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International Workshop on the Frontiers of Modern Plasma Physics

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Plasma-Wall Interaction Issues in ITER.

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Plasma-Wall Interaction Issues in ITER

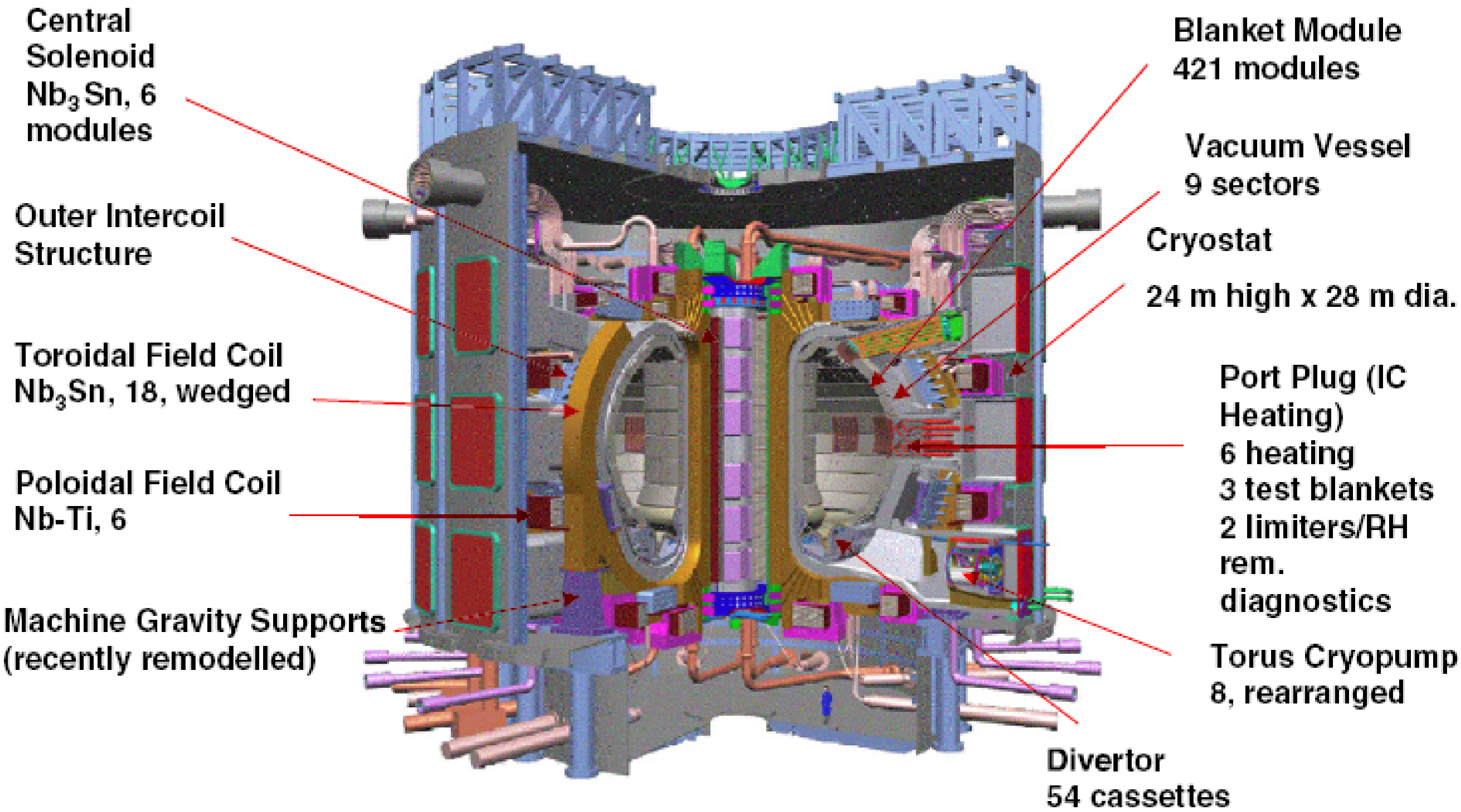
International Workshop on the Frontiers of Modern Plasma Physics

Trieste, Italy, 22 July 2008

M. Shimada, ITER Organization

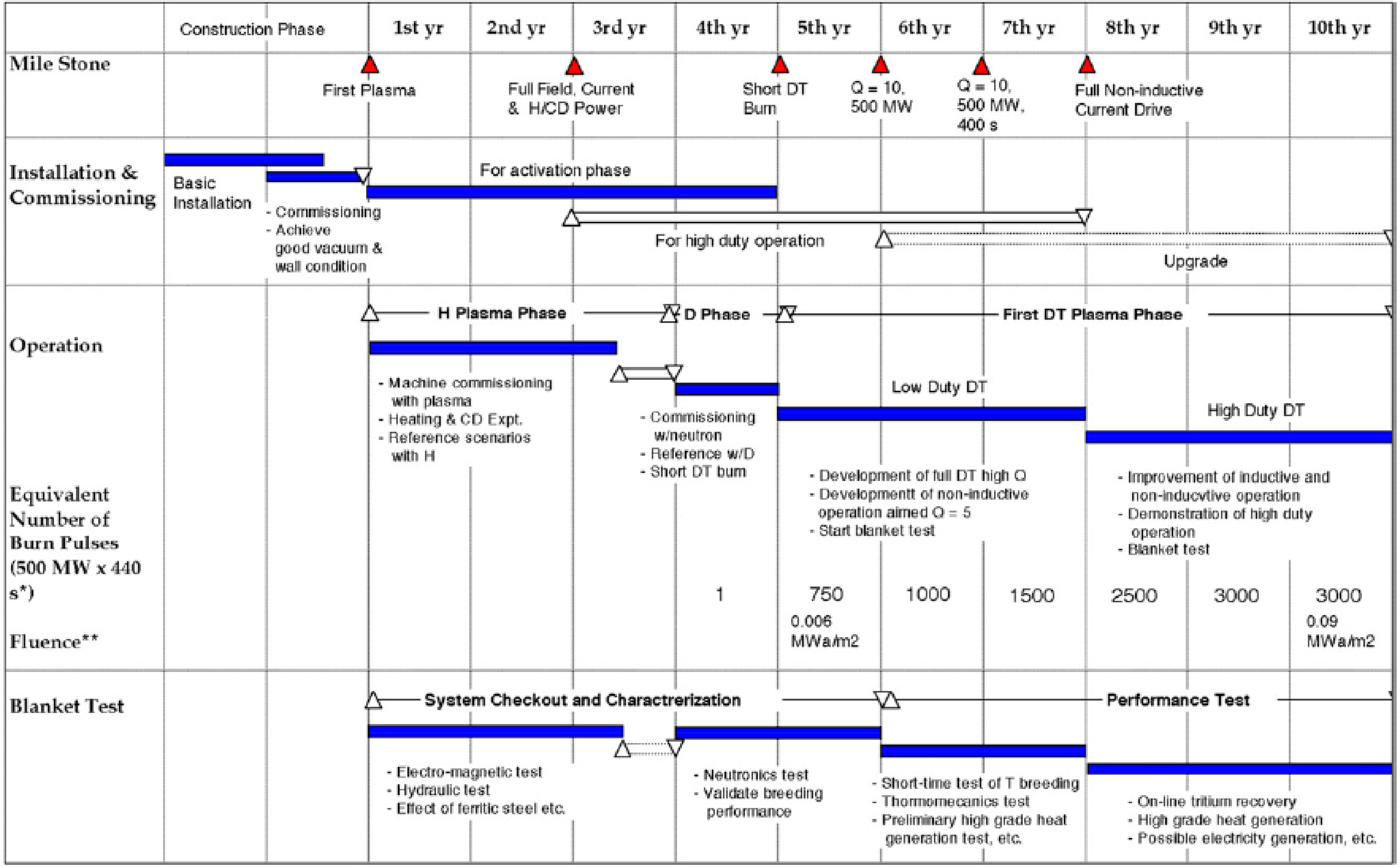
special acknowledgement: J. Roth

ITER



Fusion power: 500 MW, $Q = P_{fusion}/P_{aux} > 10$, $P_{\alpha}/P_{heat} > 0.8$, burn time = 300-500 s
Steady state (burn time ~3000 s), Q > 5

ITER Operation Schedule (Provisional)



* The burn time of 440 s includes 400 s flat top plus 40 s of full power neutron flux to allow for contributions during ramp-up and ramp-down

** Average fluence at first wall (neutron wall load is 0.56 MW/m^2 on average and 0.77 MW/m^2 at outboard equator)

Challenges in ITER

- Important step toward Demo
  - Demonstration of Q>10, long burn and Q>5 steady state
  - Avoidance or significant mitigation of disruptions and ELMs
  - Test of reactor-relevant PFCs (tungsten)
- Large stored energy (350 MJ/~10MJ in JET & JT-60U)
  - consequences of disruption and ELMs are much more serious
- Nuclear
  - Control of T retention and dust essential
- Long pulse, steady state
  - PFCs will be saturated with DT: start-up?
- Diagnostics
  - Limited access, irradiation-induced effects, first-mirror coating…

