# Benefits and Challenges of the Use of High-Z Plasma Facing Materials in Fusion Devices

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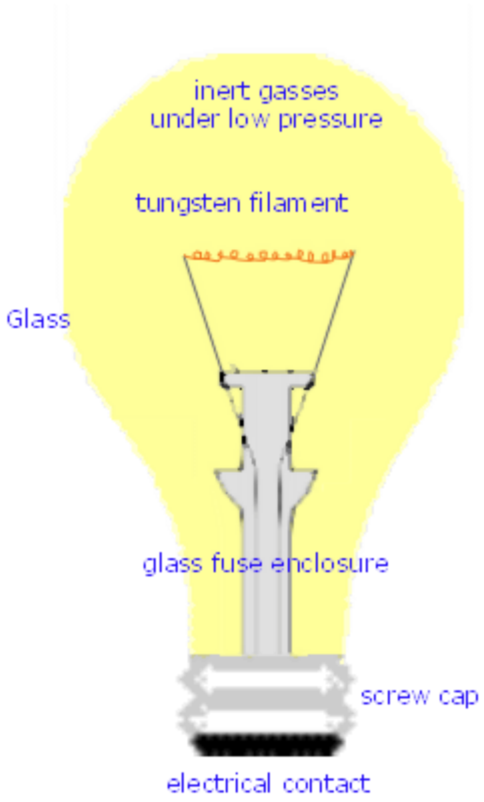
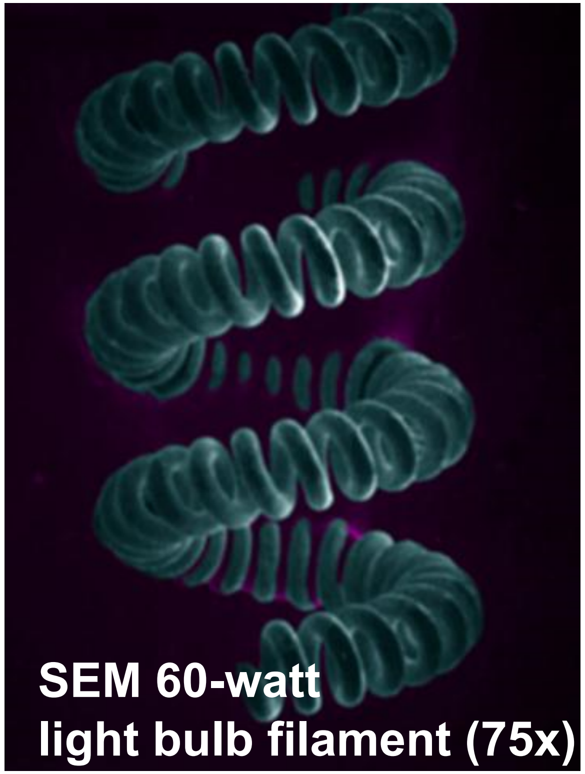
# The road to tungsten may be long and tedious…



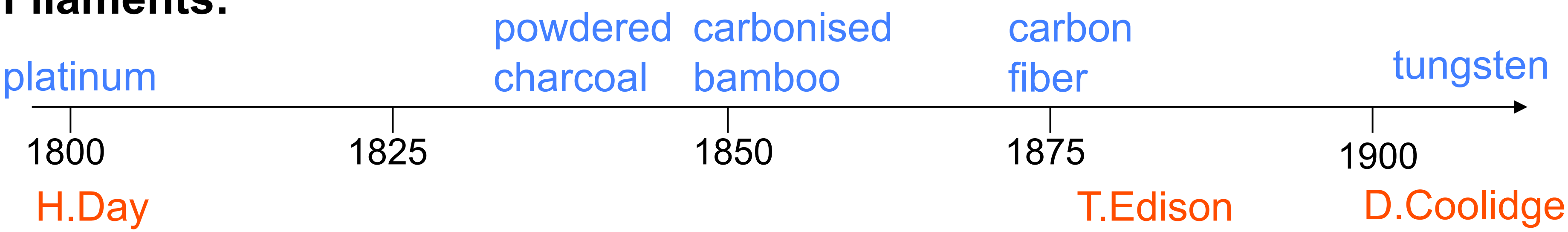
History of development of filament materials for light bulbs

- metal
- carbon
- coated carbon
- tungsten

**Driver: life time**
**Problem: production**

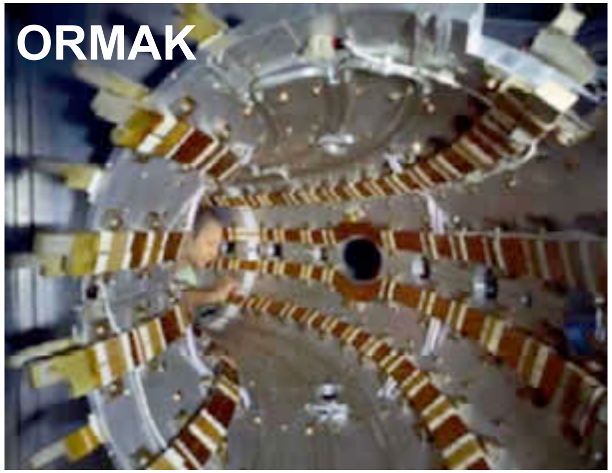

**SEM 60-watt light bulb filament (75x)**

**Filaments:**

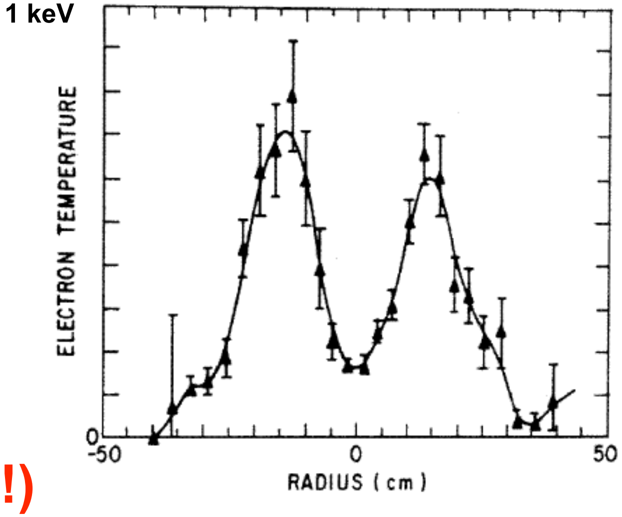


# A brief look into history

- vacuum compatibility of PFCs was first priority in early devices
  → gold plated stainless steel liners in ORMAK
- low low-Z content → higher edge temperatures & higher performance, better core confinement but higher sputtering source
  → impurity accumulation – hollow $T_e$
  in PLT when using W limiters
- need for low-Z PFMs, availability of vacuum grade graphite and benign behaviour under thermal overload
  → adoption of C PFCs in almost all fusion devices
- operation with high current high density and/or **divertor** allows to use refractory (high-Z) metals **(low plasma temperatures in contact with PFCs!)**



temperature profile in **PLT** during W accumulation



# Benefits and Challenges of High-Z PFMs

- Why do we need a substitute for C based materials
- Experiences in present day machines
  - ‚High‘-Z devices
  - diagnostic for W
  - hydrogen retention
  - W erosion
  - W concentrations and transport
  - behaviour under powerload
  - effect of n-irradiation
- Extrapolation to ITER
- Summary / remaining issues

# Why going back to refractory metals?

## Motivation to abandon C-based materials in a future reactor

- fuel retention by co-deposition with C
- high erosion of low Z materials
- stability against neutron damage

## Challenges for operation of a full high-Z device:

- tolerable impurity level much lower than for low-Z ($c_C \leq 10^{-2}$, $c_W \leq 5 \times 10^{-5}$)
- reliable tokamak operation scenarios
- compatibility of standard & advanced H-mode scenarios with a full high-Z wall
- compatibility of heating methods: ICRF

**High-Z devices: TRIAM-1M, FTU, Alcator C-Mod, ASDEX Upgrade**

**High-Z test PFCs: JET, JT-60U, TEXTOR**

## Other important constraints

Material properties, change under n-irradiation, diagnostic issues, …

# Rationales for plasma facing materials

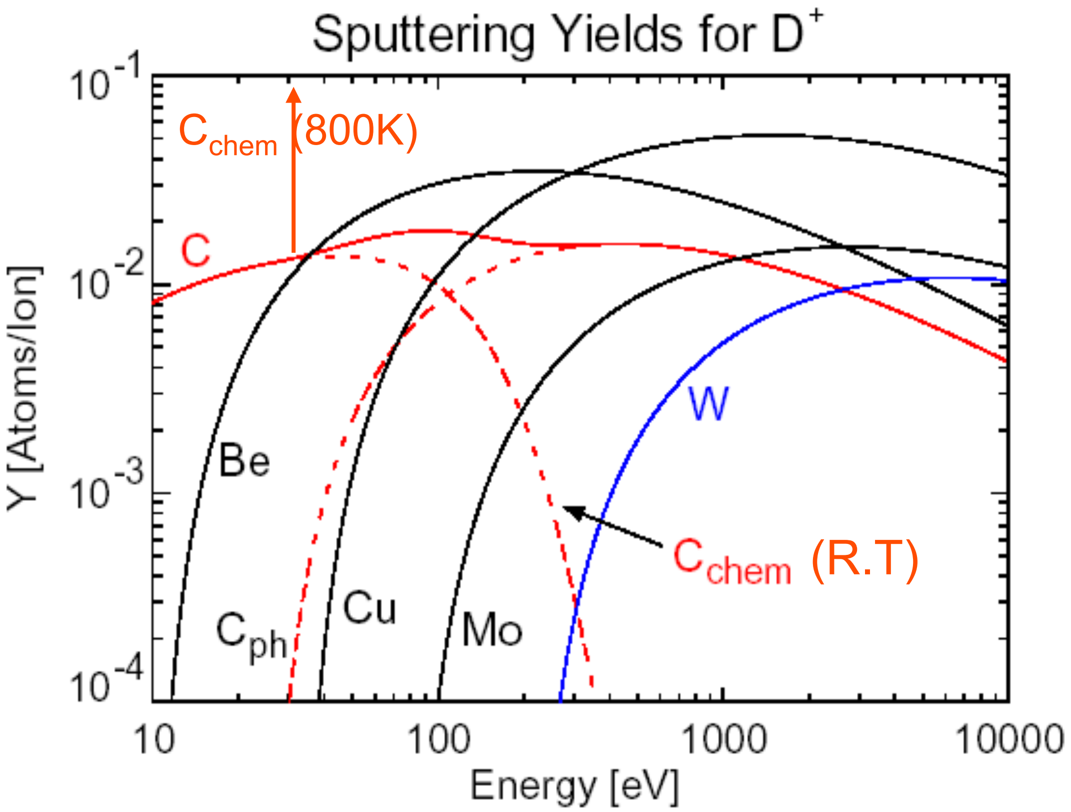
**Low erosion rates:**

→ low power loss by dilution / radiation originating from impurities

→ long lifetime of PFCs

→ low dust production

→ low T co-deposition



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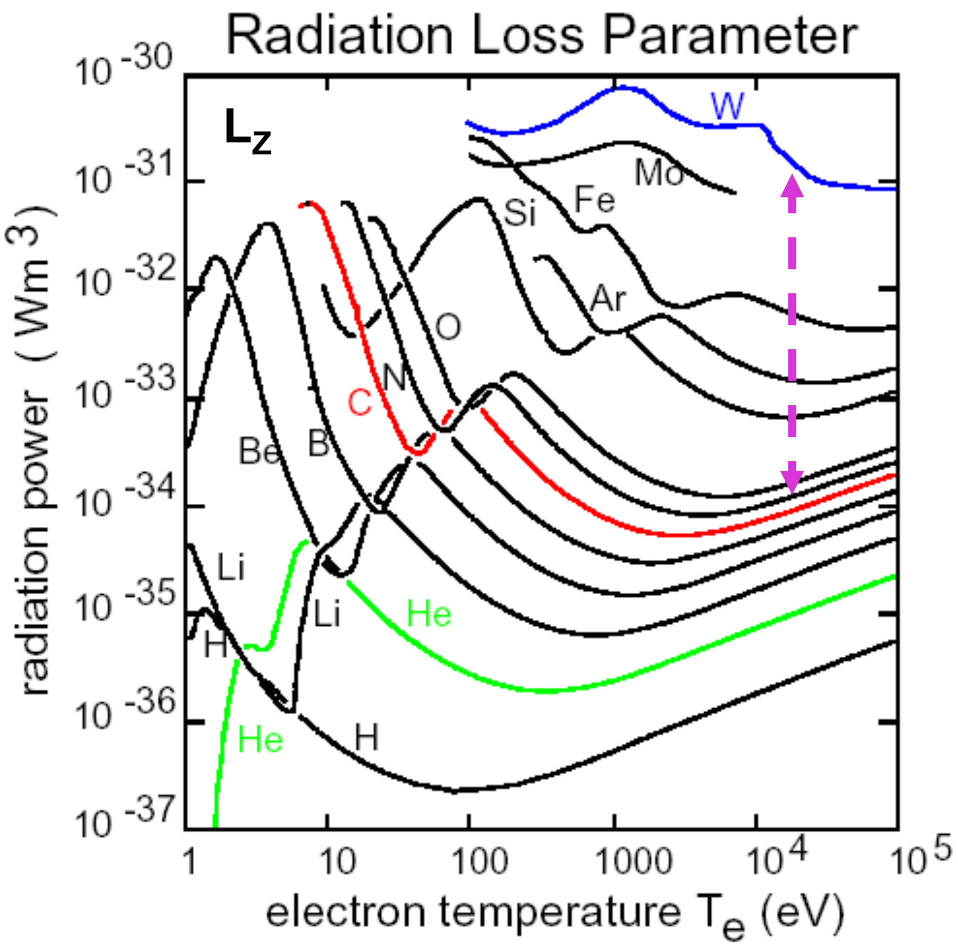
**Low atomic number**

→ low radiation loss parameter



**Losses through**

dilution (low-Z) : $n_{DT} = n_e(1 - Zn_Z)$

radiation (high-Z) : $P_{rad} / V = L_Z\, n_Z\, n_e$

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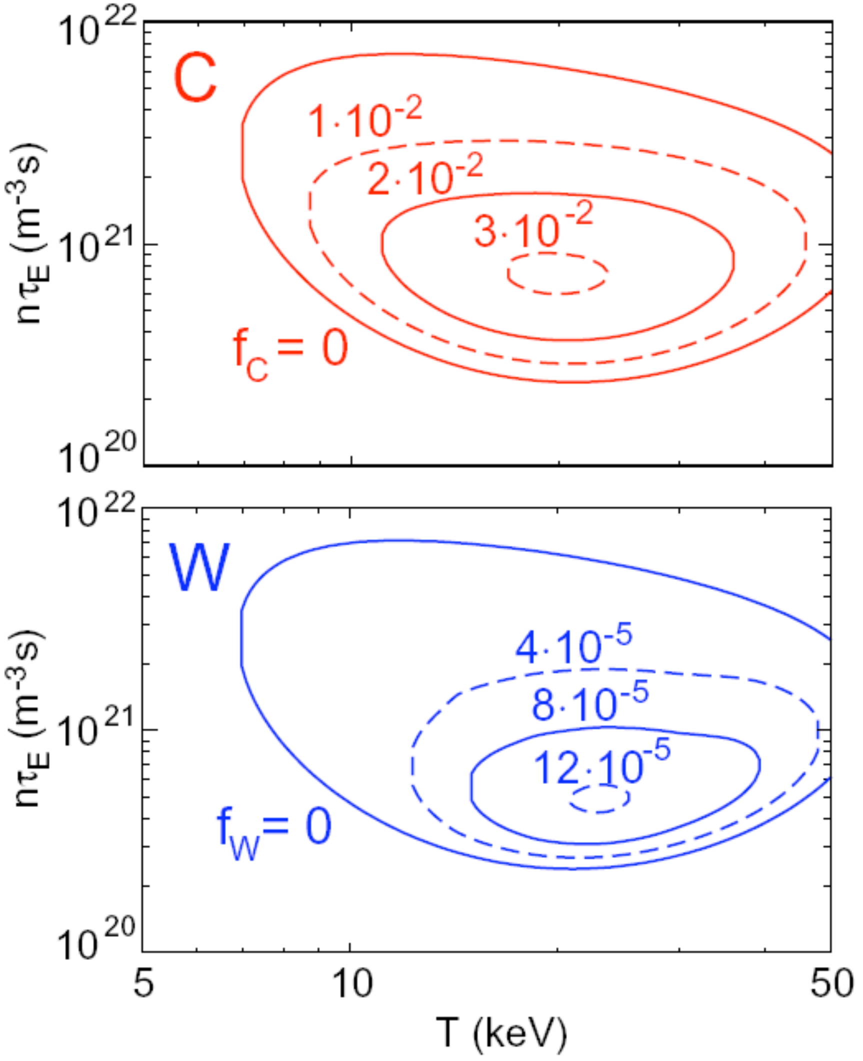

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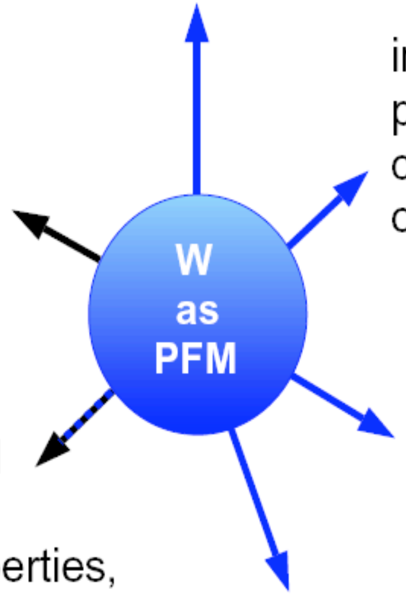
# Boundary Conditions for PFMs in a Reactor
# Integrated approach necessary



plasma behaviour:
confinement, MHD-stability,
operational limits,
threshold behaviour

impurity behaviour:
penetration, transport,
concentration, radiation,
other intrinsic impurities

erosion,
deposition,
H-retention,
migration

diagnostic:
identification,
quantification of
influx and density

technological
issues:
material properties,
machinability, ...

n-irradiation:
embrittlement,
swelling,
transmutation,
activation

# Boundary Conditions for PFMs in a Reactor
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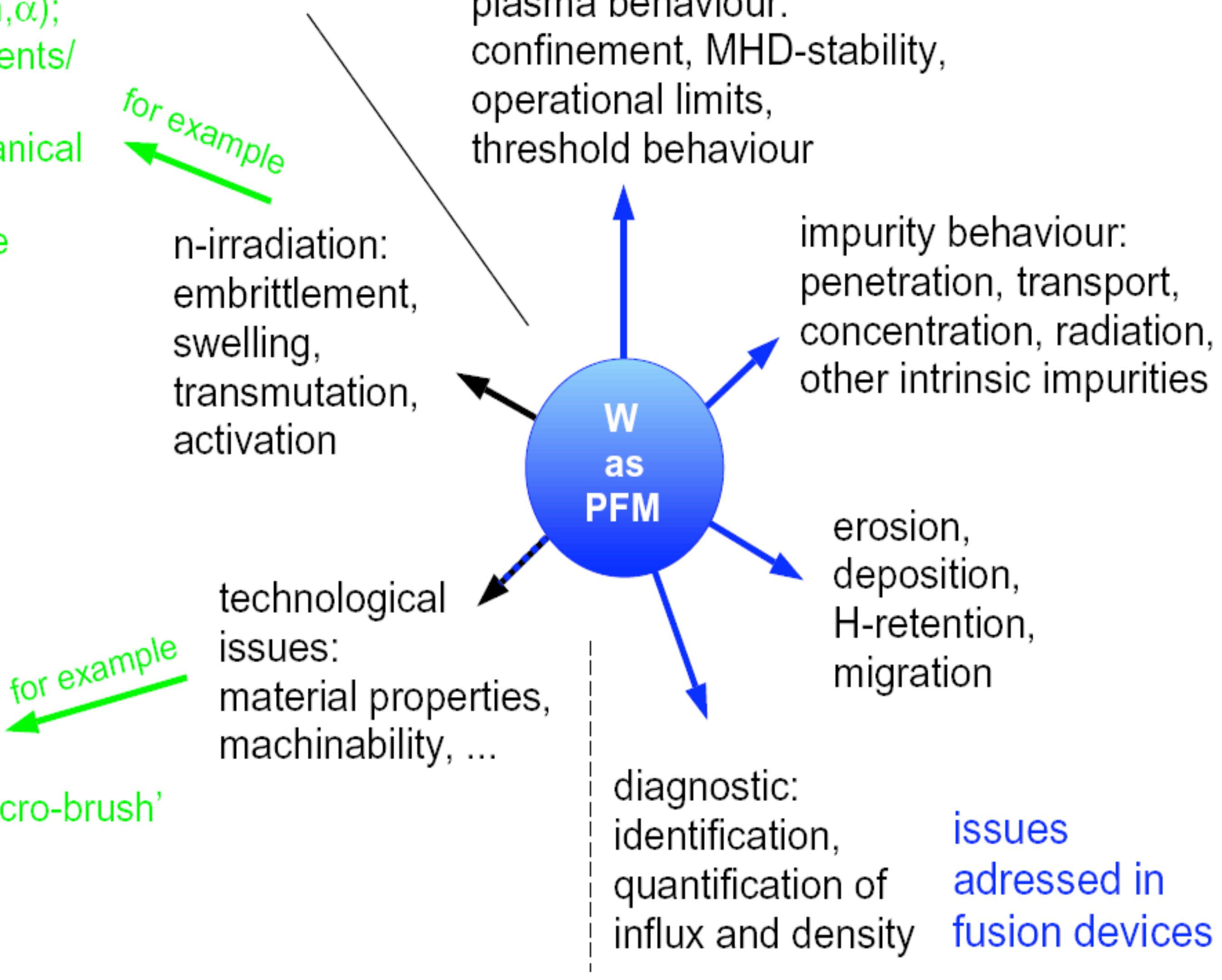

nuclear reactions
$(n,\gamma)$, $(n,2n)$,$(n,p)$, $(n,\alpha)$;
produce other elements/
isotopes:
⇒ change of mechanical
properties,
⇒ radioactive waste

embrittlement by
displacements
main concern

for example

n-irradiation:
embrittlement,
swelling,
transmutation,
activation

plasma behaviour:
confinement, MHD-stability,
operational limits,
threshold behaviour

impurity behaviour:
penetration, transport,
concentration, radiation,
other intrinsic impurities

**W**
**as**
**PFM**

erosion,
deposition,
H-retention,
migration

technological
issues:
material properties,
machinability, ...

for example

cracking after
thermal shocks
→ castellation, 'macro-brush'
arrangement

diagnostic:
identification,
quantification of
influx and density

issues
adressed in
fusion devices

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  - W Erosion
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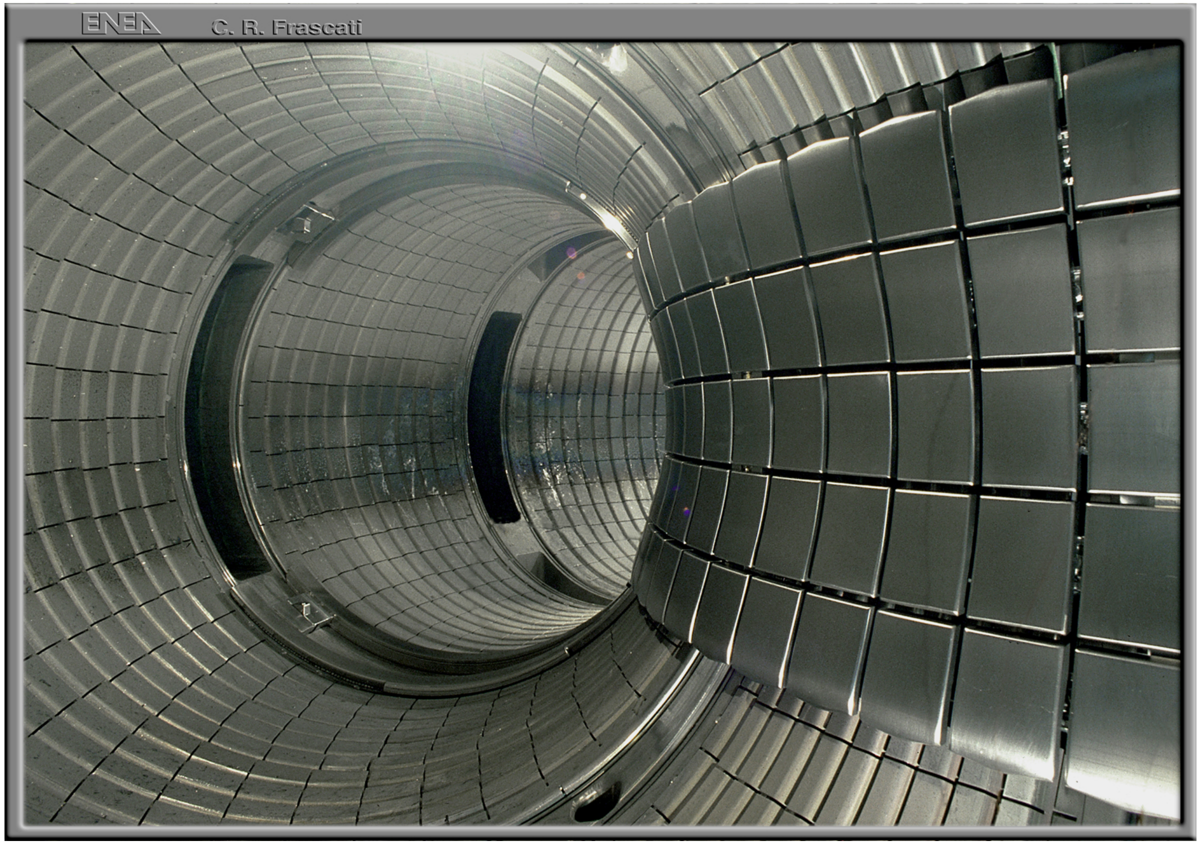
# FTU (ENEA Frascati)

