The Challenges of Plasma-Surface Interactions for ITER & Beyond

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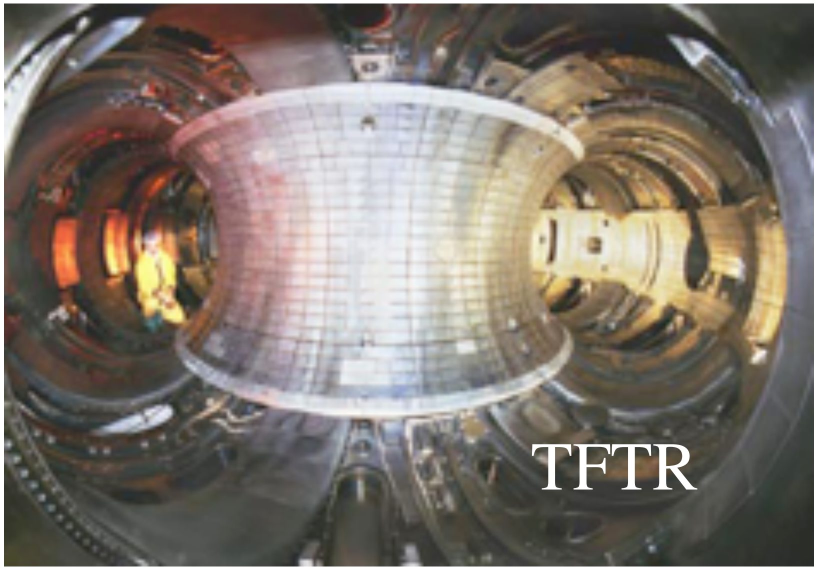
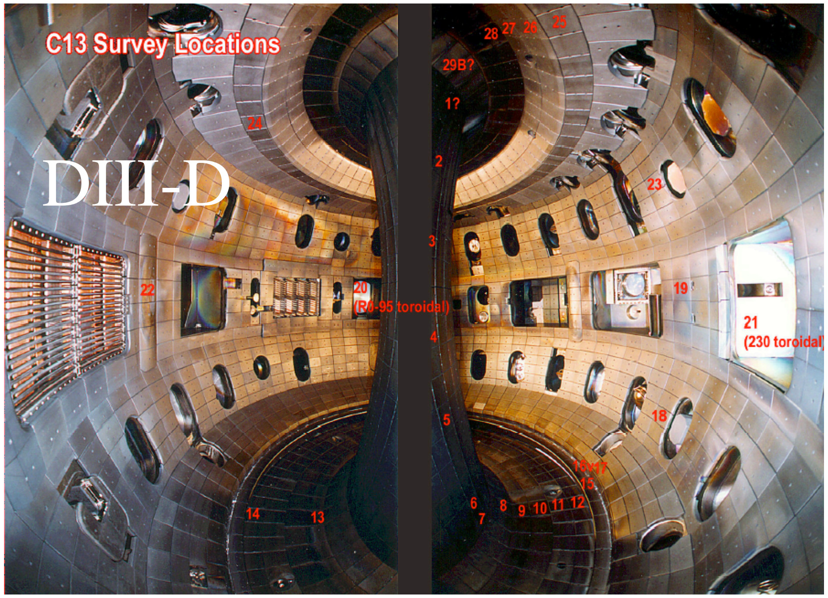
Many thanks to all my PSI colleagues

Present tokamaks require that plasma-facing materials *simultaneously* meet several requirements

- Mechanical strength
  - Large JxB and eddy current forces during disruptions
- Forgiving of temperature transients.
  - Heat flux > GW / m^2
- Erosion/radiation characteristics favorable for a wide variety of exploratory fusion core plasma scenarios.
- To-date low-Z materials, in particular graphite/CFC, have met these challenges.





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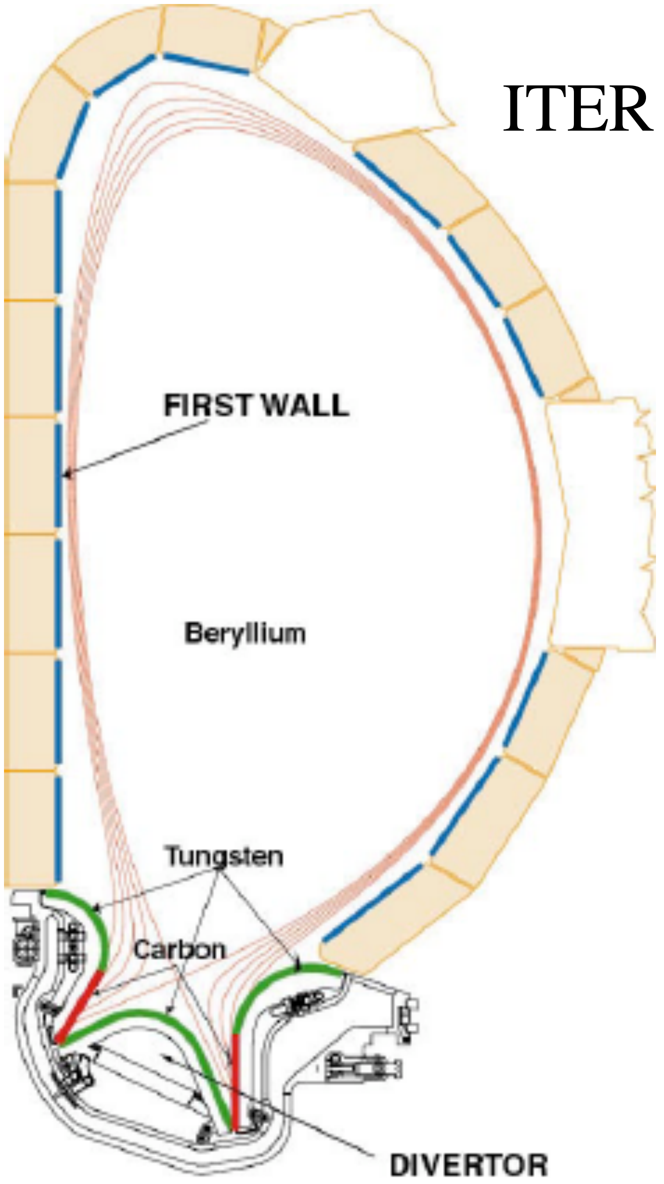
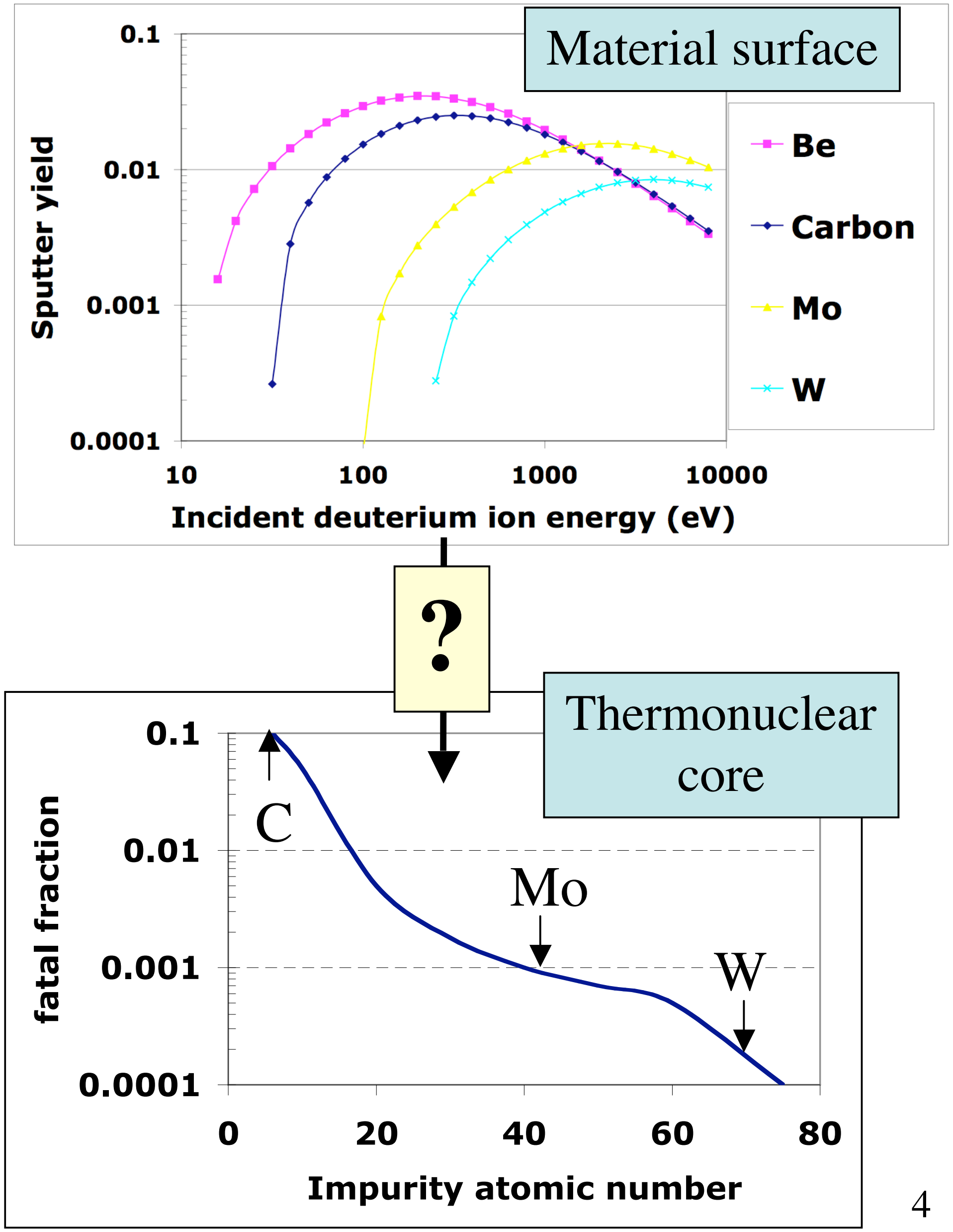
- To-date low-Z materials, in particular graphite/CFC, have met these challenges.
- **Q~1 and fusion power > 10 MW achieved with Carbon walls + low-Z coatings, paving the way for our confidence in ITER.**



So what’s the problem?

