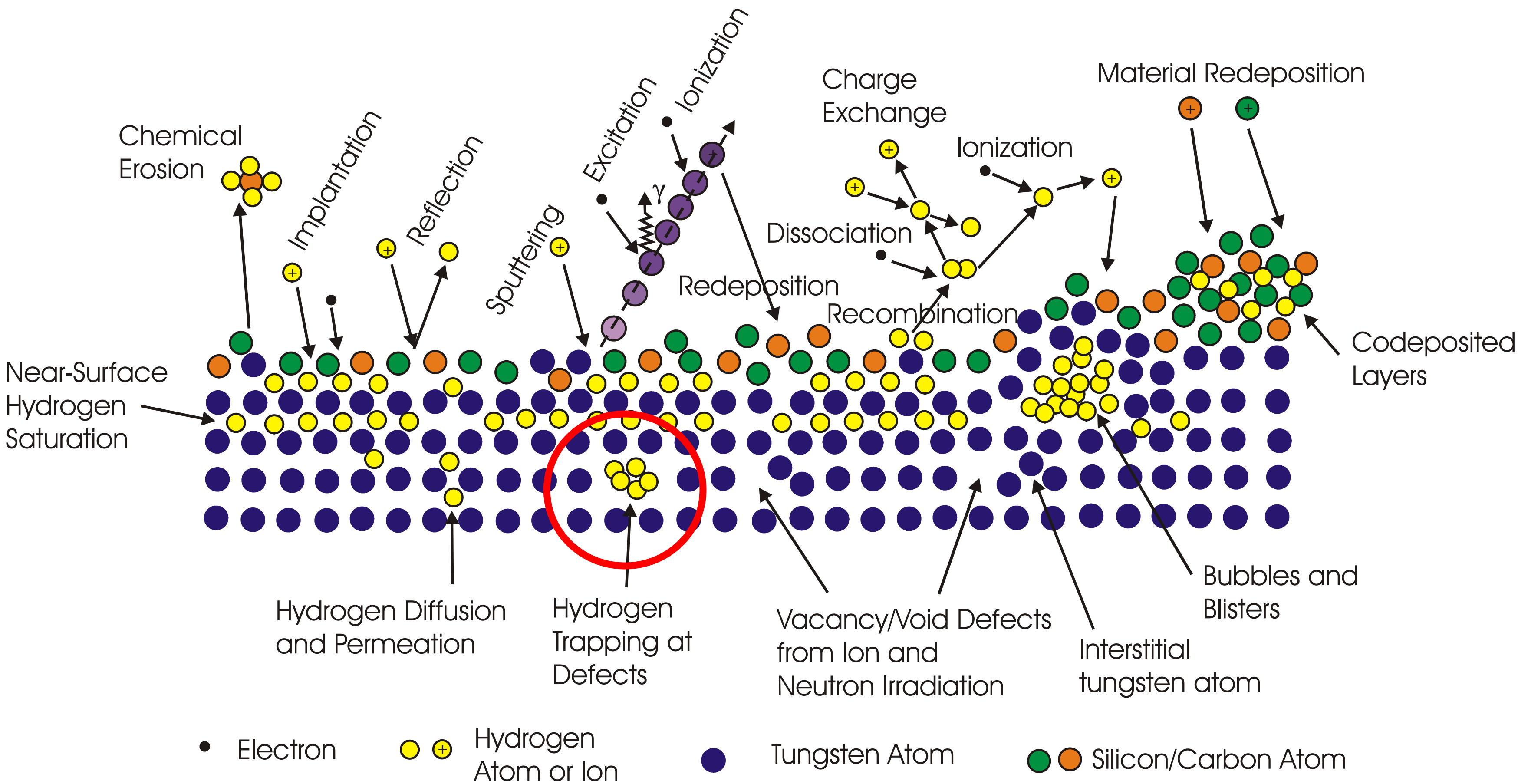

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