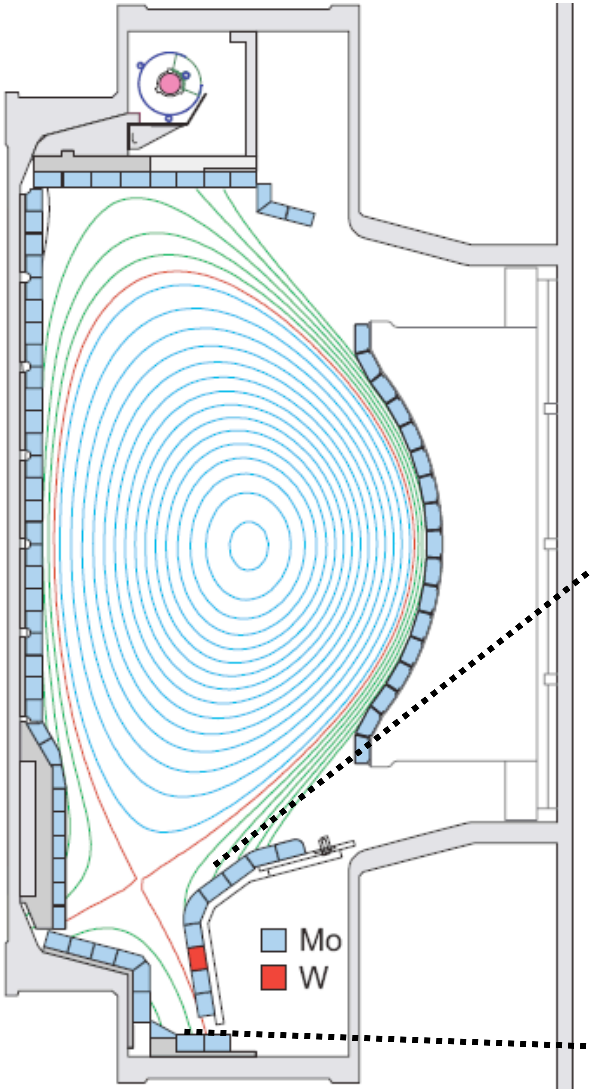
- “all metal” tokamak
  (R = 0.93 m,
  a = 0.28 m,
  $B_t \leq 8$T,
  $I_P \leq 1.6$ MA)
- first wall
  SS + boronisation
- poloidal limiter
  (untill 1994)
  SS, Inconel,
  **TZM, W**
- toroidal limiter
  (since 1995)
  **TZM** (~ 1 $m^2$)

**Toroidal limiter**



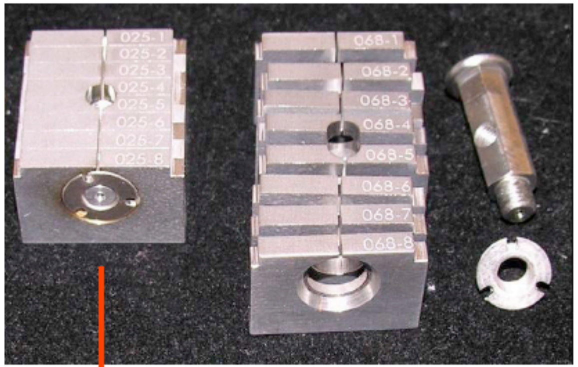
**FTU vacuum vessel**

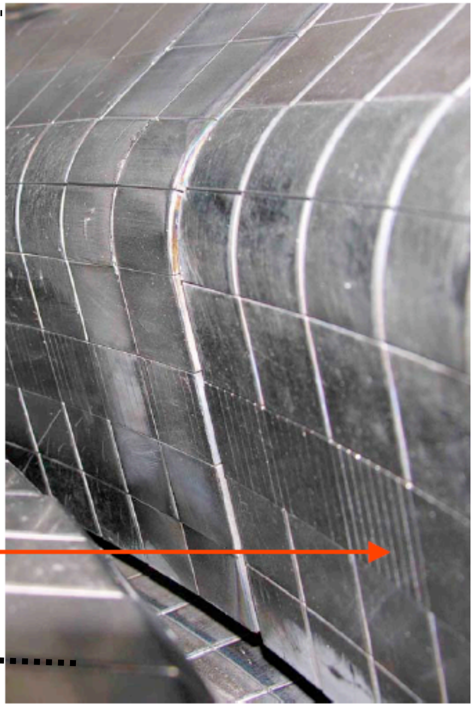
# Alcator C-Mod (MIT)



divertor configuration with a complete set of bulk Mo-tiles

one toroidal row of W lamella tiles

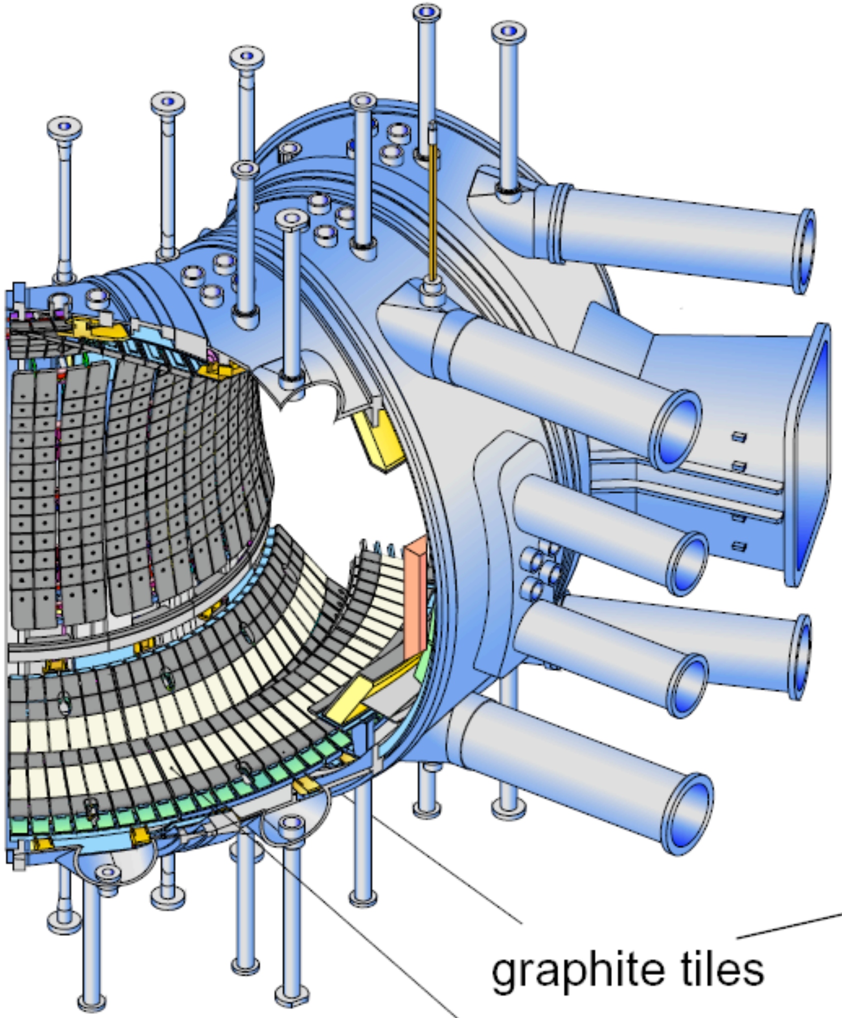


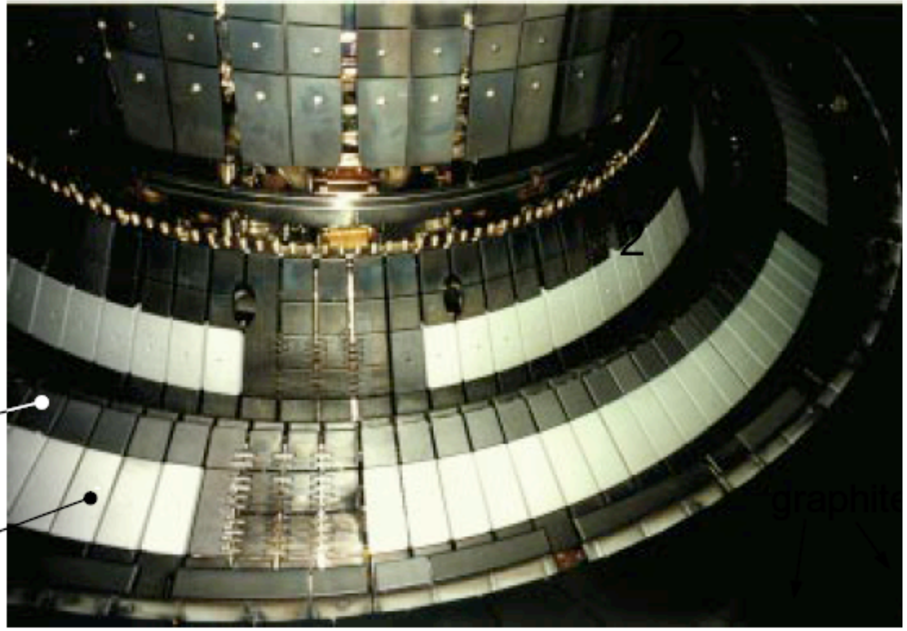


B. Lipschultz et al., PSI 2008

# W divertor in ASDEX Upgrade (1995/1996)

- 0.5 mm W (PS) on graphite tiles
- coverage of 90% of the strike zone
- no damage during operation:
  - 800 plasma discharges,
  - heating powers up to 10 MW
  - max. average heat load ≤ 6 MW/m$^2$



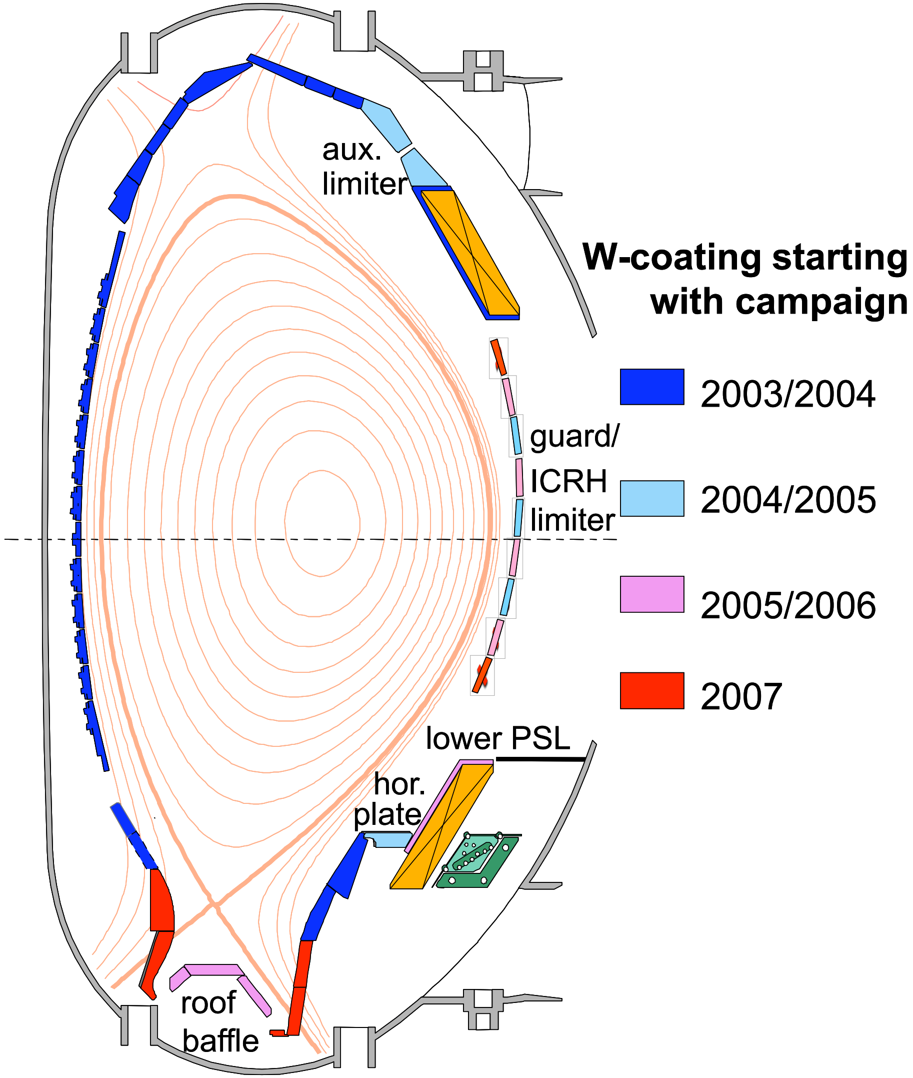


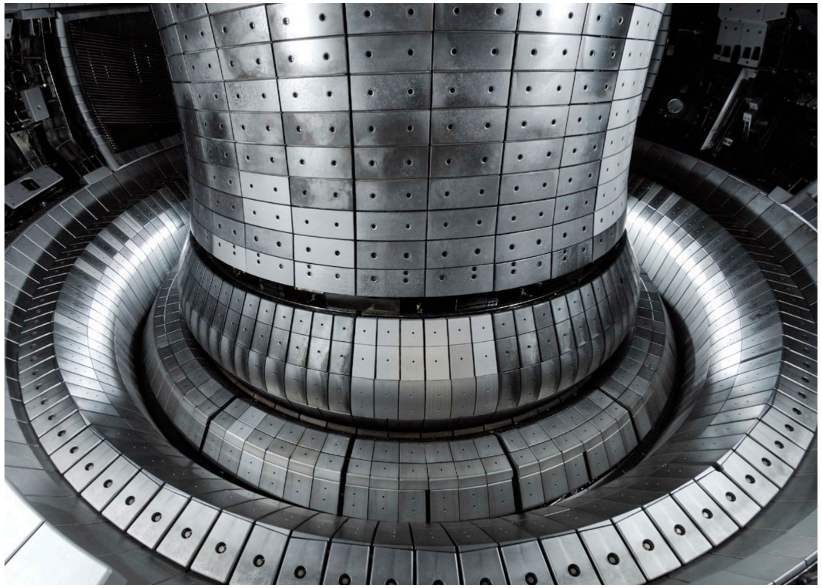
graphite tiles

tungsten tiles

# Full W ASDEX Upgrade from 2007 on

# ASDEX Upgrade (full W since 2007)





**W coatings on fine grain graphite:**

- main chamber, inner divertor:

  PVD 3-5 µm

- outer divertor

  VPS 200 µm → $\boxed{\text{PVD 10 µm}}$

**from 2009 on**

# JET ITER-like Wall Project (from 2011 on)

**Full metal device:**

**inertially cooled**

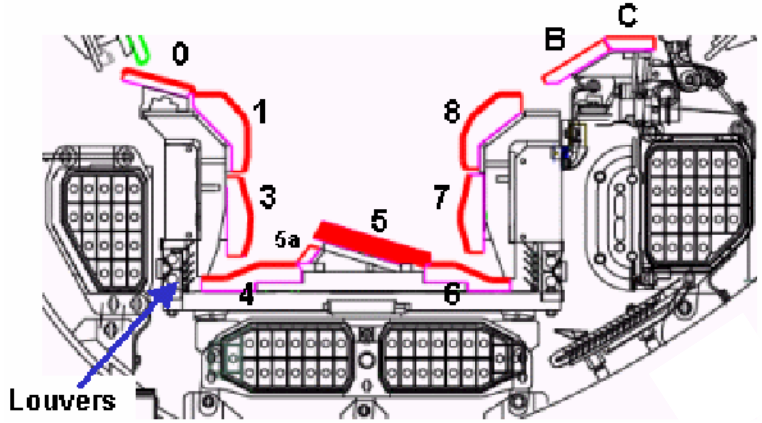
Be main chamber

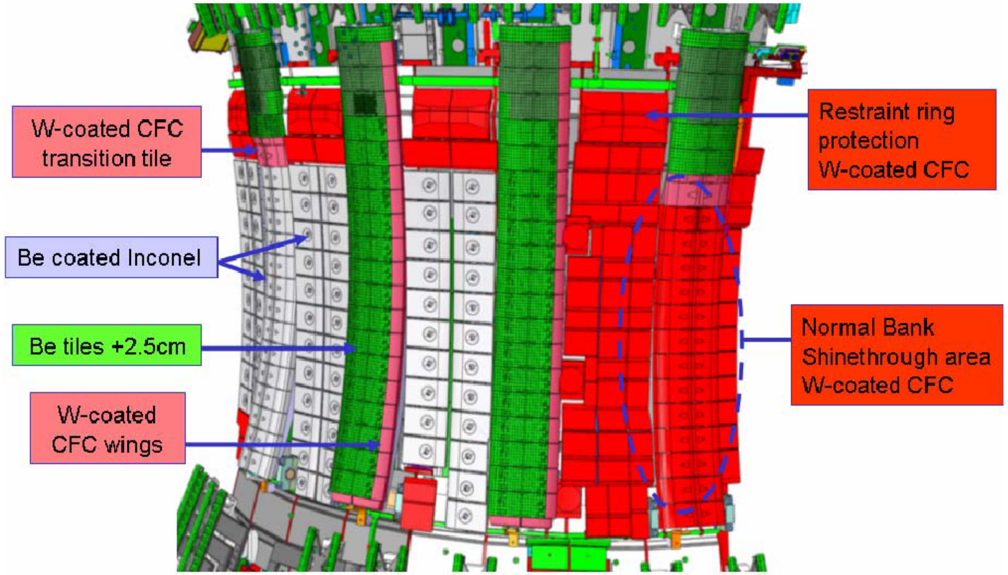
- bulk limiter and dump plates
- Be PVD coating on Inconel

W divertor /

high power / fluency areas

- tile 5: bulk tungsten
- divertor (except tile 5),
  main chamber (mainly NBI
  shinethrough areas):
  10 – 20 µm PVD coating

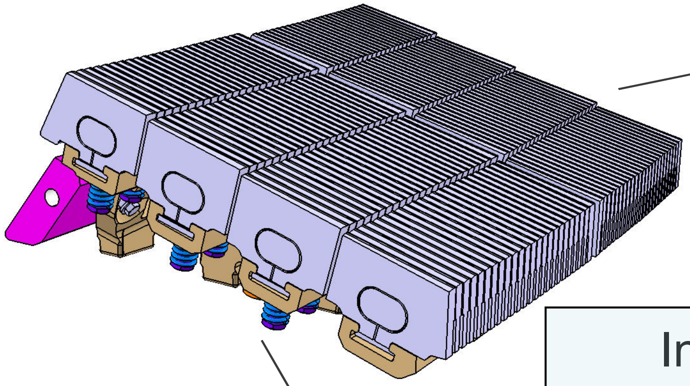




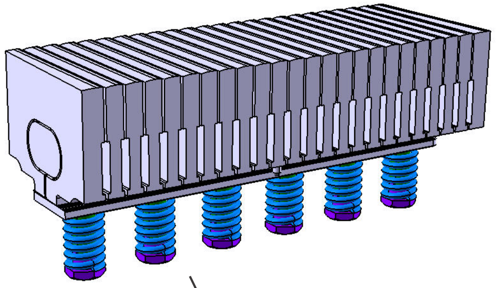
G. Matthews, Phys. Scr. T128, 2007, 137

# JET ITER-like Wall Project
# Layout of Bulk W Tile (Tile 5)

Full divertor unit
(one row in JET at outer strike point = 48 units
or 96 tiles)

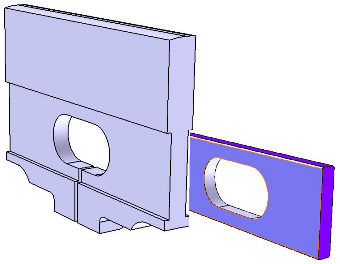


8 stacks of tungsten lamellae
with rear castellation



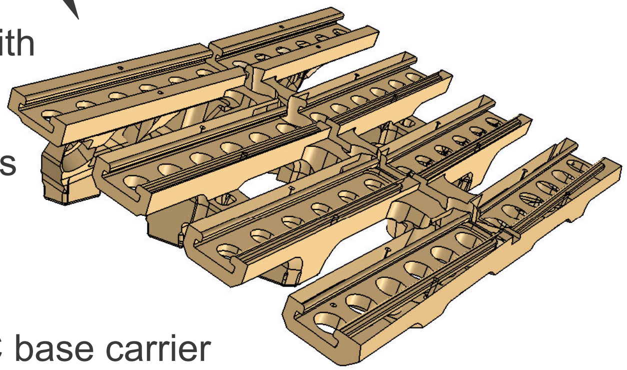
Inertial cooling +
metals (huge EM forces) +
W is a refractory metal

typically 24 bulk-W lamellae



(with sandwiched insulating TZM spacers)

‘Wedge’ carrier with
deep toroidal
cuts against
eddy current loops



8 feet
rest on the CFC base carrier

Ph. Mertens (FZ Jülich)

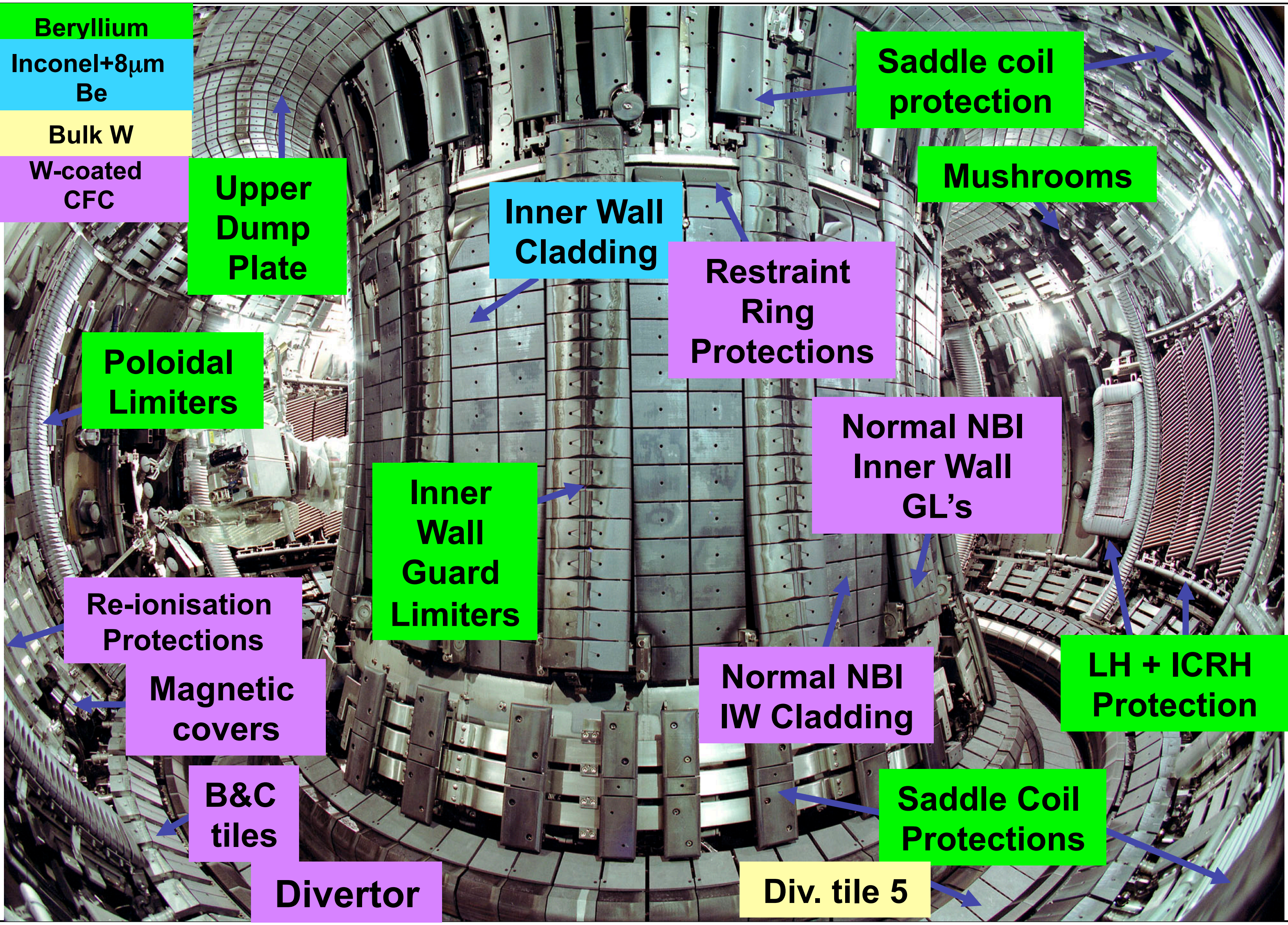
# JET ITER-like Wall Project (from 2011 on)