Lack basic understanding and diagnosis of PSI processes in fusion devices → Uncertain extrapolation

- Intermediate steps uncertain between sputtering and core plasma.
  - Intense power flux density
    - Materials placed near thermal limits.
  - Surface layers of plasma facing materials are rapidly and continually being reconstituted by plasma erosion and redeposition.
    - Peak ion flux ~ 100 kA /m^2
  - Plasma transport ensures large gradients in plasma conditions across magnetic flux surfaces.
  - Turbulent plasma transport
  - While plasma is axisymmetric, real armor geometry leads to 3-D effects.



Overview

- **Highlight five prominent PSI issues as one steps from present devices to ITER to Demo.**
  - ➢ Each issue is quantitatively and qualitatively “worse” in ITER, then Demo.
  - ➢ Every issue pushes our PSI knowledge up-to and past our limits.
  - ➢ Despite its severe challenges, ITER will not address most Demo PSI issues.

- **Way forward**: PSI diagnosis critical to advancing PSI science.

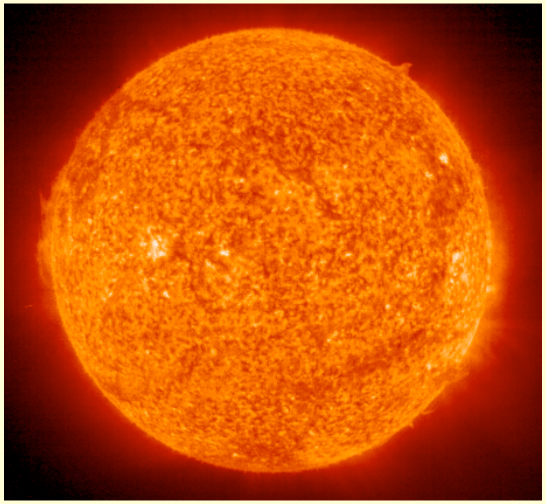
- **Limitations**
  - ➢ Cannot include all research topics
  - ➢ Discussion mostly restricted to “conventional” solid plasma-facing materials.
  - ➢ Personal opinion : PSI & fusion materials, particularly in ITER, remain contentious issues and the views stated are not consensus.

Controlling PSI becoming increasingly important and difficult as we move from present tokamaks → ITER → demonstration fusion power plants

Issue / Parameter	Present Tokamaks	ITER	DEMO	Consequences
Energy exhaust (production) *GJ / day*	~ 10	3,000	60,000	- active cooling - max. tile thickness ~ 10 mm

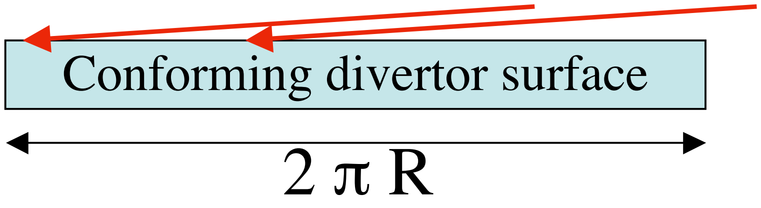
Heat exhaust is primary design point for edge materials, since this is directly related to fusion power density

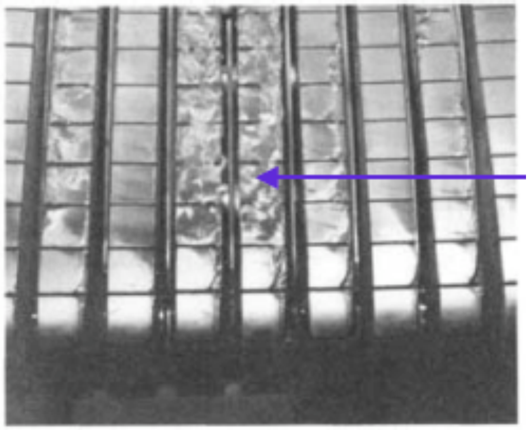
$$q_{\text{target}} = \frac{\frac{1}{5}P_{fusion}}{A_{divertor}} \sim 10-20\,\frac{MW}{m^2}$$



$$\approx 40\,\frac{MW}{m^2}$$

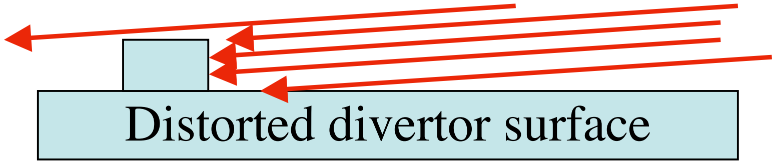
Grazing Field lines





Melted
Be tiles
On JET

Field lines

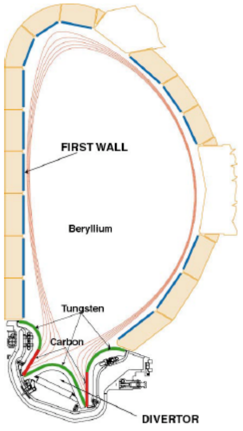


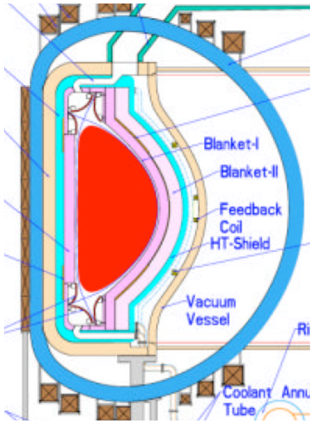
Distorted surface "proud" to the field line receives $q_{//} \sim 500\ MW/m^2$ and is immediately melted/ablated.

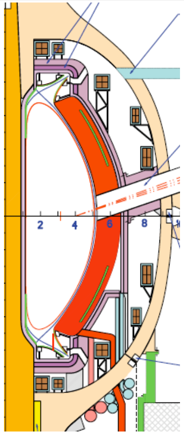
Even ITER falls short of Demo power density $P/S \sim 1\ \mathrm{MW/m^2}$ and energy throughput

	ITER	**ARIES-AT**	**ARIES-RS**	**ARIES-ST**
Duration (s)	**400**	**$3\mathrm{x}10^7$**	**$3\mathrm{x}10^7$**	**$3\mathrm{x}10^7$**
Ambient T (C)	**~ 200**	**1000**	**850**	**> 700**
R (m)	6.2	5.2	5.52	3.2
$A \equiv R/a$	3.1	4.0	4.0	1.6
P_{exh} (MW)	150	390	515	624
P/S ($\mathrm{MW/m^2}$)	**0.21**	**0.85**	**1.1**	**0.99**
P/A_{div} ($\mathrm{MW/m^2}$)	**2.4**	**10**	**12**	**20**

$A_{div} / S \sim$ 5-10%



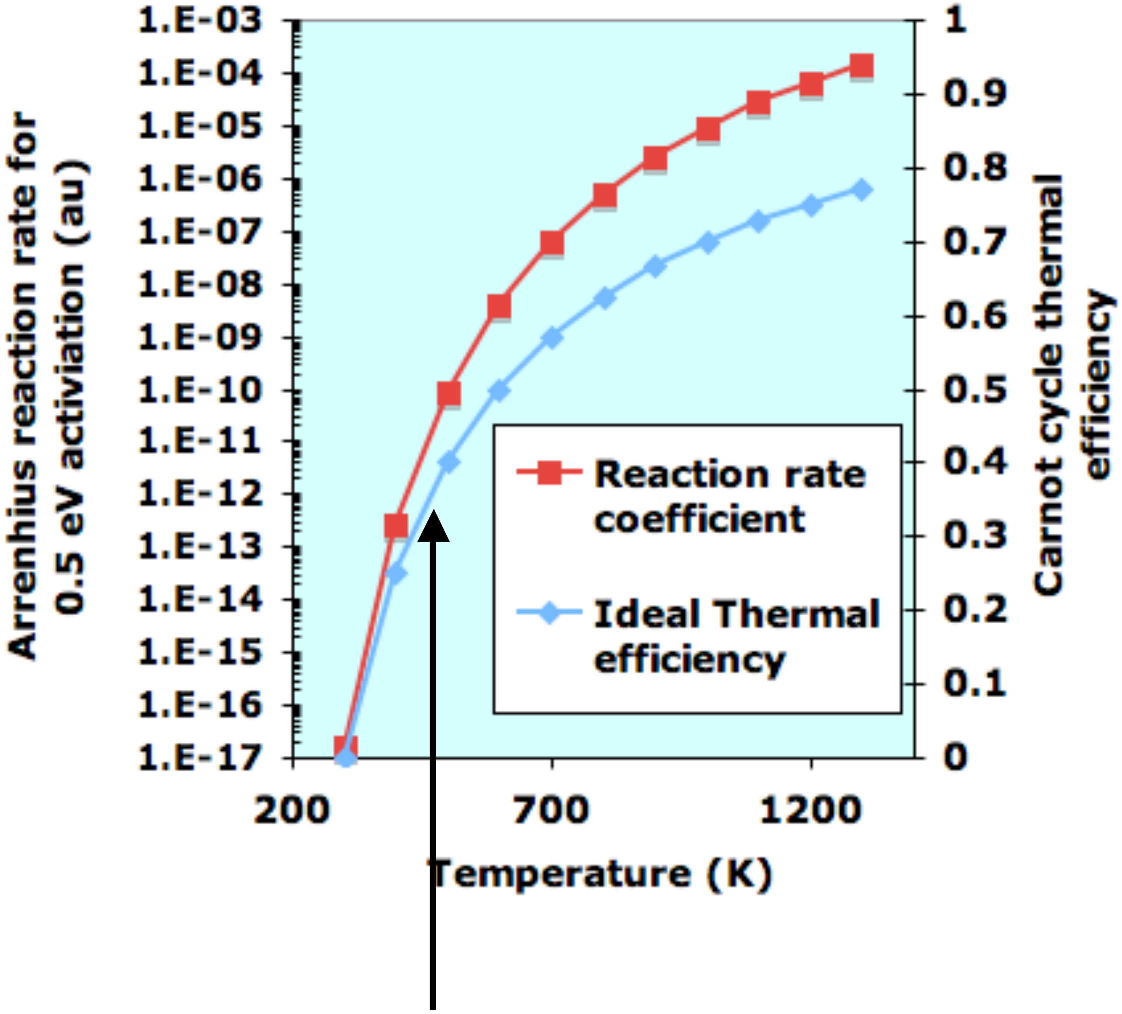




Thermal efficiency dictates high ambient T → Fundamentally different Physical Chemistry regime for wall that is completely unexplored in fusion devices

- Rate equations follow Arrhenius relationship reaction rate ∝ $\exp(-E_o/kT)$
  - Activation energies $E_o \sim 0.5$ -1 eV.