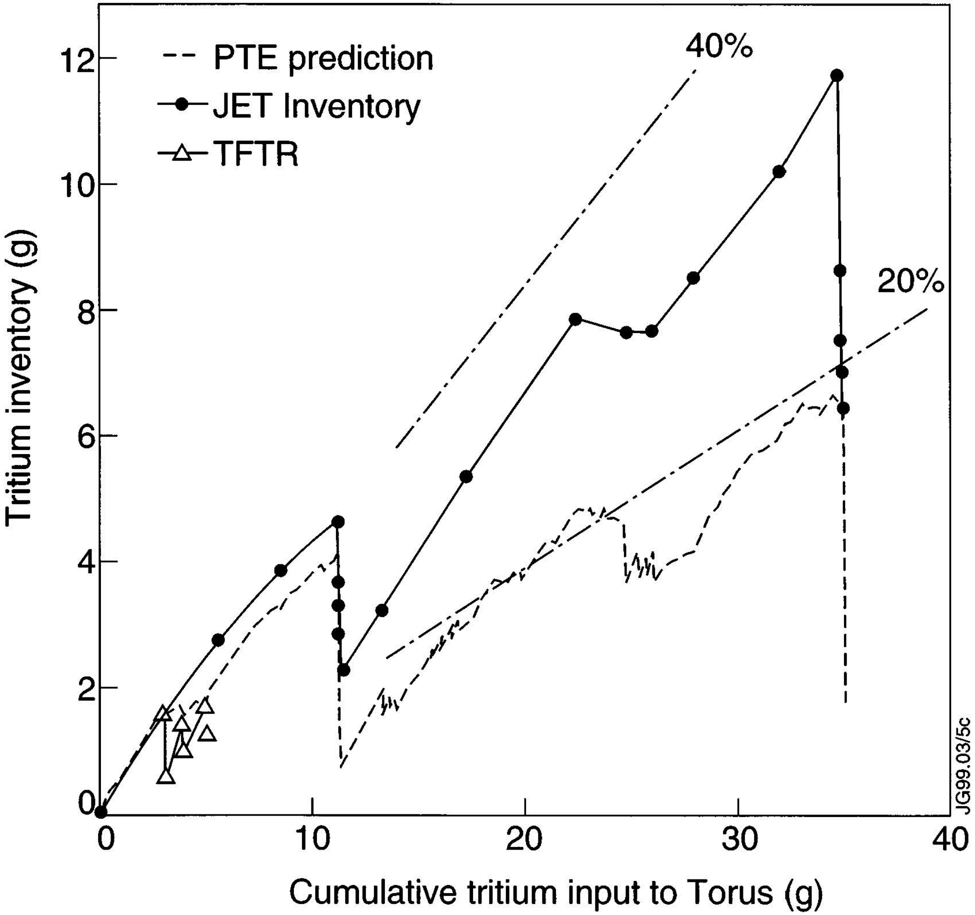

Andrew FED 1999

- Where does all the hydrogen go?