Beryllium

Inconel+8µm Be

Bulk W

W-coated CFC



Upper Dump Plate

Saddle coil protection

Mushrooms

Inner Wall Cladding

Restraint Ring Protections

Poloidal Limiters

Normal NBI Inner Wall GL's

Inner Wall Guard Limiters

Re-ionisation Protections

Magnetic covers

Normal NBI IW Cladding

LH + ICRH Protection

B&C tiles

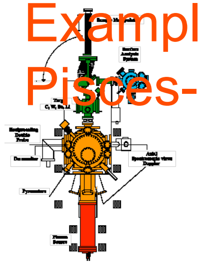
Saddle Coil Protections

Divertor

Div. tile 5

# Devices for plasma irradiation: linear plasma simulators

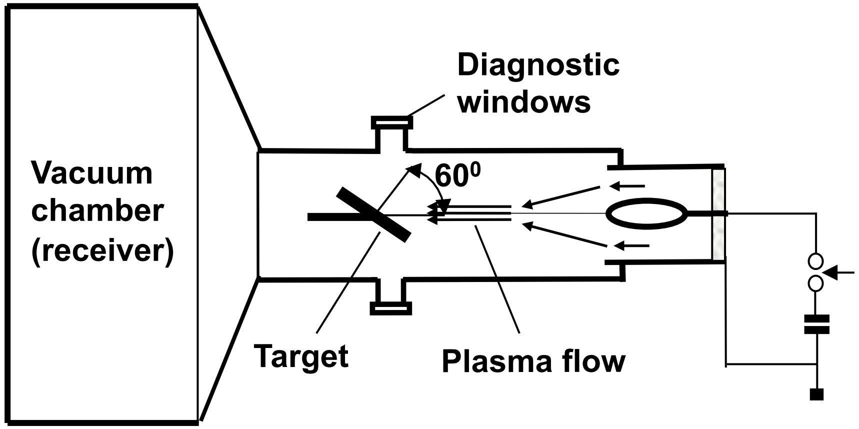
Example:
Pisces-B



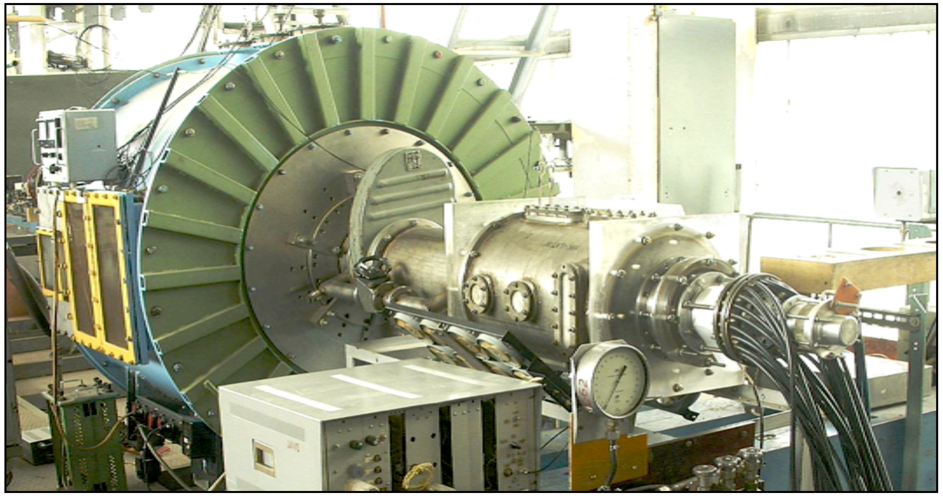
| | **PISCES-B** | **Confinement Devices** |
|---|---|---|
| Ion flux ($m^{-2}\ s^{-1}$) | $10^{23}$ | $10^{23}$ - $10^{24}$ |
| Ion energy (eV) | 20-300 (bias) | 10-300 (thermal) |
| Heat flux ($MW/m^2$) | 1-10 | 1-10 |
| $T_e$ (eV) | 2-40 (thermal) | 1-100 (thermal) |
| $n_e$ ($m^{-3}$) | $10^{17}$-$10^{19}$ | $10^{18}$-$10^{20}$ |
| Impurity fraction (%) | 0.03-10 | 1-10 |
| B (Gauss) | 200-1000 | 10,000 |
| Pulse length | continuous | 10-30 sec |
| Fluence/disch.($m^{-2}$) | up to $10^{27}$ | $10^{24}$ - $10^{25}$ |
| Target materials | C,W,Be,Li | C,W,Be,etc. |
| and coatings | (any unirradiated) | |
| Surface Temp(°C) | RT-1100 | RT-500 |
| Plasma species | H,D,He | H,D,T,He |

R. Doerner et al., UCSD

# Devices for power loading of (W) PFCs



A. Zhitlukhin, 17th PSI, 2006



steady state:
plasma generators,
ion beams, e beams

transients:
e beams, plasma guns, quasi stationary plasma accelerators

**QSPA plasma parameters (ELMs):**

| | |
|---|---|
| Heat load | 0.5 – 2 MJ/m$^2$ |
| Pulse duration | 0.1 – 0.6 ms |
| Plasma diameter | 5 cm |
| Magnetic field | **0 T** |
| Ion impact energy | ≤ 0.1 keV |
| Electron temperature | < 10 eV |
| Plasma density | ≤ $10^{22}$ m$^{-3}$ |

# Benefits and Challenges of High-Z PFMs

- Why do we need a substitute for C based materials
- Experiences in present day machines
  - ‚High‘-Z devices
  - diagnostic for W
  - hydrogen retention
  - W erosion
  - W concentrations and transport
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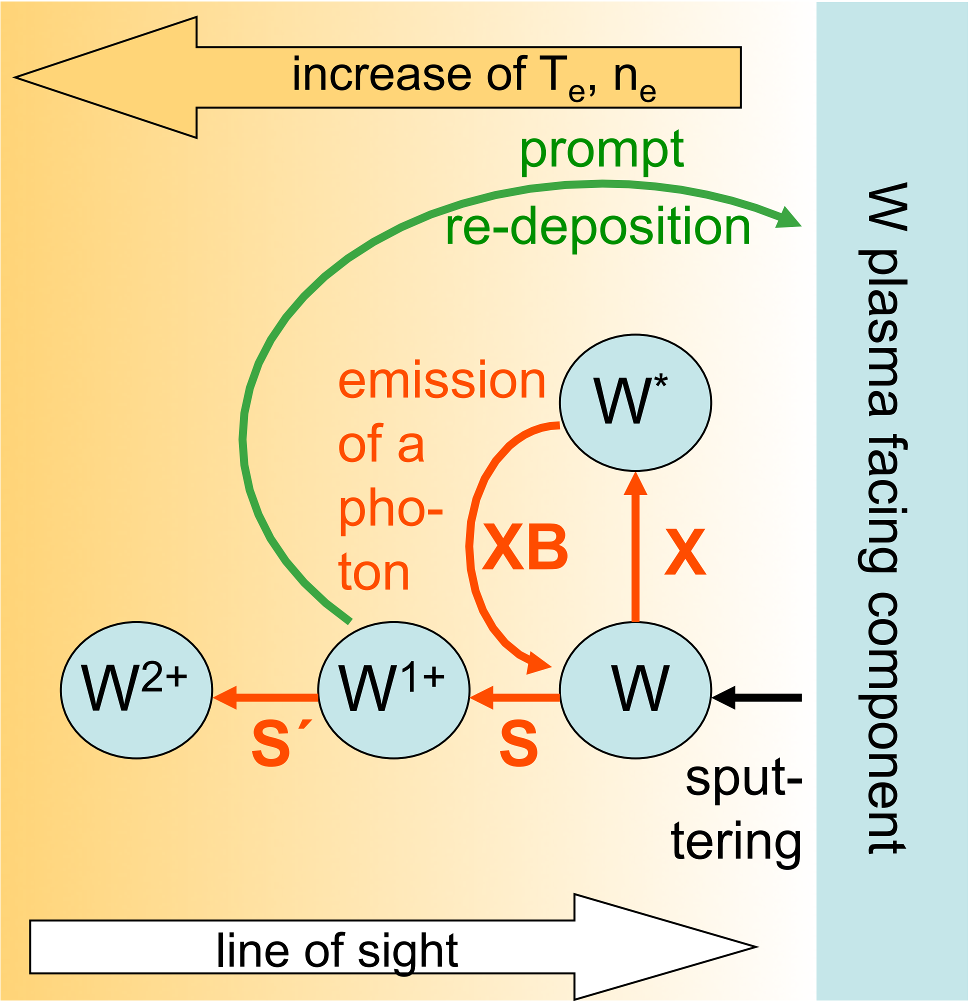
# Spectroscopic diagnostic of fusion plasmas
# S/XB method for influx measurements

schematic view of processes involved in W-flux measurements



**prerequisite:** recombination negligible

- influx

$$\Gamma_{Z+1} = \int_{los} n_e n_Z S \, dx$$

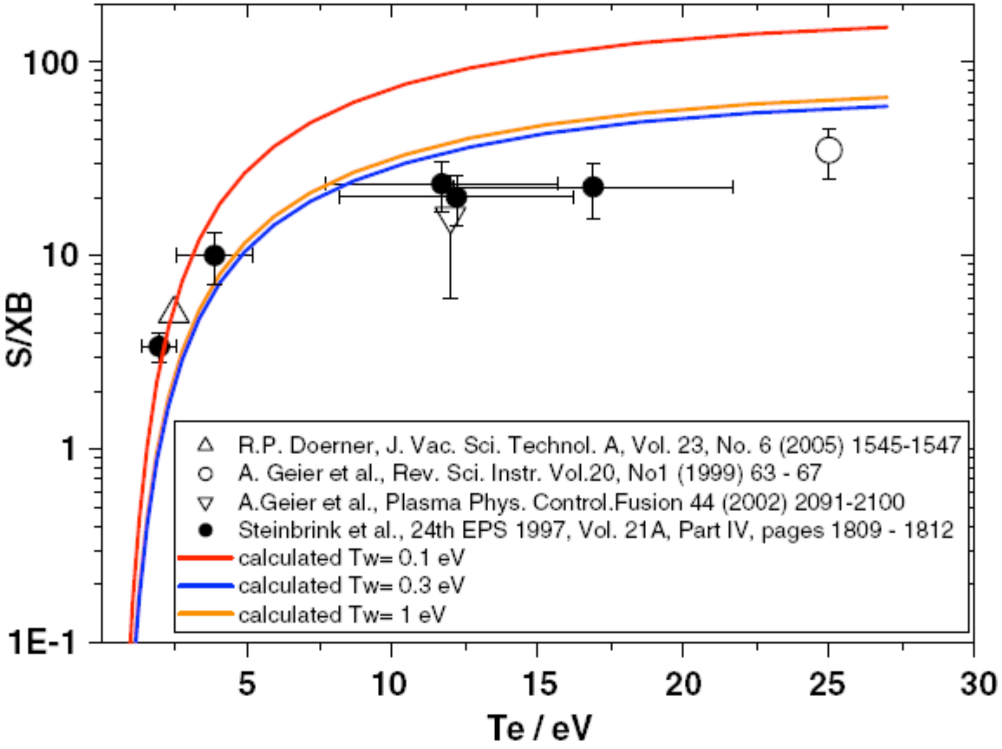
- photon flux

$$\Gamma_\gamma = \int_{los} n_e n_Z XB \, dx$$

$$\Rightarrow \Gamma_{Z+1} / \Gamma_\gamma \approx S/(XB)\,(x_0)$$

S: ionisation, X: excitation
B: branching ratio

# S/XB for W I (400.9nm)



## Calculations of S/XB for W I (400.9 nm)

I Beigman et al. PPCF 49 (2007) 1833

- ionisation rate

  ATOM code calculations
  (lowest configurations)

- excitation rate:

  - semi-empirical v. Regemorter formula (complicated coupling scheme + configuration mixing)
  - corona approximation: only excitation from ‘ground’ state

# Spectroscopic diagnostic of fusion plasmas
# Ionisation shells in the central plasma

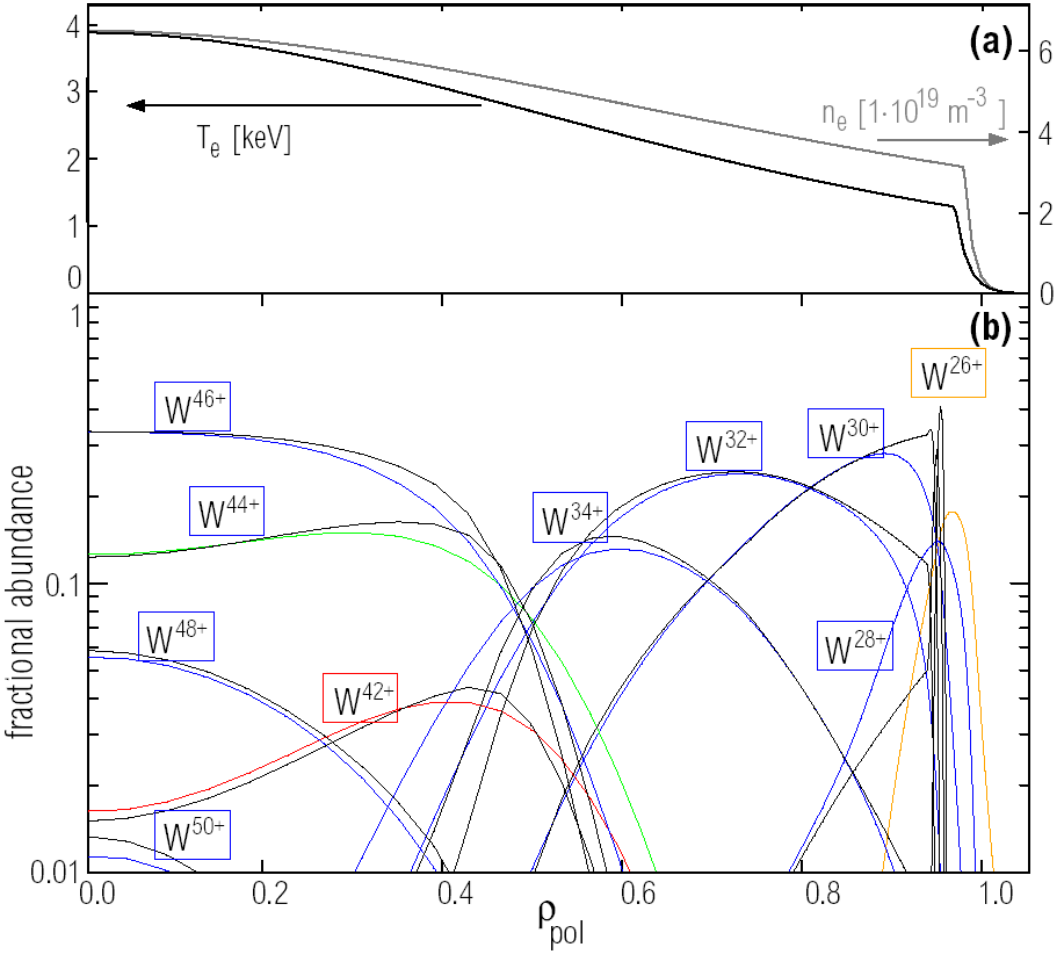
ionisation equilibrium governed by Coronal approximation

$$\frac{\partial}{\partial t} n_Z + \nabla \vec{\Gamma}_Z = n_e(n_{Z-1}S_{Z-1} + n_{Z+1}\alpha_{Z+1} - n_Z S_Z - n_Z \alpha_Z)$$

weak influence of plasma transport on shell structure

$$\vec{\Gamma}_Z = D_Z \nabla n_Z + v_Z n_Z$$

typical radial plasma profiles



ionisation shells with (colored) / without (black) transport

# Spectroscopic diagnostic of fusion plasmas
# Impurity concentrations from LOS measurements

## Comparison of measured $I_M$ and calculated $I_C$ intensities

$$I_c = \frac{1}{4\pi} \int_\ell h\nu n_x n_e \langle \sigma v_e \rangle dl$$

$n_x$ density of impurity in ionisation state x

$n_e$ electron density

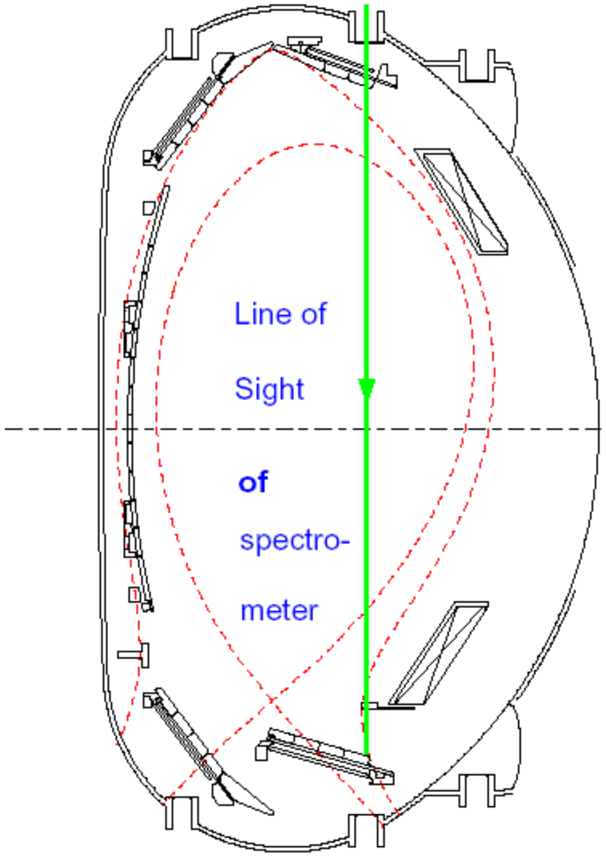
$<\sigma\upsilon>$ excitation rate coefficient

$$n_x = C_{imp} \cdot f_x \cdot n_e$$

$f_x$ fractional abundance of the impurity ionisation state x

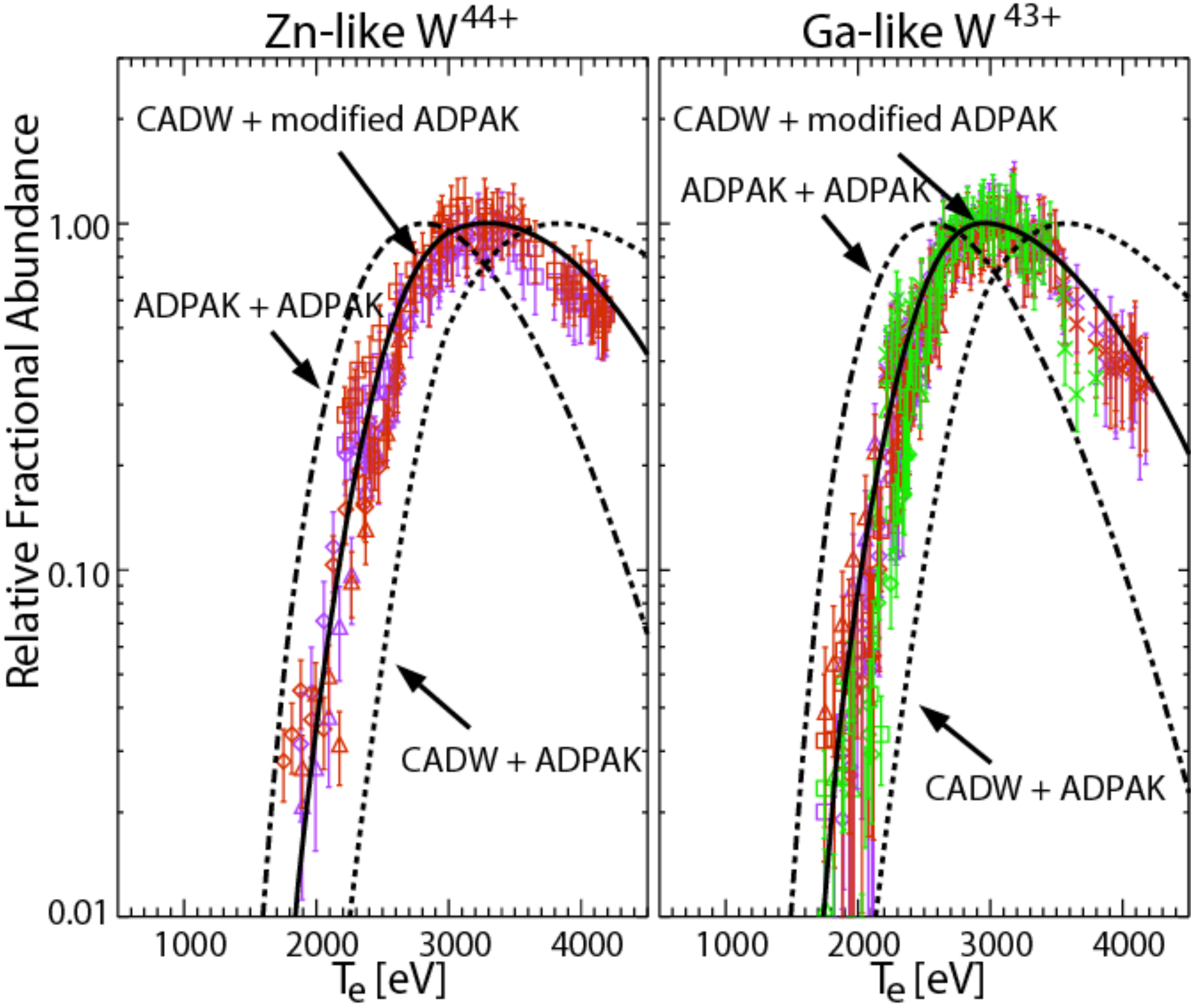
$C_{imp}$ impurity concentration

**$C_{imp}$ only valid within the emission shell!**



$$\boxed{C_{imp} = \frac{4\pi \cdot I_m}{\int_\ell h\nu f_x n_e^2 \langle \sigma v_e \rangle dl}}$$

# W Spectroscopy in the VUV and SXR
## Revision of ionization equilibrium



Deduced fractional abundance versus temperature

different discharges: symbols

different spectral lines: colours

Use of CADW ionisation rates (S.D. Loch, PRA 2005) and adjustment of recombination rates allows good description of emissions of $W^{24+}$ - $W^{48+}$

Th. Pütterich (PPCF 50 2008 085016)

