Plasma operation with metallic walls: direct comparison with the all carbon environment

Guy Matthews (CCFE) on behalf of :
JET-EFDA Contributors
with help from the ASDEX-Upgrade Team

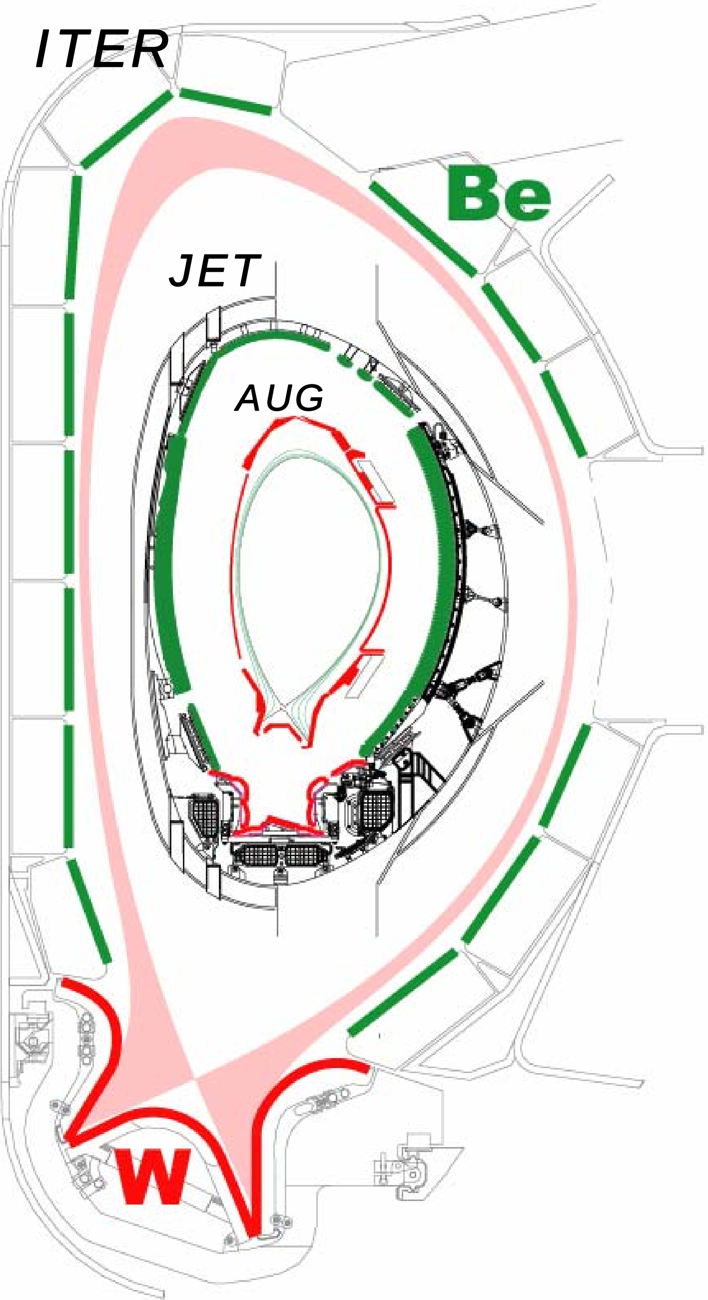
MASCO-PFC Meeting Princeton 20th June 2012

Overview

1. Introduction

2. Residual impurities
3. Retention
4. Impurities from PFCs
5. Disruptions and density limits
6. Power handling
7. Scenarios

8. Conclusions



W divertor and Be wall selected for ITER DT:

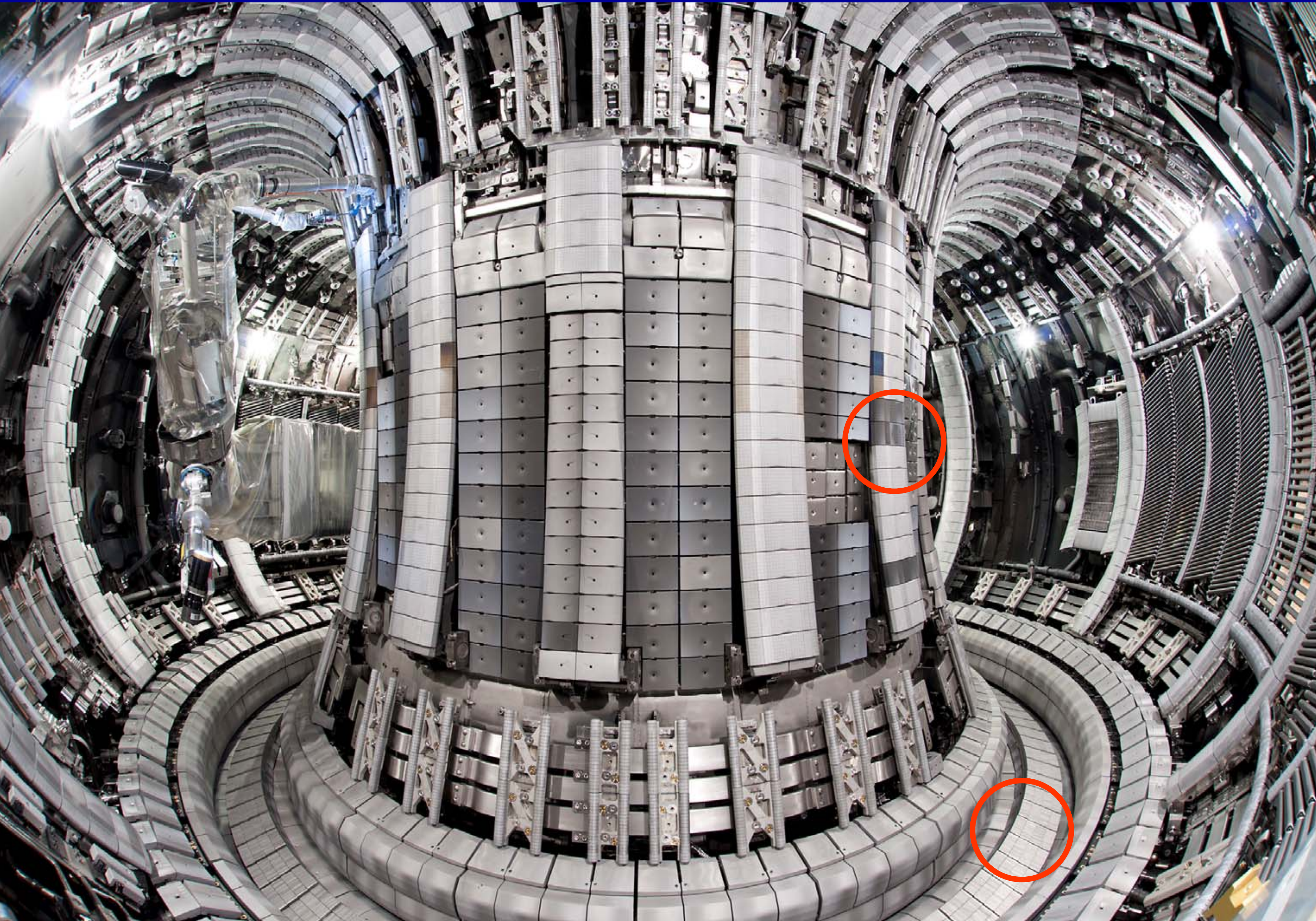
1. To maximise operating space (Be)
2. To reduce T retention compared to CFC