- Precludes water cooling technology in reactor



Limit for Water-cooling

Helium gas (or molten metal) cooling/heating required for hot walls (T > 700 C)

- **Actively controlled temperature of all plasma-facing components.**
- **US Engineering demo peak heat removal ~ 10 MW/m^2**
  - ➢ **He and PFC joining sets the limit for peak heat removal in divertor.**
- **The heat removal challenge: P_{exh} / A_{div} ~ 10 MW / m^2 right at the technology limit!!**
  - ➢ Radiation / geometry effects must be invoked to find solutions.

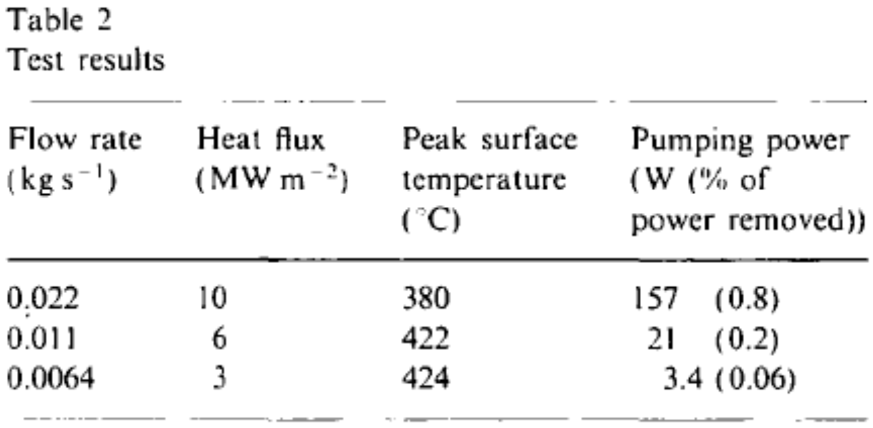


Table 2
Test results

Flow rate (kg s^{-1})	Heat flux (MW m^{-2})	Peak surface temperature (°C)	Pumping power (W (% of power removed))
0.022	10	380	157 (0.8)
0.011	6	422	21 (0.2)
0.0064	3	424	3.4 (0.06)

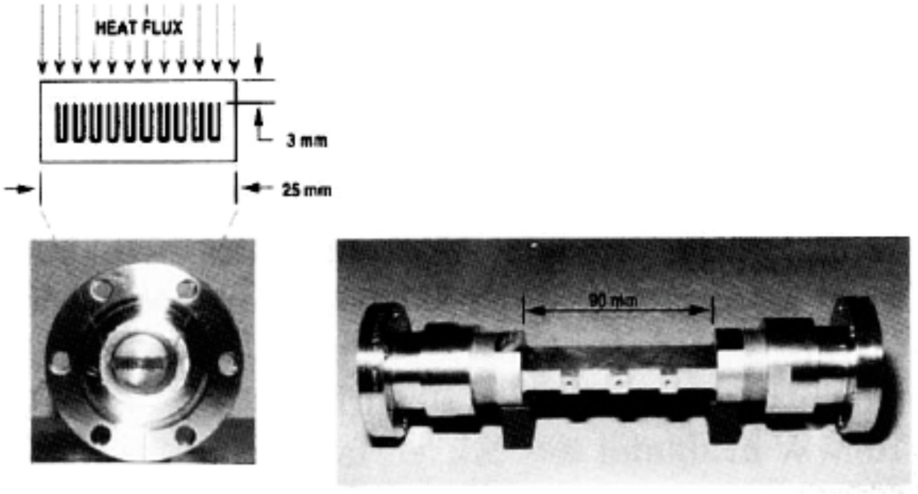


Fig. 1. GA divertor module.

C.B. Baxi / Fusion Engineering and Design 25 (1994) 263–271

Energy sustainment chasm to Component Test Facility (CTF) & DEMO

- **CTF** (Q < 3) cares about energy fluence, period.
  - Power density x Δt: BOTH MATTER!
  - Must also have a closed Tritium fuel cycle!

- **DEMO**: Burn Q > 25 + Power/m^2 x Δt.
  - **P_{exh}/S** ~ 1/4 P_n/S ~ **1 MW/m^2 x 3x10^7 s** ~ 1 full-power year
  - Ambient temperature > 700 C for thermal efficiency
    - Therefore CTF must also have high T walls to test components.

- Present track of devices, including ITER, do *not* address energy sustainment issues required for CTF or DEMO
  - P/S and pulse duration too small.
  - Water-cooled, low-T walls.
  - Open fuel cycle.

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Quiescent energy exhaust *GJ / day*	~ 10	3,000	60,000	- active cooling - max. tile thickness ~ 10 mm
Transient energy exhaust from plasma instabilities $\Delta T \sim MJ / A_{wall}(m^2) / (1\ ms)^{1/2}$	~ 2	15	60	- require high $T_{melt/ablate}$ - limit? ~ 40 for C and W - surface distortion

Rapid dissipation of plasma thermal energy poses major challenges in any Demo

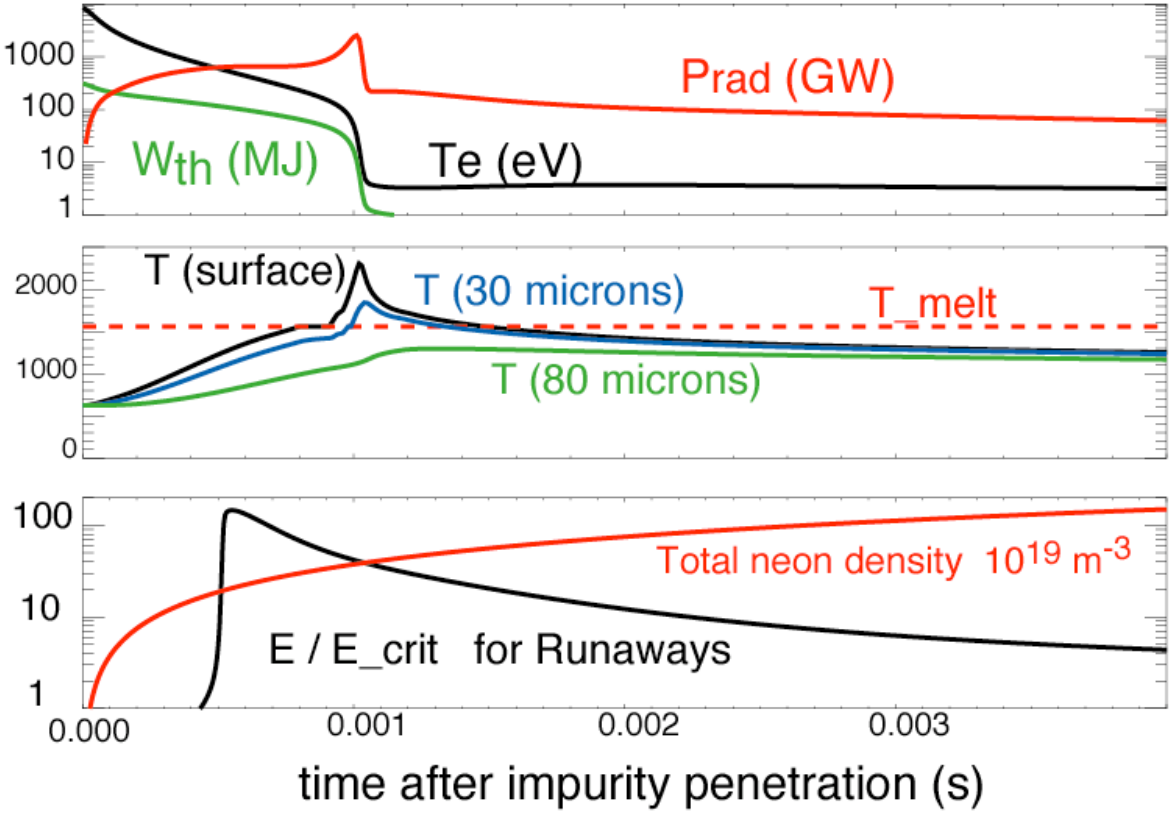
$$T_{surface,\max} = T_{ambient} + C \frac{W_{th}}{A_{wall}\,\tau^{1/2}}$$

Material	T_{max} (K)	Limit MJ m^{-2} $s^{-1/2}$
Be	1550	8
C	**4000**	**42**
Mo	2900	28
W	**3680**	**45**

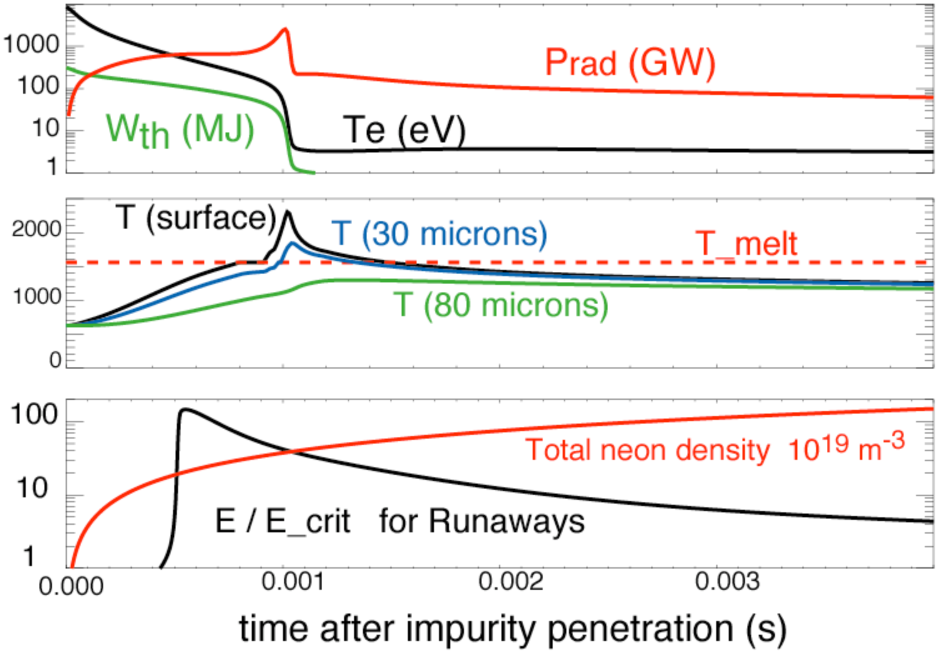
Transient thermal limits
($T_{ambient}$ ~ 1200 K)