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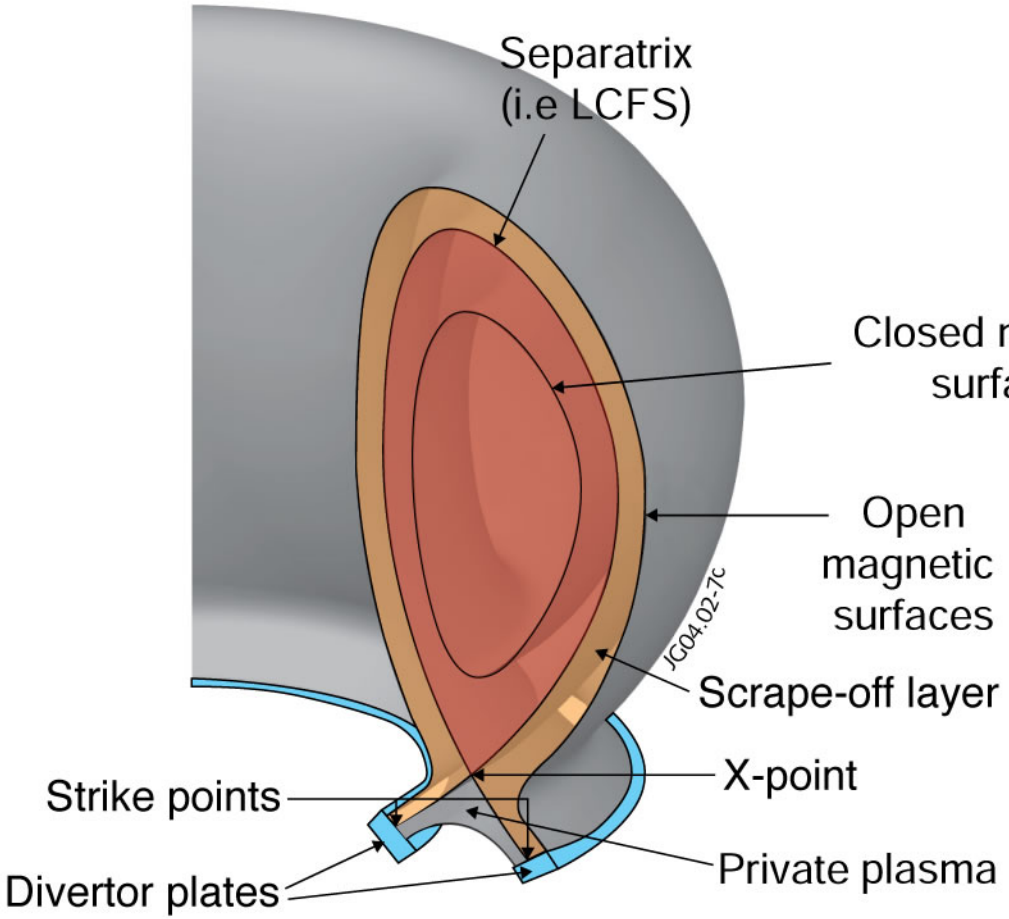
- ITER
- PWI issues
  - Impurity
  - Heat loads and erosion
  - Tritium retention
  - Material
  - Dust
- summary

Tokamak divertor configuration



Impurity

- Radiation
  - radiation in the core is detrimental for confinement

$$dW/dt + W/\tau_E = P_{heat} - P_{rad}$$

  - e.g., with tungsten concentration of $>10^{-5}$, H-mode confinement cannot be sustained
  - radiation in the divertor is beneficial for reduction of divertor heat load
- Dilution
  - electron density has a limit

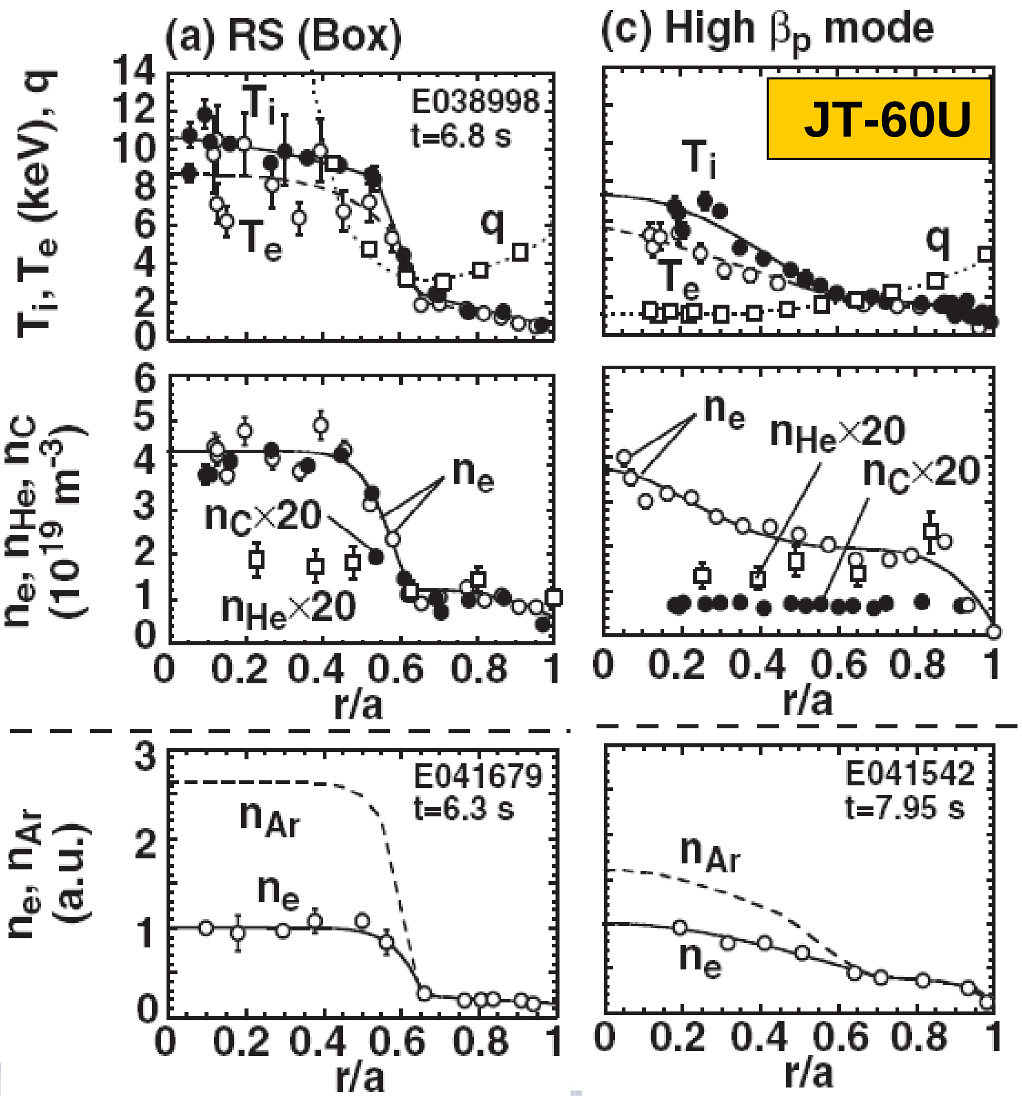
$$n_e = n_{DT} + \Sigma Z_i n_i$$

  - too much impurity would reduce the fuel density and fusion power

Impurity accumulation in the core

with ITB | **without ITB**

$Z_{eff} - 1 \sim P_{rad} / n_e^2$



Impurity density roughly uniform in the absence of an ITB

ITB acts as a barrier for impurity transport as well as for transport of fuel ions and energy

Inward velocity of impurities (neoclassical and turbulent pinch) overcomes outward diffusion