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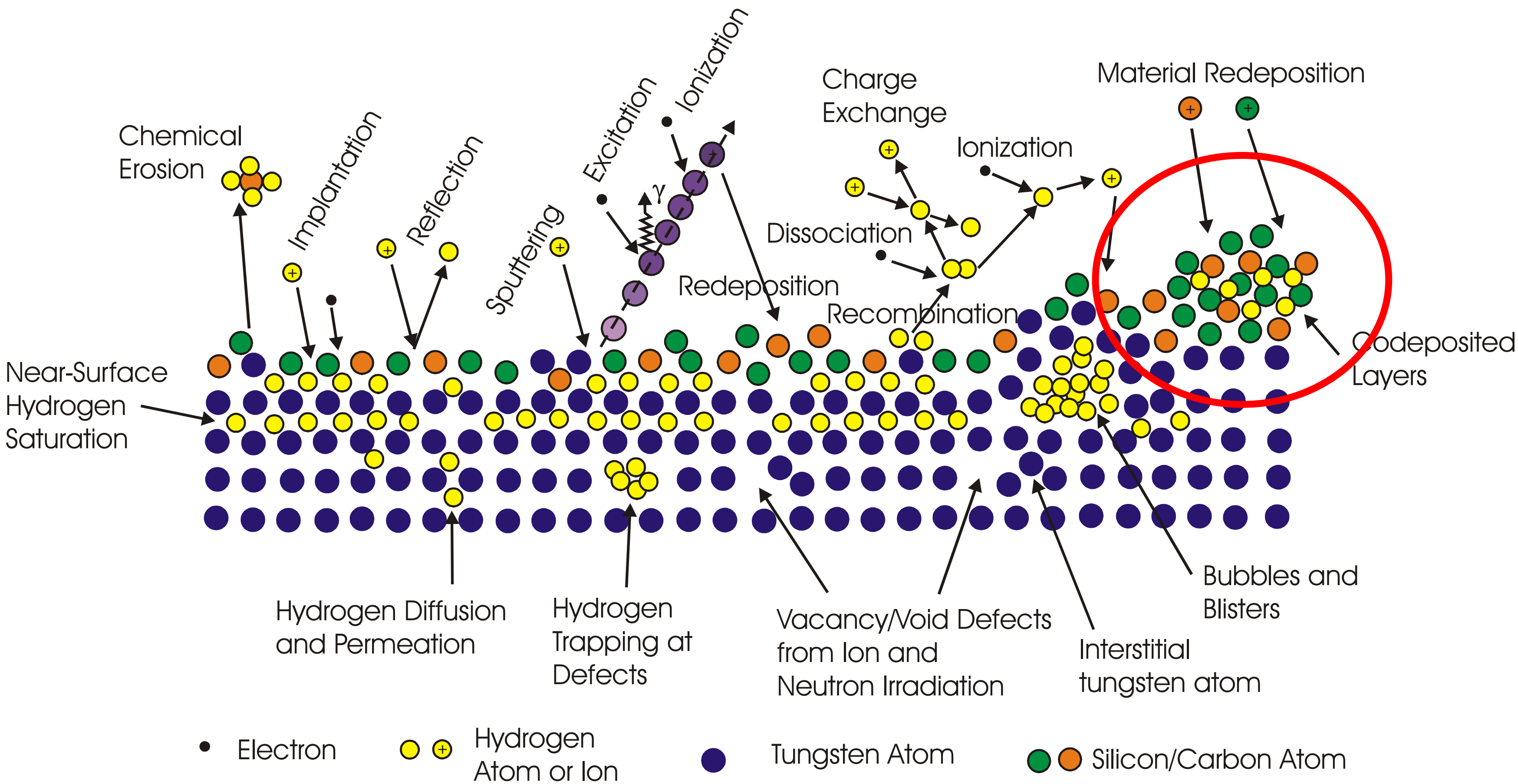
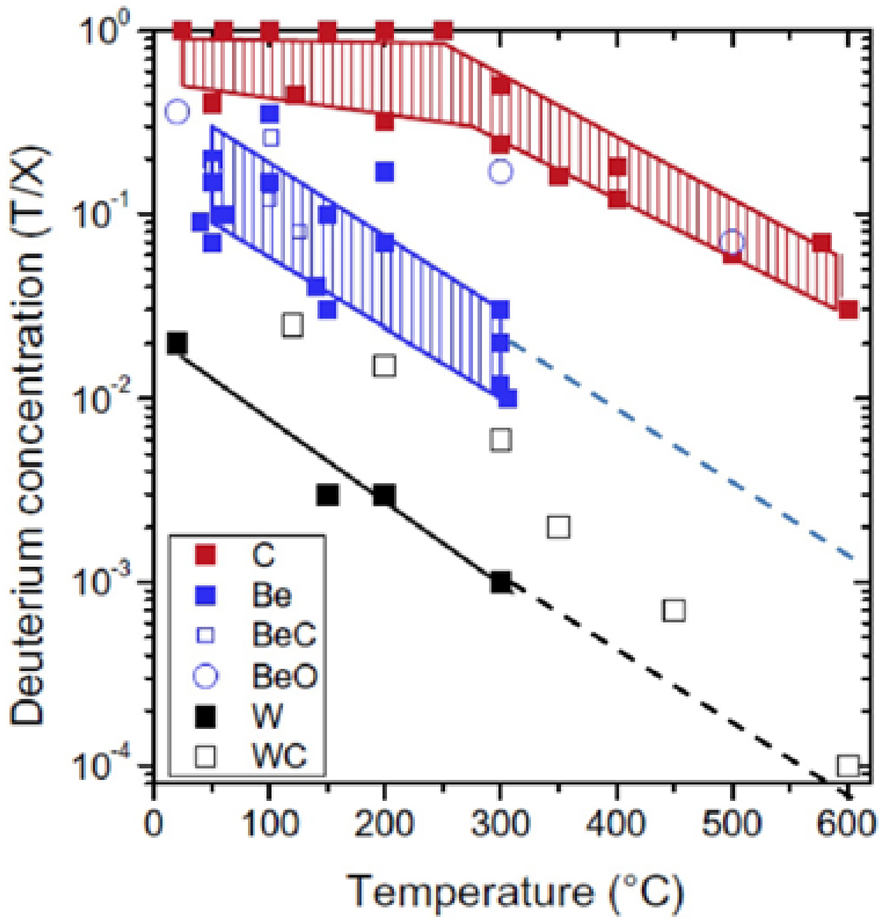