Thermal energy dissipation timescale τ ~ ms. Set by both atomic physics & MHD

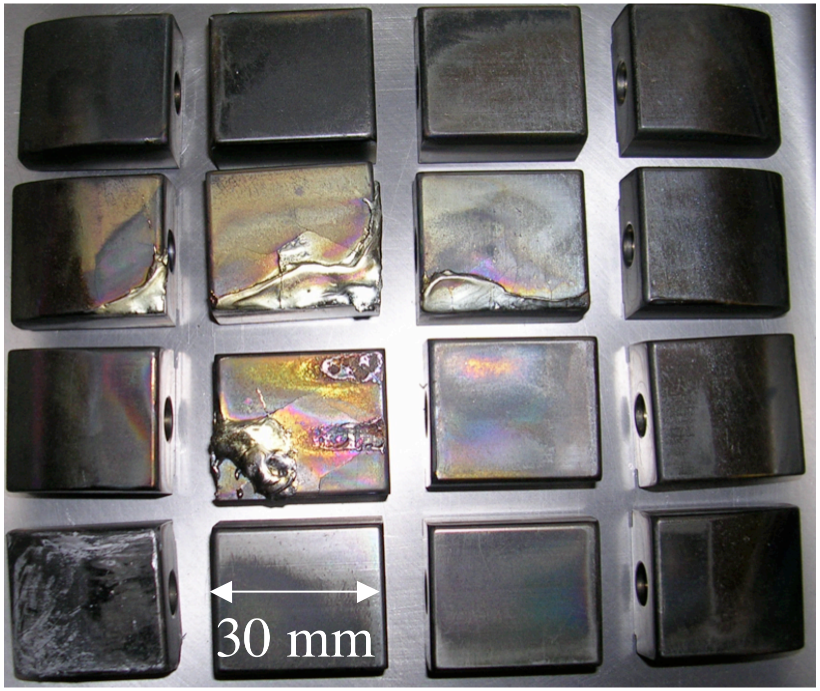
Global energy balance model of ITER disruption mitigation By neon injection



Thermal energy dissipation timescale ~ ms. Can be easily triggered by PSI "failure"



C-Mod Molybdenum (T_{melt}=2900 K) limiter melted during disruptions



- Dilute MFE plasma (n~10^{20} m^{-3}) extinguished by small particulate
  - ➢ 2 mm "drop" of W == $N_{e,ITER}$

Plasma thermal energy intimately linked to fusion power efficiency. Near “perfect” dissipation will still be major challenge in any Demo

$$\frac{W_{th}}{A_{wall}\,\tau^{1/2}} \sim \frac{pV}{A(R/c_s)^{1/2}} \sim P_{fusion}^{1/2}\,\varepsilon R^{1/2}$$

- Only flexibility is in τ.
  - Will large-scale tokamaks & stellarators have τ > ms?
  - Can we trick the plasma into having τ > ms, opacity?
  - Liquid walls?

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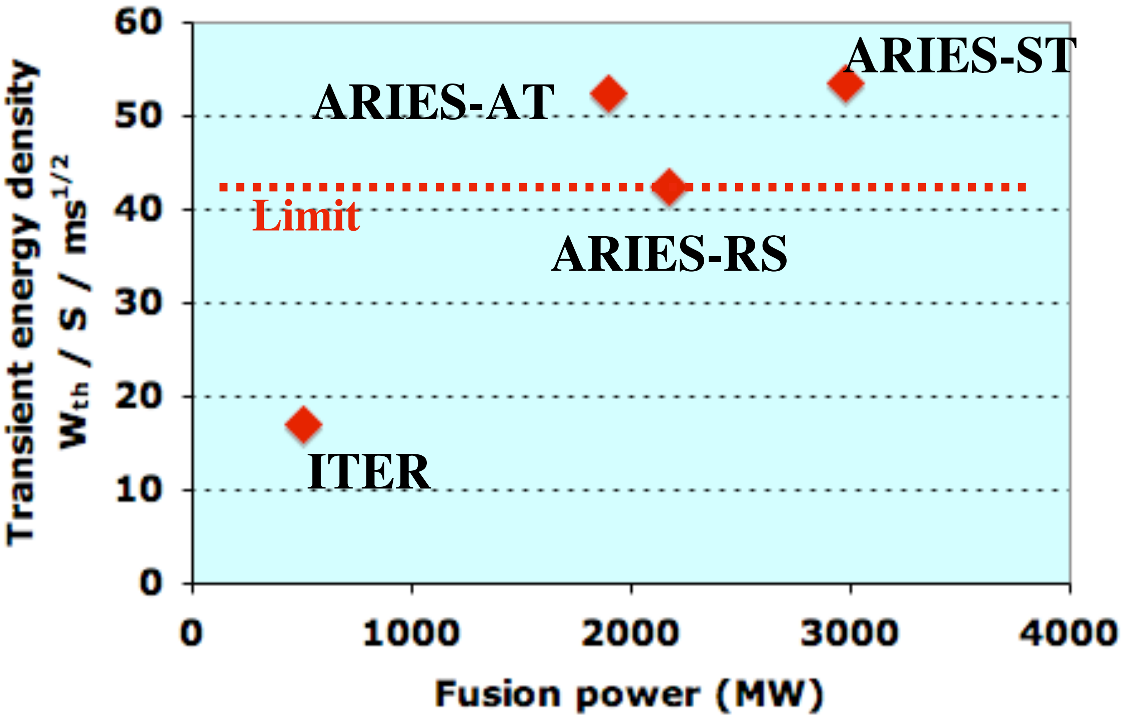
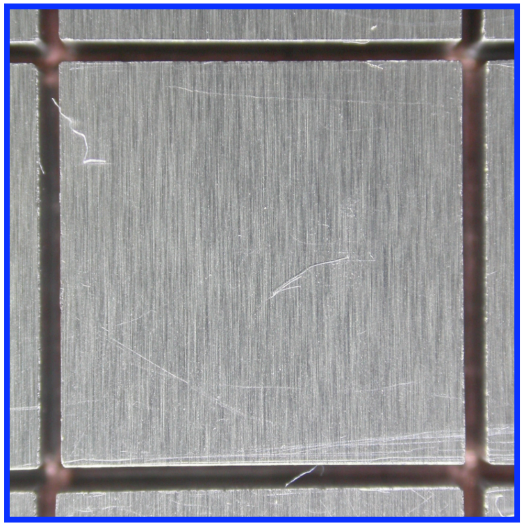


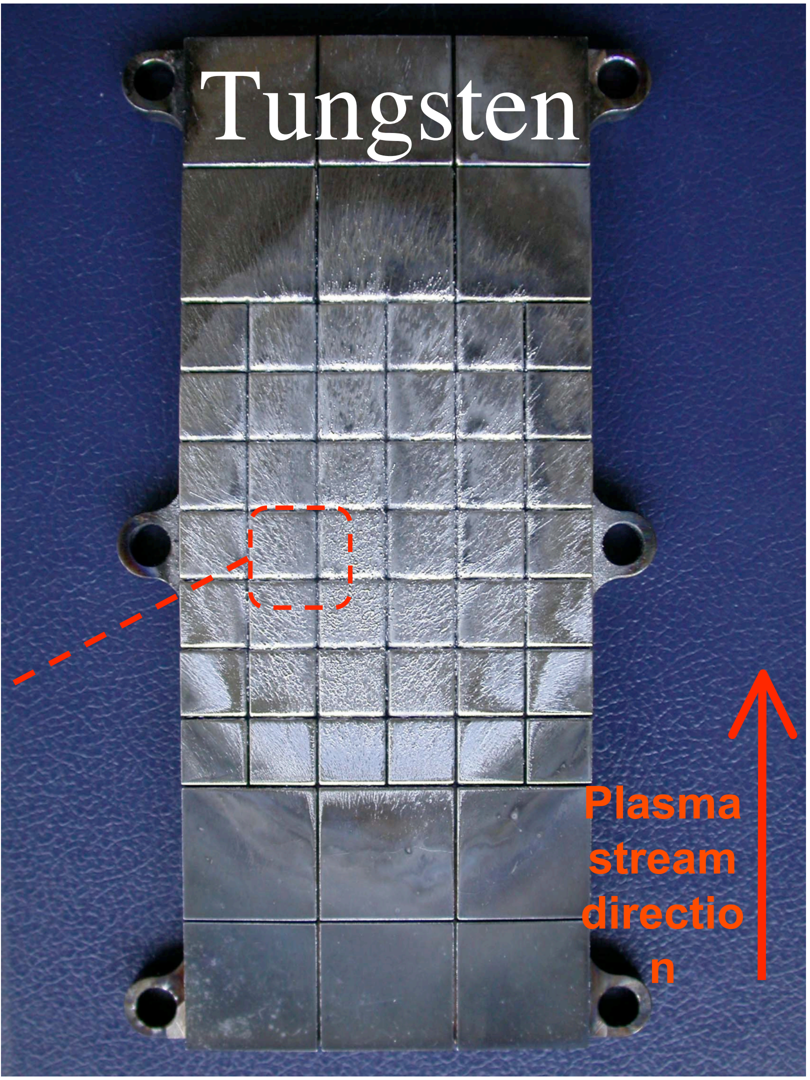
Transient thermal limits

Similar arguments apply to even “minor” transient heating in reactor-class devices. E..g. Material heating limits lead to very restrictive ELM size in ITER

Before exposure



After
5 “large”
ELMs
(~2 MJ / m^2)