Impurity accumulation increases with ion charge

Cause for concern for both medium and high-Z impurities

*H.Takenaga et al, NF **43** (2003) 1235*

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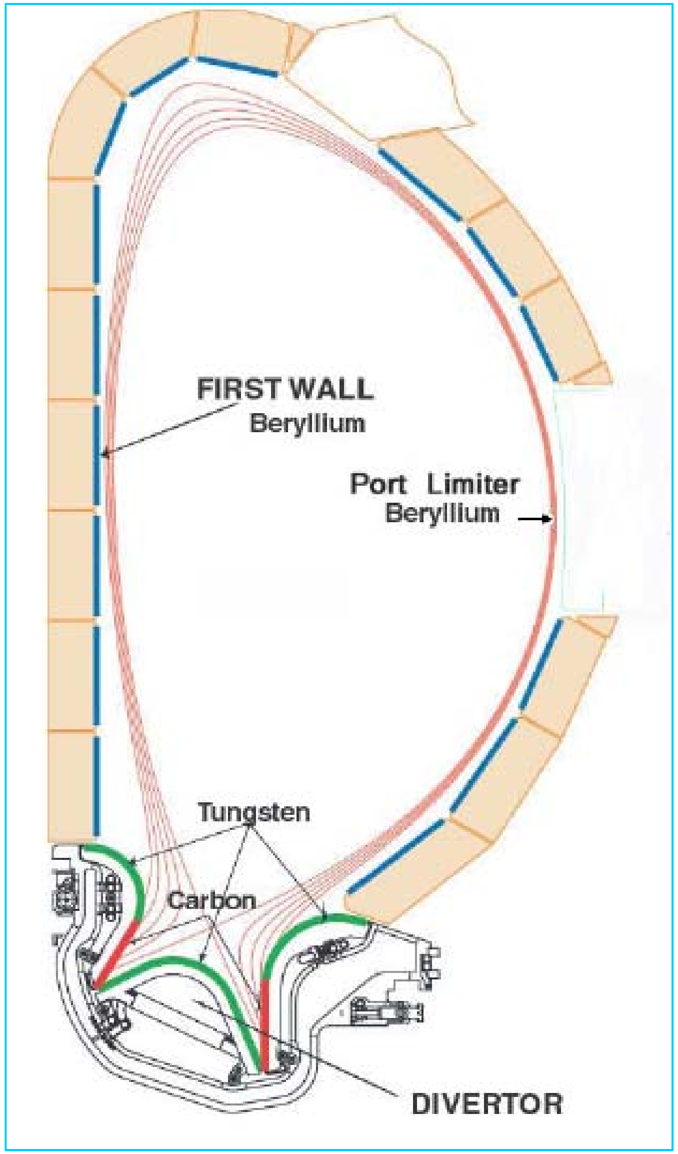
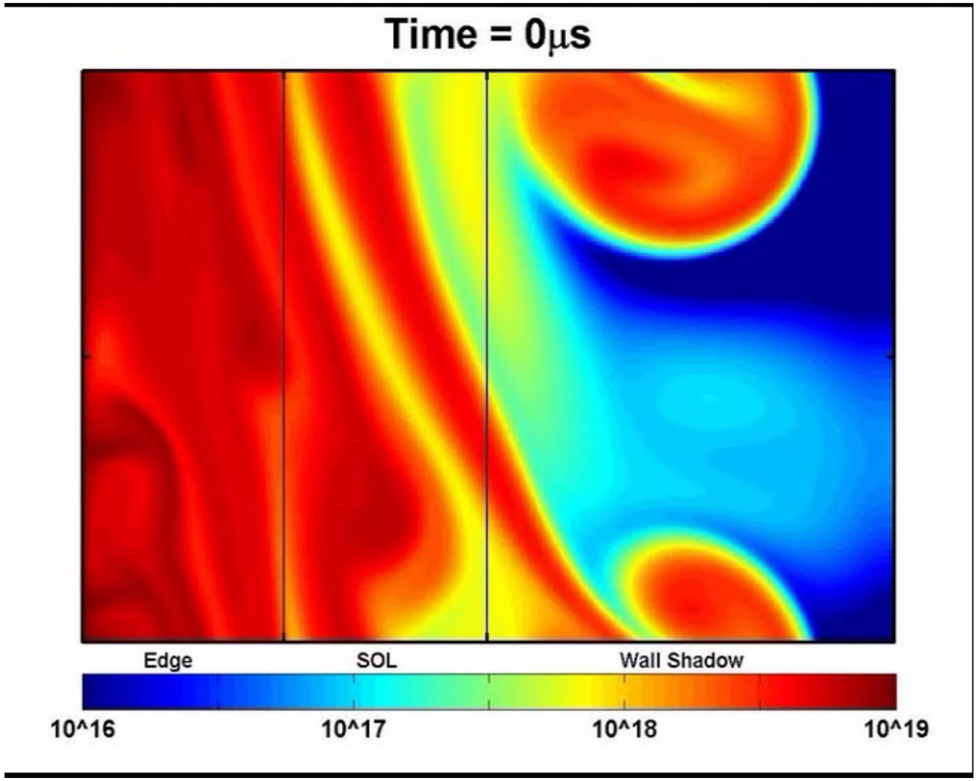
Divertor configuration and PFCs



New Understanding of Intermittency

- **2D fluid turbulence simulations reproduce some scaling and dynamics**



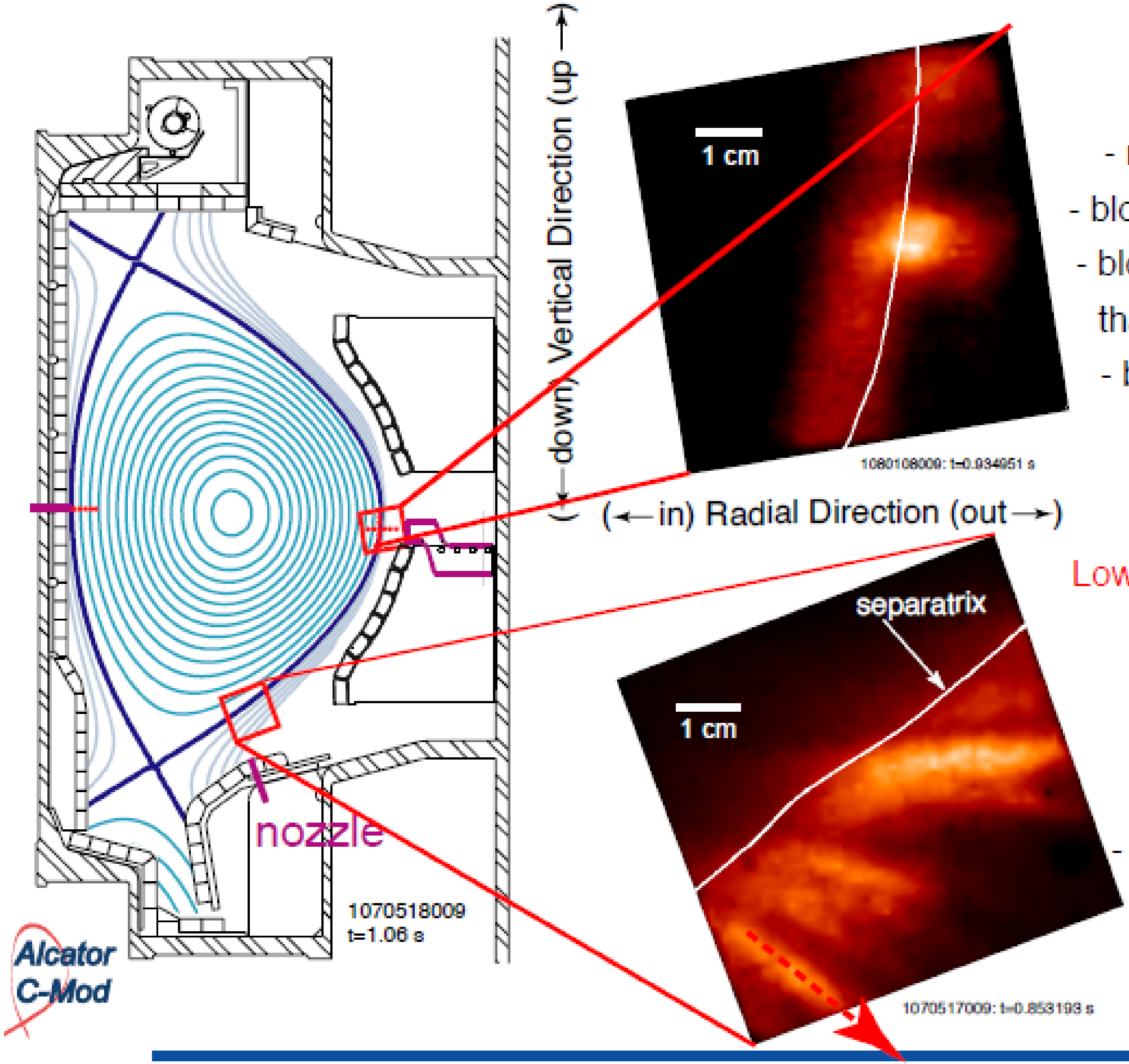
2D electrostatic fluid turbulence simulations of TCV midplane SOL plasma (ESEL code, Risø) – successfully benchmarked against turbulence measurements

O. E. Garcia et al., PPCF (2006) , J. Nucl. Mater., (2007)

Russell et al, PoP 2006

Turbulence Imaging at Outboard Midplane and Lower X-pt Region

J. Terry PSI-2008



Midplane Characteristics:

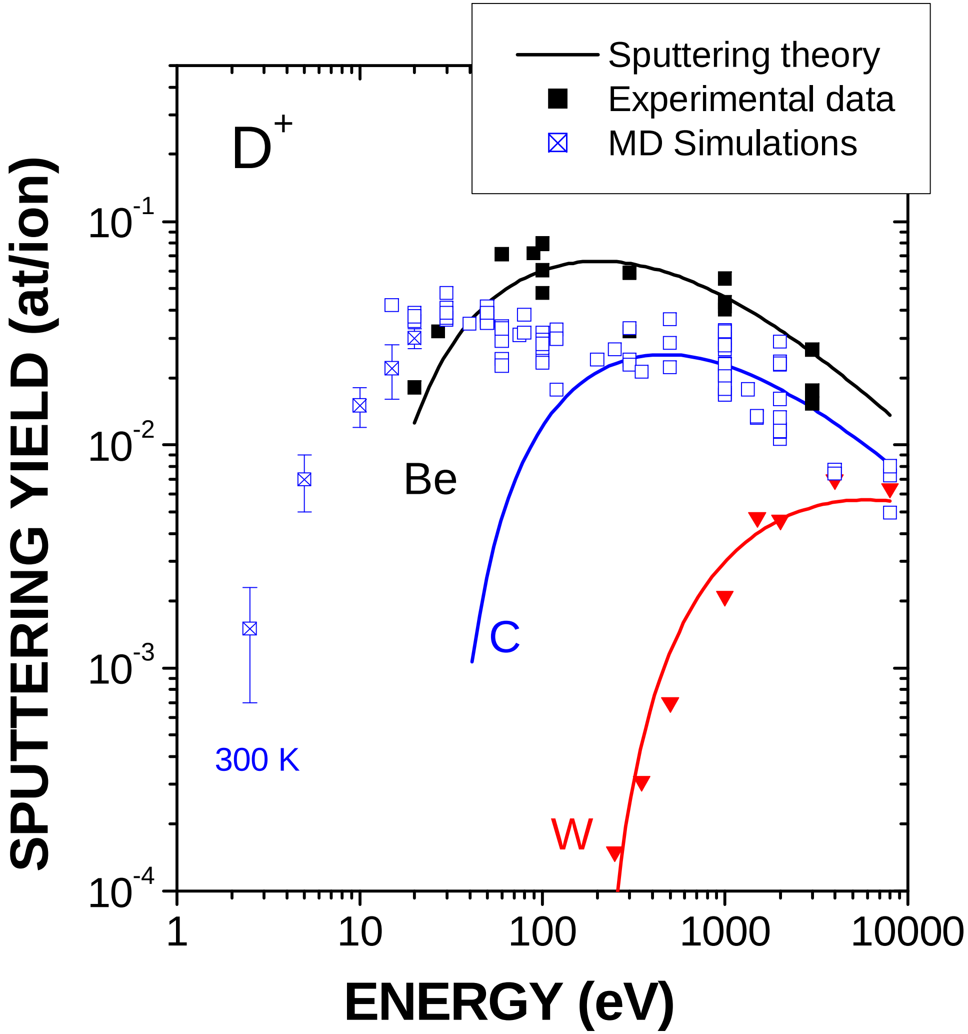
- intermittent/bursty
- not seen at inboard midplane
- blobs roughly circular ~1 cm diam
- blobs co-exist with potential pert. that has dipole spatial structure
- blobs are X-sects of filaments

Lower X-pt-region Characteristics:

- bursty/intermittent
- finger-like structure
- fingers very tilted wrt hor. in lower part of image
- motion perp to flux surfaces

Lifetime of PFCs

Erosion assessment from laboratory data:



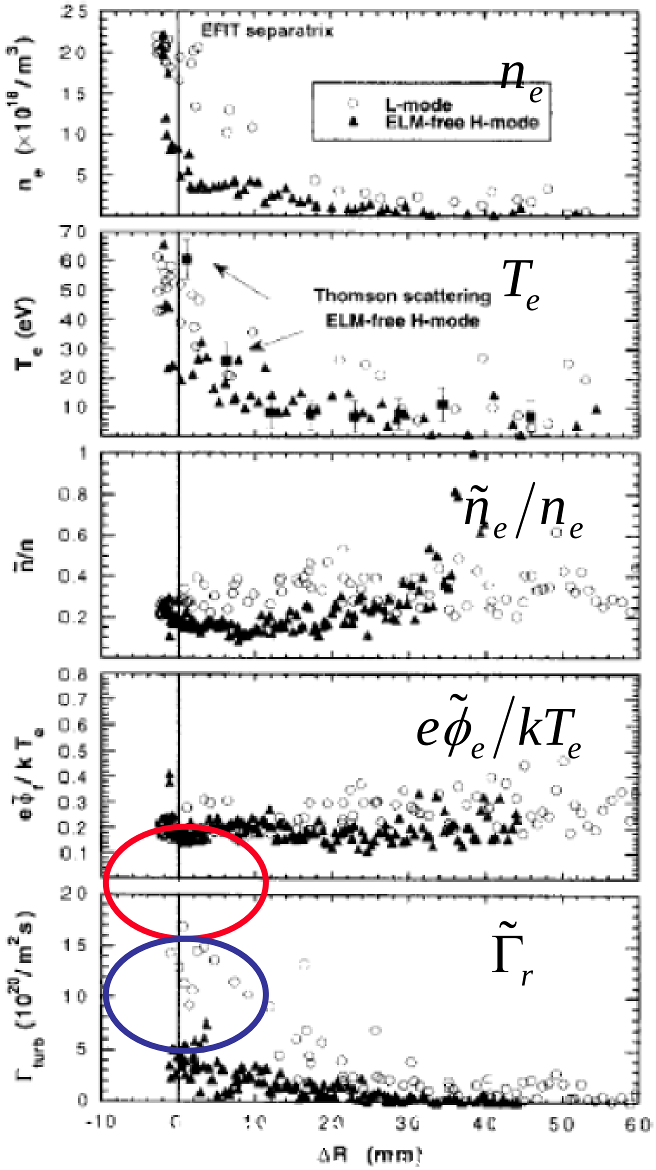
E. Salonen, Phys.Rev.B 2001, M. Balden, J.Nucl.Mat. 2000

Physical sputtering understood and well predictable

Chemical sputtering widely investigated and well described

The multi-step process can be strongly modified by material mixing

Core-Edge-SOL Interplay



Turbulence and transport lower in H-mode

Fueling to the SOL is reduced

Edge turbulence stabilization by Velocity Shear leads to H-mode

R. Moyer, et al, JNM, 96
C. Ritz, et al; Hidalgo et al,
Endler et al

J. Boedo et al, PRL 99, Taylor et al
Weynants et al; Jachmich et al
Tynan et al,

Endler et al

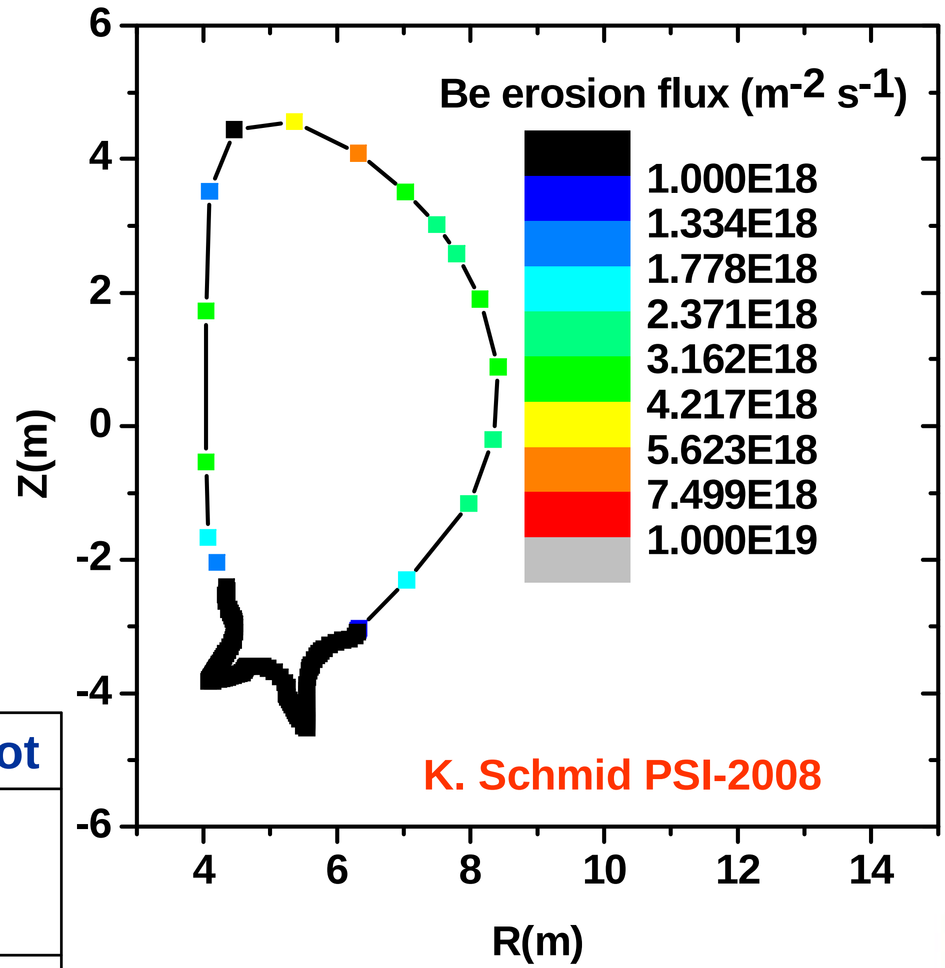
Lifetime of PFCs

Roth, PSI-2008

Wall erosion in steady state:

Be **first wall erosion is calculated based on B2-Eirene results**
Toroidal peaking may reduce wetted area to ≈ 50m²

For W **erosion due to impurity sputtering is taken into account; here: 0.1% Ar in SOL plasma**



Wall material	nm/s	atoms/s	g/shot
Be average	0.12	8×10^{21}	48
peak 50m²	8		
W average	0.05		
peak poloidal	0.12	2×10^{20}	26