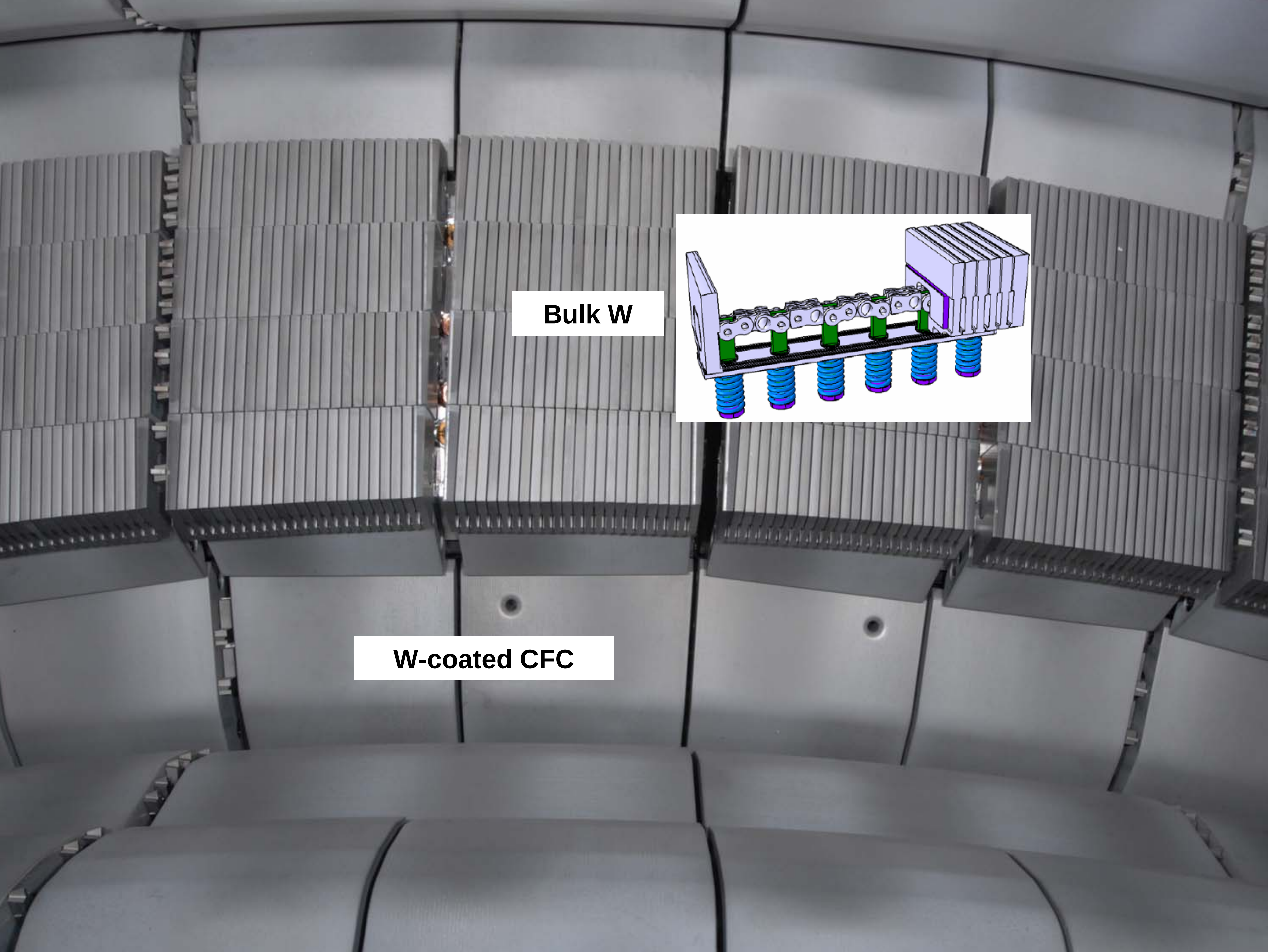
All W wall considered for DEMO:

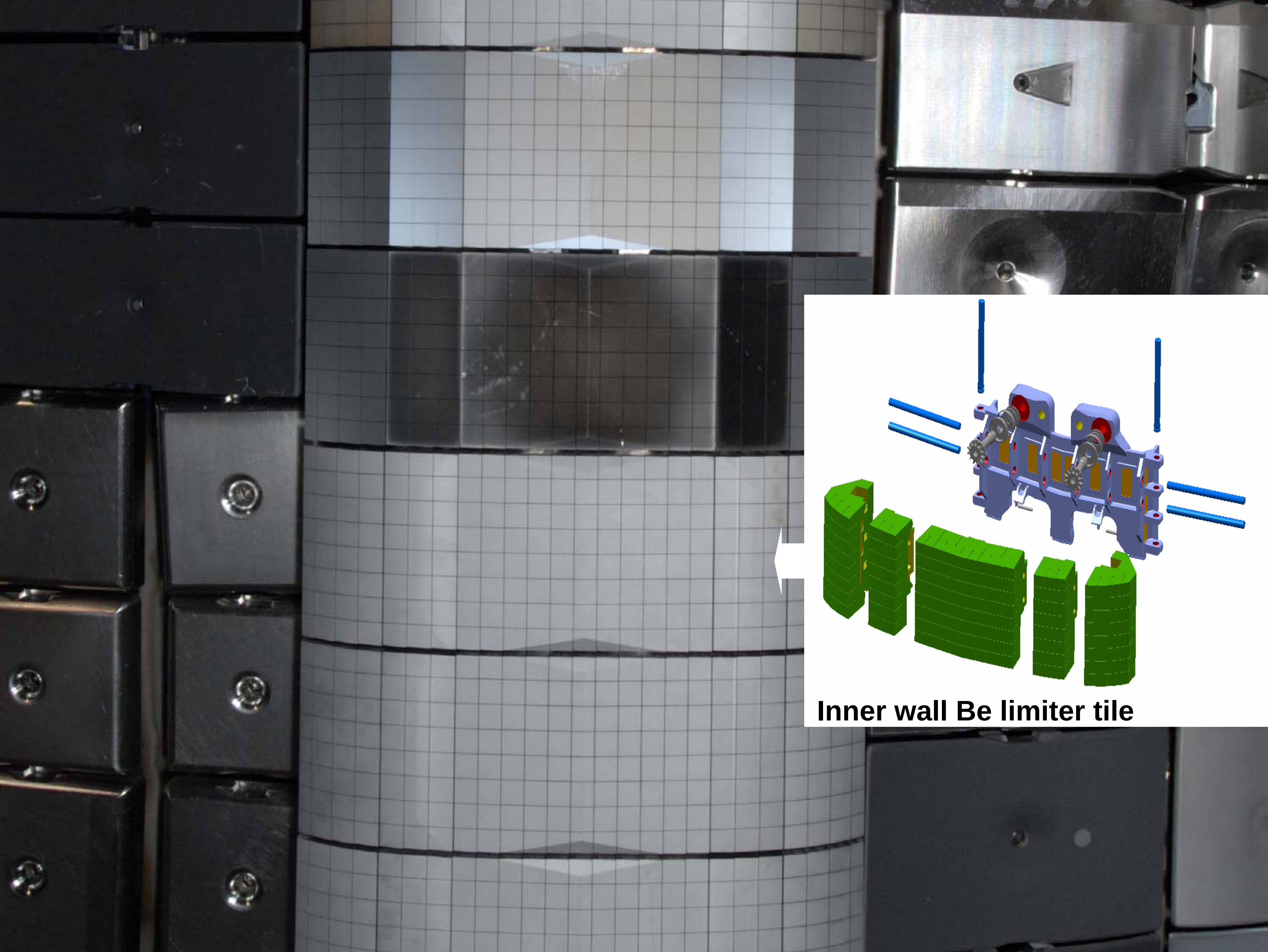
1. To provide sufficient lifetime (PWI/neutrons)
2. Best possible power handling

Risk to operational flexibility too high for ITER

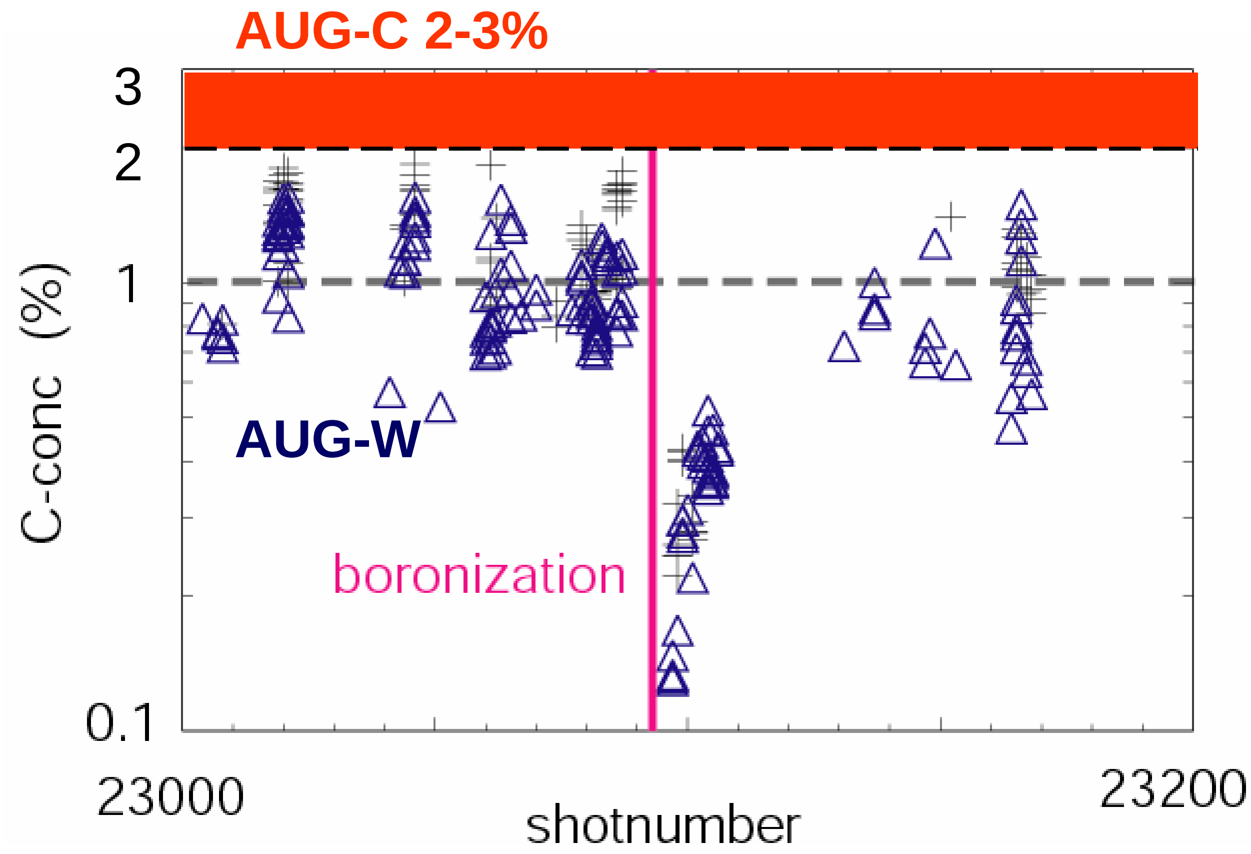
1. JET-ILW Be/W ITER-like Wall completed - 8th May 2011