Klimov PSI08

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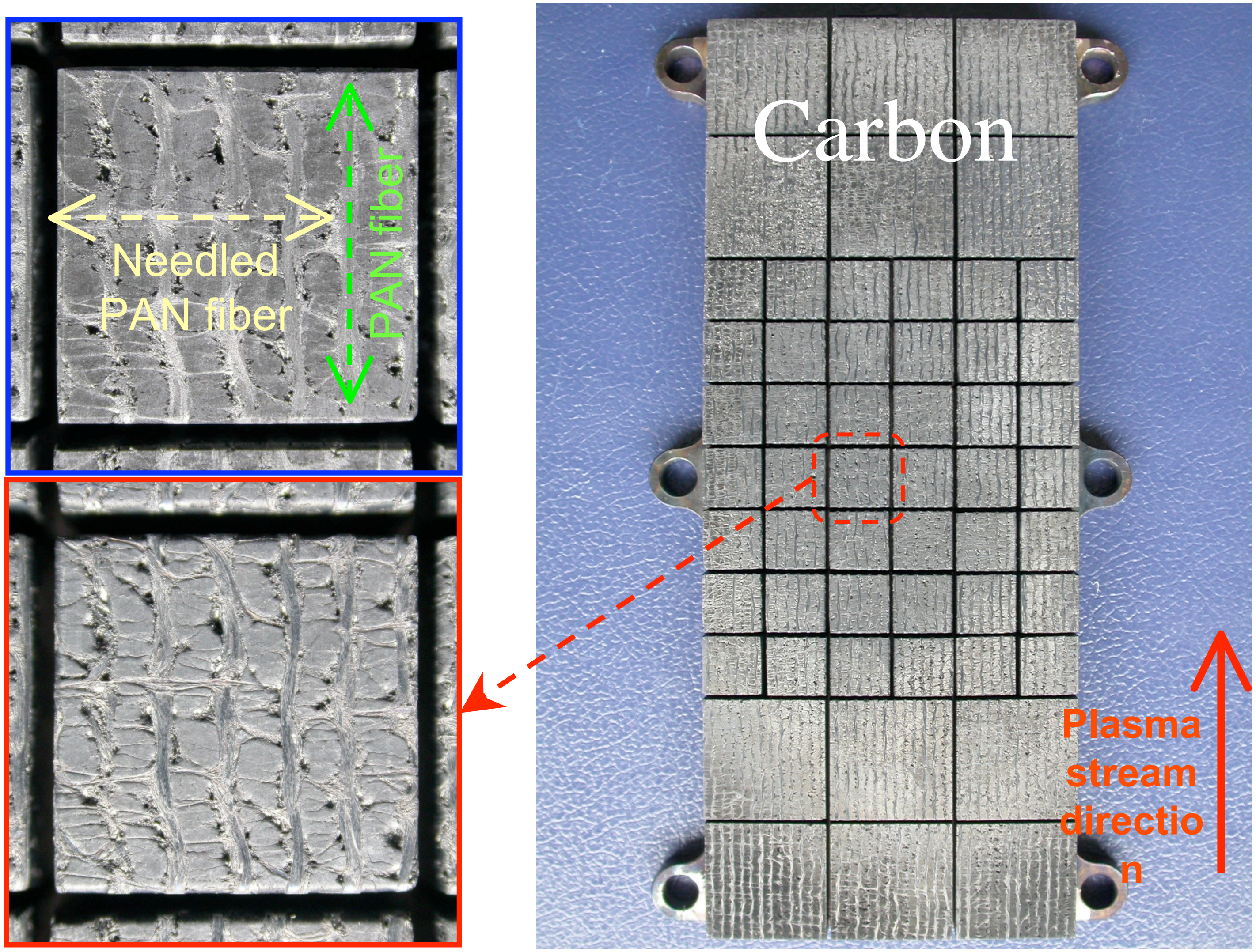
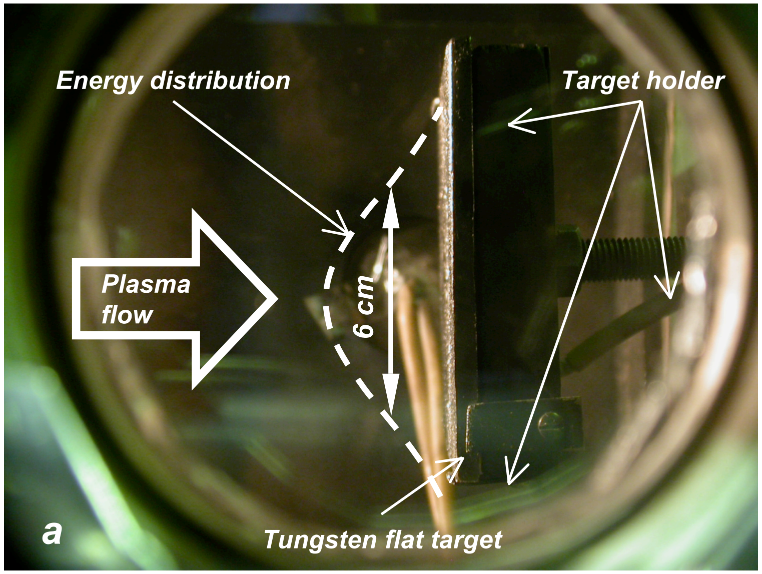
Before exposure

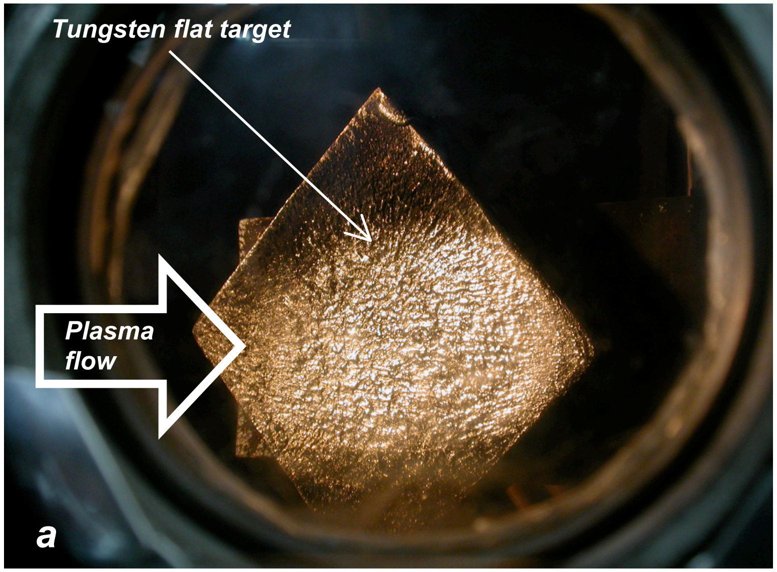
After 5 pulses

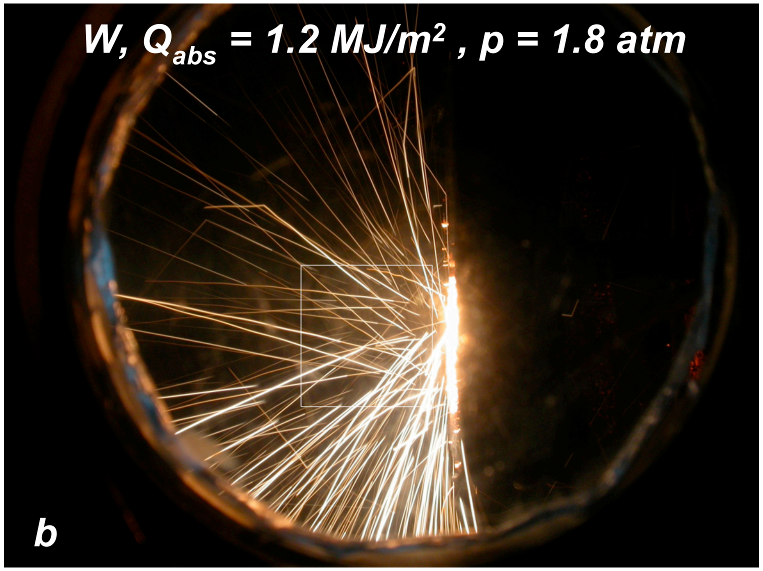


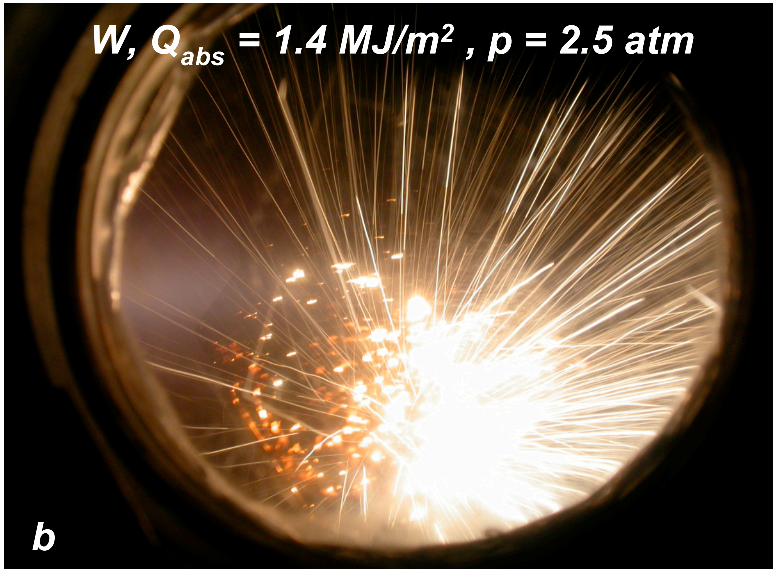
Klimov PSI08

The consequences of large particulate removal on both plasma survival & safety are unknown






W, Q_{abs} = 1.2 MJ/m^2 , p = 1.8 atm


W, Q_{abs} = 1.4 MJ/m^2 , p = 2.5 atm

Klimov PSI08

Controlling PSI becoming increasingly important and difficult as we move from present tokamaks → ITER → demonstration fusion power plants

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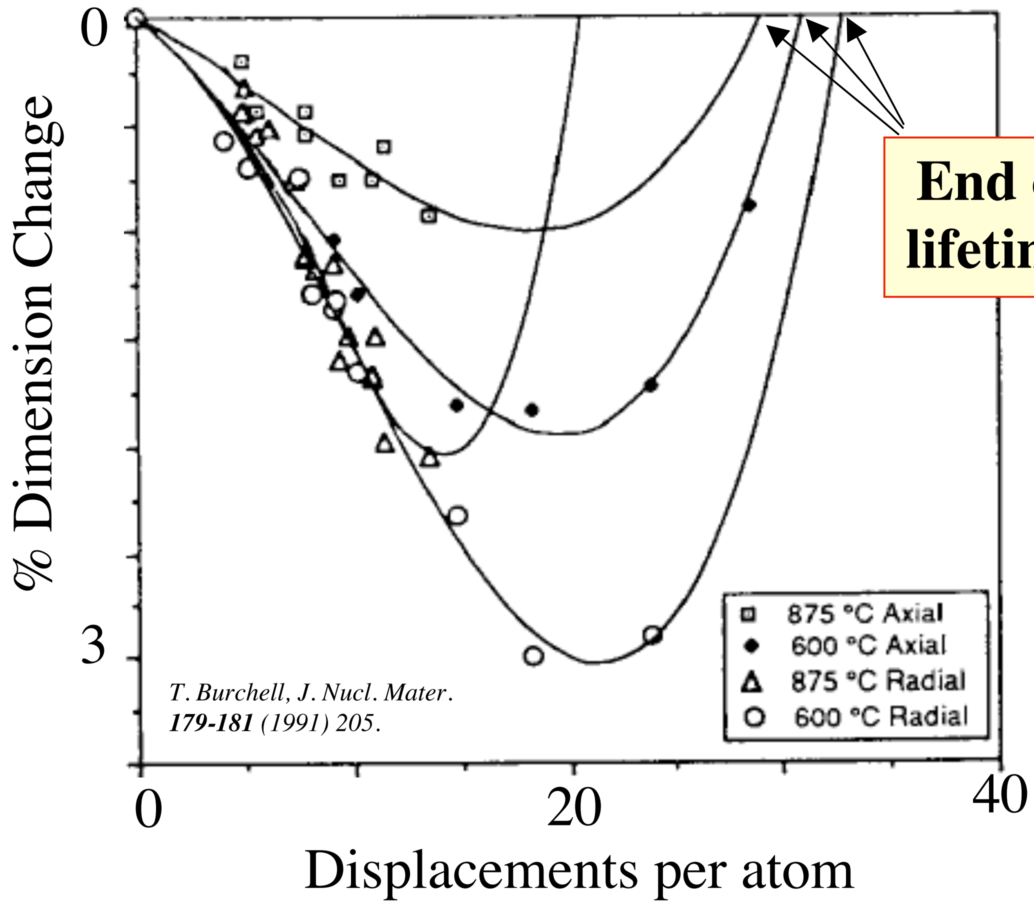
Yearly neutron damage in plasma-facing materials *displacements per atom*	~ 0	~ 0.5	20	- evolving material properties: thermal conductivity, swelling, traps for tritium