Erosion of Be first wall may become a lifetime problem for inhomogeneous loading

Lifetime of PFCs

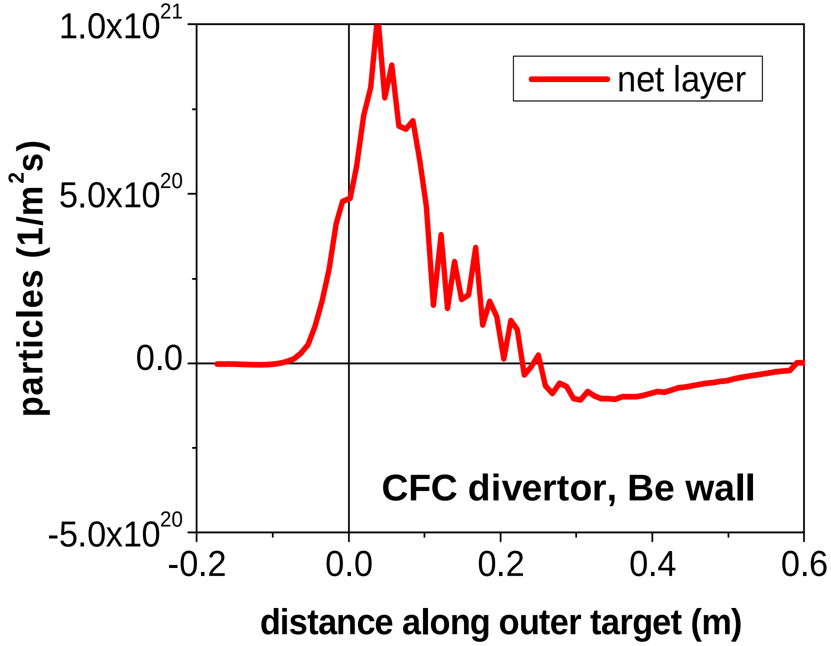
Roth, PSI-2008

Divertor erosion in steady state:

CFC **divertor erosion is calculated using ERO based on B2-Eirene results**
(including 0.1% Be^{2+}, but reduction of chemical erosion due to Be not included)

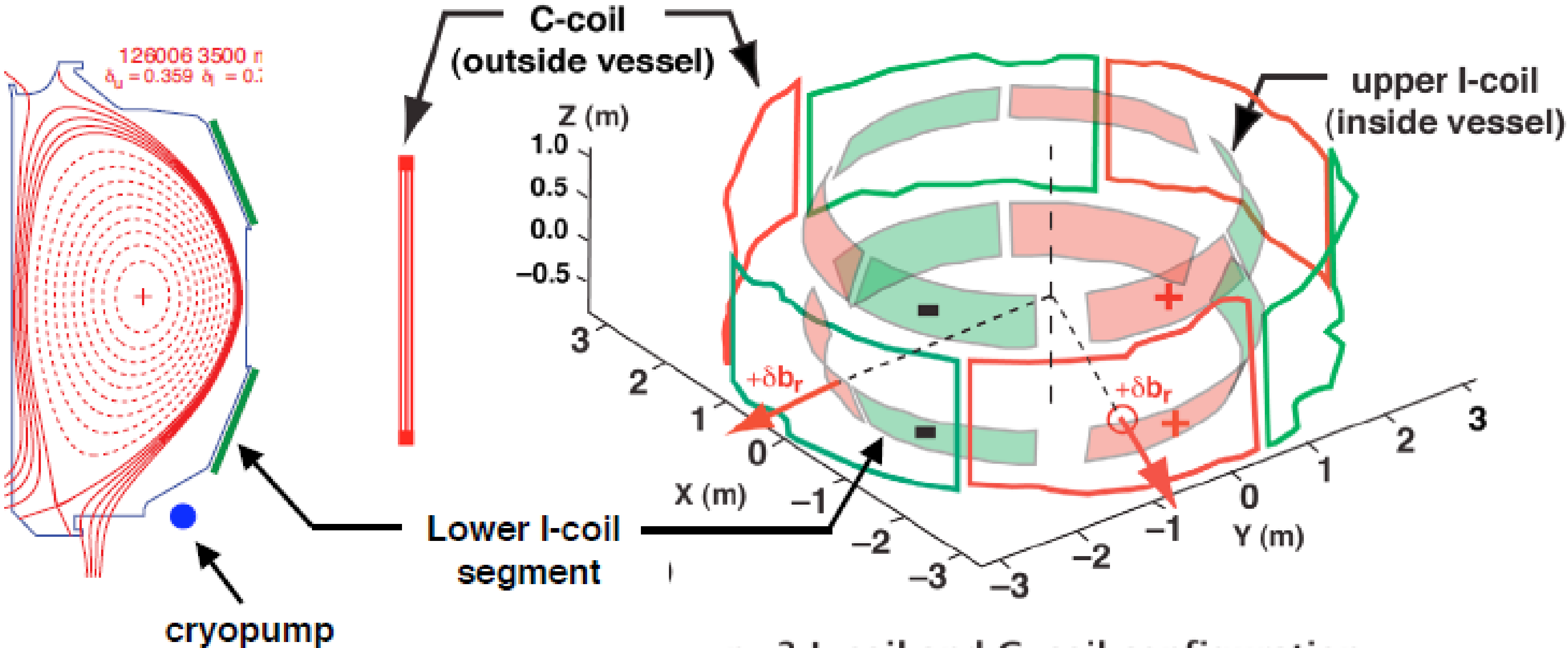
W **erosion mainly due to Ar impurities (0.1 %) (DIVIMP)**

Divertor mat.	nm/s	atoms/s	g/shot
CFC gross	100	4×10^{22}	330
net	1	4×10^{20}	3
W gross	2	4×10^{20}	48
net	0.3	6×10^{19}	7



A. Kirschner PSI-2008

Two sets of coils produce a variety of RMPs in DIII-D



n=3 I-coil and C-coil configuration
(with even parity I-coil)

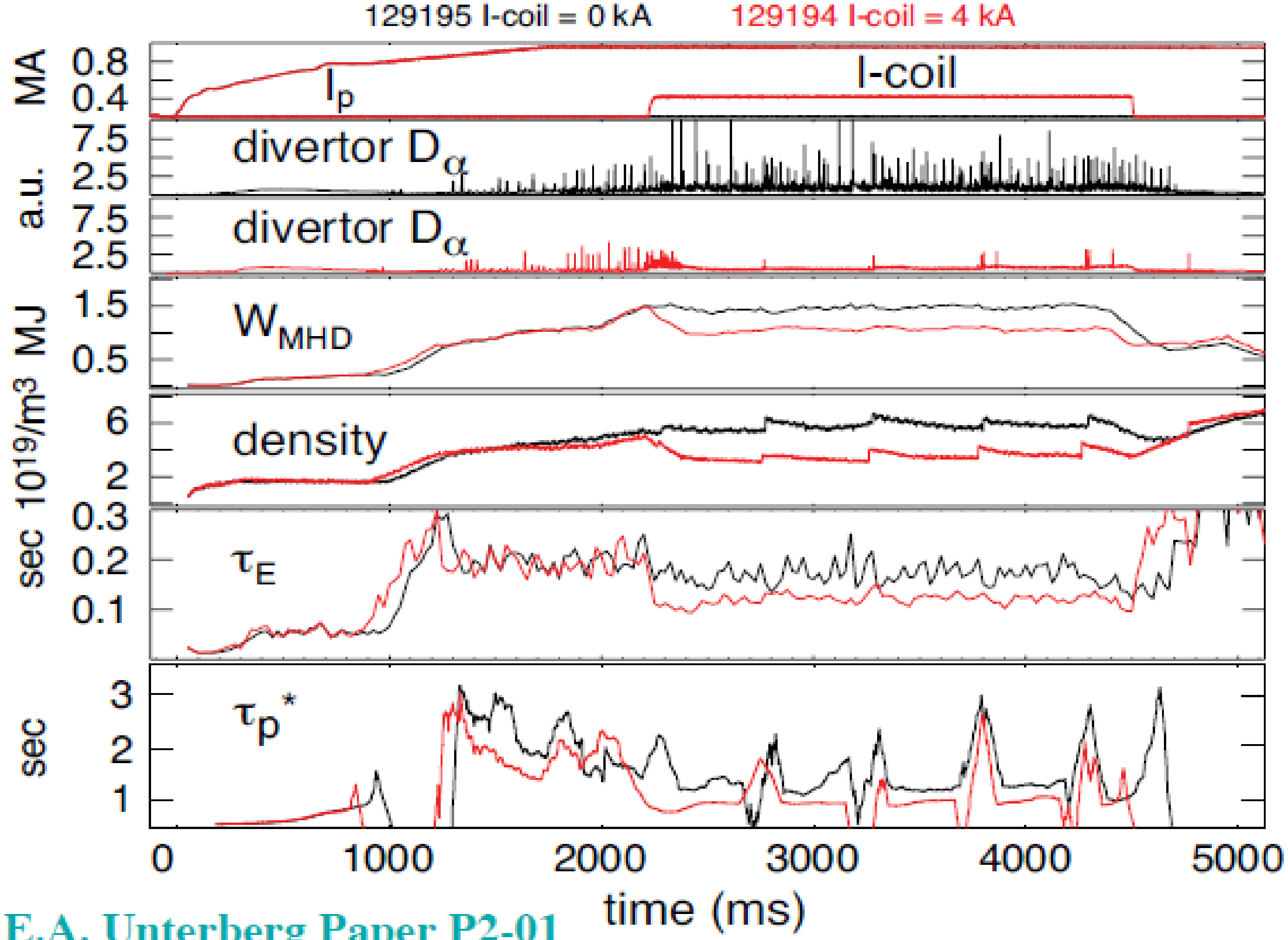
- The 4-turn C-coil and single-turn upper/lower I-coil can be configured for n=3 RMP experiments or n=1 field-error correction

DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

Moyer PSI08 – 4

Particle transport is enhanced during the RMP pulse.