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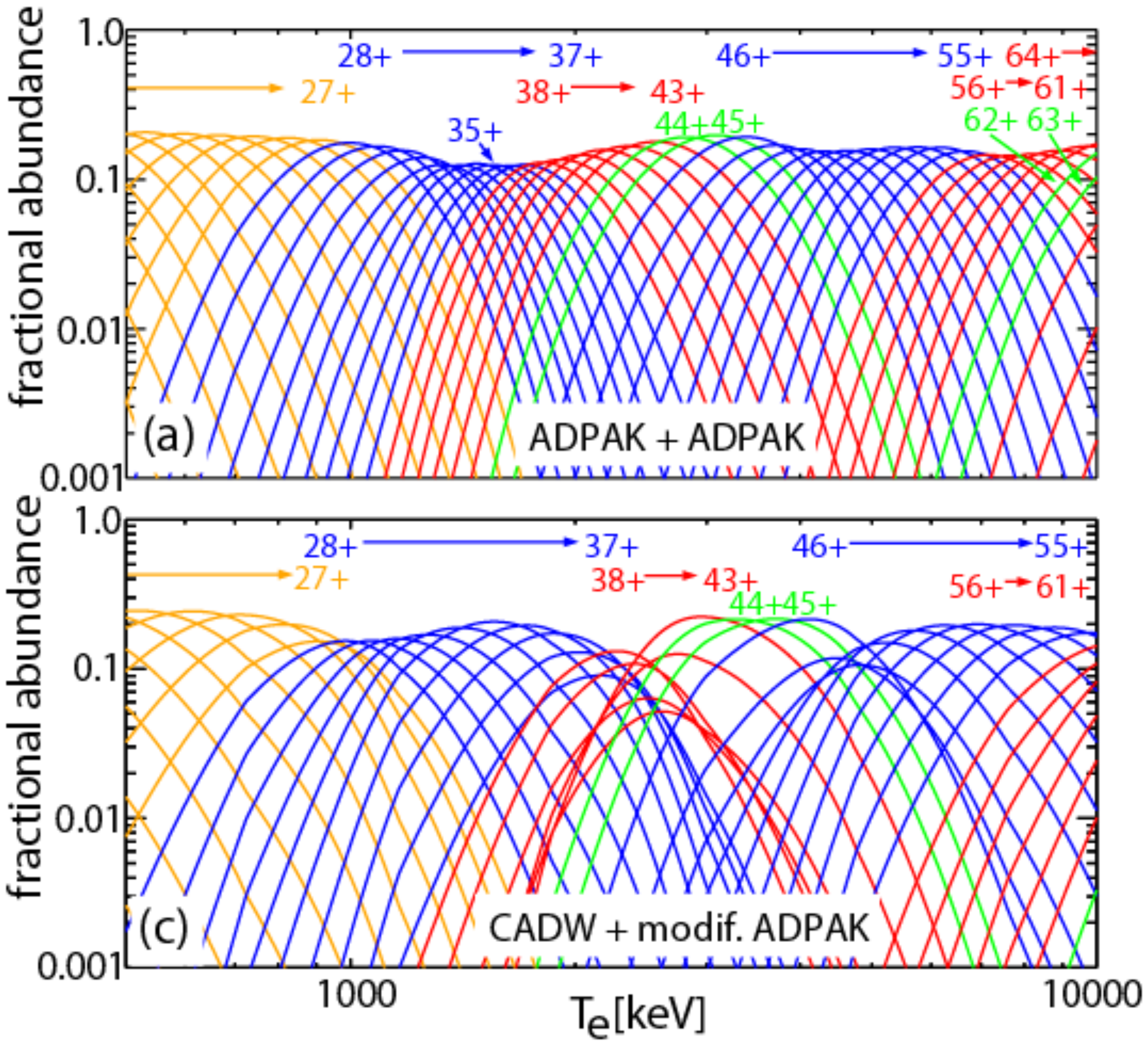


standard
‚ADPAK‘

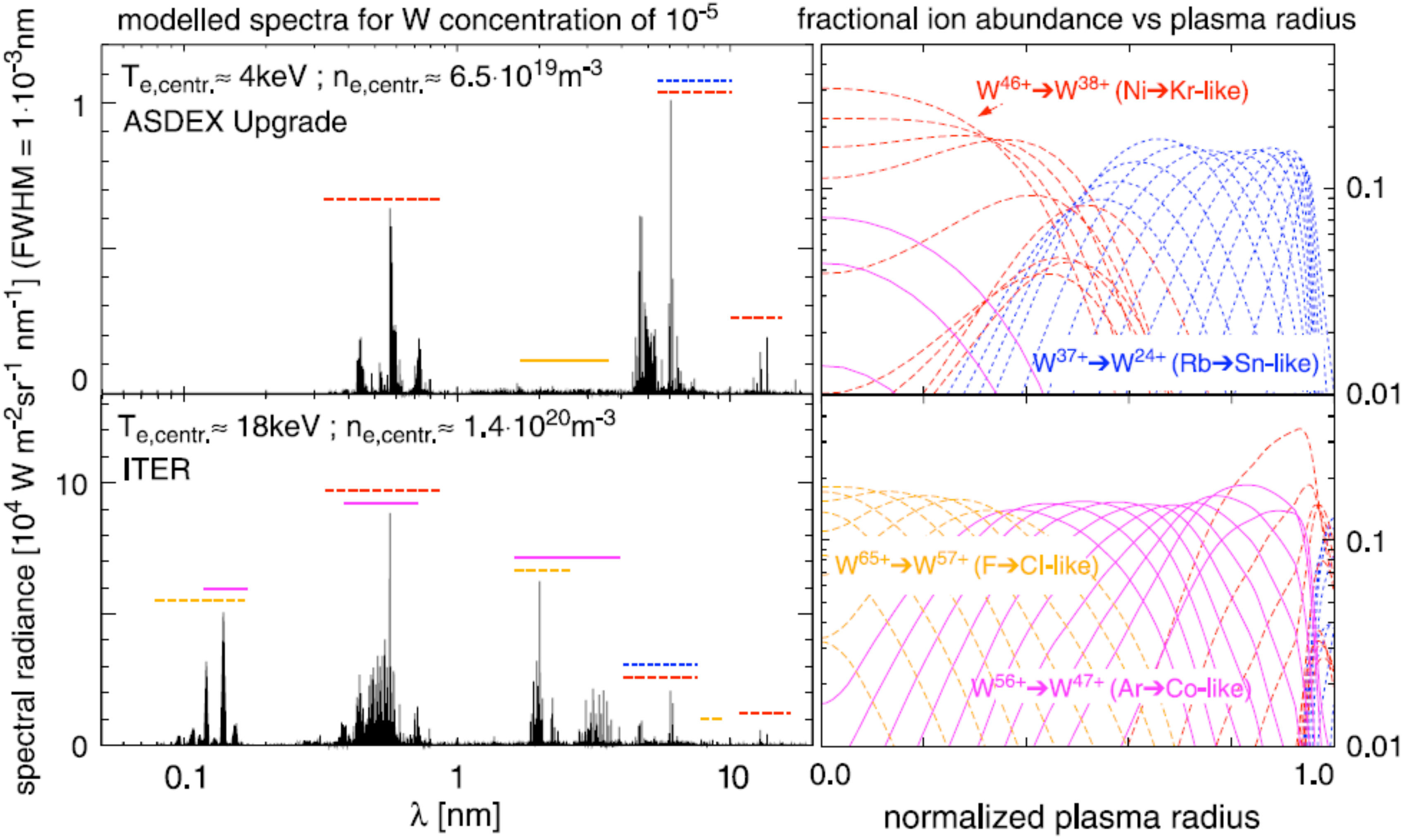
ionisation/
recombination
rates

CADW
ionisation rates

ADPAK
recombination
rates
(adjusted to
experiment)

# Calculation and (Benchmarking) of Spectra for AUG and ITER

## Modelled W emission (ADAS) @ different temperatures



Th. Pütterich, PPCF 50 (2008) 085016

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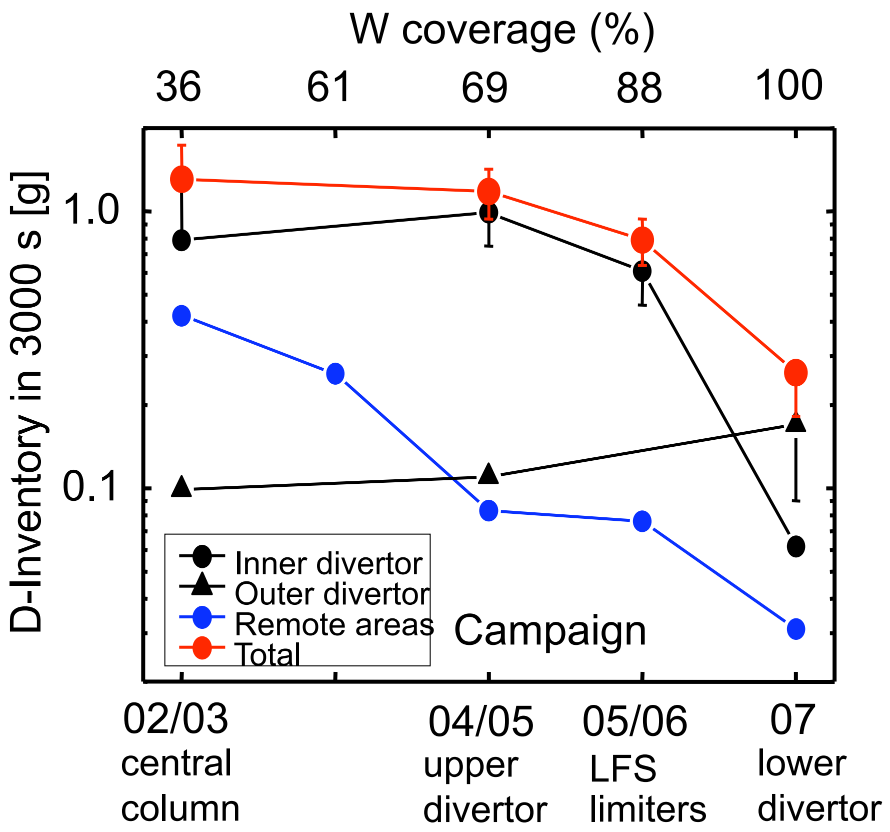
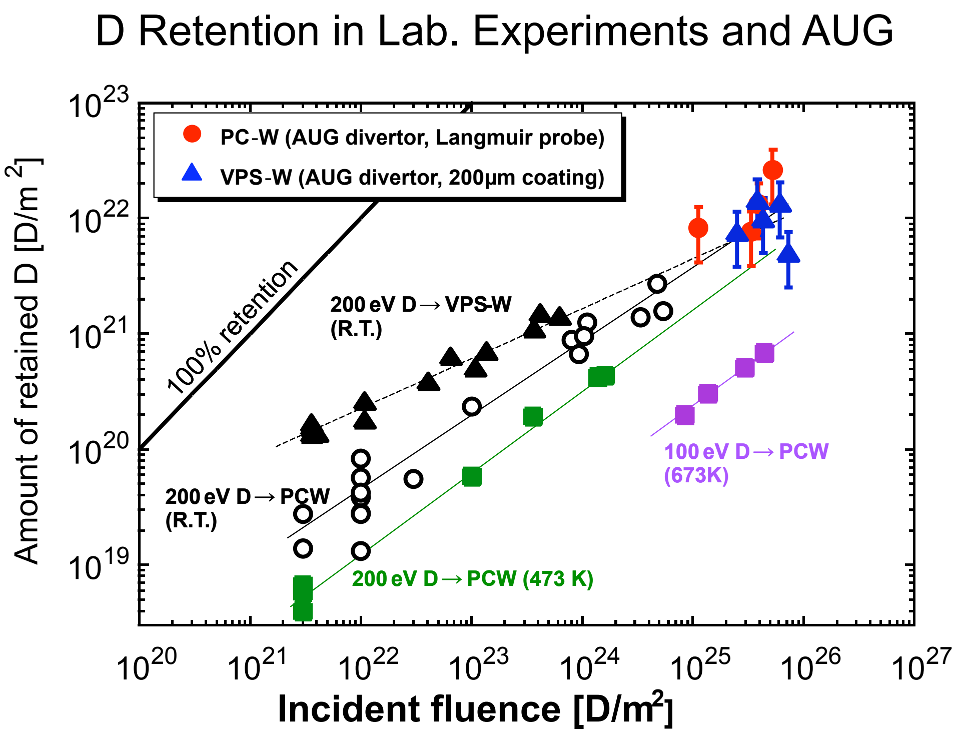
# Strongly reduced D retention after transformation to W PFCs in ASDEX Upgrade





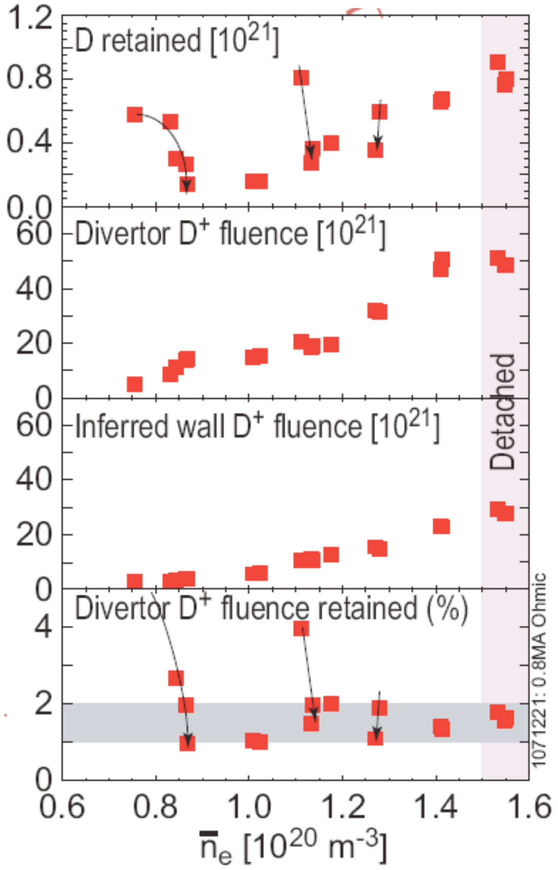
K. Sugiyama et al., subm. to NF

deposition areas: strong reduction of D co-deposition with C
erosion areas: slight increase due to diffusion in W

**consistent with laboratory results and particle balance measurements**

# (Surprisingly) large D retention in Mo observed in C-Mod

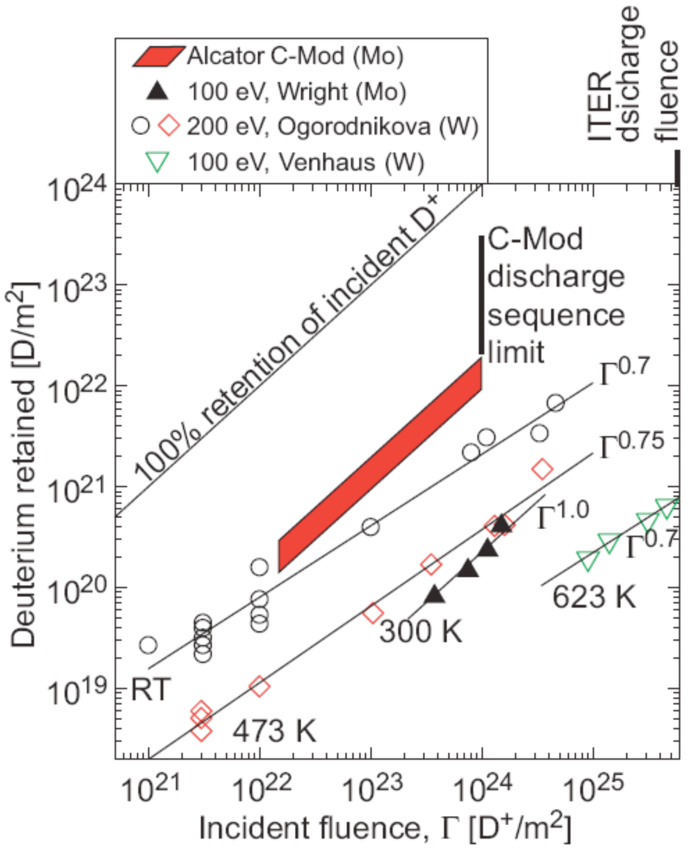
retention ~ independent of density when normalized to divertor ion fluence



- implantation of ions drives retention
- reaches 1-2%, >> that predicted for Mo
- stronger fluence dependence than from laboratory data

reason(s) for discrepancy not yet clear:

- trap creation by impinging ions
- reduction of recombination by impurities



B. Lipschultz et al., PSI 2008 and NF49 (2009) 045009

# Co-deposition ratio from laboratory and linear devices

Dependent on temperature, energy, flux ratio:

$(D+T)/C = (2.0 \cdot 10^{-2})\, E^{-0.43}\, (\Gamma_{(D+T)}/\Gamma_C)^0\, e^{(2268/T)}$

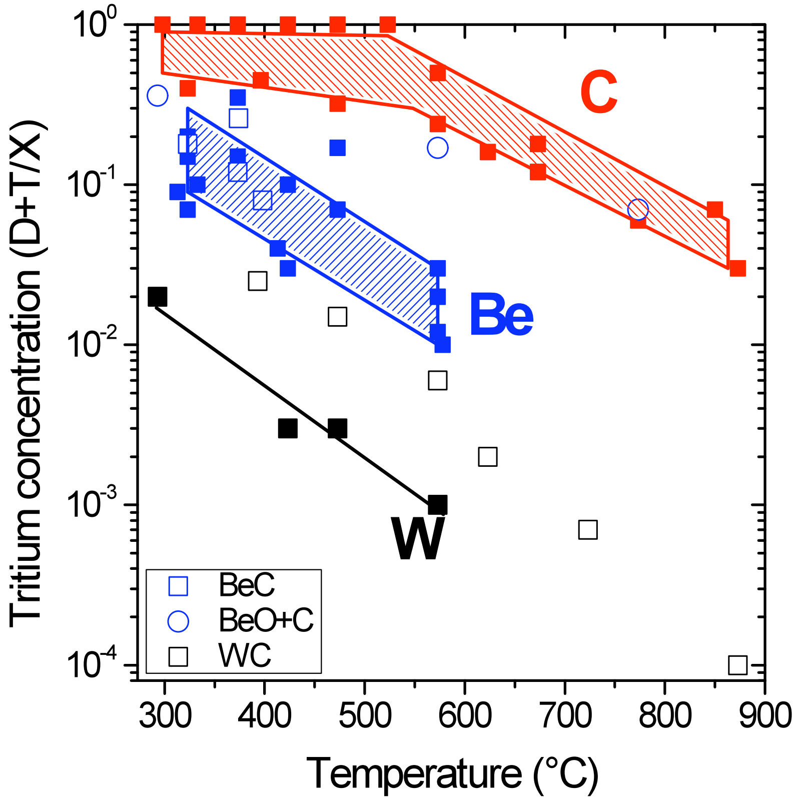
$(D+T)/Be = (5.82 \cdot 10^{-5})\, E^{1.17}\, (\Gamma_{(D+T)}/\Gamma_{Be})^{-0.21}\, e^{(2273/T)}$

$(D+T)/W = (5.13 \cdot 10^{-8})\, E^{1.85}\, (\Gamma_{(D+T)}/\Gamma_W)^{0.4}\, e^{(736/T)}$

Example:

T= 500K, $\Gamma_{(D+T)}/\Gamma_{imp}=100$

(D+T)/C = 0.6
(D+T)/Be = 0.04



R. Doerner, UCSD

# Benefits and Challenges of High-Z PFMs

- Why do we need a substitute for C based materials
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  - diagnostic for W
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  - W erosion
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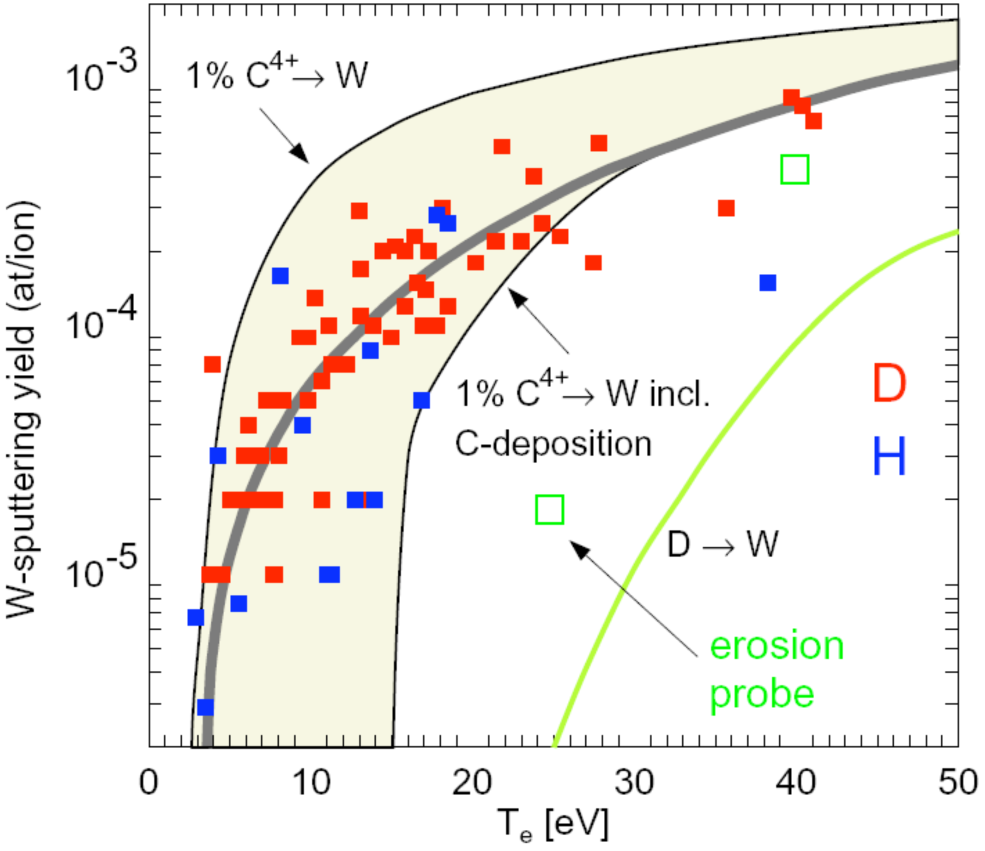
# W erosion yield

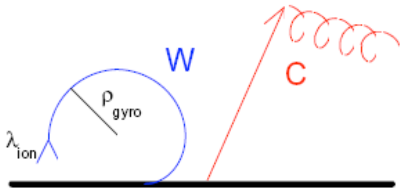
- W sputtering yields 100-1000 times smaller than for C, but strongly dominated by low-Z intrinsic impurities
- hints for prompt redeposition of W
- very small migration into main chamber
- even larger yields (> $10^{-2}$) in TEXTOR

K. Krieger JNM 266-269 (1999) 207



prompt redeposition

C : $f_r \leq 0.2$
W: $f_r \geq 0.9$



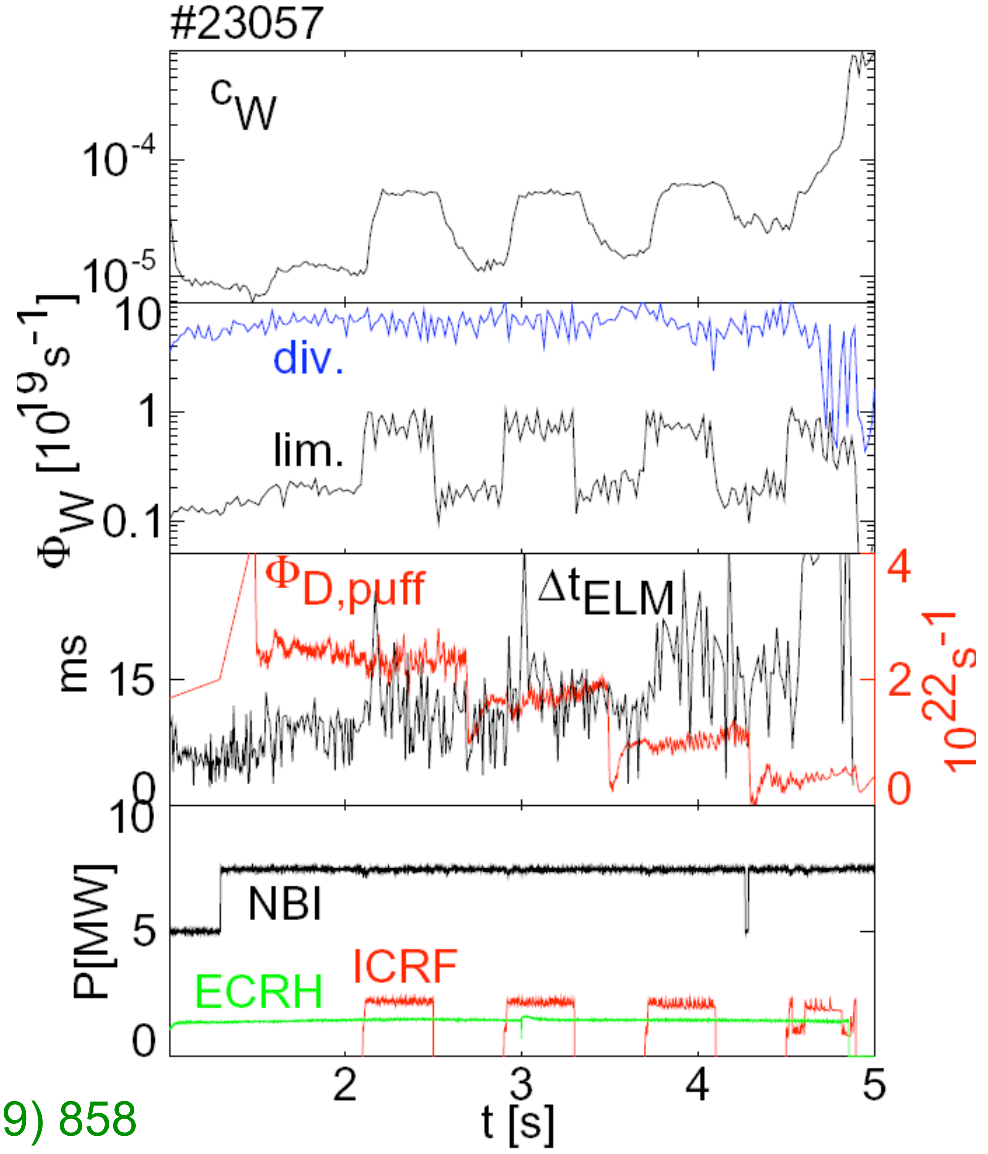
# Increase of limiter W sources and W concentration with ICRH in AUG