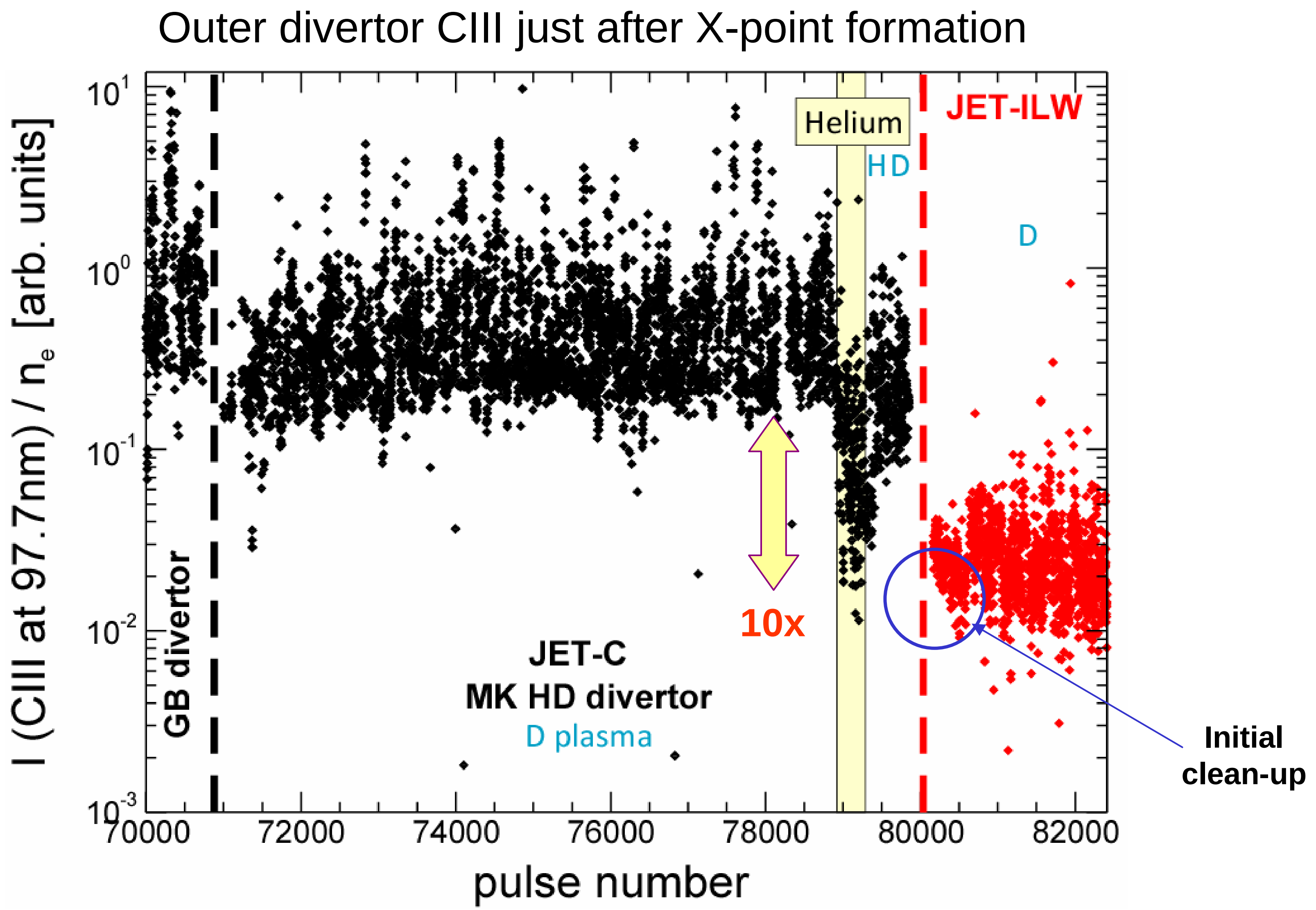

Bulk W
W-coated CFC


Inner wall Be limiter tile

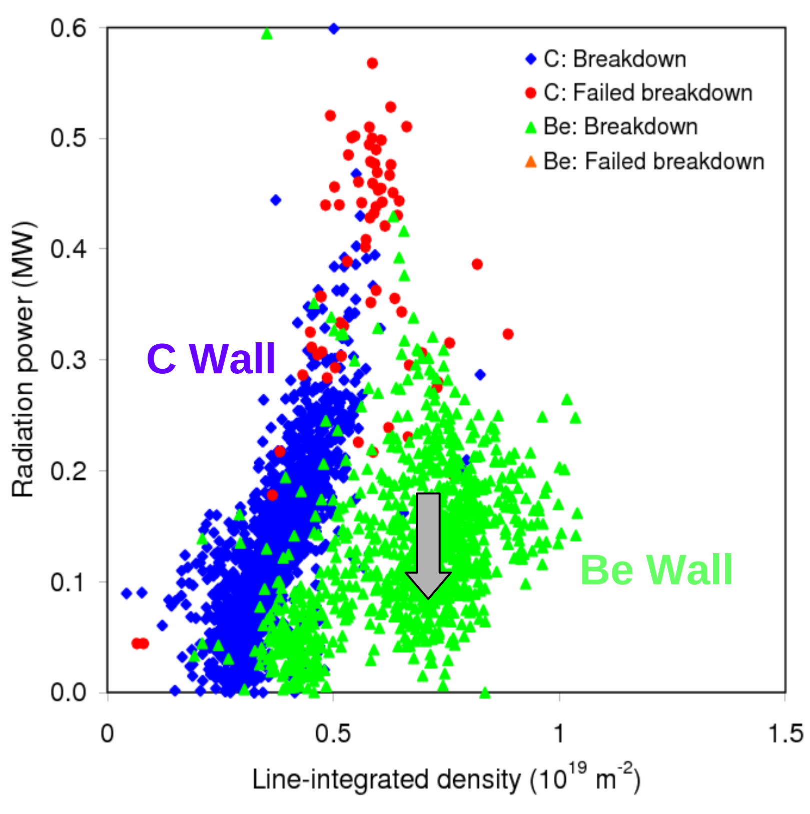
2. Residual carbon: AUG-C to AUG-W?



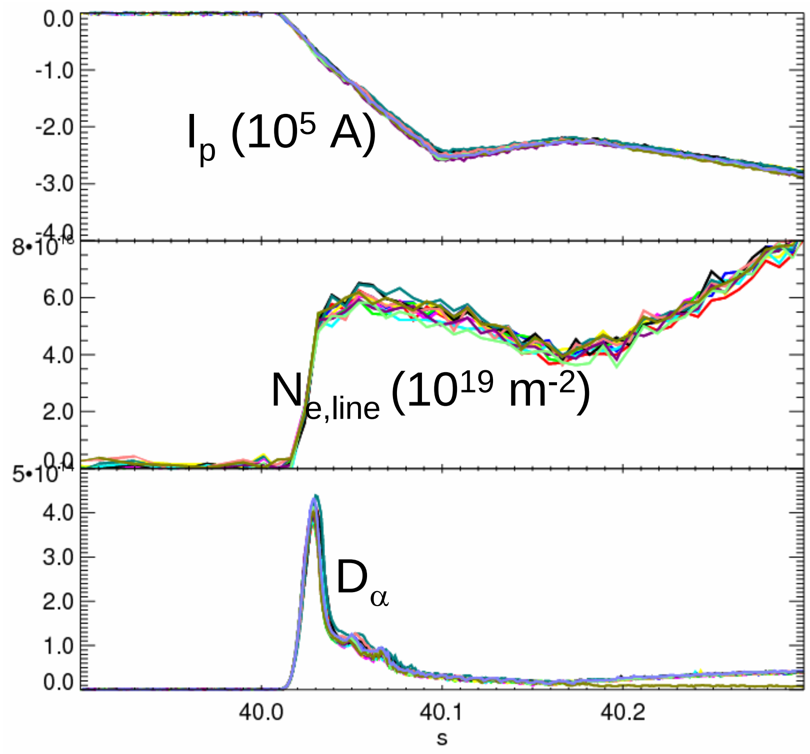
2. Residual impurities JET-C to JET-ILW: Carbon