Adapted from B.D. Wirth et al., MRS Bulletin 36 (2011) 216

Codeposition:

- Redeposited layers can trap large amounts of hydrogen
- The amount trapped does not saturate
- Higher temperatures are better



Doerner NME 2019

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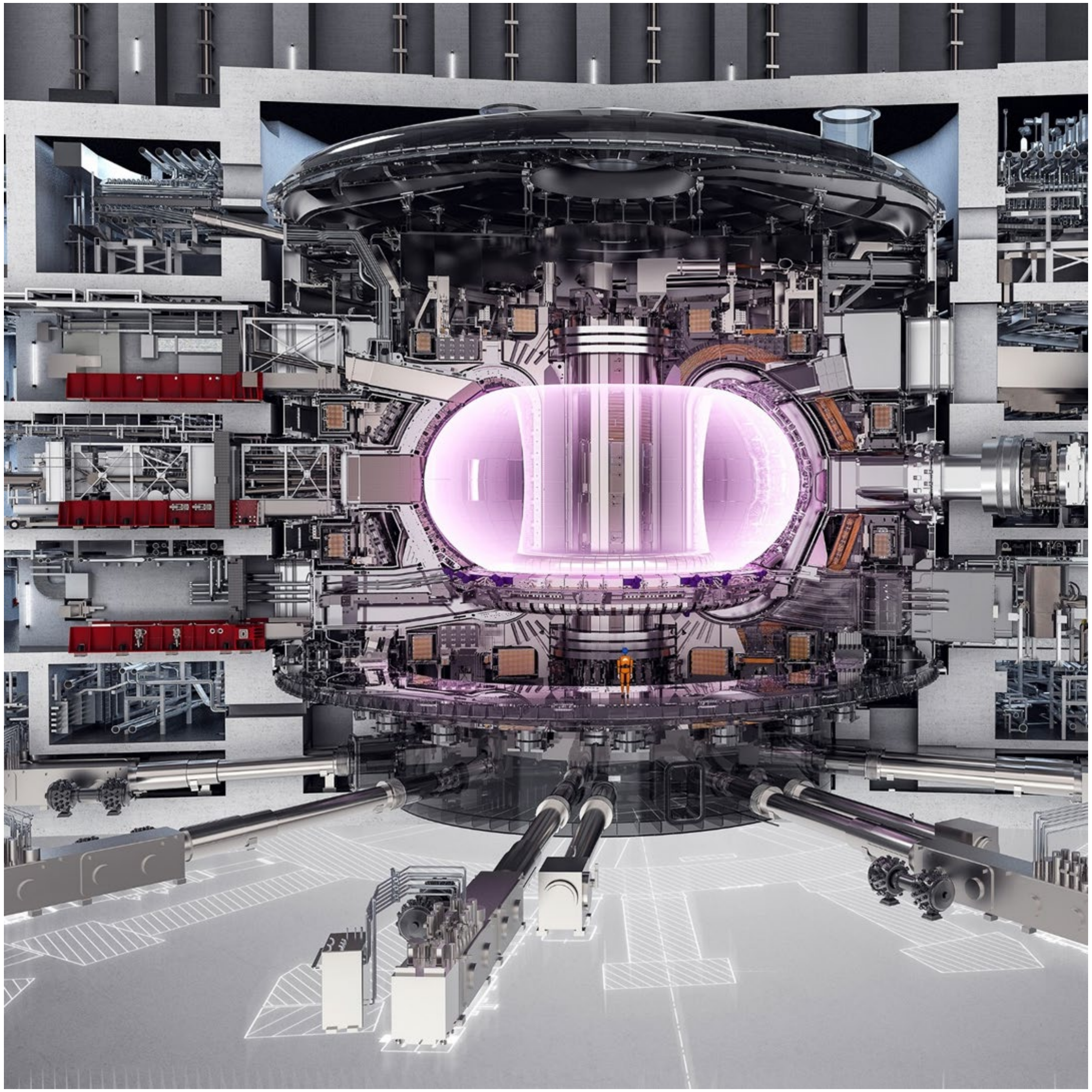