**ICRF heating causes strong increase of limiter erosion and W concentration**

- W sputtering induced by accelerated particles in rectified sheath
- limiter source much more ‚efficient‘ than divertor source (> 5 times, depending on discharge parameters)

**similar results for Mo sputtering at C-Mod**

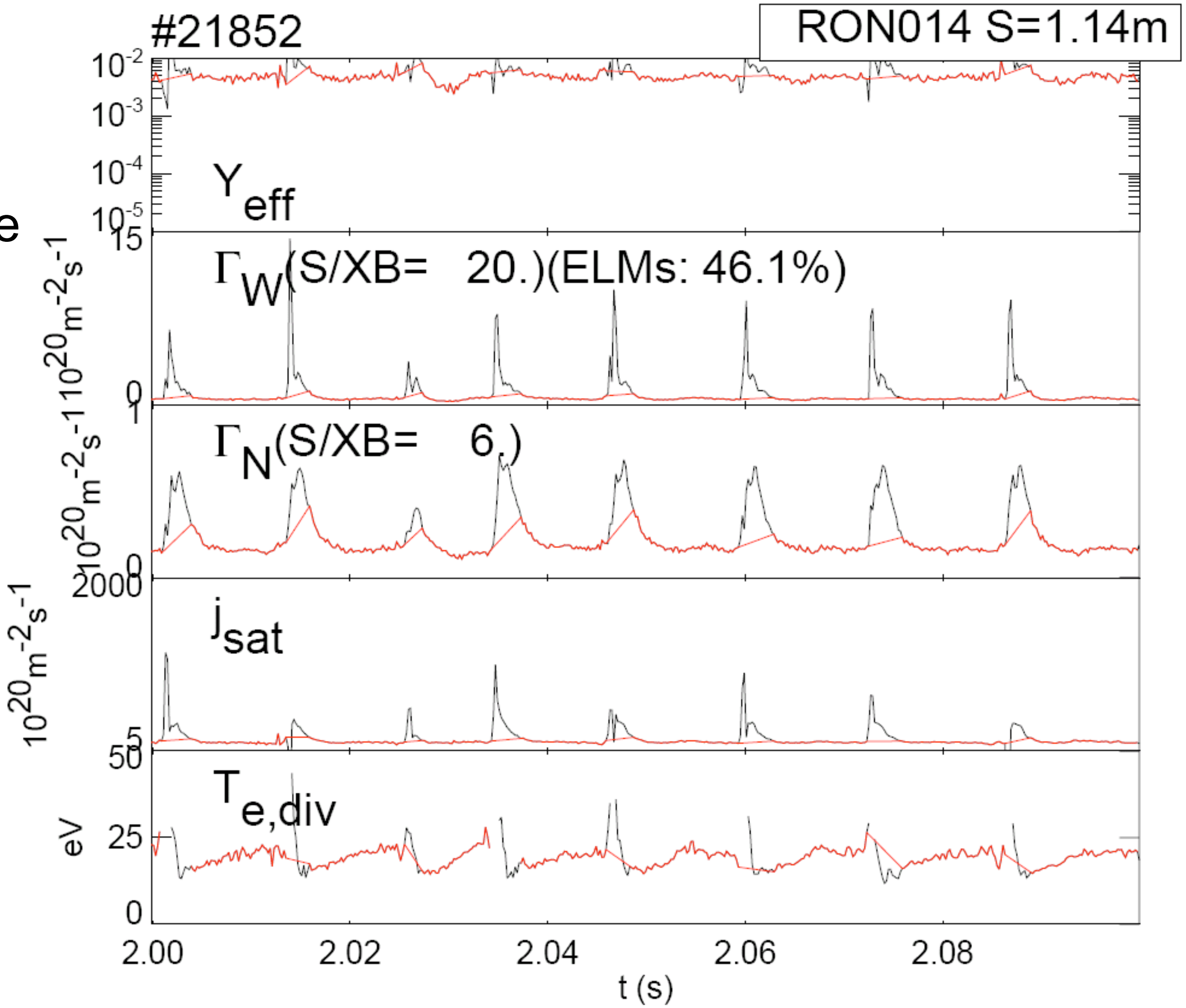
**correlation also found for increased limiter source in radial scans**



R. Dux, JNM 390-391 (2009) 858

# ELM Cycle at Low Divertor Density

- divertor temperature between ELMs: ≈ 20eV
- Considerable influx also inbetween ELMS
- ELMs contribute ≤ 50% to the W-influx



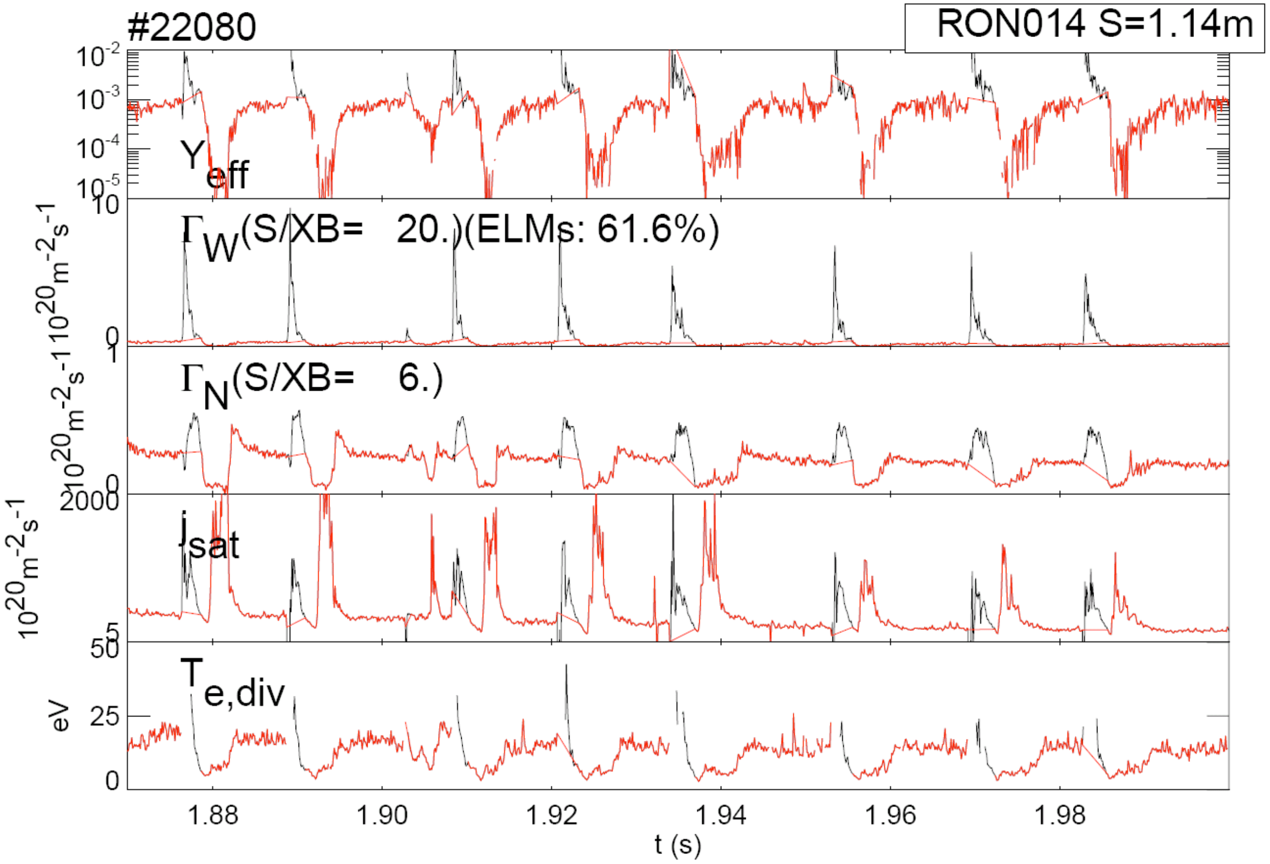
R. Dux, JNM 390-391 (2009) 858

# ELM Cycle at Higher Divertor Density

divertor temperature
is low after the ELM

⇒ erosion yield is lower
inbetween ELMs

⇒ ELMs contribute
\> 50% to W-influx



R. Dux, JNM 390-391 (2009) 858

# ELM resolved W erosion in the outer divertor of AUG

**ELM: edge localized modes**

→ periodic release of energy
and particles at the edge

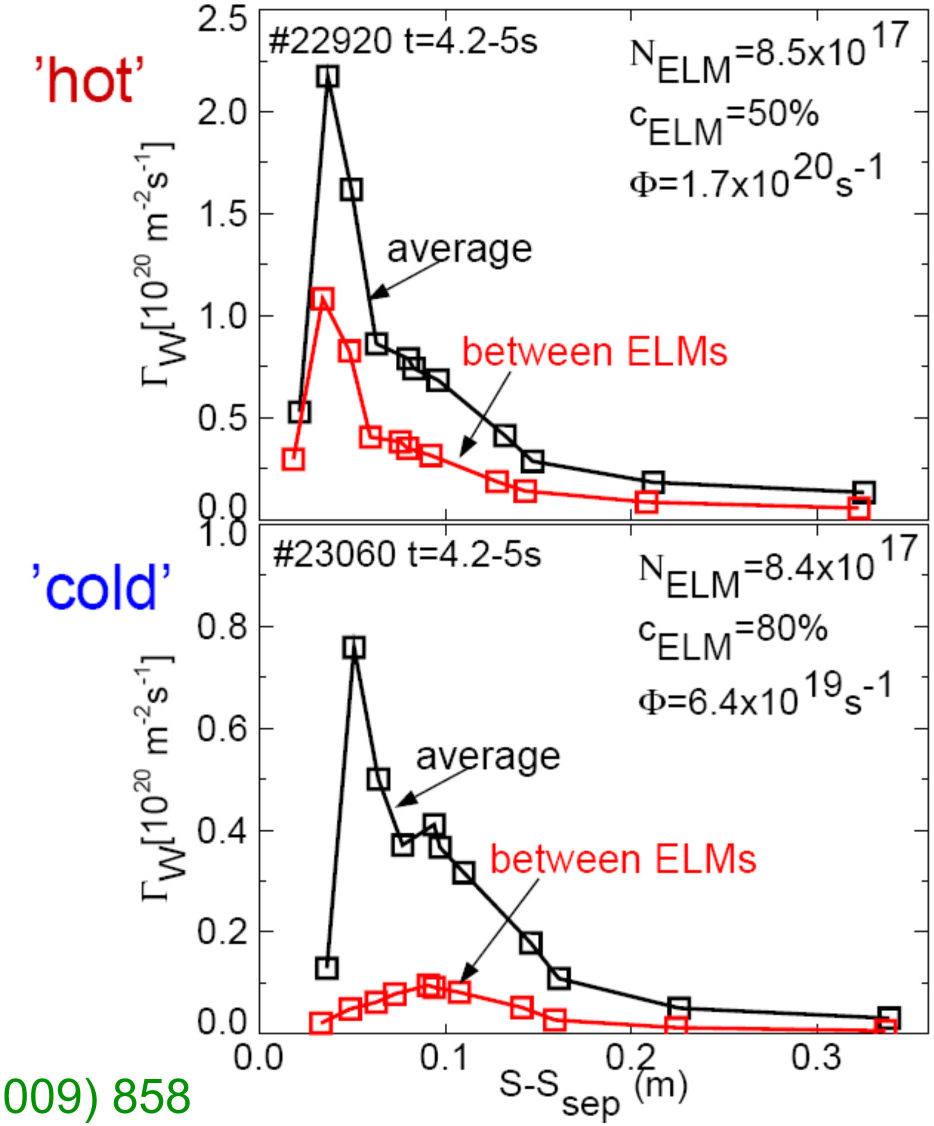
'hot' divertor: $T_e \sim 20$ eV

- similar erosion profiles during ELMs and between ELMs
- ELM contribution ~ 50%

'cold' divertor: $T_e \sim 6$ eV

- between ELMs erosion much smaller, highest erosion far in the scrape of layer → 'semi'-detached
- ELM contribution > 80%

**erosion mainly by intrinsic low-Z impurities**



R. Dux, JNM 390-391 (2009) 858

# Benefits and Challenges of High-Z PFMs

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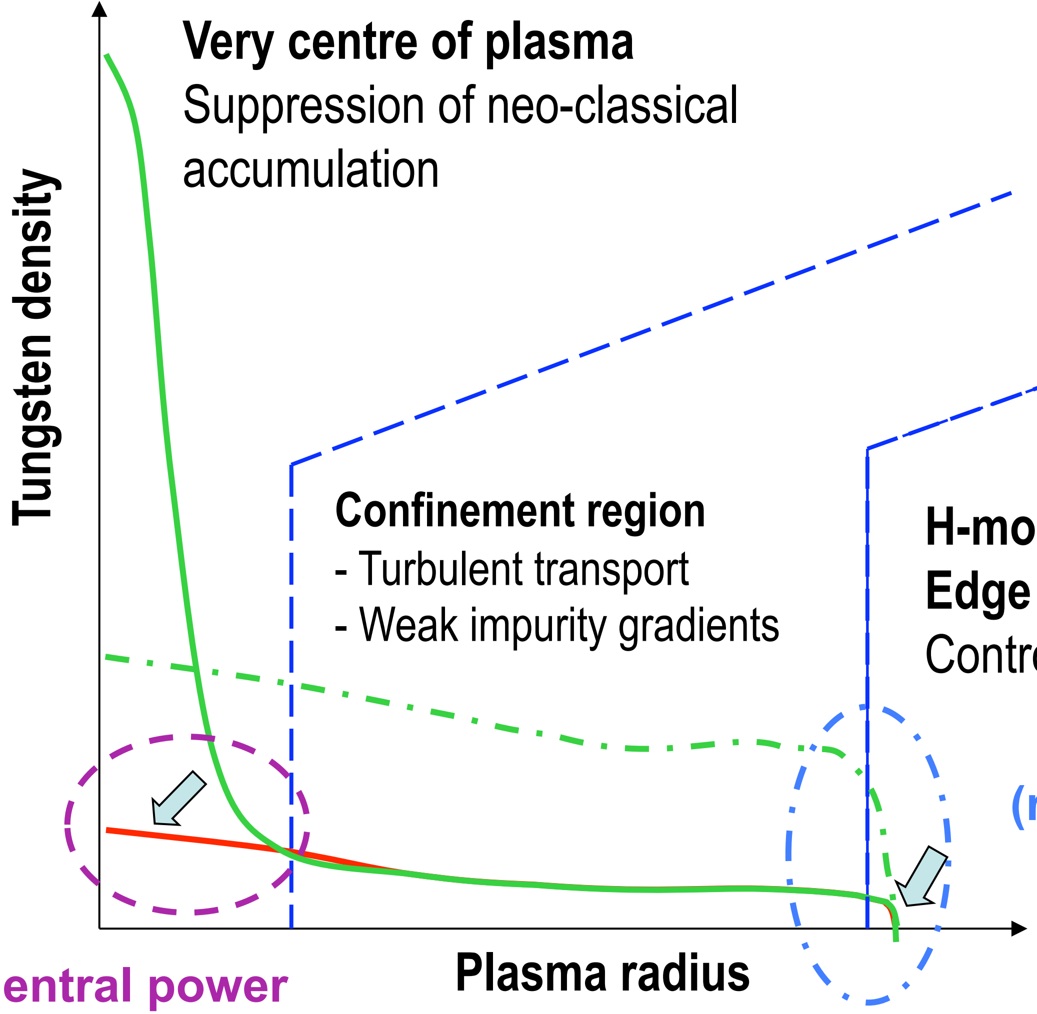
# Control of high-Z transport

**Prevent too high W-concentration ($C_W<5\cdot10^{-5}$) and W-accumulation**



**Very centre of plasma**
Suppression of neo-classical accumulation

**Confinement region**
- Turbulent transport
- Weak impurity gradients

**H-mode**
**Edge Transport Barrier**
Control W-influx

**Control of ELM frequency**
**(reduce inward transport of W)**
- **Gas puffing**
- **Input power**
- **other methods**

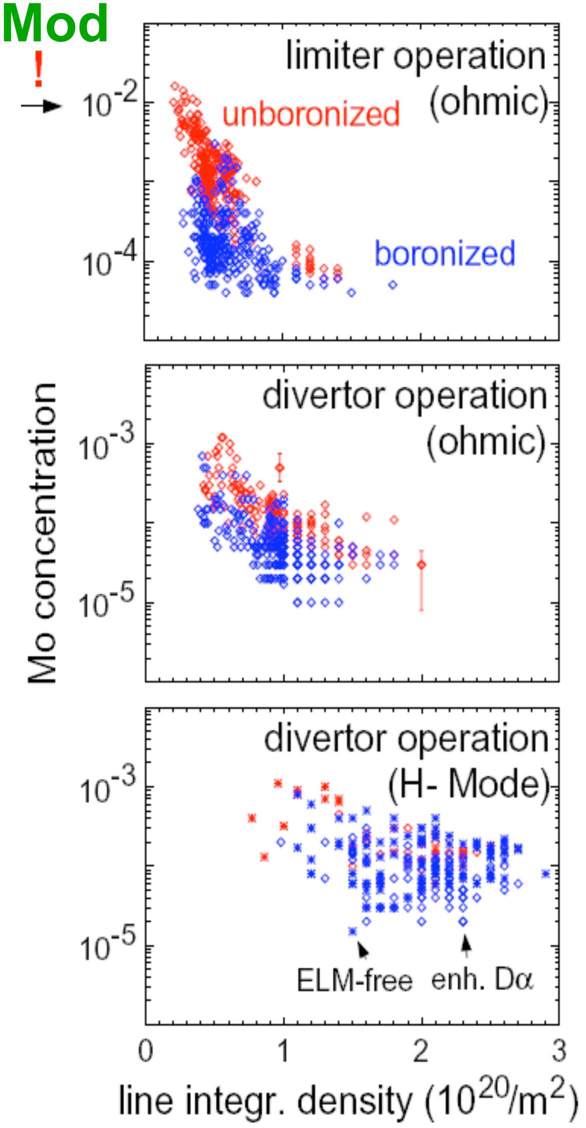
**Central power**
**NBI, ECRH, ICRH**

# Impurity behaviour
# Alcator C-Mod / FTU

**General behaviour ($c_{Mo}$)**

- (very) high during low density limiter phase
- strongly decreasing with density
- at high density 2-3 lower in divertor phase
- (also from comparison with FTU)
- 2-5 times higher in H-Mode compared to L-Mode
- reduction by 2-10 through boronisation

**$c_{Mo}$ in C-Mod**

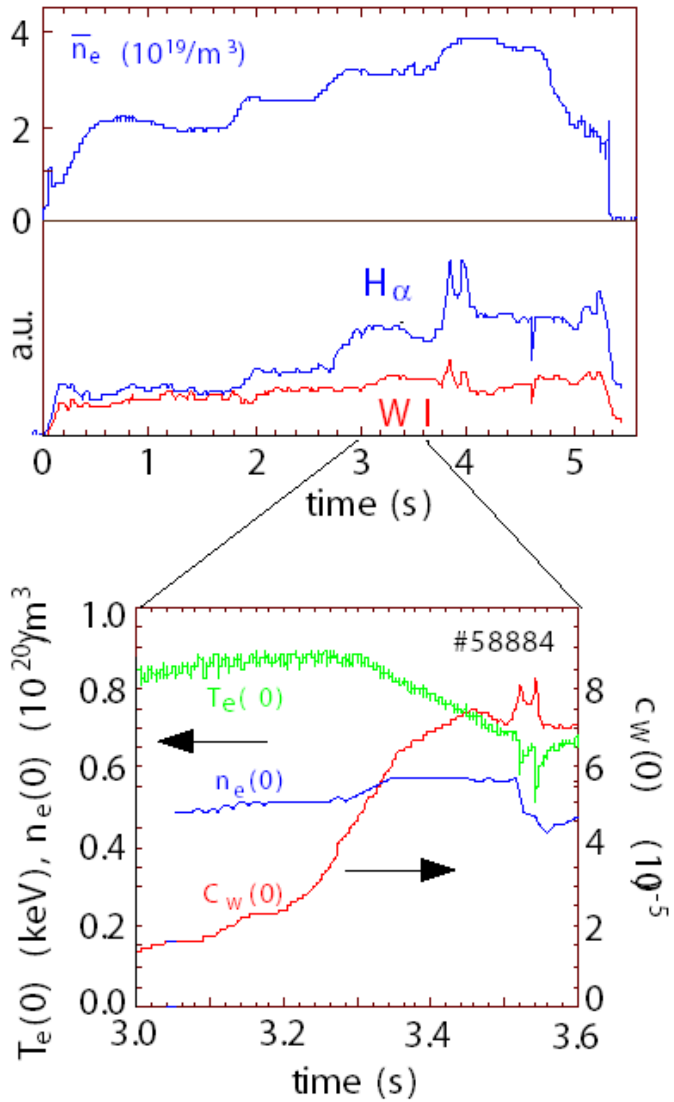


# Impurity Behaviour
# TEXTOR (FZ Jülich)

usually no high-Z accumulation, but only small fraction (< 10%) of PWI (particle/ power flux) on high-Z components

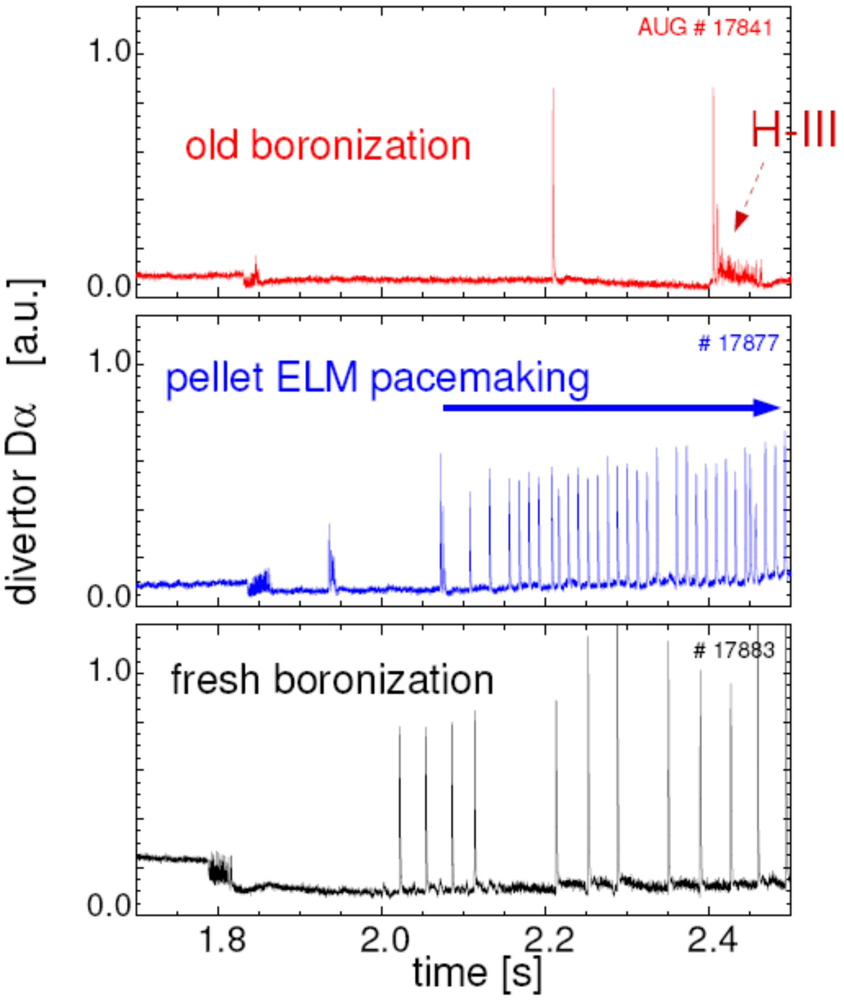
W accumulation for
- ohmic discharges above critical plasma density
- high level of (edge) radiation