JET ILW: No failed breakdowns



Breakdown in a disruption series

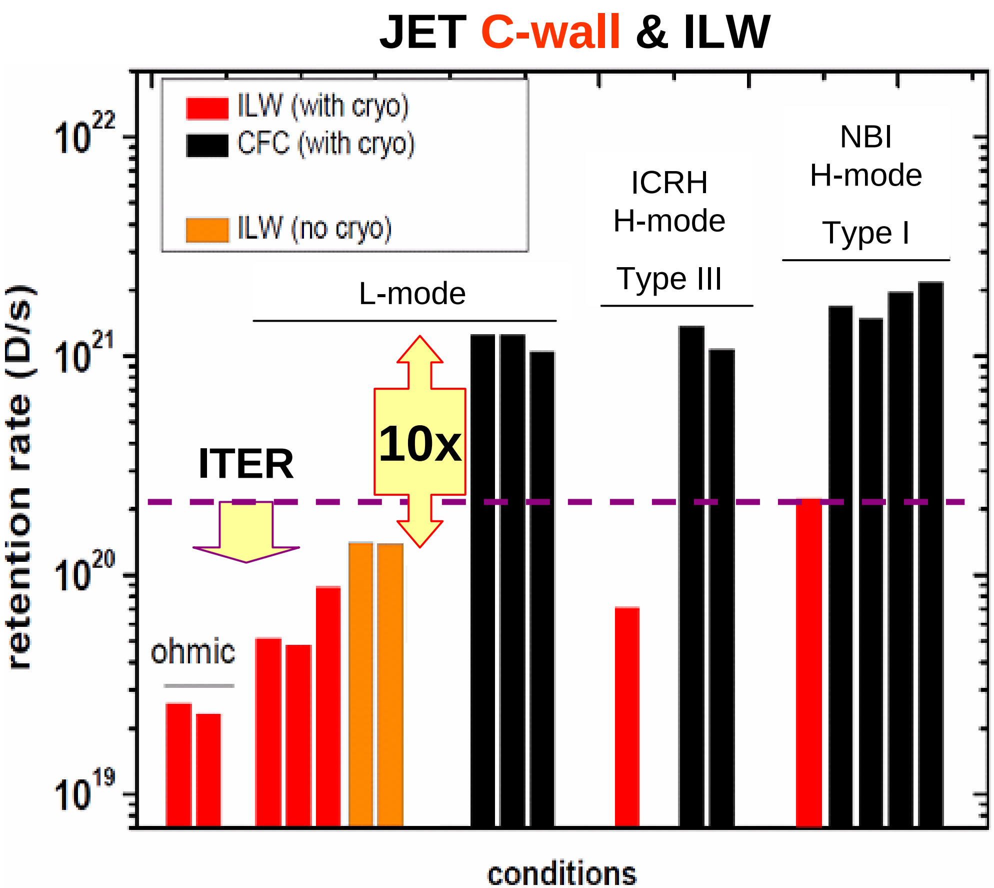


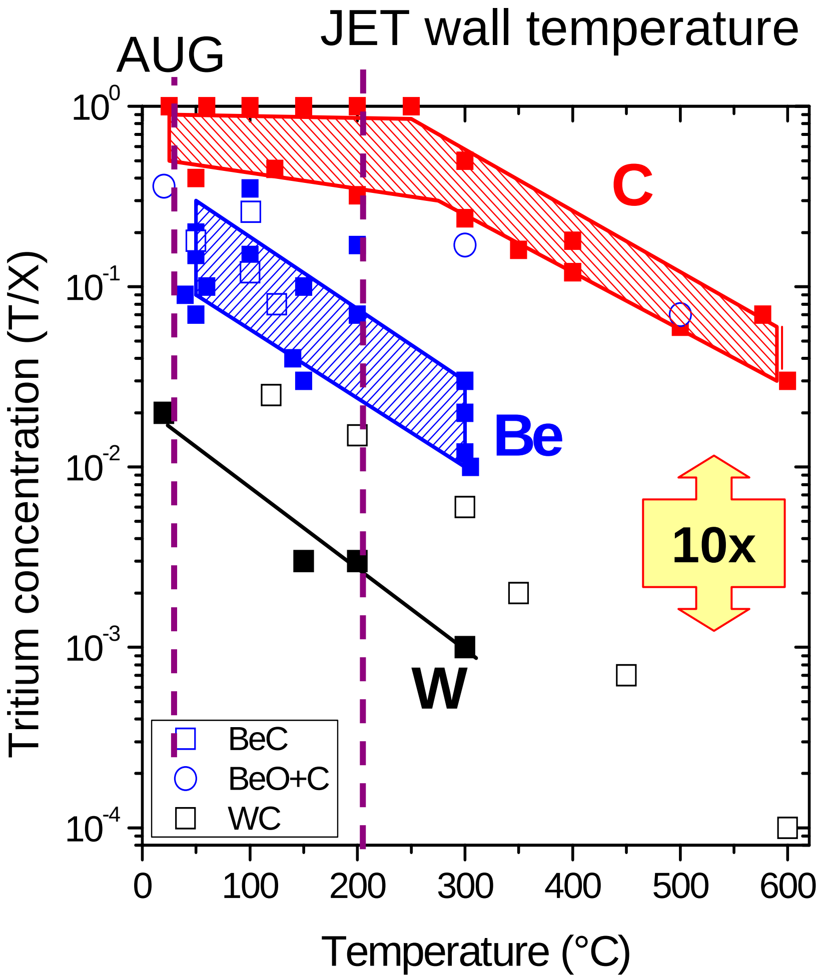
JET-ILW: No Be evaporation and no GDC required since first plasma

AUG-C: He GDC 2min every pulse **AUG-W:** D_2GDC 2min each day

AUG-W&JET-ILW: Breakdown not affected by N_2 seeding or MGI (Ar/D2)

3. Long Term Retention: rate normalised to divertor time





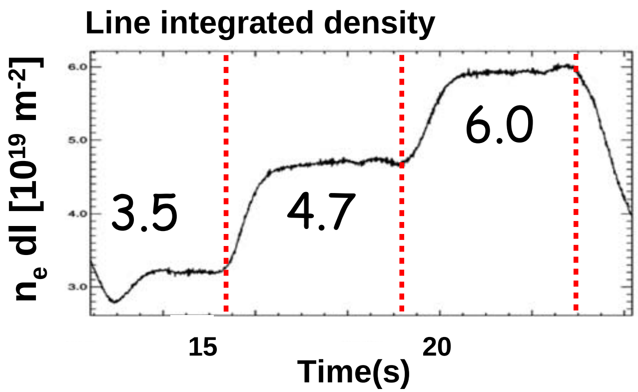
JET-ILW: Is the absolute value low enough?