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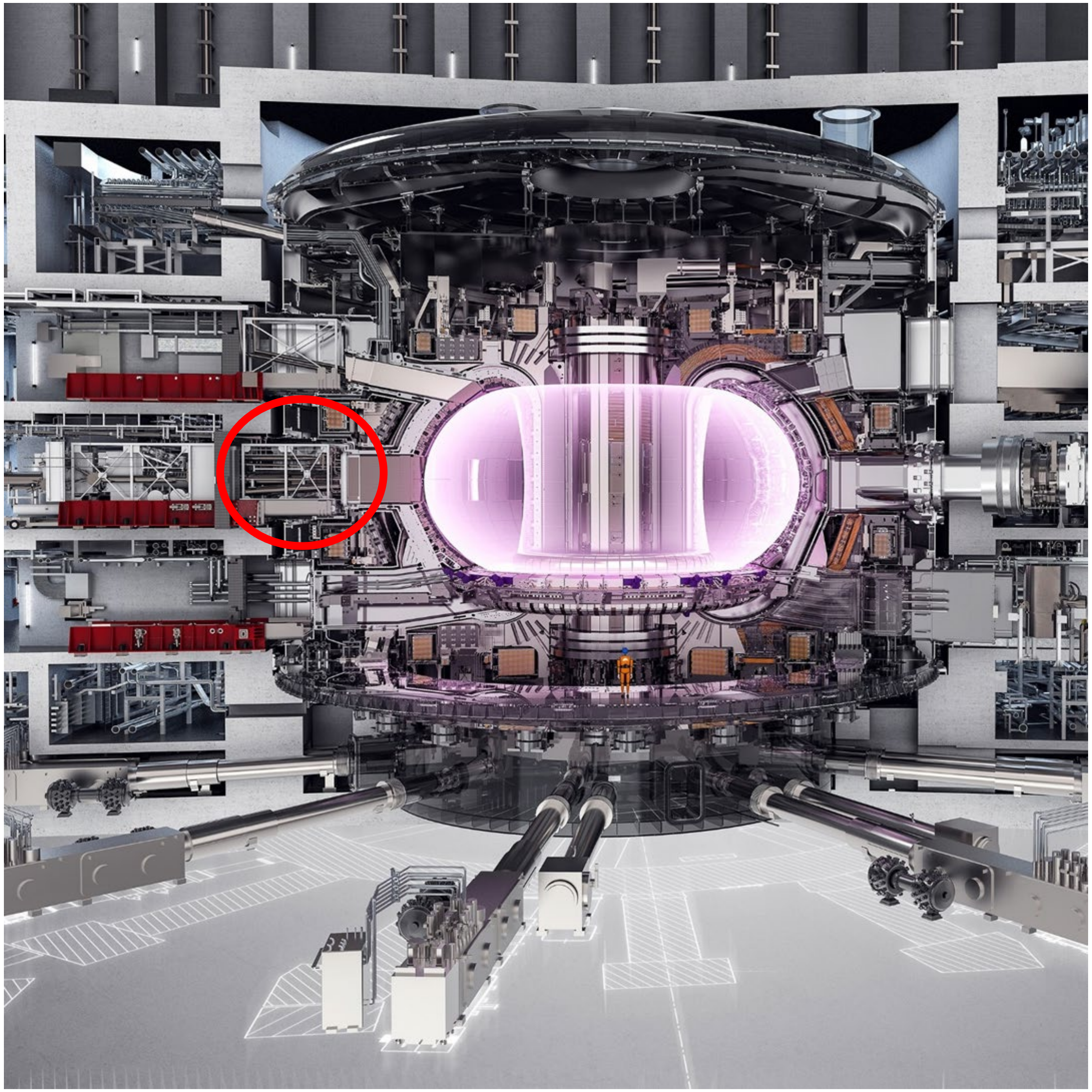
  - Inertially-cooled W first wall
- Full D-T operation 2039
  - Water-cooled W first wall