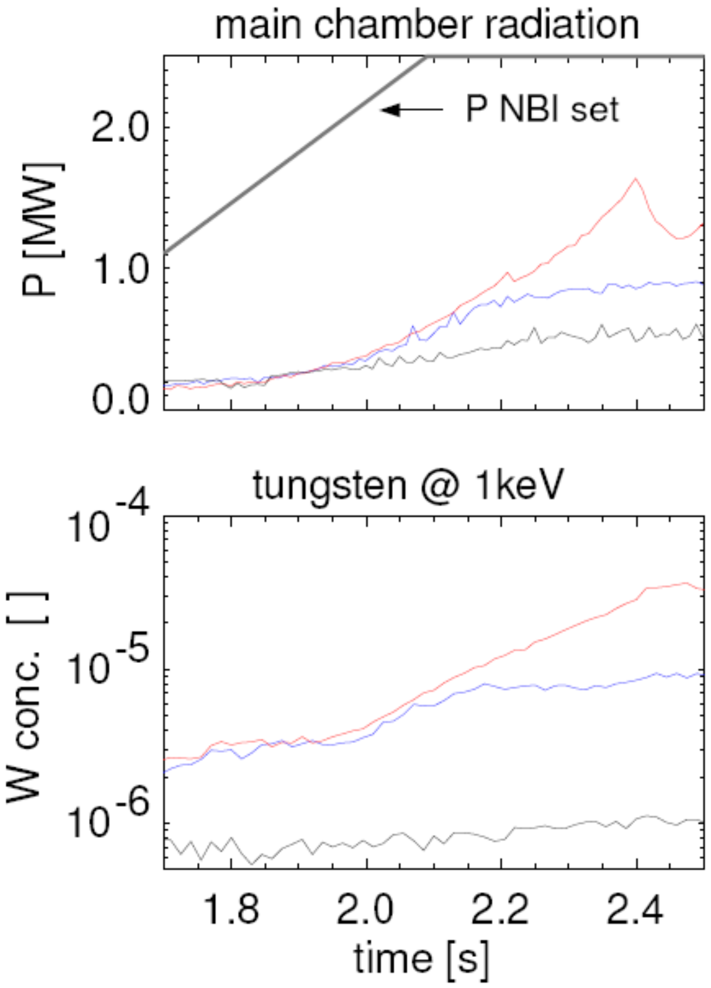
central high-Z contamination depends strongly on transport (RF heating beneficial)



V. Philipps et al., EPS 1995, p.321

# W behaviour in AUG
# Reduction of W content by increasing ELM frequency

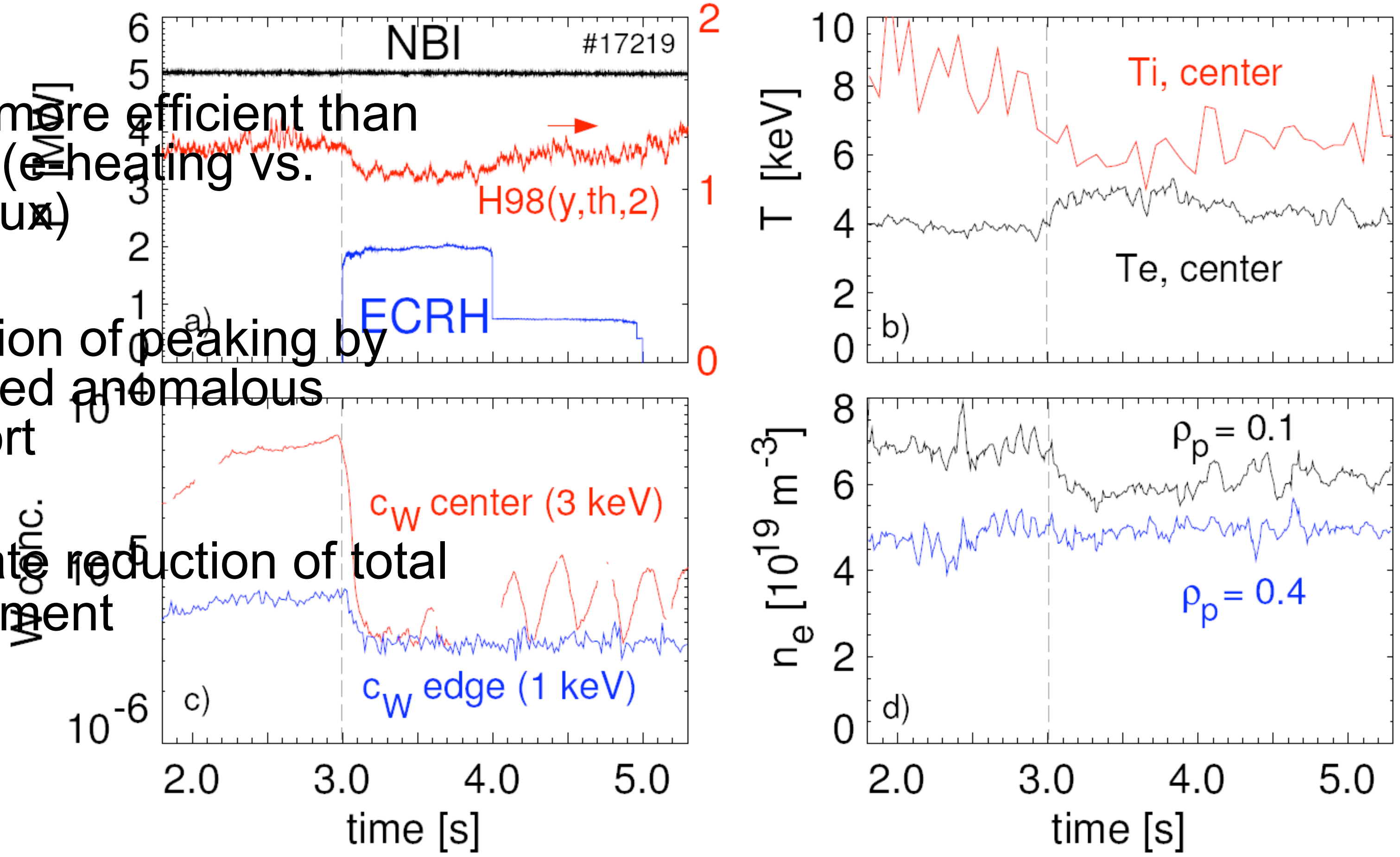




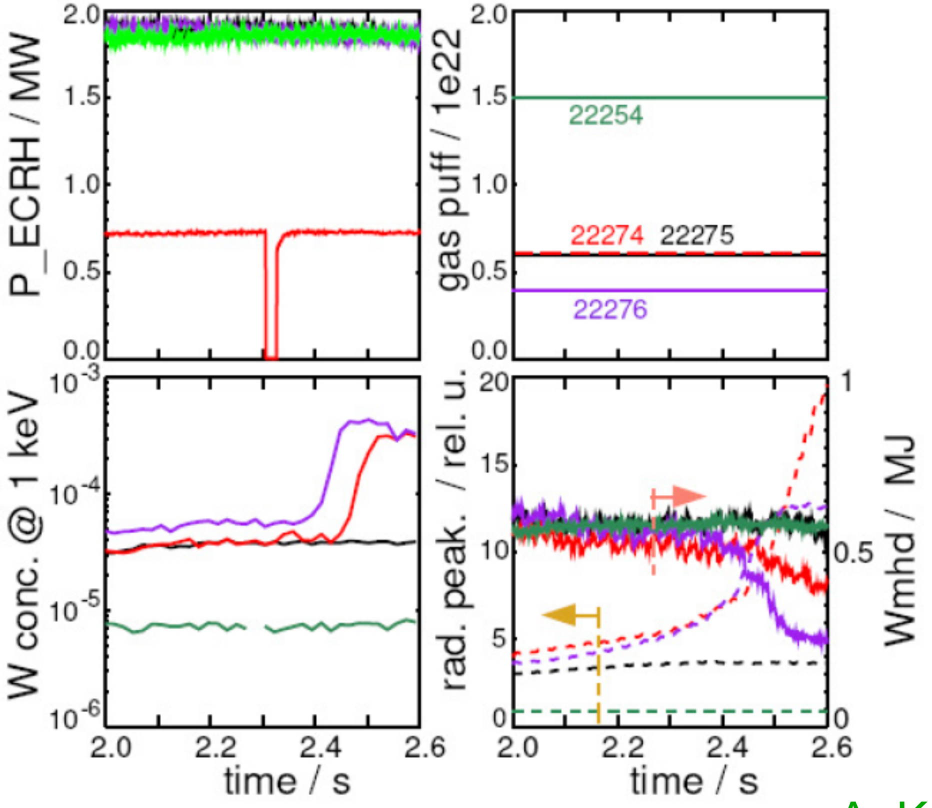
# W behaviour in AUG
# Suppression of central impurity peaking

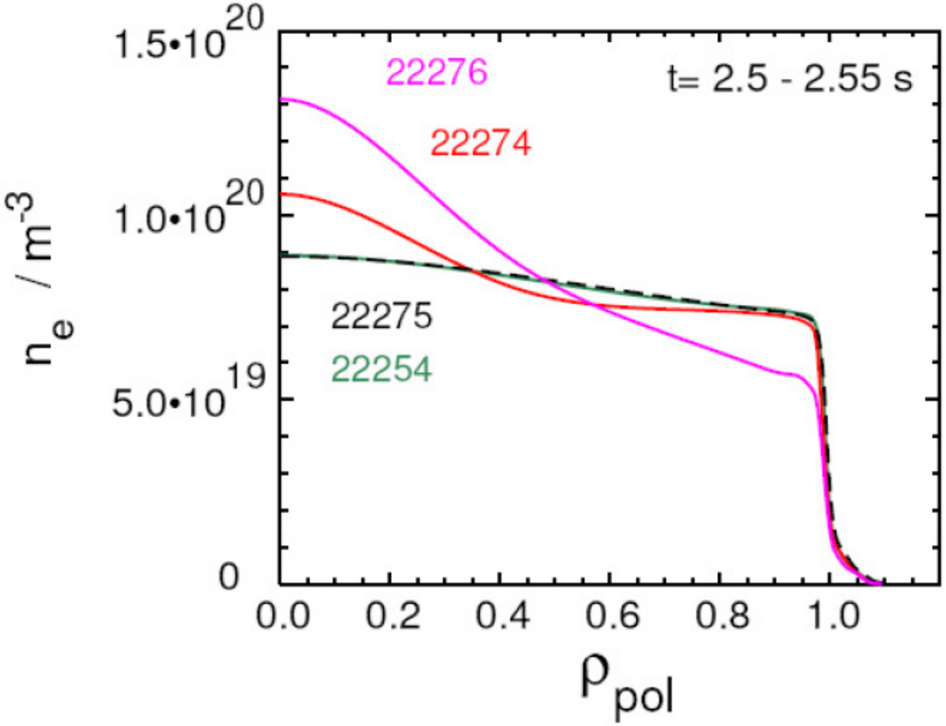
## Central wave heating strongly suppresses impurity peaking

- ECRH more efficient than ICRH (e-heating vs. powerflux)
- Reduction of peaking by increased anomalous transport
- Moderate reduction of total confinement



# Suppression of W accumulation in AUG





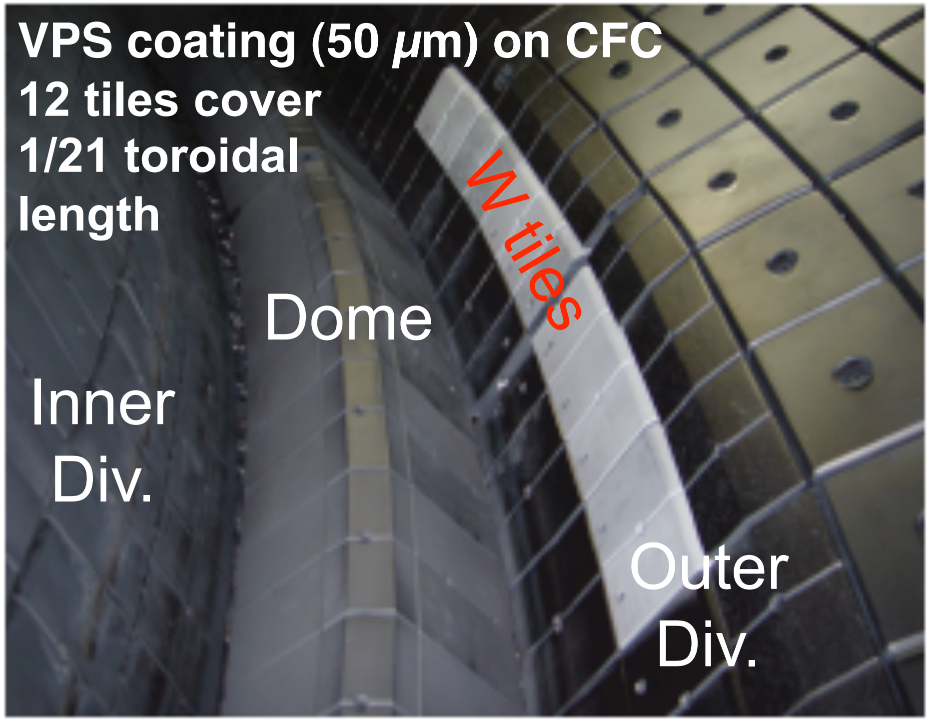
A. Kallenbach et al., NF 49 (2009) 045007

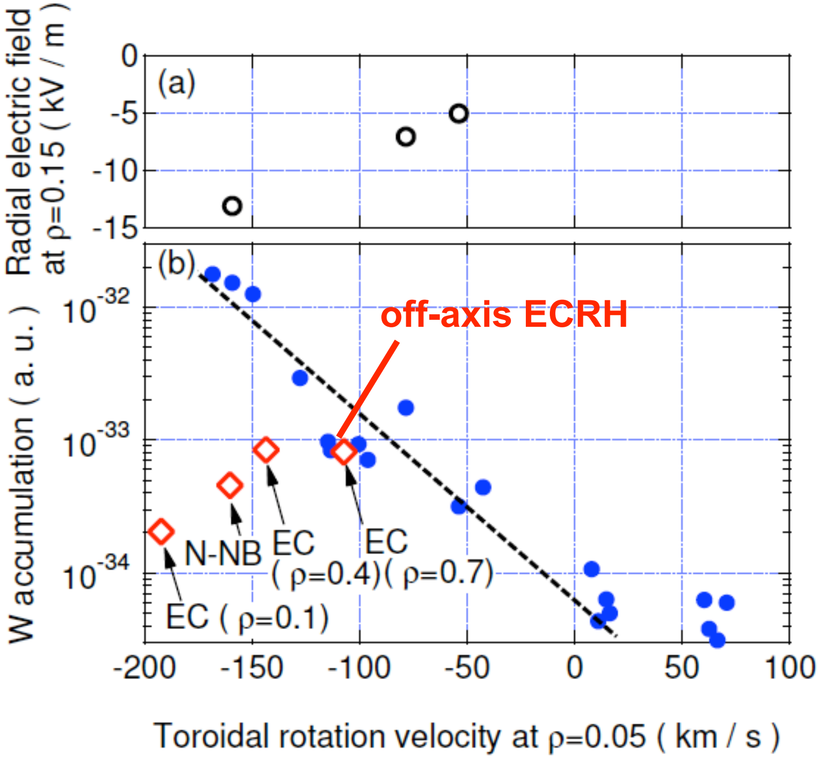
central W accumulation connected to electron density peaking

can be controlled by central heating and/or gas puff

neoclassical transport decreases with Z small increase of anomalous transport sufficient

# Suppression of W accumulation in JT-60U





**JT-60U**

- W accumulation provoked by counter NBI
- Strong suppression of W accumulation by central heating
  (increase of turbulent transport / destabilization of sawteeth)
- AUG results confirmed

T. Nakano et al., 22nd IAEA FEC 2008, EX/P4-25

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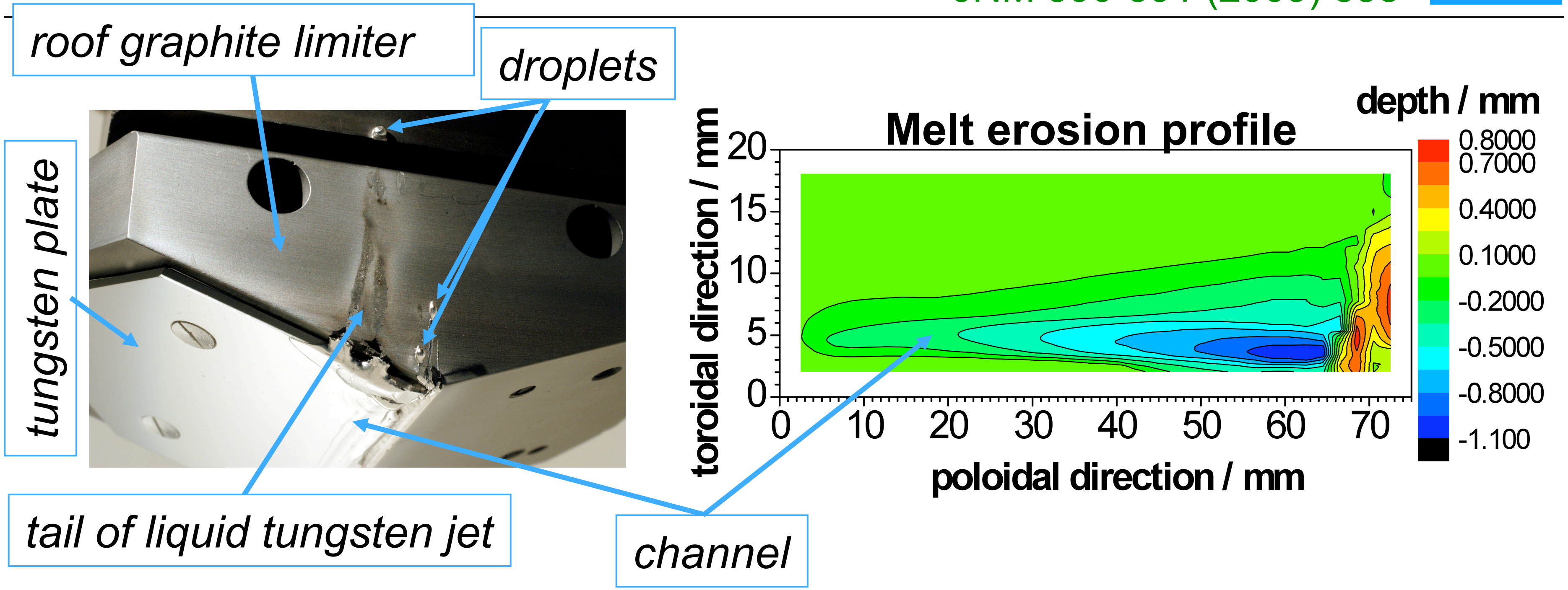
# Tungsten melt layer behaviour

G. Sergienko et al.,
JNM 390-391 (2009) 858

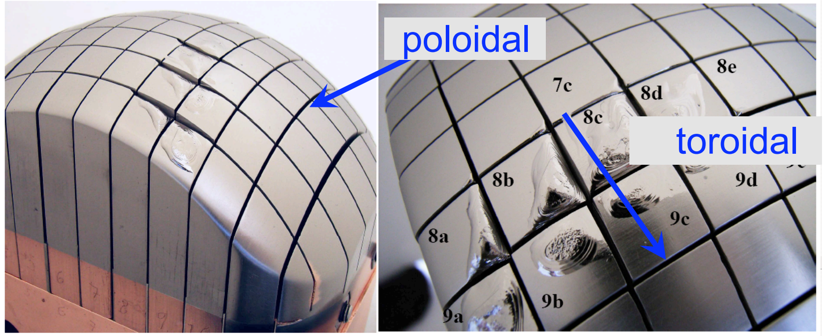


- Liquid W jet moves up with velocity of about 1.5 m/s
- Material loss: 2.85 g of W removed from the ero. channel in 1s
- Motion of molten W and outward propagation of the jet are due to the thermo-emission current
- Variation of the depth of the erosion channel in pol. direction probably due to additonal heat transfer by liquid metal flow

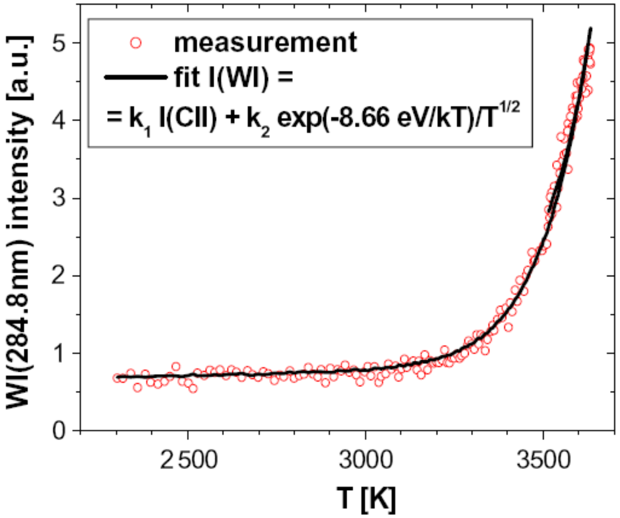
# W behaviour under high heat loads

- recrystallisation starts above ~1200° C (lower fracture toughness)
- no enhanced erosion found close to melting
- re-solidified surfaces are prone to increased power loads

TEXTOR test limiter experiments with W-macrobrush structures

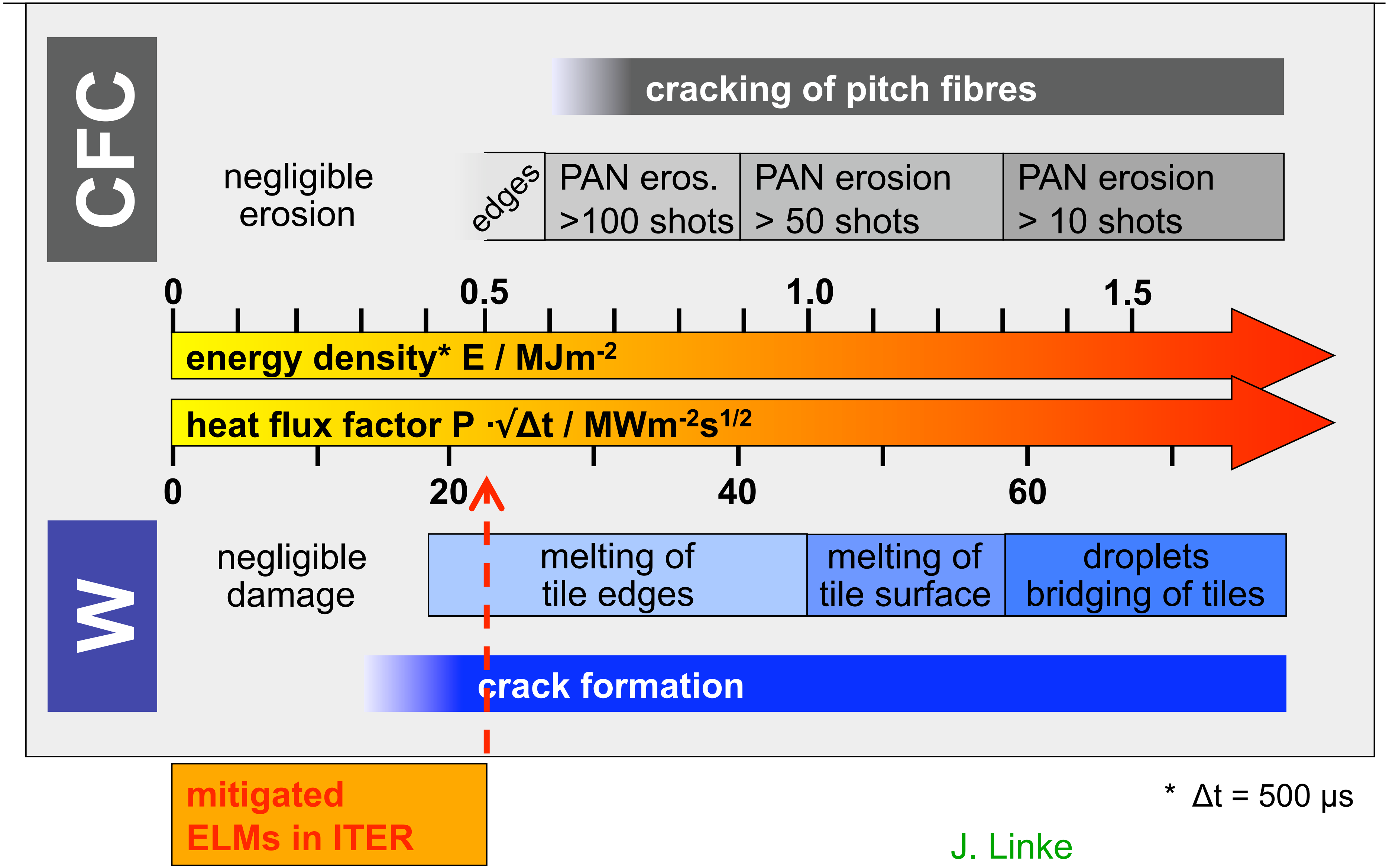


Under transient heat loads
- development of cracks
 (fatigue, below melt-temperature)
- melt layer movement and losses due to jxB force, plasma pressure, …
  (e-beam, plasma gun, QSPA experiments:
   very difficult to adjust to ITER parameters)