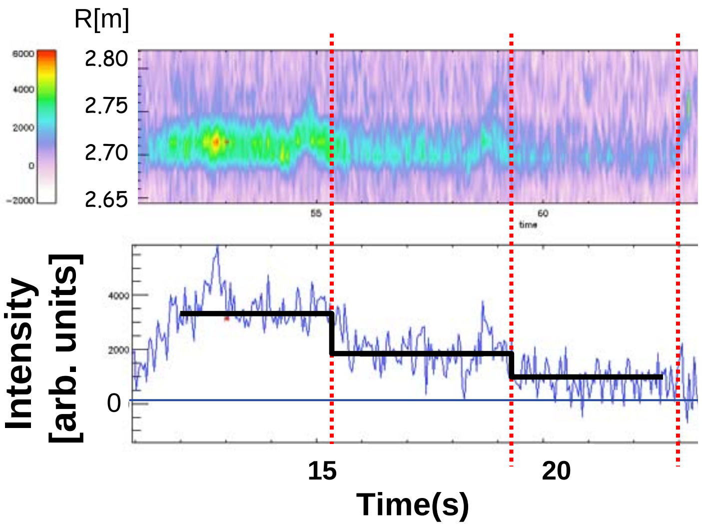
⇨True long term value could be much lower (surface analysis)