- W_{MHD} drop is due to the density pump-out
- W_{MHD} drop often much smaller
- Significant density pump-out
- τ_p* reduced 6x at start of RMP pulse, 1.5–2x in steady state



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

τ_p* : E.A. Unterberg Paper P2-01

Moyer PSI08 – 7

Lifetime of PFCs

Roth, PSI-2008

ELM induced erosion: CFC

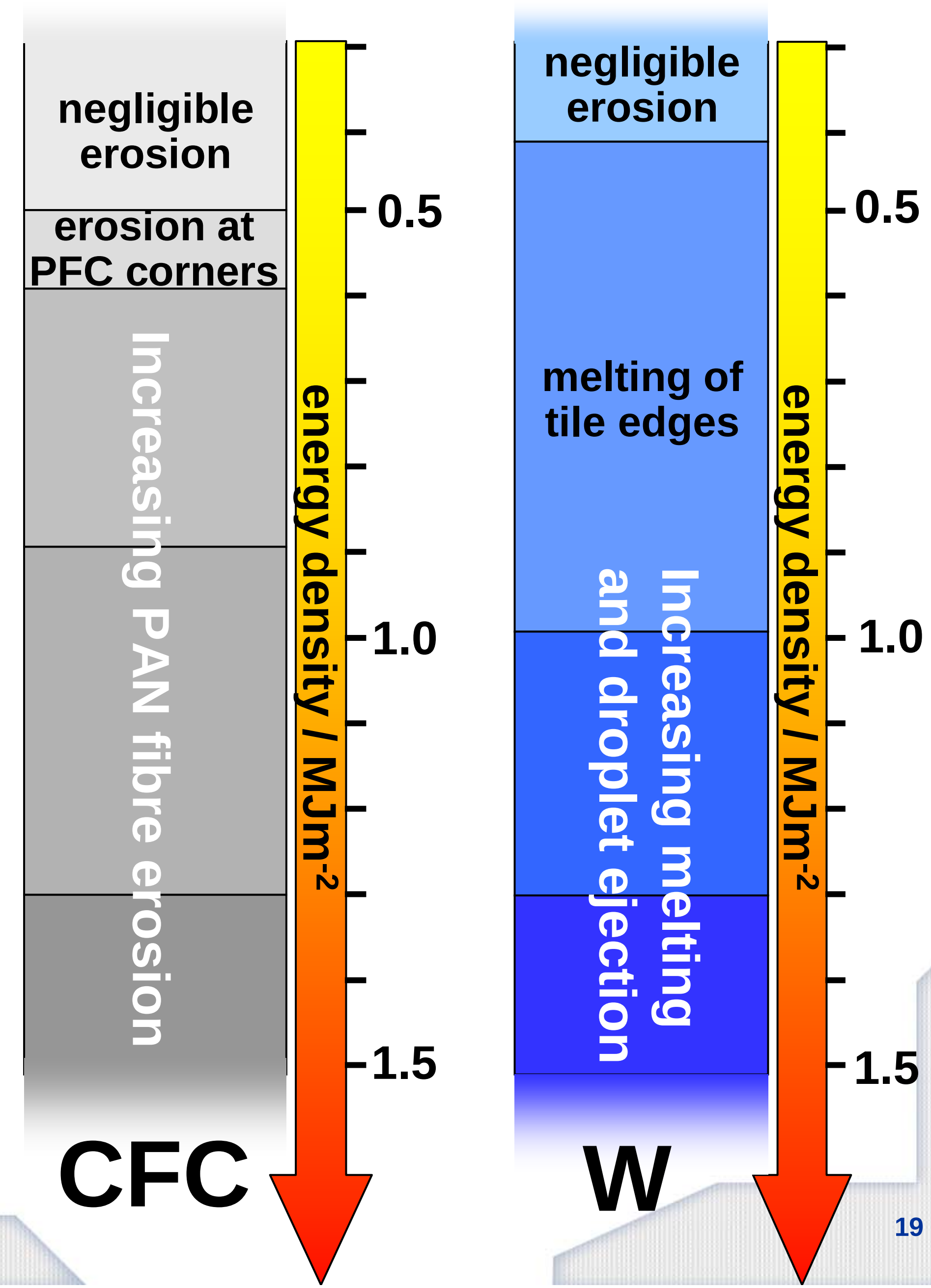
Results from Russian plasma simulators:

- ❑ Erosion limit for CFC reached due to PAN fibre erosion
- ❑ Erosion limit for W reached due to melting of tile edges

Crack formation was observed at energy densities ≥ 0.7 MJ/m². Repetitive sub-threshold ELM investigations ongoing in JUDITH2

Recommended threshold for damage 0.5 MJm^{-2} ⇨ adopted by ITER

Efficient mitigation methods needed

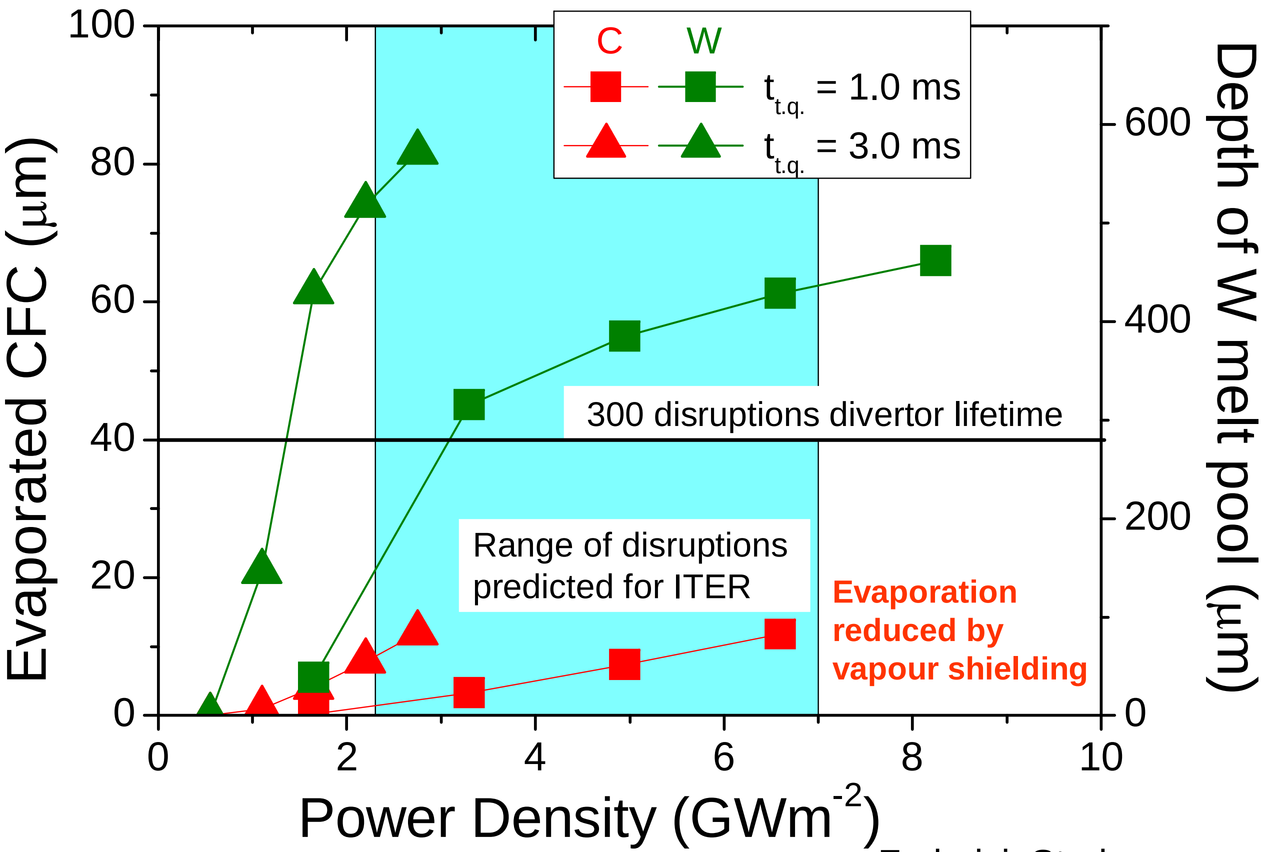


Lifetime of PFCs

Roth, PSI-2008

Disruption induced erosion:

- Vapour shielding reduces CFC evaporation by factor 10
  S. Pestchanyi PSI-2008
- Predicted ITER disruptions exceed the 300 disruptions lifetime limit for W
- **Efficient mitigation methods needed**