G. Sergienko et al.,
JNM 390-391 (2009) 858

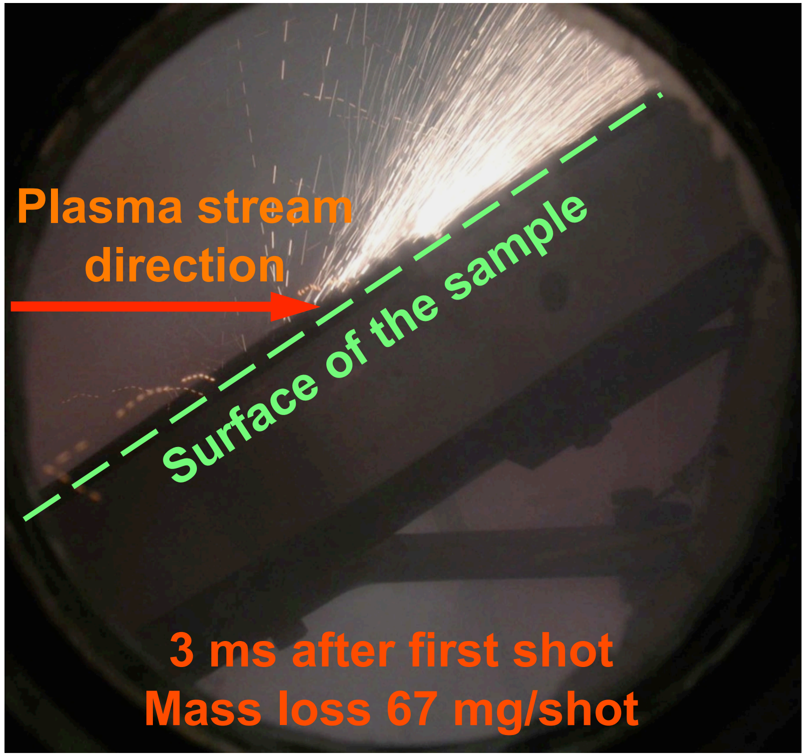
# Damage thresholds for CFC and W under ELM-loads

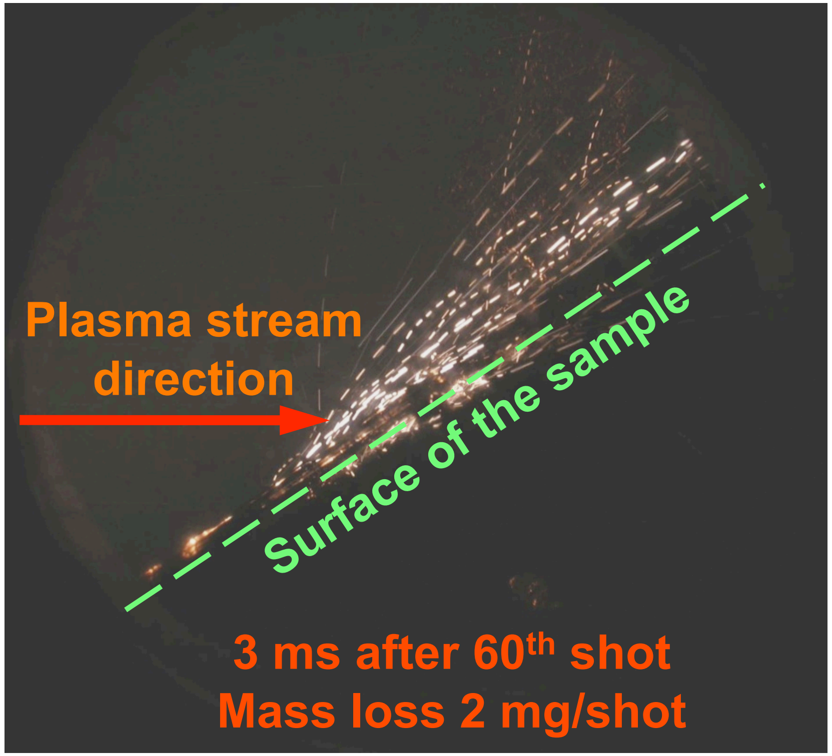


* $\Delta t = 500\ \mu s$

J. Linke

# Droplet ejection @ E = 1.6 MJ/m$^2$





- During the first shot droplets ejected mainly from the edges of the tiles.
- As a result of edge smoothing and bridging of gaps the droplet ejection was reduced and mass losses were decreased.

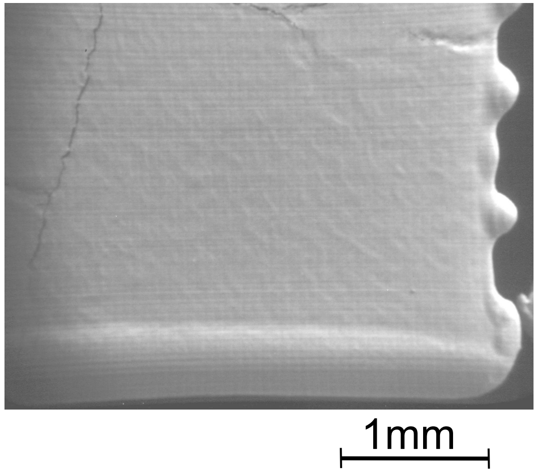
A. Zhitlukhin et al., SRC RF TRINITI, Troitsk

# Bridge formation @ E ≥ 1 MJ/m²

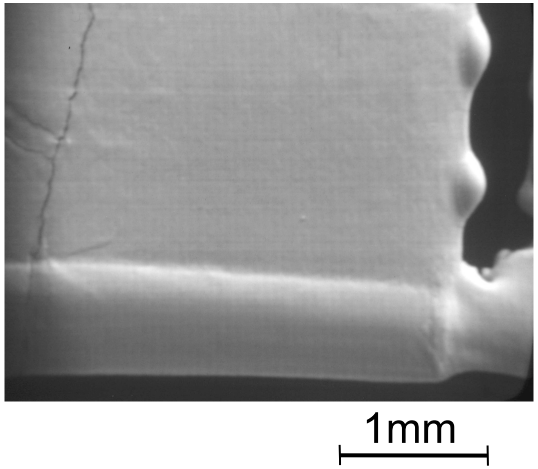
B. Bazylev et al.,
JNM 390–391 (2009) 81

$w = 1.0\ MJ/m^2$

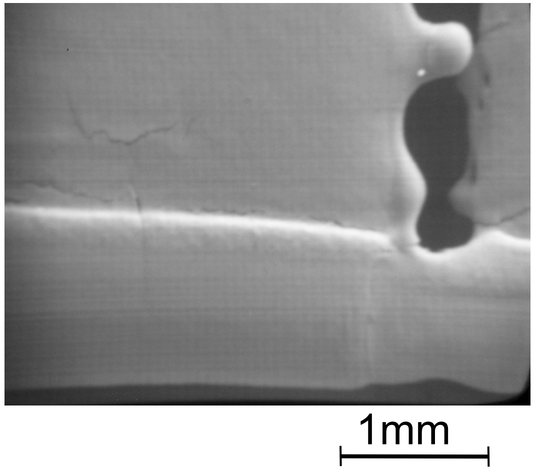
W3,R3, 20 exposures



W3,R3, 50 exposures

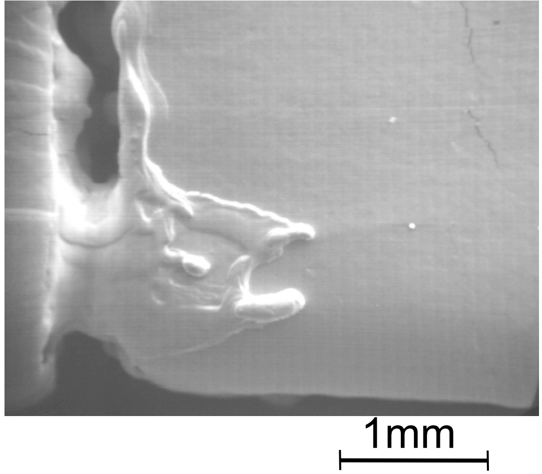


W3,R3, 100 exposures

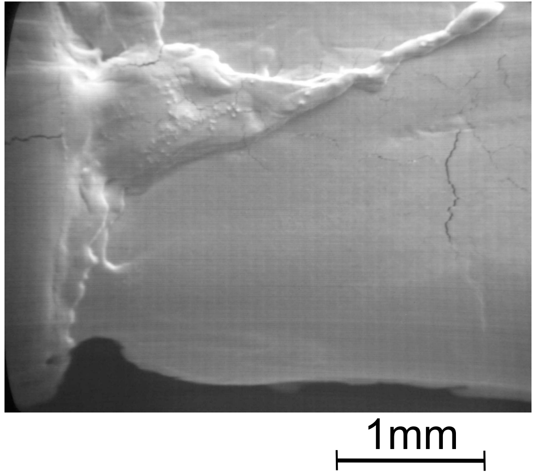


$w = 1.6\ MJ/m^2$

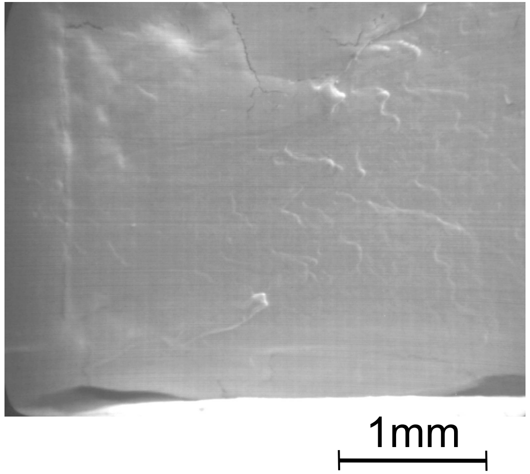
W4,L3, 10 exposures



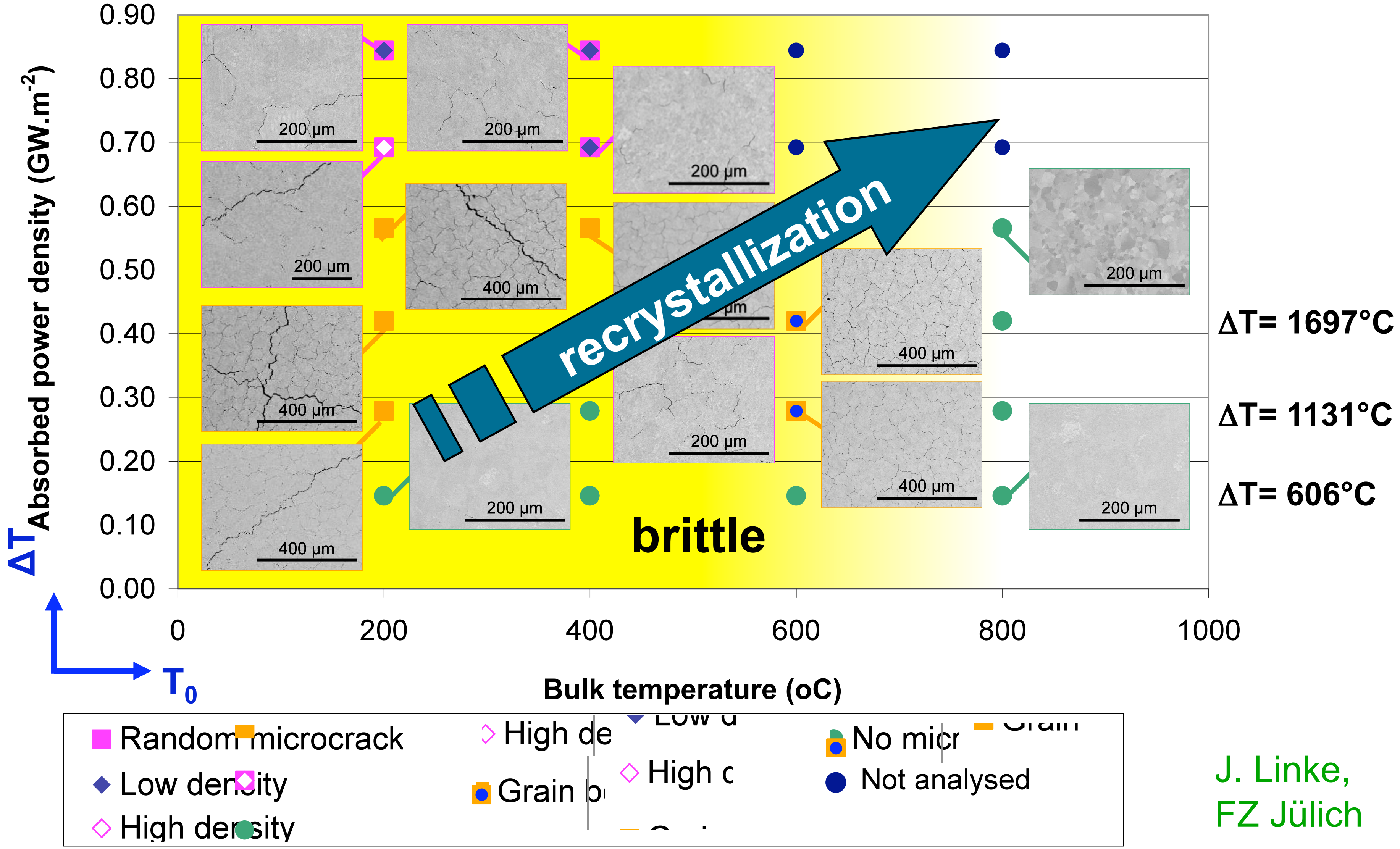
W4,L3, 20 exposures



W4,L3, 50 exposures



# JUDITH electron beam experiment ($\Delta t$ = 5 ms); major cracks, microcracks and surface modification



J. Linke,
FZ Jülich

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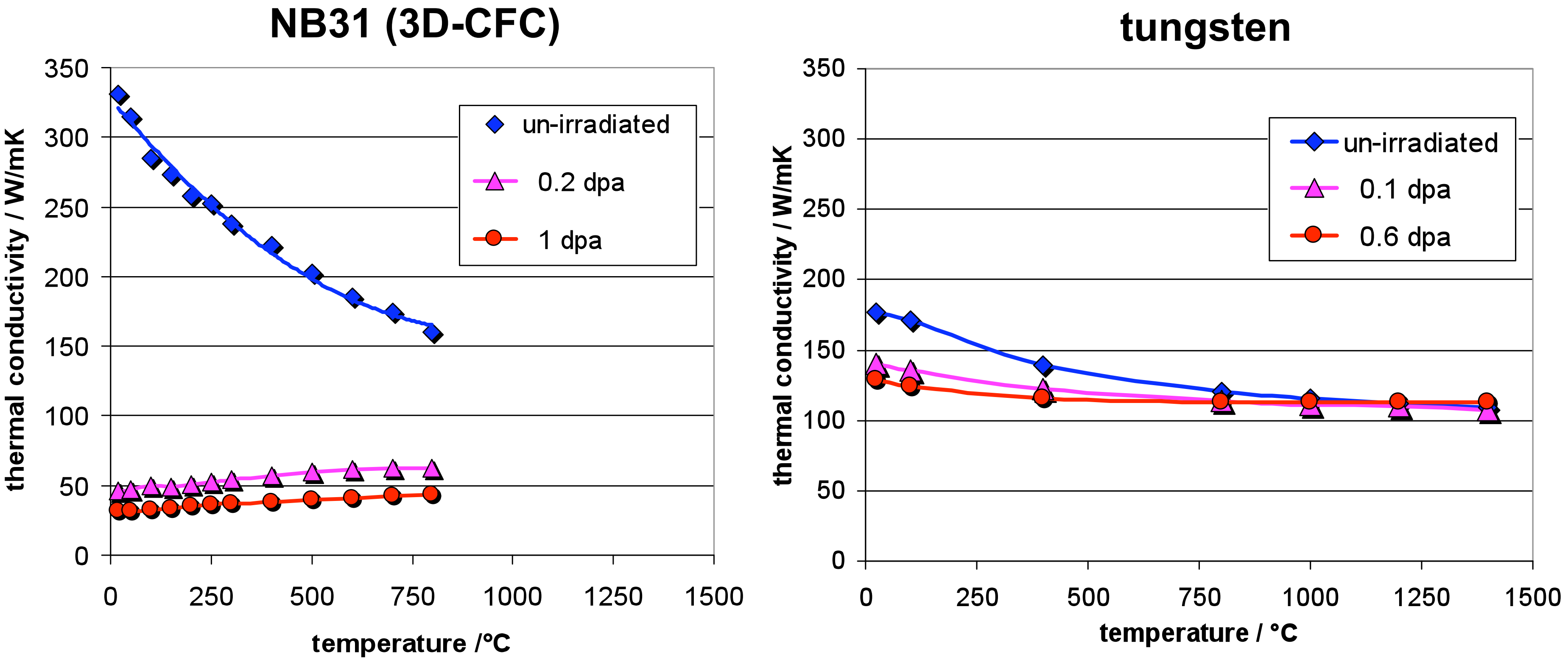
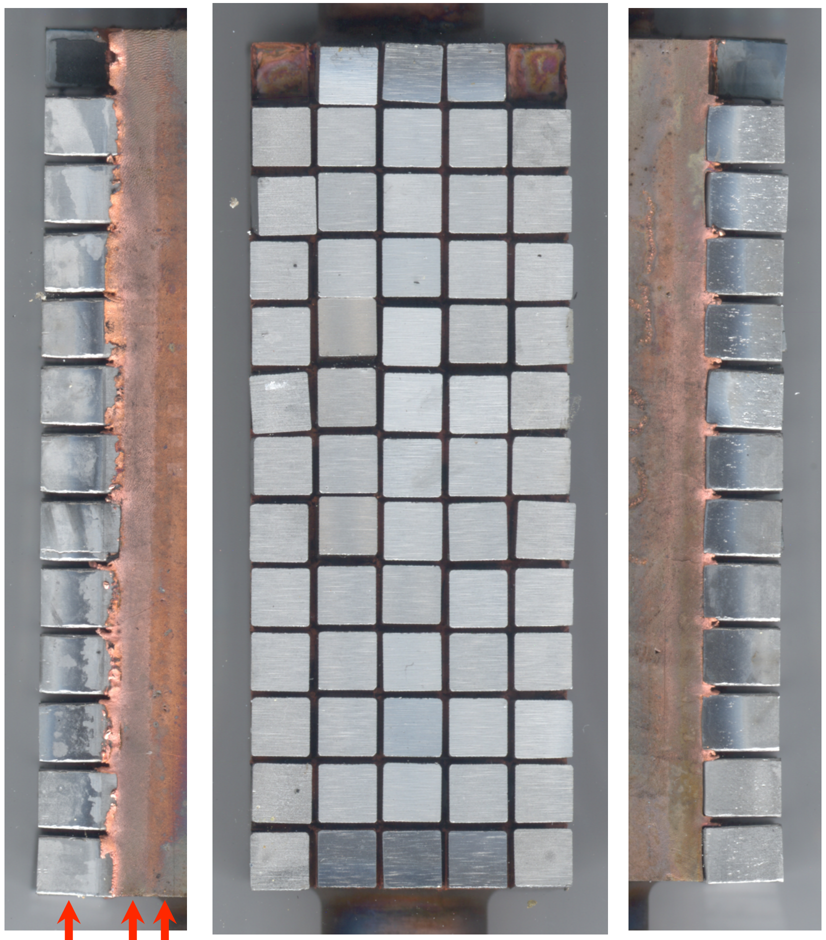
# Neutron irradiation effect on thermal conductivity

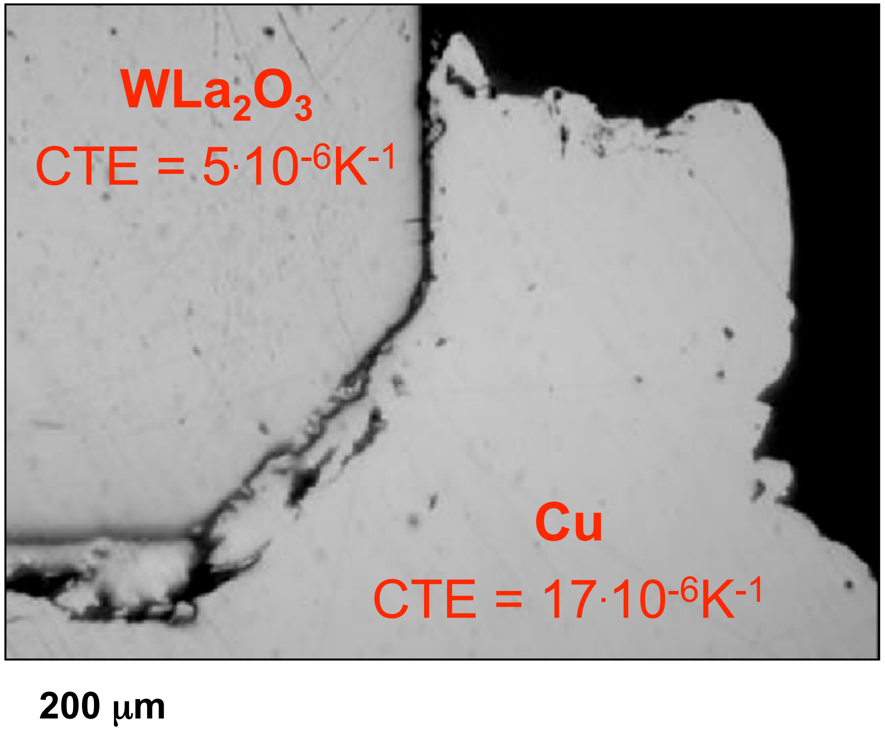


J. Linke,
Phys. Scr. T123 (2006) 45–53

# Thermal fatigue testing of a W macrobrush module irradiated in the HFR-Petten



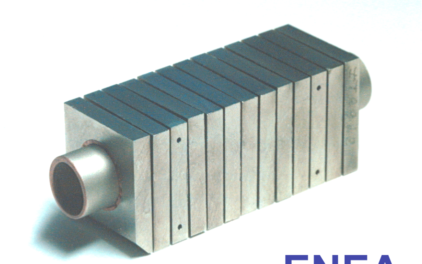
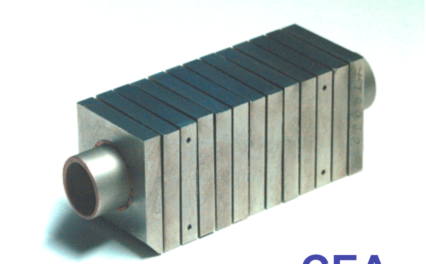
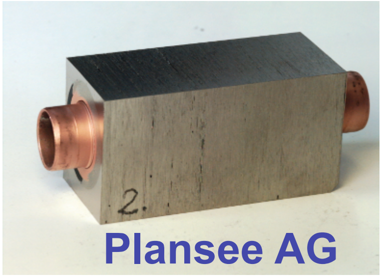
J. Linke,
Phys. Scr. T123 (2006) 45–53



irradiation condition:
200°C – 0.1 dpa (in W)

loading condition:
1000 cycles at 10 $MW/m^2$

# Thermal fatigue testing of W monoblock mock-ups

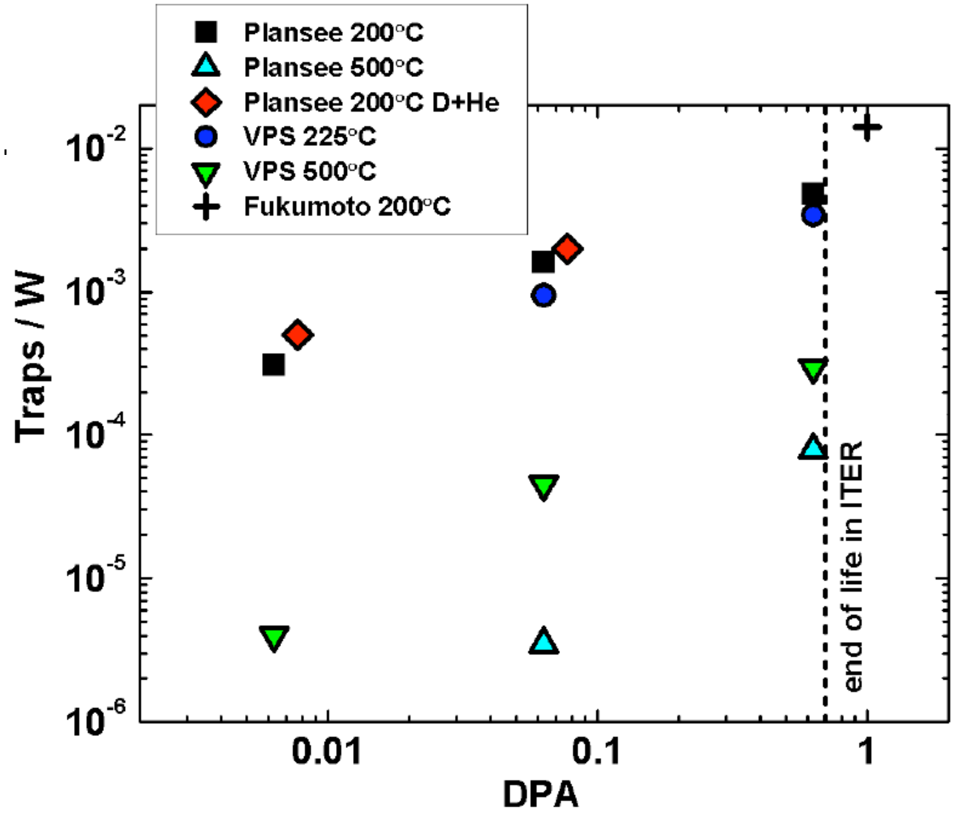
| | W-monoblock  ENEA | W-monoblock  CEA | W-lamellae design  Plansee AG |
|---|---|---|---|
| **unirradiated** | 1000 x 14.5 MW/m$^2$ | 1000 x 9.6 MW/m$^2$<br>1000 x 18.0 MW/m$^2$ | 1000 x 7.5 MW/m$^2$<br>1000 x 14.4 MW/m$^2$ |
| **0.1 dpa**<br>**$T_{irr}$ = 200ºC** | 1000 x 10.0 MW/m$^2$<br>100 x 13.7 MW/m$^2$<br>1000 x 17.9 MW/m$^2$ | | 1000 x 10.0 MW/m$^2$<br>1000 x 13.7 MW/m$^2$<br>1000 x 18.1 MW/m$^2$ |
| **0.6 dpa**<br>**$T_{irr}$ = 200ºC** | | 1000 x 10.0 MW/m$^2$<br>1000 x 13.7 MW/m$^2$<br>1000 x 18.0 MW/m$^2$ | 1000 x 14.0 MW/m$^2$<br>1000 x 17.1 MW/m$^2$ |