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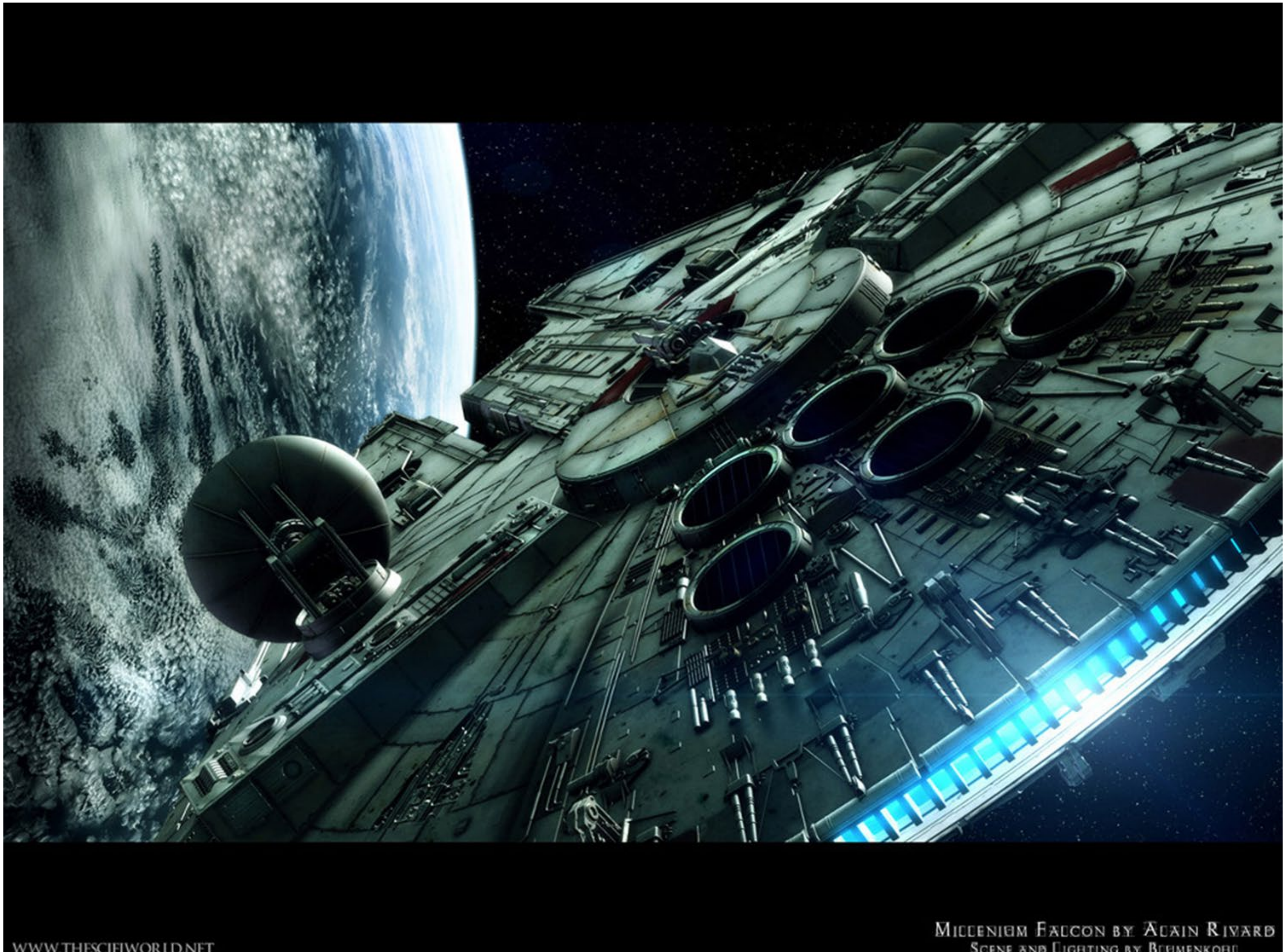
Summary

"Taming the plasma-wall interface" remains one of the greatest challenges in the quest to develop commercial fusion reactors.