Federici, Strohmayer
RACLETTE
Riccardo, Federici
Nuclear Fusion 2005

ITER assumptions:

30 disruptions in about 2000 discharges

10 % of melt layer lost in the case of W divertor plates

5 kg erosion per disruption

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Tritium inventory

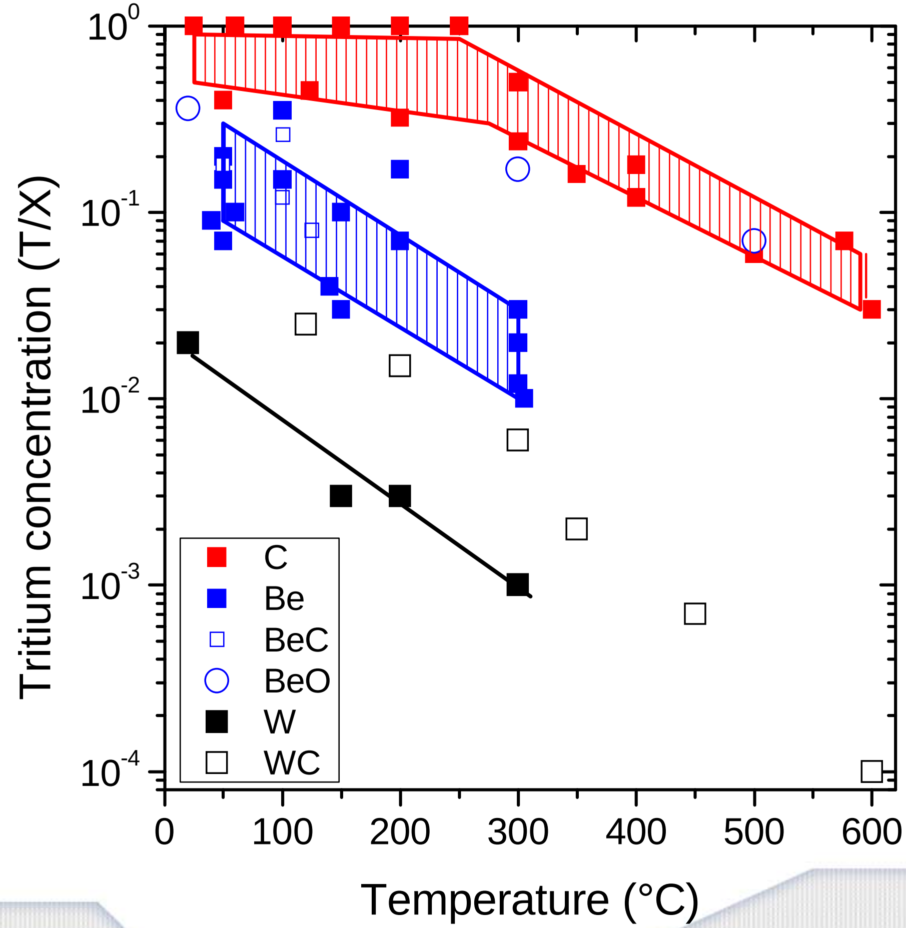
G. De Temmerman

Erosion determines co-deposition:

- ❑ Rough estimate: total net erosion rate x co-deposition concentration
- ❑ Detailed evaluation: impurity transport including re-erosion, co-deposition concentration depending on final deposition conditions

Co-deposition with C and Be depends on deposition conditions: energy, deposition rate, temperature

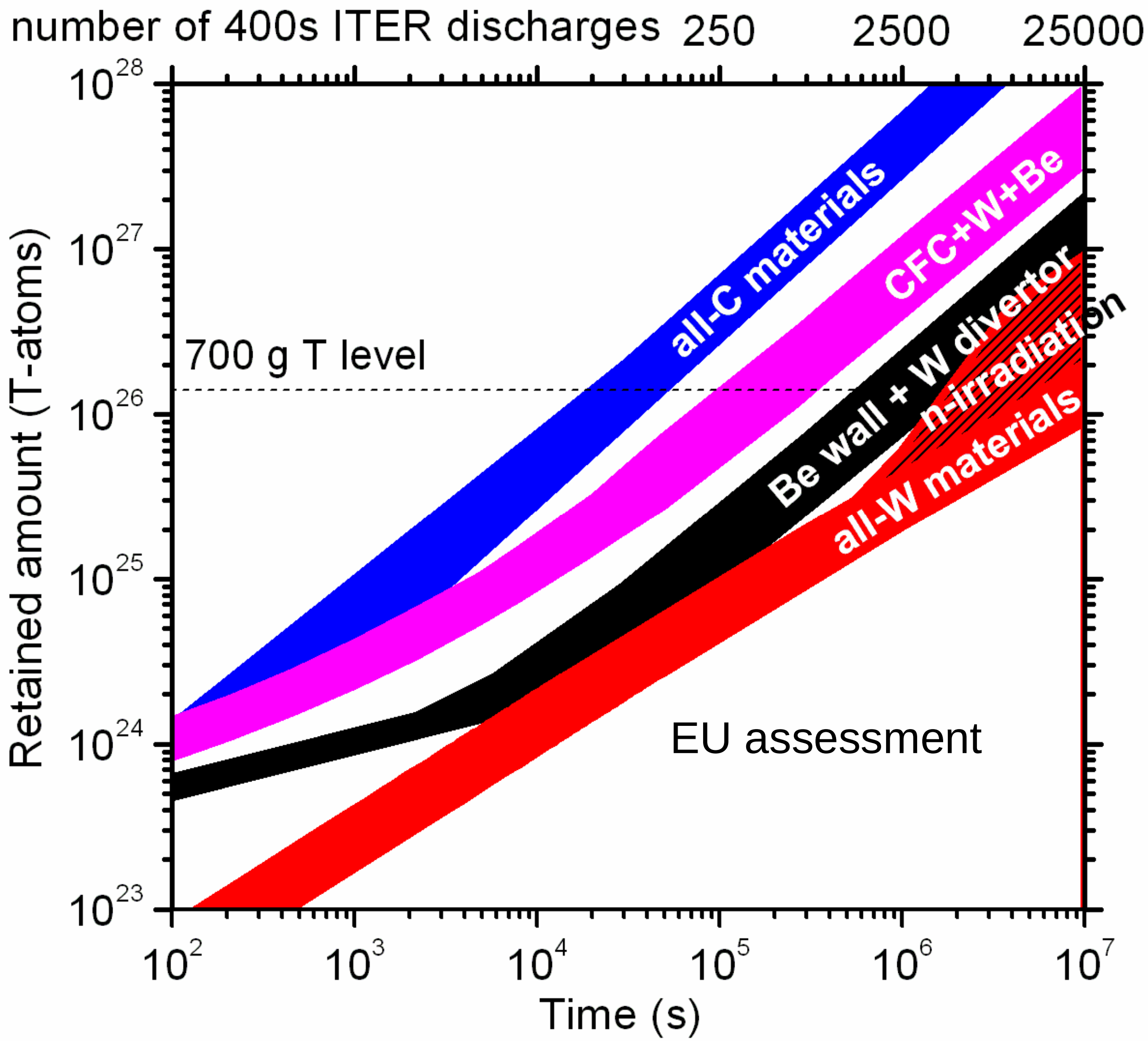
	atoms/s	g/shot
Be wall	$3x10^{20}$	1.8
CFC divertor	$2x10^{21}$	3.2
W divertor	$4x10^{17}$	$8x10^{-4}$



Tritium inventory

Roth, PSI-2008

Sum of both processes: comparison of materials options



Review for PPCF, submitted March 2008

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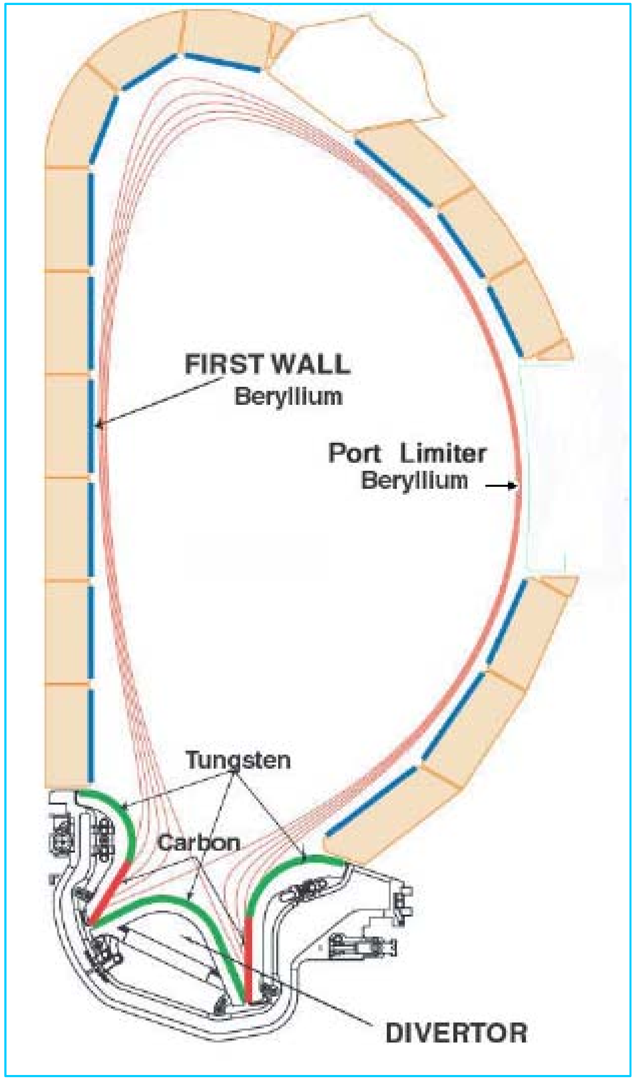
Plasma Facing Material Choice