14 MeV neutron-induced damage set lifetime limits for graphitic fusion materials

Neutron induced shrink/swell in N3M graphite

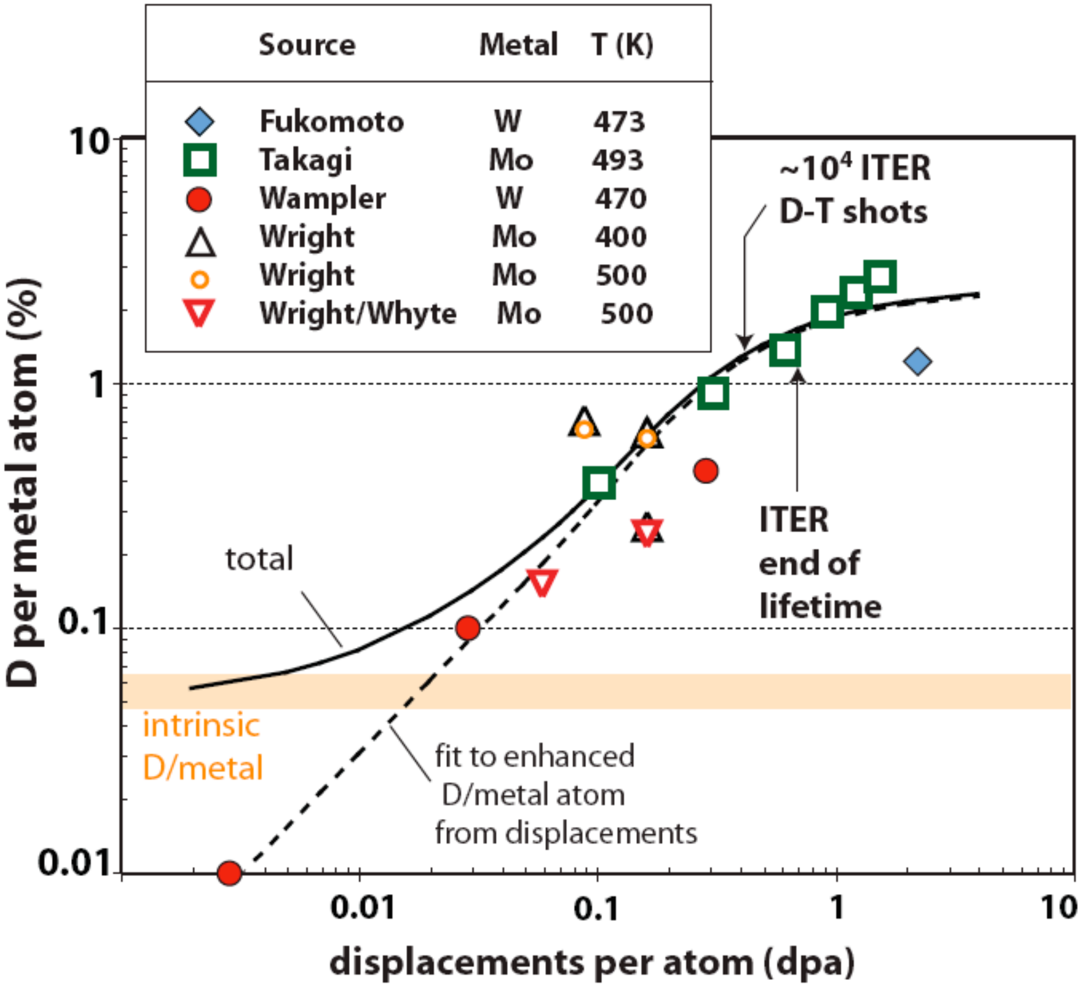


T. Burchell, J. Nucl. Mater. ***179-181*** *(1991) 205.*

End of lifetime

An emerging area of study: Neutron damage producing Tritium trap sites in refractory metals like tungsten

- Neutron-induced displacements produce damage “trap” sites for D/T fuel in bulk of material
    - Lab studies ~ 0.1 - 0.3 trap / dpa that saturate 1% traps / atom.



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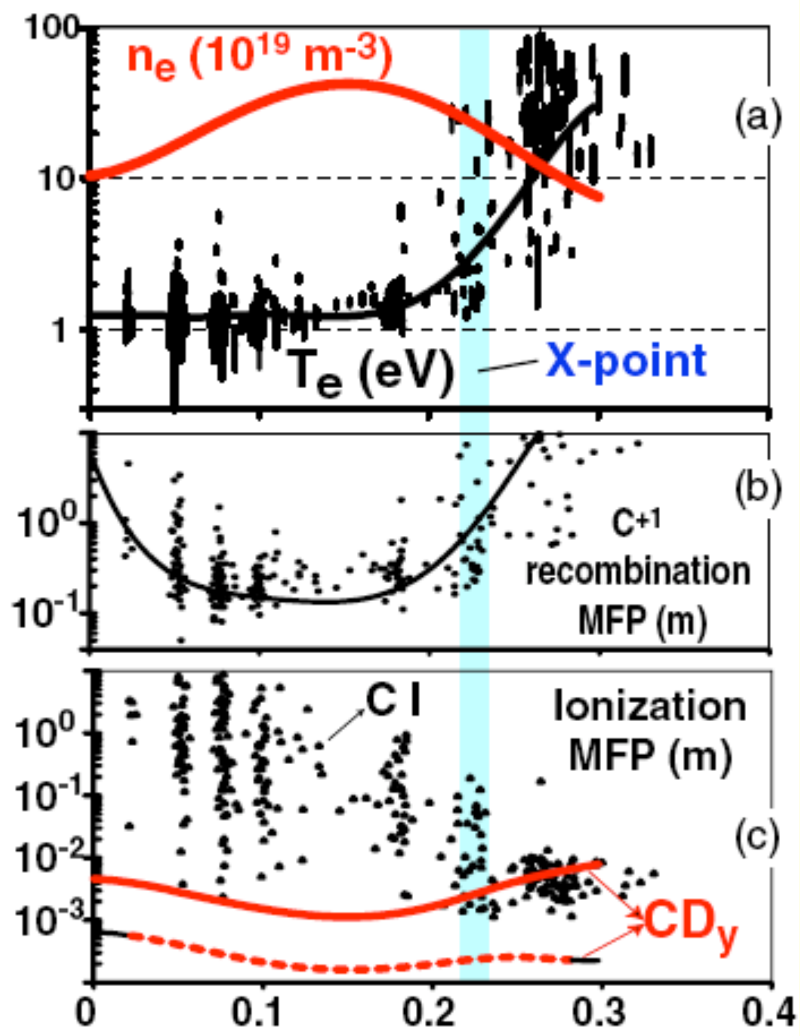
Max. gross material removal rate with 1% erosion yield *(mm / operational-year)*	< 1	300	3000	- must redeposit locally - limits lifetime - produces films

Tokamak edge plasmas feature extreme spatial gradients and fluctuations levels, making erosion prediction and control very difficult

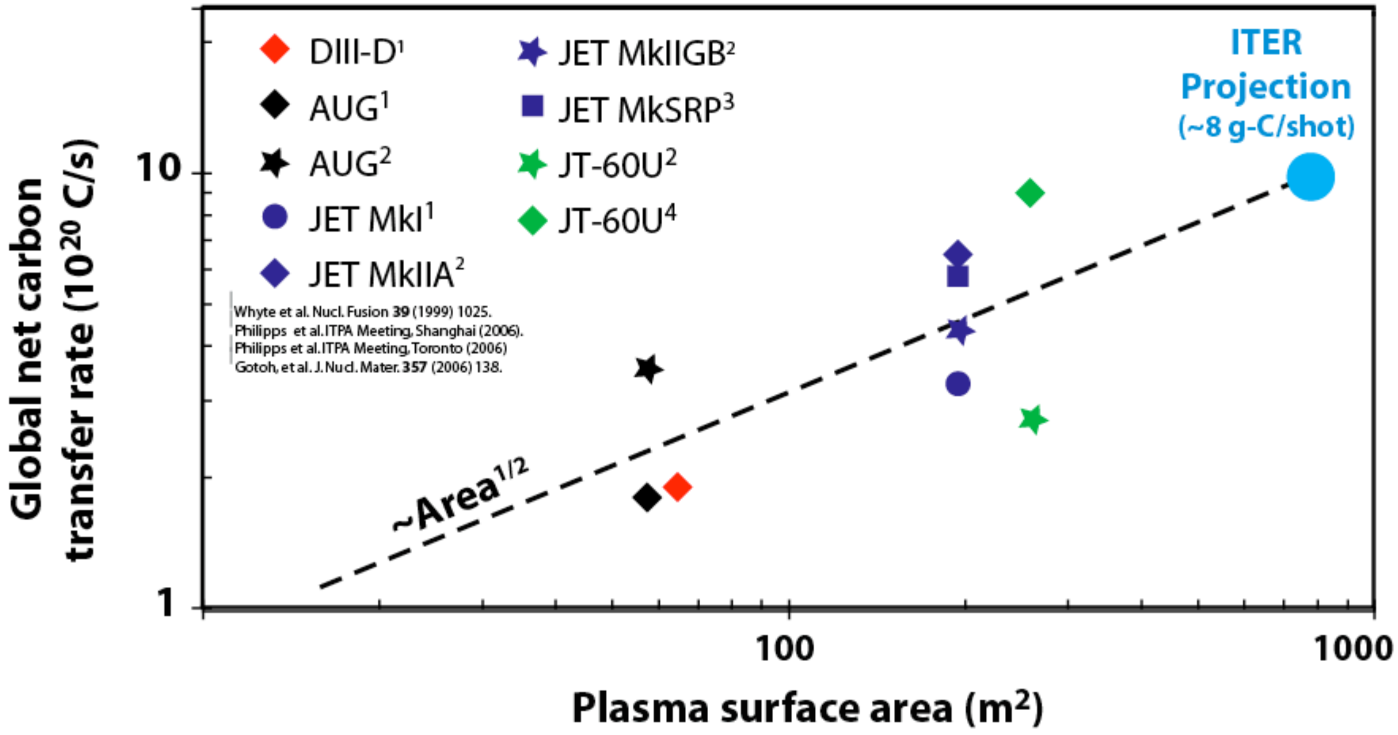
- Extreme range (100 eV → 1 eV) is possible for plasma temperatures
    - Highly ionizing → recombining.
    - Physical sputtering → chemical removal.
- Develops large-scale sonic flows to surfaces.
    - Particle flux density ~ 10^5 A / m^2
- **Key result: PFC species have ionization distances << linear size of divertor targets**
    - **Every atom removed from surface has already been removed and replaced by plasma many times over.**
    - **Plasma and surfaces are strongly coupled to each other**