WWW.THESCIFIWORLD.NET
Millenium Falcon by Alain Rivard
Scene and Lighting by Blumenkohl

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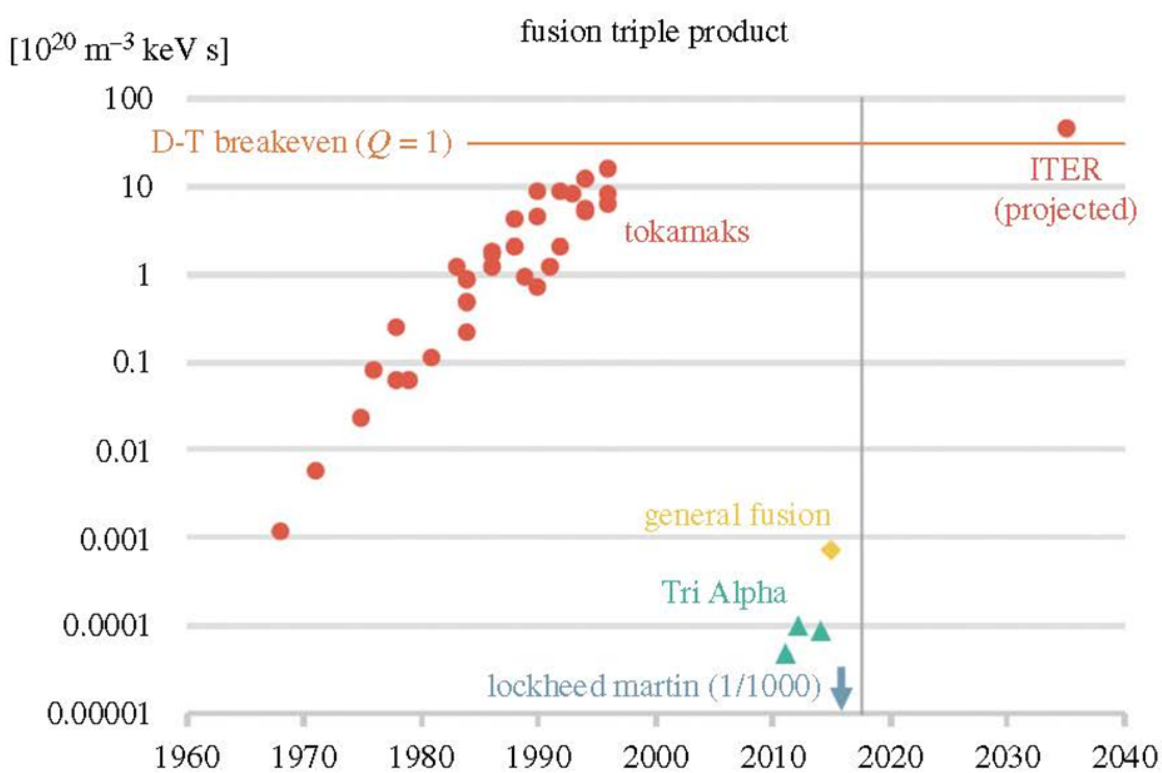

Figure 7. Evolution of fusion triple product. Tokamak researchers have worked long and hard to gradually improve performance to the point where devices are approaching energy gain. Alternative approaches have a long way to go but proponents believe they can accelerate development. (Points shown for Tri Alpha used deuterium as fuel, not the proton-boron fuel it hopes to use.) (Figure courtesy of Dan Brunner, Commonwealth Fusion Systems). (Online version in colour.)