AUG-W: Reduction factor only 5-10x due to residual carbon

⇨ Surface analysis shows retention by W is acceptable

W source decreases with density





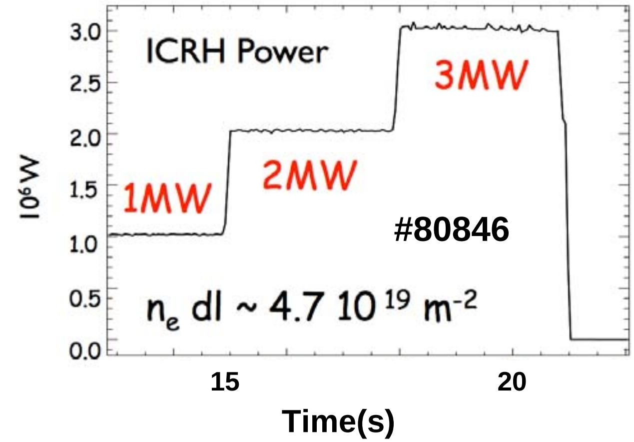
WI 400.8nm

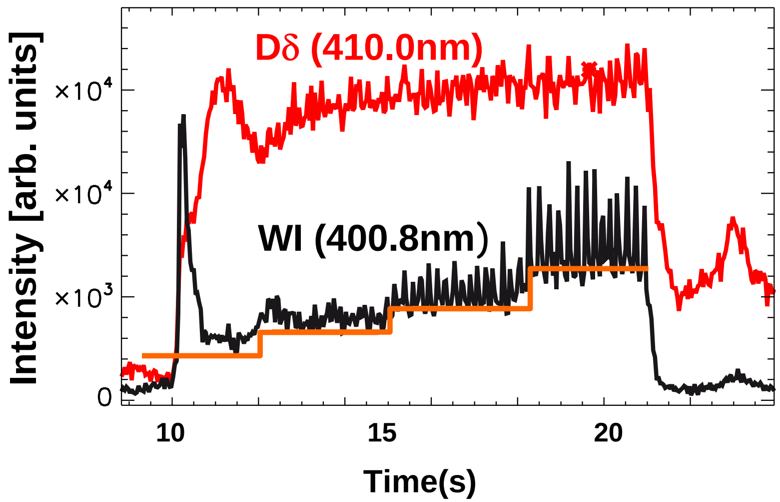
#80768

WI 400.8nm

#80768

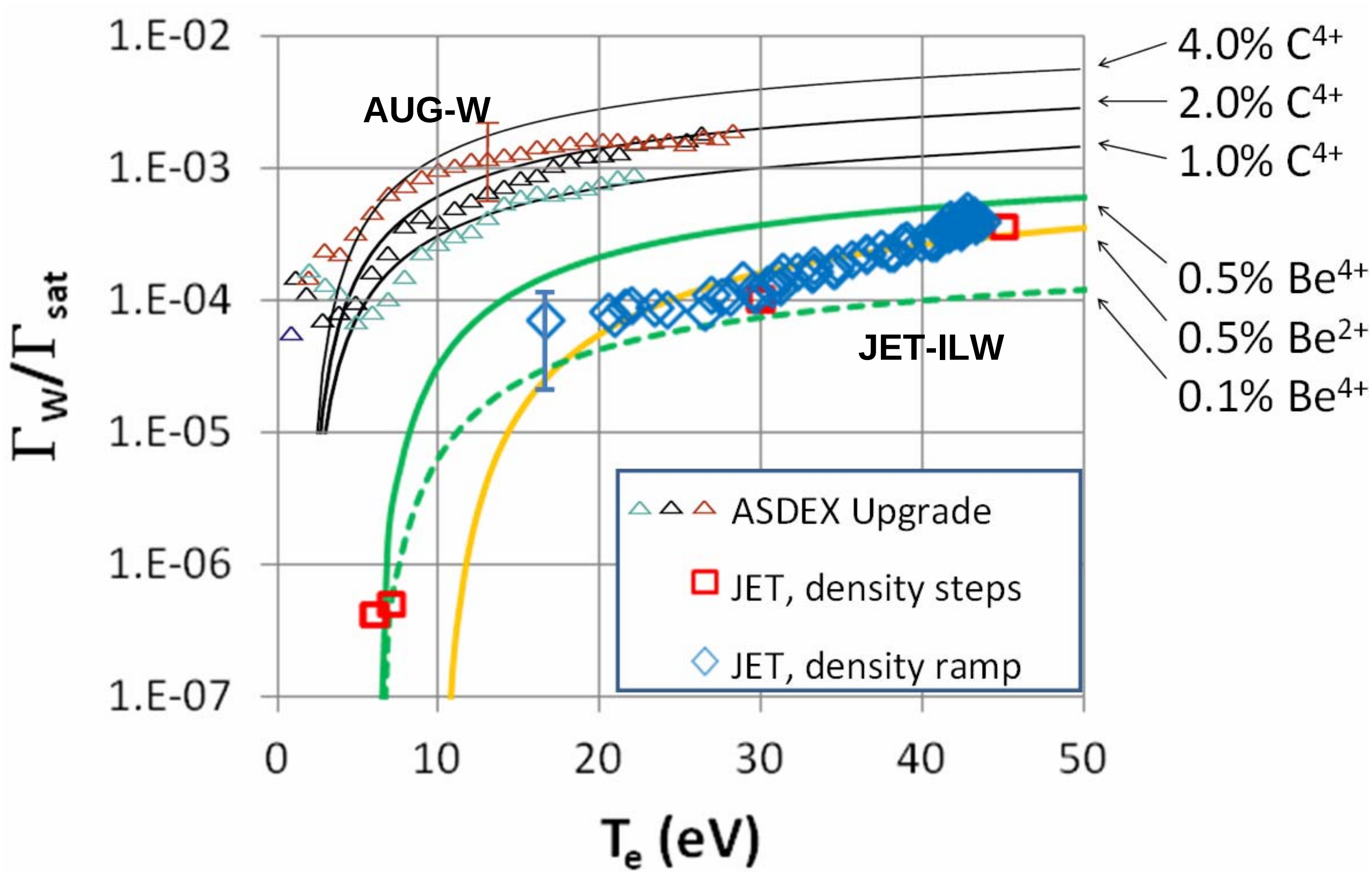
and increases with power





Text book behaviour as seen in AUG-W

4. Tungsten sputtering yields: Impurity dominated

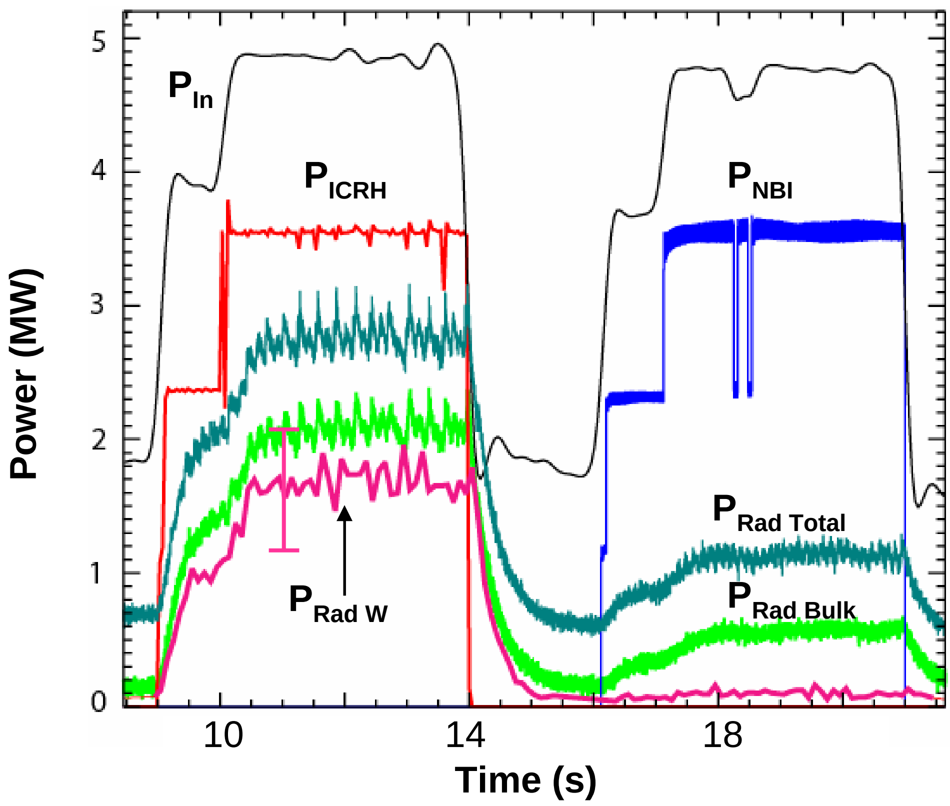


W sputter yield lower for Be than C

JET-ILW is cleaner than AUG-W
⇨ particularly at high density / low T_e where Be sputter yields fall rapidly