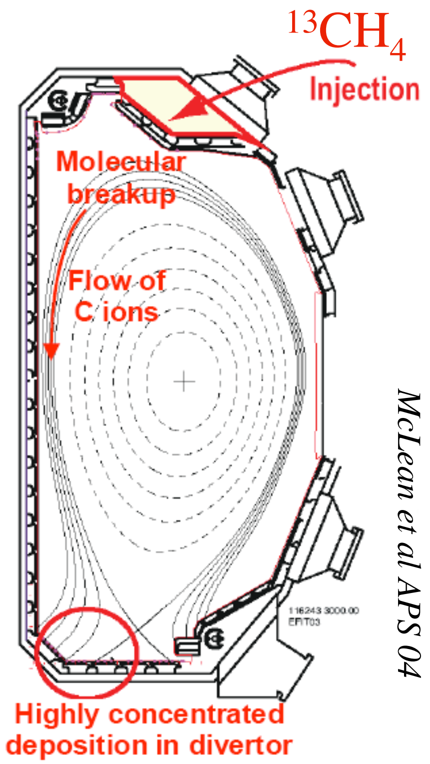


Vertical distance from divertor surface (m)

Whyte et al. Nucl. Fusion ***41*** *(2001) 1243*

“Archeological” deposition measurements: Tokamak plasmas effectively net “transfer” carbon from one location of the wall to another





McLean et al APS 04

- Controlling mechanisms of erosion sources, long-range transport and deposition balance are not understood.

A new generation of innovative in-situ PSI diagnostics are being developed on C-Mod

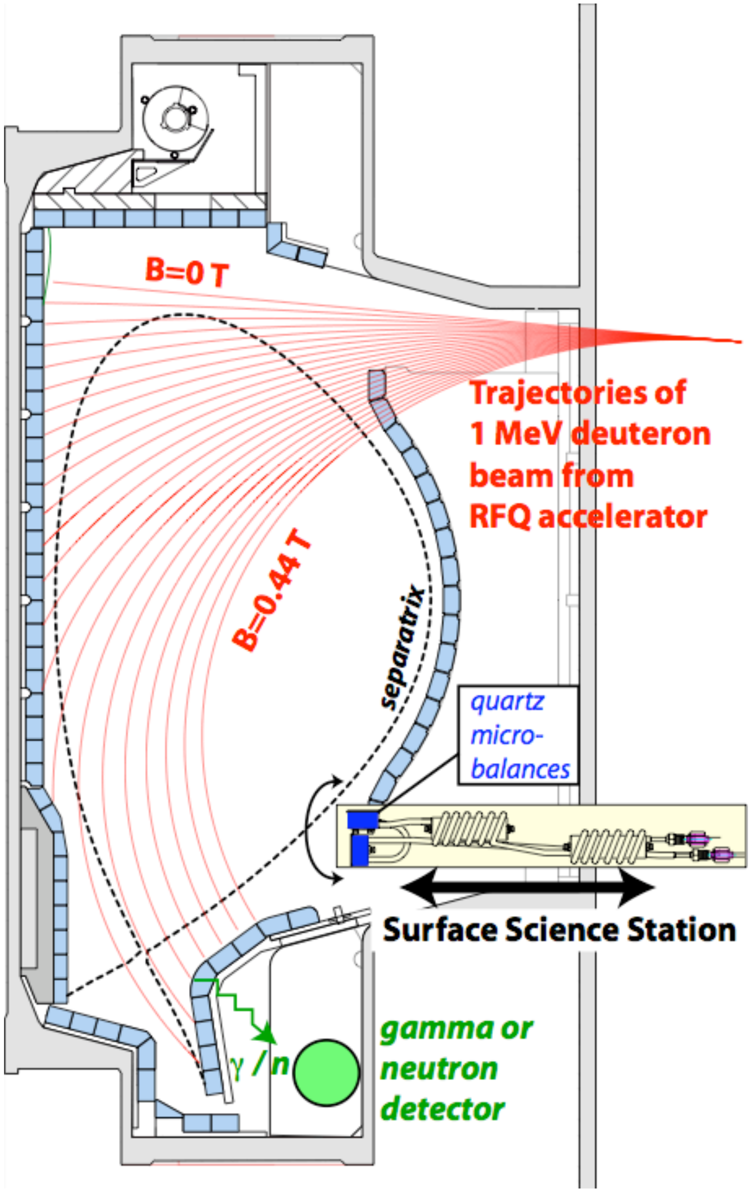
Example: RFQ accelerator

- High-current cw RFQ accelerator attached to the tokamak

- Innovation: Exploit intrinsic magnetic fields to steer beam to any poloidal (toroidal) location.

- Shielded neutron + gamma detection from MeV D beam nuclear reactions with PFCs

- Shot-to-shot “maps” of erosion, redeposition and tritium retention, depth resolved to penetration distance of beam (~10 microns).



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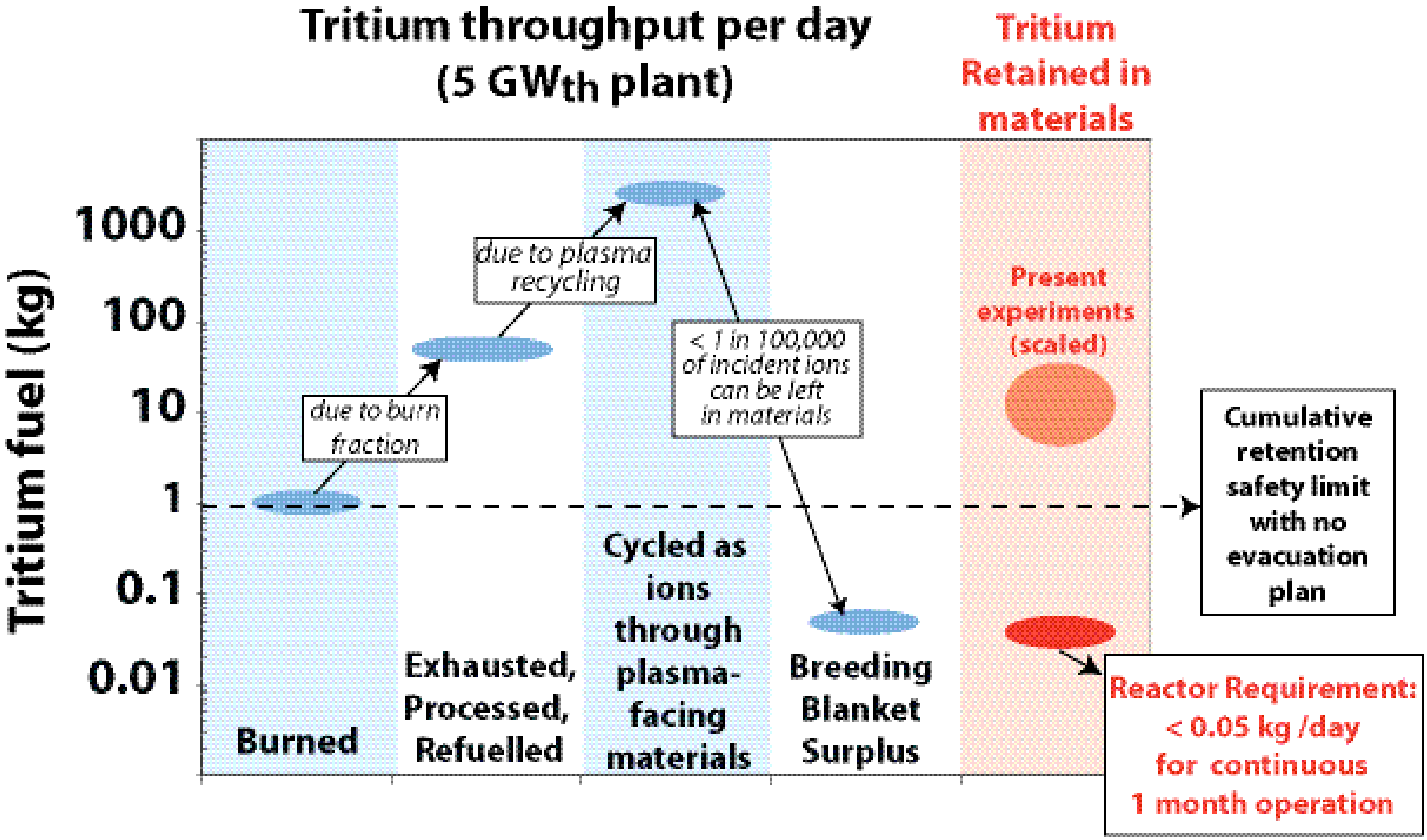
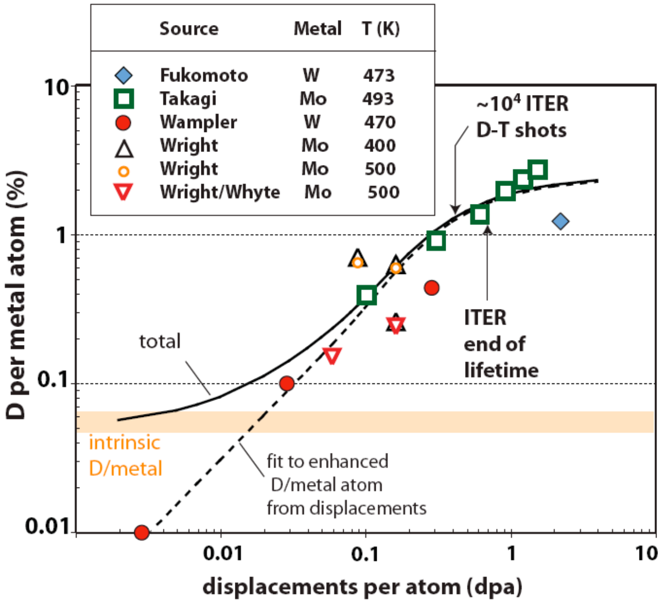
Max. gross material removal rate with 1% erosion yield *(mm / operational-year)*	< 1	300	3000	- must redeposit locally - limits lifetime - produces films
Tritium consumption *(g / day)*	< 0.02	20	1000	- Tritium retention in materials and recovery