Cleary, Phil. Trans. R. Soc. A, 2019

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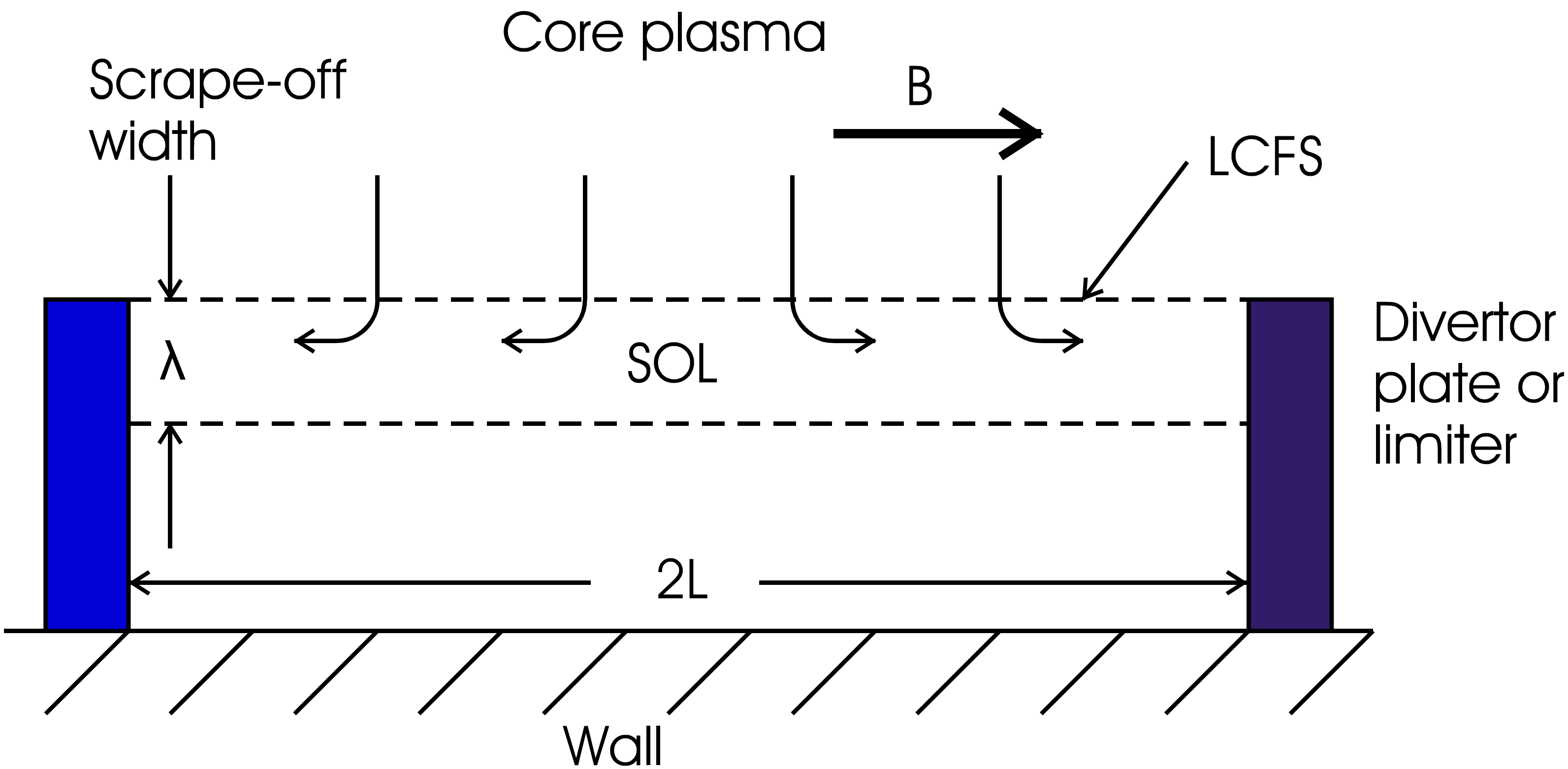
Technology Development

- Tritium breeding – materials, tritium extraction
- Tritium handling technology
- Neutron damage – materials studies
- High temperature cooling – He gas cooling
- High temperature superconductors
- Remote maintenance – radioactive environments

2.3 Plasma Transport: 1D SOL Model



From Stangeby, 2000