**no failure observed !**

J. Linke,
Phys. Scr. T123 (2006) 45–53

# T retention in (neutron) induced traps

- traps produced during ITER lifetime neutron fluence: ~0.005/W @ 200ºC, ~0.0001/W @ 500ºC.
- 200ºC: trapped D is limited by slow kinetics, i.e. permeation. (uptake rate and D concentration in solution, is three orders of magnitude smaller than predicted by model based on diffusion and surface recombination!)
- 40ºC: smaller trapping due to slower kinetics
- 500ºC: smaller trapping due to annealing of damage.



results deduced from Si irradition

B. Wampler et al. PFMC Jülich 2009

**⇒ low T inventory in W from trapping due to neutron damage in ITER.**

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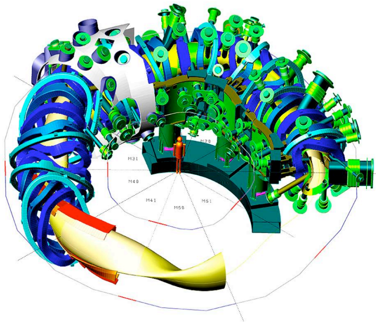
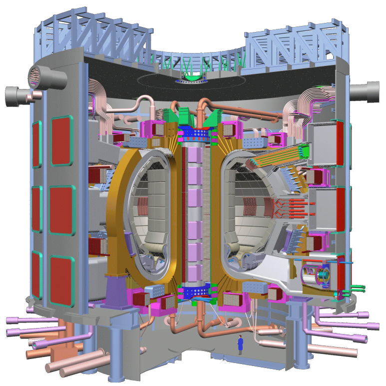
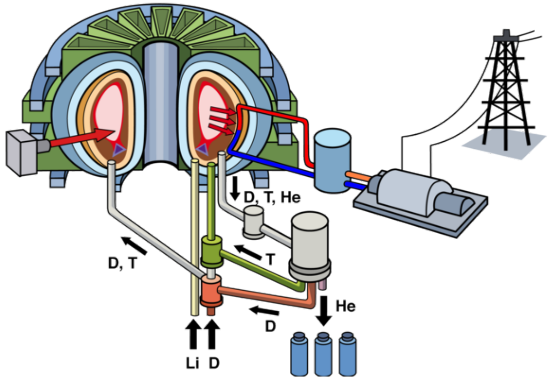
# Wall loads in future confinement experiments







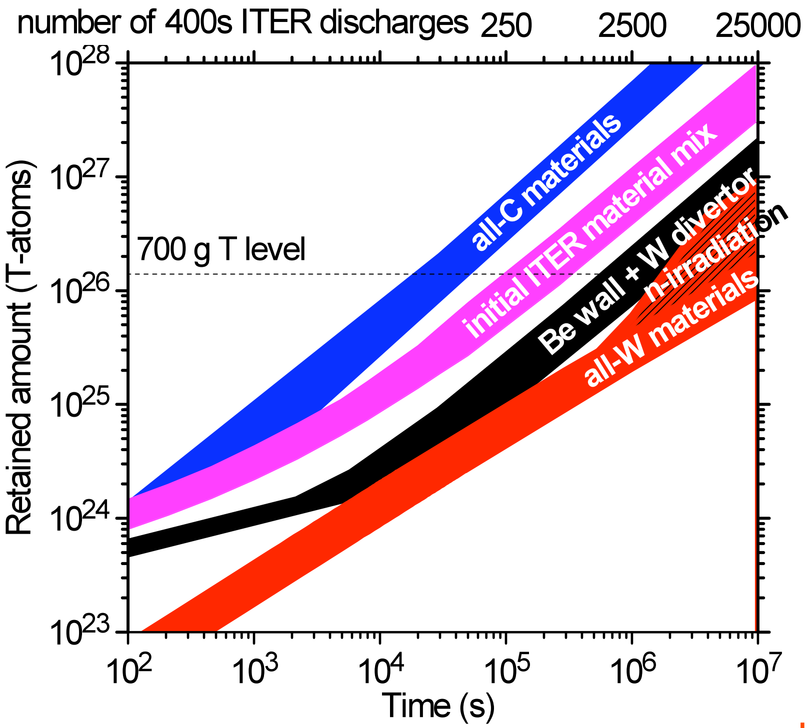
| | W7-X | ITER | reactor |
|---|---|---|---|
| heat flux FW / $MWm^{-2}$ | < 0.2 | < 1 | < 1 |
| heat flux divertor / $MWm^{-2}$ | 10 | 5 - 20 | ≈ 5 - 20 |
| VDEs / $MJm^{-2}$ | ? | 60 | - |
| disruptions / $MJm^{-2}$ | | ≈10 | - |
| ELMs / $MJm^{-2}$ | ? | <1 | ? |
| neutron fluence / dpa | | | 0 |

thermal fatigue

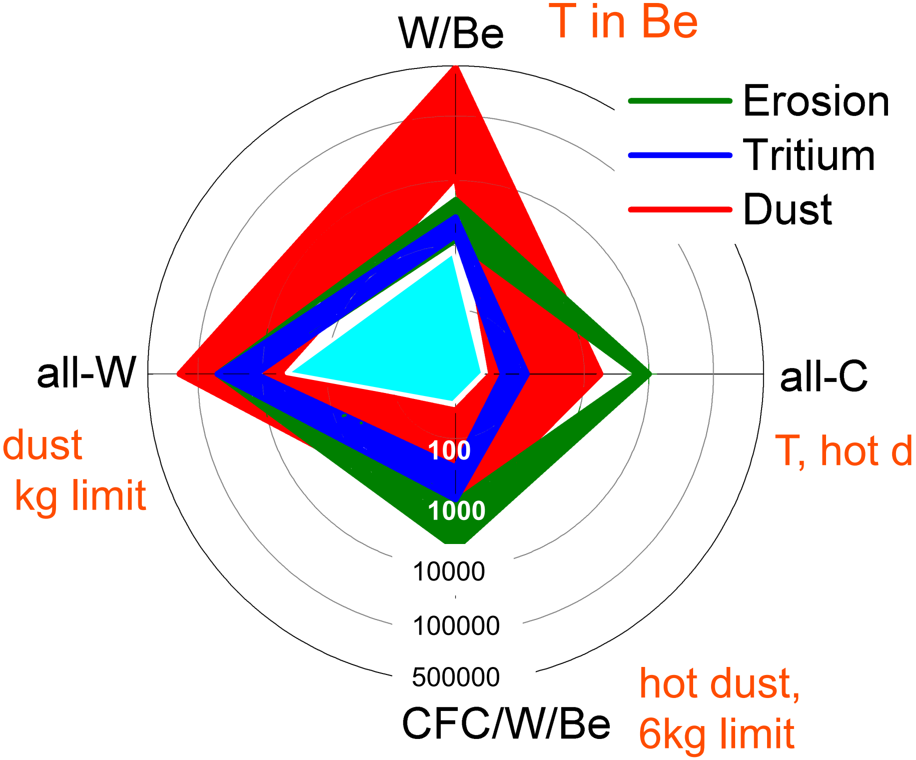
thermal shock

degradation, embrittlement

# Extrapolation to ITER: Safety Limits



Number of discharges to reach ITER safety limits:



T in Be

hot dust
230 kg limit

T, hot dust

hot dust,
6kg limit

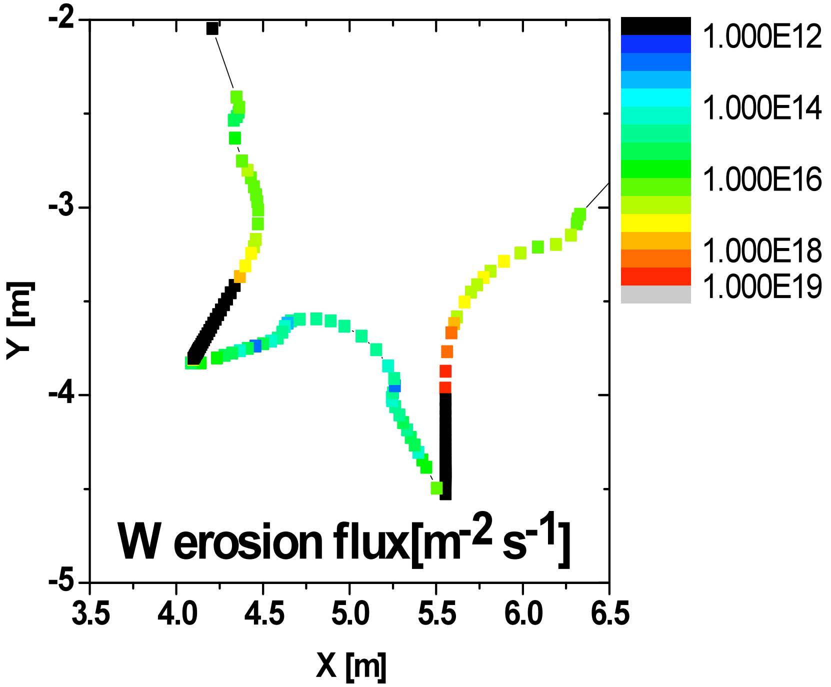
all metal / W solution would be best in respect of safety limits

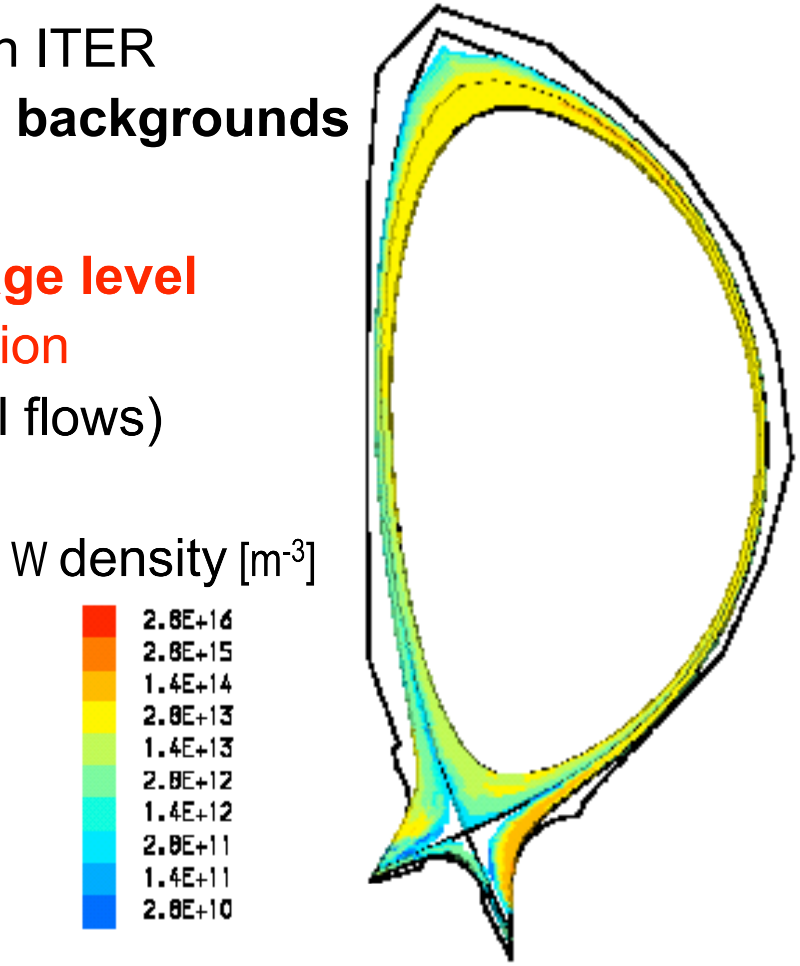
J. Roth et al., JNM 390-391 (2009) 1

# Extrapolation to ITER: Edge W concentrations

W erosion and edge plasma contamination in ITER
from **DIVIMP calculations for several B2-E backgrounds**
(edge transport not fully understood!)

W conc. remain under 2·$10^{-5}$ **for any coverage level by W PFCs in ITER** and high density operation
(weakly influenced by seeding, $D_{an}$ & parallel flows)





K. Schmidt, JNM 363-365 (2007) 674

# Extrapolation to ITER: Central impurity transport

**No W accumulation expected in ITER if $D_{an} \geq D_{neo}$, $(v/D)_{an}$ not increasing with Z**

(as predicted, see C. Angioni et al., PPCF 49 (2007) 2027)

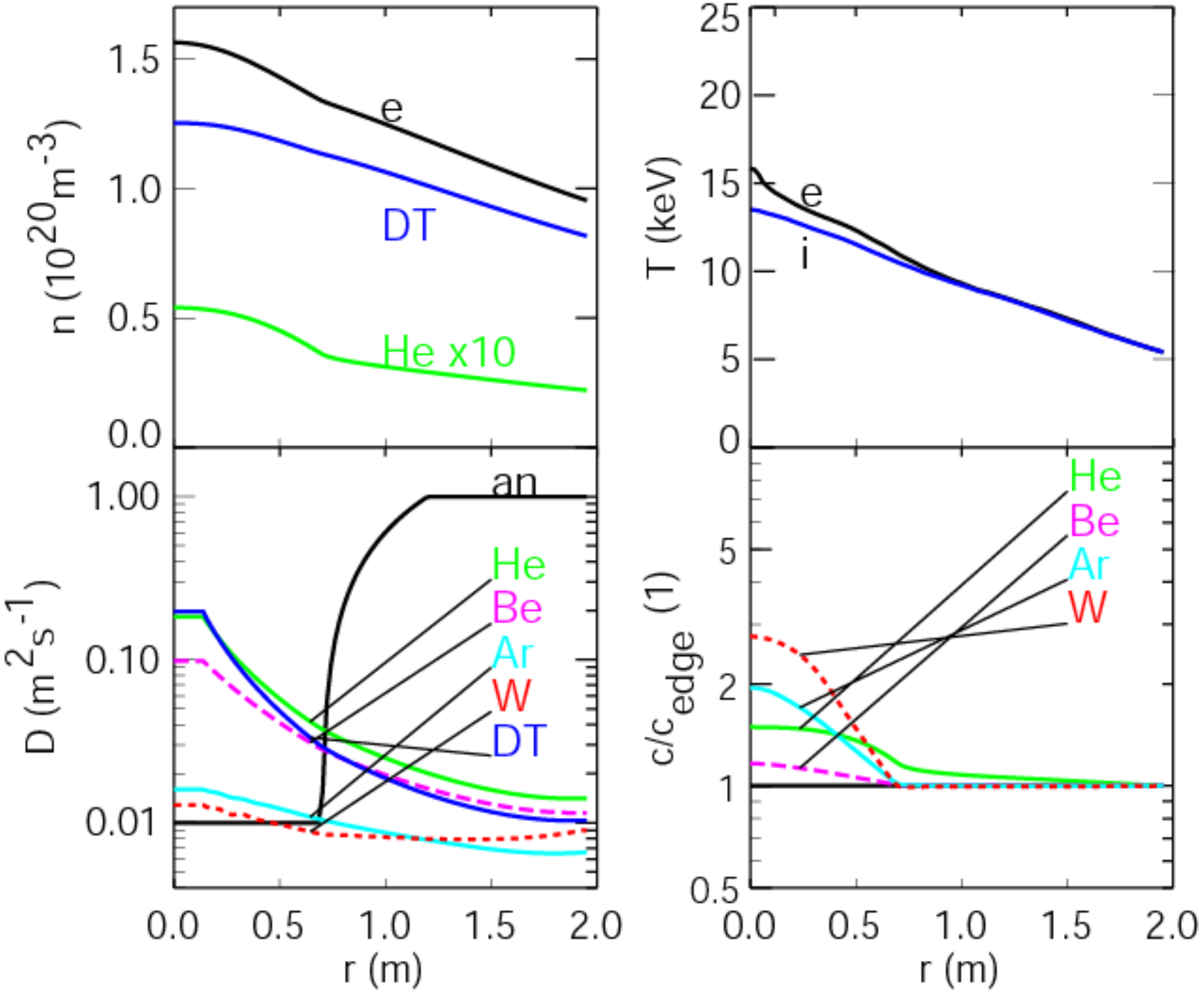
calculations using

Q=10, $P_{NBI}$=40 MW, $U_{loop}$=75 mV

$D_{neo}$, $v_{neo}$ from NEOART

$(v/D)_{an}$ from fit to GLF23

$D_{an}$ varied



R. Dux et al., 20th IAEA FEC 2004, EX/P6-14

# Summary

- D-retention in metals low (lab. exp., AUG), but high retention in C-Mod not yet resolved
- ‘destructive’ transients (large ELMs, disruptions) not accessible in present day machines (except large ELMs in JET, disruptions in C-Mod)
- erosion of high-Z materials mainly by low-Z impurities – transients and accelerated particles (ICRF) play significant role
- main chamber sources dominate plasma impurity density although much lower than divertor source
- AUG achieves similar performance as in boronized C device, using
  - sufficiently high particle transport in the plasma centre by central heating
  - flushing of pedestal by sufficiently high ELM frequency
- safety limits (T retention / Dust / Erosion) best for full metal / full W ITER
- extrapolation of edge/central transport seems favourable for ITER

# Remaining Issues and Extrapolation to ITER and DEMO

- mixed materials effect (He, low-Z) on surface morphology / D retention
- effect of divertor damage / behaviour of melt layers under tokamak conditions
- optimization of plasma edge / antenna design (reduction of parasitic electrical fields) for reduction of W source during ICRF
- effect of pellet ELM pacemaking and RMP ELM suppression:
  - evolution of edge plasma parameters / W source
  - penetration into confined plasma / flushing

⇒ JET ILW and lab experiments combined with modelling may close some of the gaps to ITER in the near future

**DEMO: step in plasma physics much smaller compared to step in PWI!**

- PFC: full W (or and W and steel)
- high PFC temperature necessary: good for annealing of defects and T-retention but low margin for transients, large T diffusion
- high n-fluence: dpa ~100 times larger as in ITER

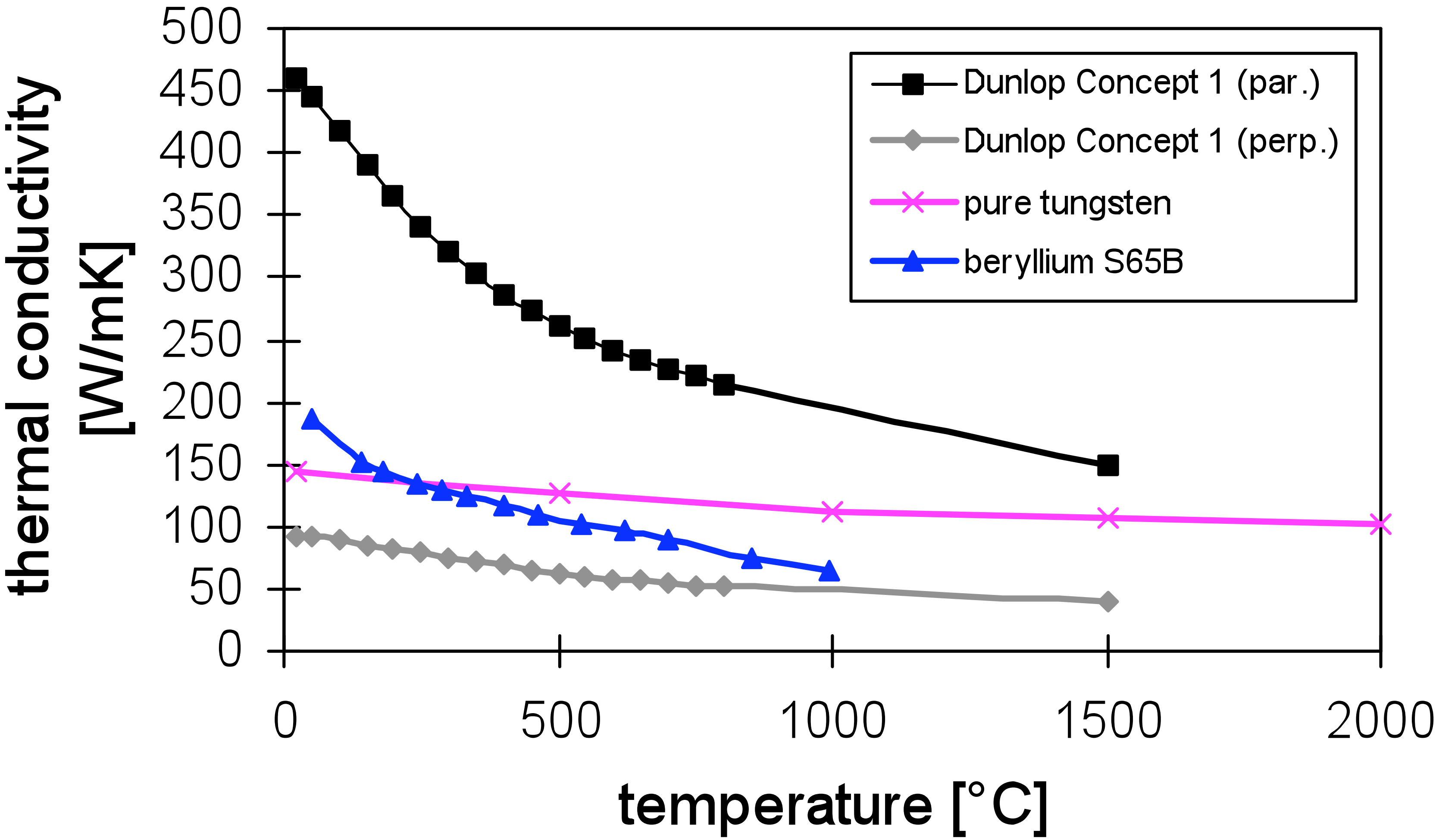
# Properties of candidates as PFM

| | Be | CFC | W |
|---|---|---|---|
| **atomic number Z** | 4 | 6 | 74 |
| **max. allowable concentration in the plasma** | ~3 % | ~2 % | **~20 ppm** |
| **thermal conductivity λ [W/mK]** | 190 | 200 ... 500 | 140 |
| **melting point [°C]** | **1285** | >2200 (subl.thr.) | 3410 |
| **coefficient of thermal expansion [$10^{-6}$ $K^{-1}$]*** | 11.5 | ~ 0 ** | 4.5 |
| **n-irradiation behaviour** | swelling | **decrease in λ** | activation |

* CTE copper = $16 \cdot 10^{-6}$ $K^{-1}$

** NB31 in pitch fiber direction

# Thermal conductivity of different plasma facing materials



# Optimization of ICRH in AUG

ITER: substantial amount if ICRH, high power densities at antenna:

⇒ erosion of Be first wall / limiters and W baffles must be kept low

present design

AUG ICRH antenna

proposed design

calculated local electrical field (1 MW power)

strong reduction foreseen, using
- 4 straps (shaping)
- increased width

- further investigations on acceleration mechanism (near field/far field)
- optimization of operational conditions (density, phase, …)
- reduction of box currents / electrical fields by improved antenna design