- In the initial operation ITER uses beryllium FW, tungsten divertor baffle and dome, and carbon target plates to maximize the operation flexibility
- Before DT operation, the divertor target will be changed to tungsten to minimize the tritium retention
- Scenarios with Be/W PFC must be developed



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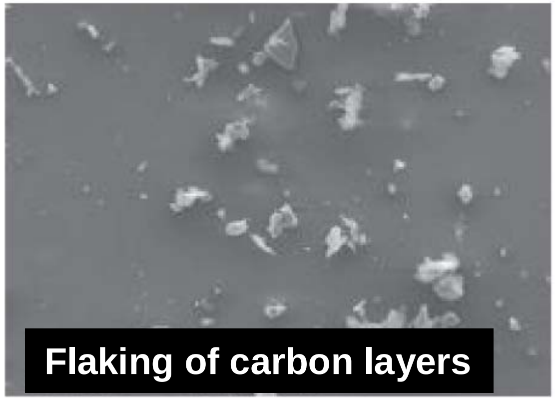
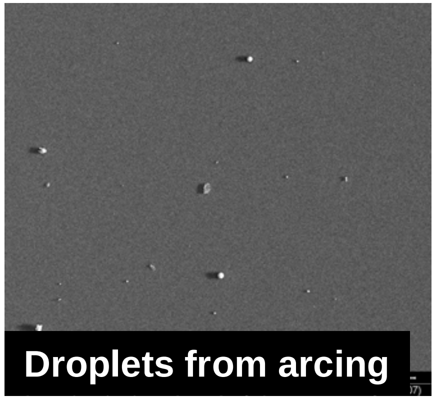
Dust generation

Roth, PSI-2008

Collection July 2000



Collector probes 2007



AUG

full-C and full-W phase

J. Sharpe, V. Rohde et al., JNM 2003

M. Balden et al, PSI-2008

Potential safety concerns:

Potential release in environment ⇨ **1000 kg limit**

W is the major radioactive source

Dust contains trapped Tritium

Hydrogen production when hot dust reacts with steam

Be major contributor

with carbon: ⇨ **6 kg C, 6 Be, 6 kg W limit**

without carbon: ⇨ **11 kg Be, 230 kg W limit**

Possible pure Dust or Hydrogen/Dust explosion

Be, C, W involved

Dust generation

Roth, PSI-2008

Total dust generation:

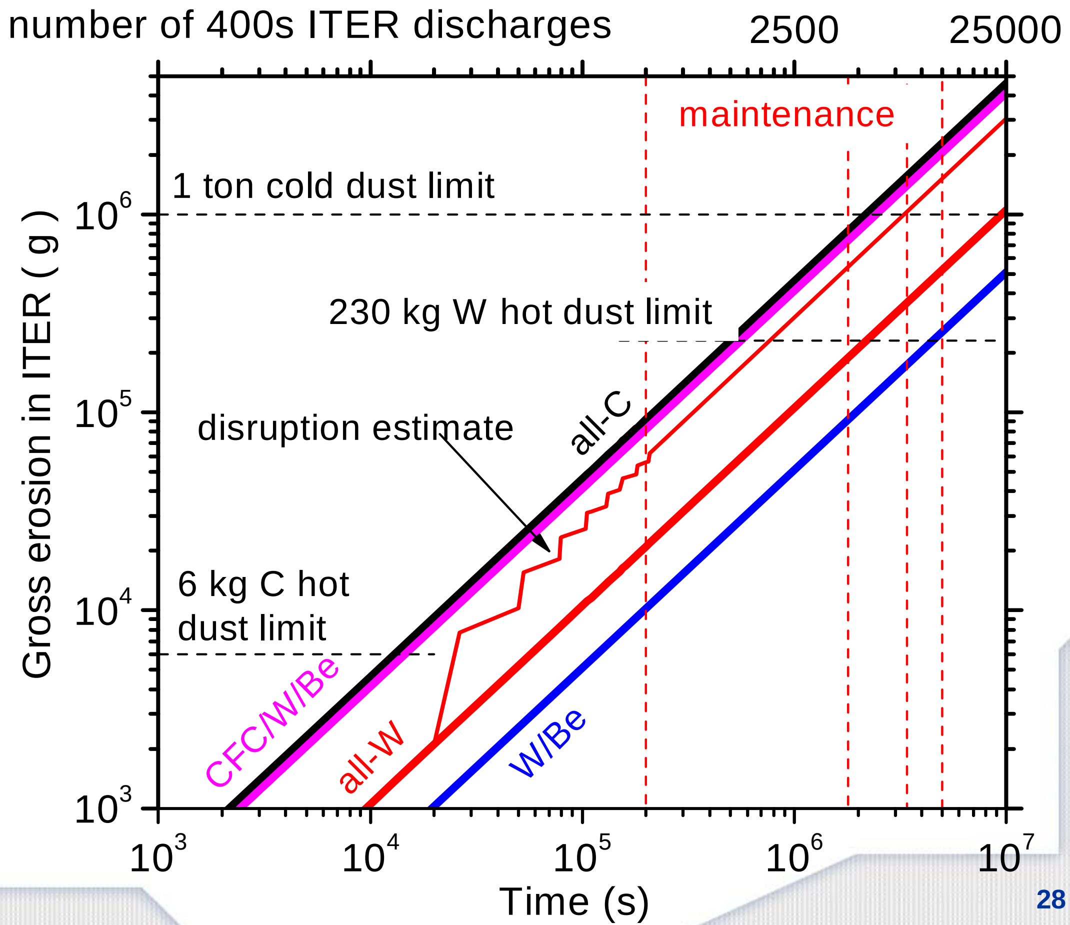
Assumption:

- ❑ Dust generation dominated by erosion, deposition, layer disintegration
- ❑ Conversion from erosion to dust for safety reasons: 100 %

(about 10 % in Tore Supra and JT-60U)

Total dust limit not reached before scheduled maintenance and exchange of divertor cassettes

What fraction of dust resides in hot (>600°C) areas?



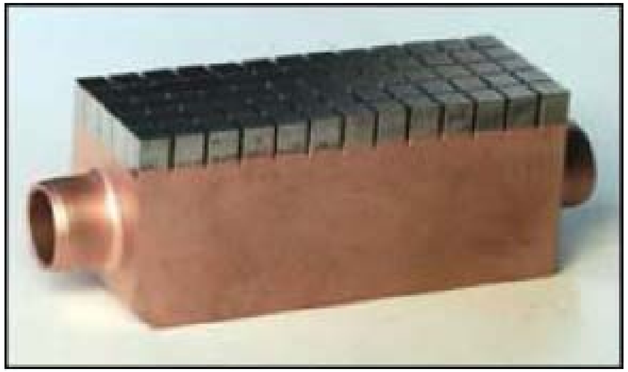
Dust generation

Roth, PSI-2008

Dust on hot areas:

Assumption:

- On hot plasma (>600°C) wetted areas deposits and dust will only survive in castellation
- Need to estimate the fraction of impurity deposition in gaps from experimental data base **see A. Litnowski PSI-2008**



Assume dust at hot area collects only in gaps:

Flux of Be to outer target hot zone (DIVIMP): $2\times10^{19}/m^2s$

Area of hot zone: $8 m^2$

⇨Total Be flux: $1.6\times10^{20}/s \approx$ 1g/discharge

Gap area 2%

⇨Hot Be dust rate: 0.02g/discharge

⇨ **11kg Be dust for W/Be wall in 60000 disch.**

If tugnsten dust is produced on hot surfaces in the order of a few kg, significant cleaning efforts must be made before the next operation (the acceptable amount of tungsten in the core is ~0.2 mg)

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Summary

- To facilitate ITER operation, R&D in following areas are essential
  - Avoidance or significant mitigation of disruptions/VDEs and ELMs
  - Development of scenarios with Be/W PFCs
  - Control of T retention and dust
  - Development of understanding of sol transport during steady state and off-normal events
  - Development of wall conditioning scenarios

Useful **Free** URLs

Invited talks at PSI-2008 (International Conference on Plasma Surface Interactions in Controlled Fusion Devices) :
http://psi2008.ciemat.es/talks.shtml

Proceedings of IAEA Fusion Energy Conferences:
http://www-naweb.iaea.org/napc/physics/ps/conf.htm

Progress in the ITER Physics Basis (comprehensive review paper ~400 pages):
http://www.iop.org/EJ/toc/0029-5515/47/6

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http://www.iop.org/EJ/toc/0029-5515/47/6

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PROGRESS IN THE ITER PHYSICS BASIS

PREFACE

Summary: Chapter 1

PWI: Chapter 4