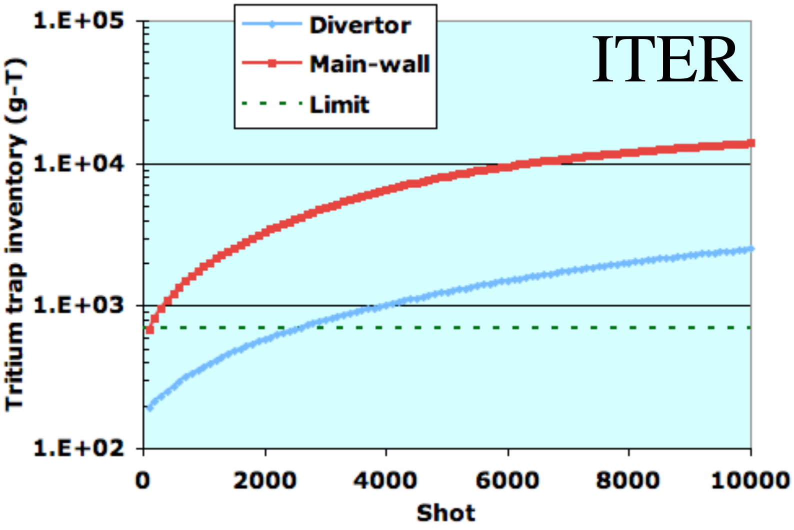
Tritium retention in Demo must satisfy fuel cycle and regulatory limits: Orders of magnitude improvement required.



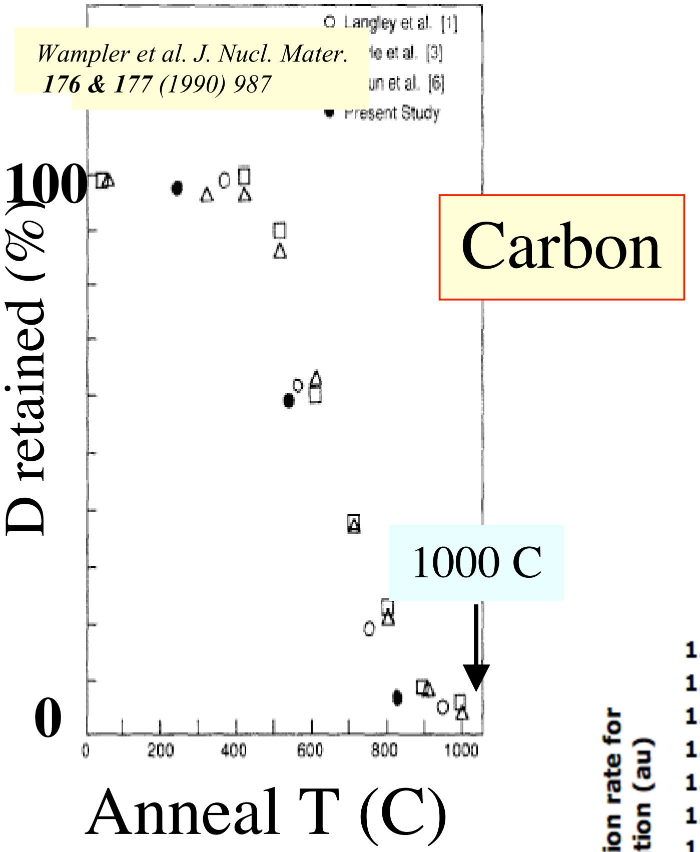
An emerging area of concern:
Neutron damage producing Tritium trap sites in refractory metals

- Neutron-induced displacements produce damage “trap” sites for D/T fuel in bulk of material
  - ➢ Lab studies ~ 0.1 - 0.3 trap / dpa that saturate 1% traps / atom.
- High temperature MUST heal these traps since in a D-T reactor ~ 20 kg Tritium can be stored in (Traps / atom) ~ 10^{-2}
  - ➢ Surpassed in a few hours in Demo due to high permeability of the D/T in tungsten at high ambient temperature.
  - ➢ Entire world supply of tritium.



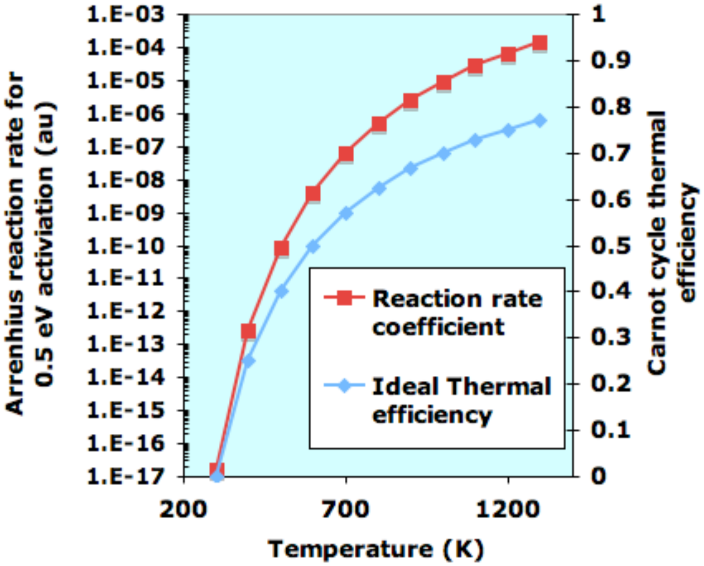


It is hard to overstate the importance of ambient temperature for fuel control & T retention

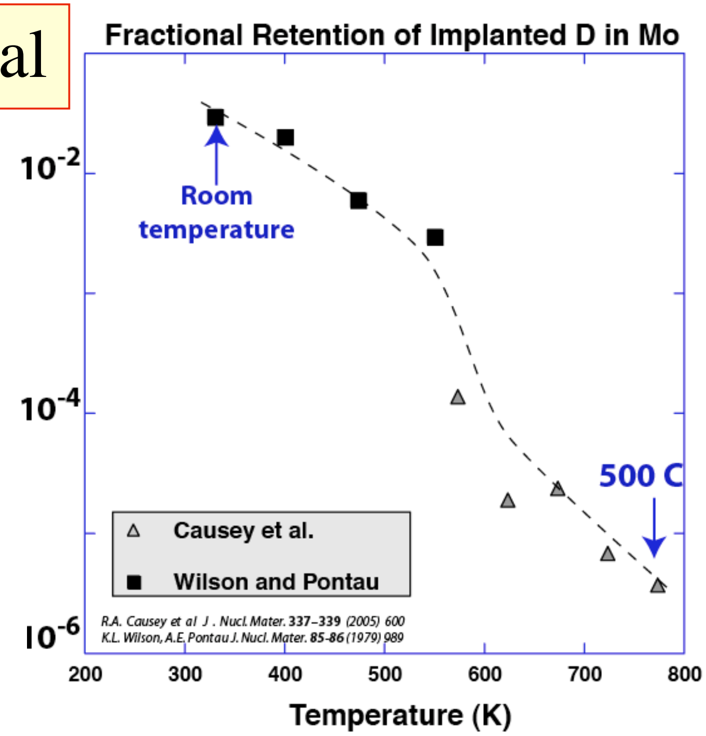


Carbon

Wampler et al. J. Nucl. Mater. ***176 & 177*** *(1990) 987*



High-Z metal



R.A. Causey et al J. Nucl. Mater. 337–339 (2005) 600
K.L. Wilson, A.E. Pontau J. Nucl. Mater. 85-86 (1979) 989

30+ years of experience in confinement devices tells us we should be worried/excited about all this, and in particular the effects of having "hot walls"

- Every major (and minor) modification to the wall surfaces had profound effects on core performance.
  - E.g. lithium layers (TFTR, NSTX), He discharge cleaning (TFTR, DIII-D, etc), boronizations (DIII-D, C-Mod, etc.), ad infinitum

- **Can we be so naïve that ~10 orders of magnitude modifications to boundary condition of wall will not have profound effects on the core?**

- Must assess effects experimentally but can make educated guesses
  - **Fuelling balance: surface strongly desorbed of H_2 --> no retention?**
  - **Recycling: depleted walls?**
  - **Safety: flakes/dust fully T depleted, reactivity?**
  - **Impurity control: ~ ZERO vacuum impurities (H_20, C_2O)**
  - **High-Z materials: fuel permeated through wall, no sputtering?**
  - **Erosion control: Hydrogen activity with materials fundamentally modified.**

Conclusion: The PSI chasms to ITER, then Demo, are so large we must start to address them now

- Every PSI issue pushes us to our science and technology limits
  - Power density (P/S ~ 1 MW/m^2) x duration (30,000,000 s)
  - Transient energy dissipation: all materials at / past thermal limits.
  - Erosion and fuel control
  - Evolving quasi-equilibrium due to neutron damage.

- Where do we start?
  - We must assess materials in the proper physical chemistry range (T_{wall})
  - Establishing quasi-equilibrium between PFC materials and plasma will be a key scientific advancement.
  - A new generation of innovative in-situ PSI diagnostics are essential.

- The fusion community must realize this is not “just” a technology issue, but rather a grand “fusion science” challenge since it deals with nearly every aspect of plasma and material science.