4. Tungsten: ICRH compared to NBI

JET-ILW: 81856 L-mode



Constant density

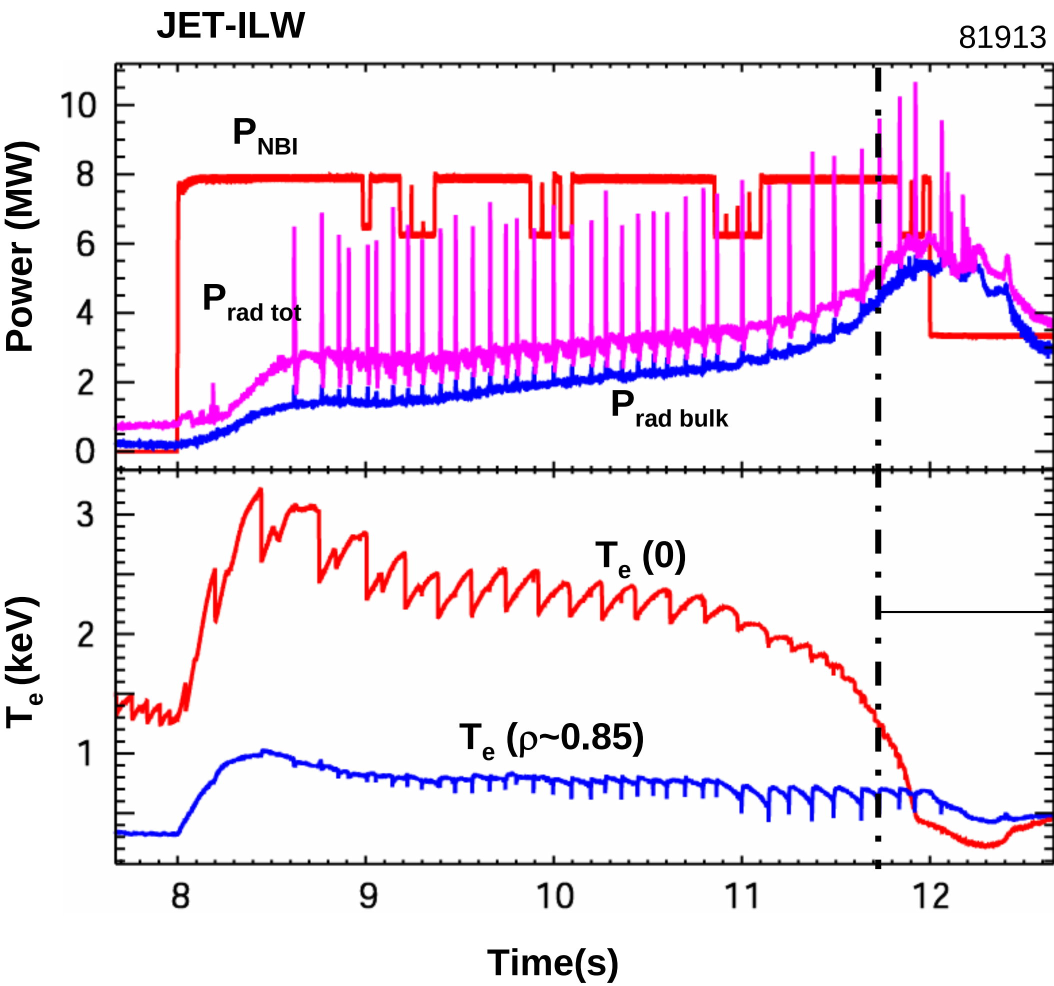
Similar rise in stored energy

Higher $P_{rad\ bulk}$ for ICRH

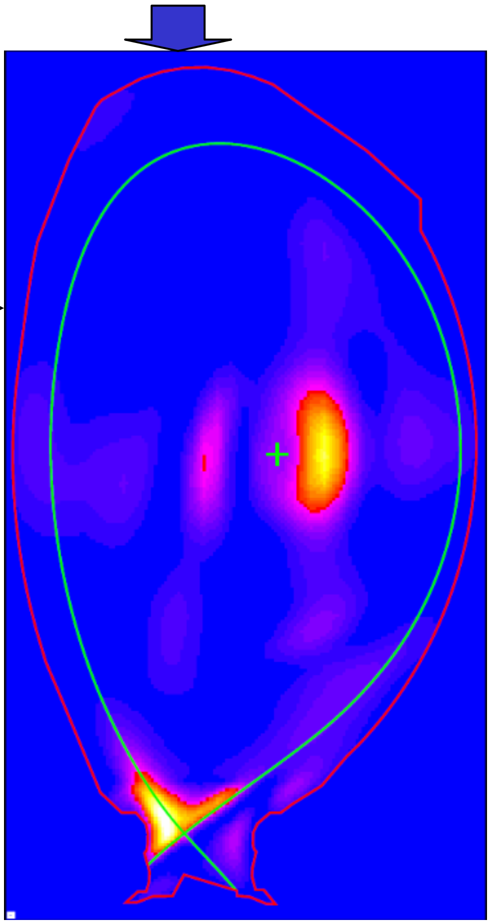
Outer divertor W source is 40% lower with ICRH compared to NBI!

AUG-W: Similar behaviour <u>but</u> ICRH W-limiter source dominates

4. W accumulation & peaking: an extreme example

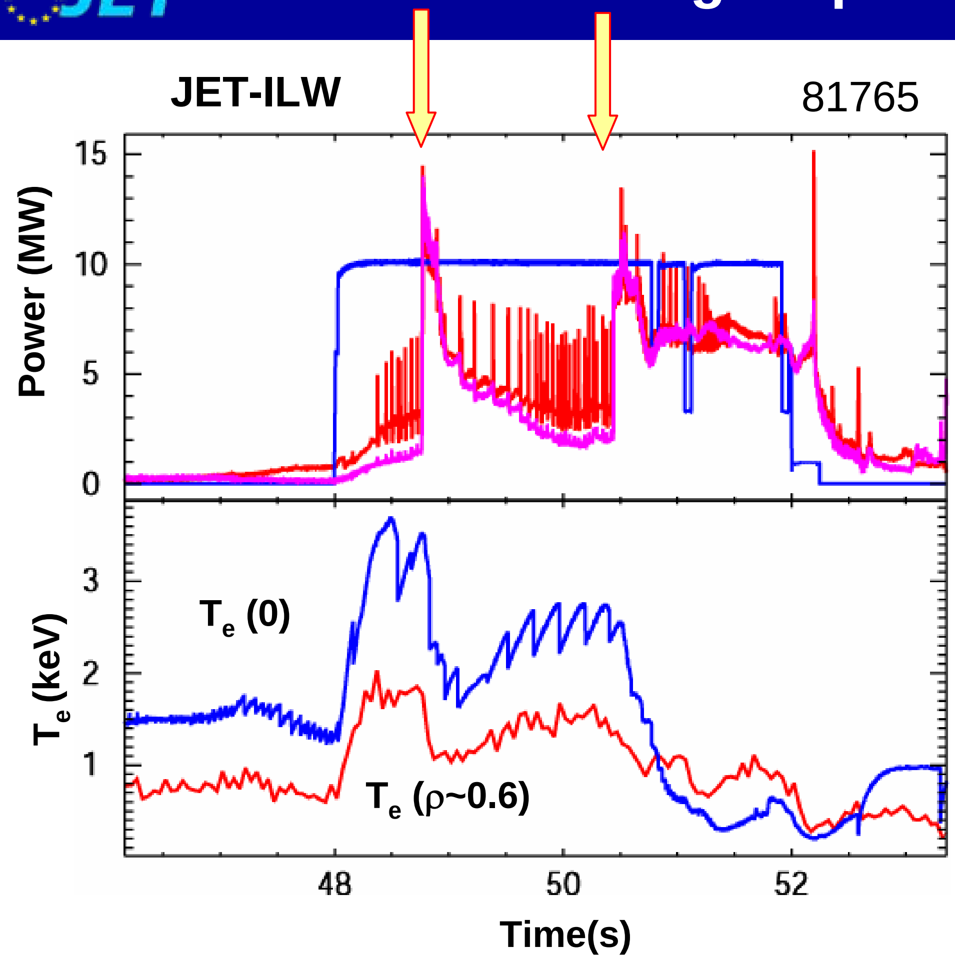


ELM freq. too low (10Hz)
W peaks
Sawteeth die out
Radiation peaks ⇨ $T_e(0)$ collapse



AUG-W: Similar to JET-ILW
Cure = high fuelling, central heating, high f_{ELM}

4. Medium to high Z particle influxes: an extreme example



AUG-W: Fewer W particle events

FGG a better match to W than CFC

No horizontal divertor surfaces

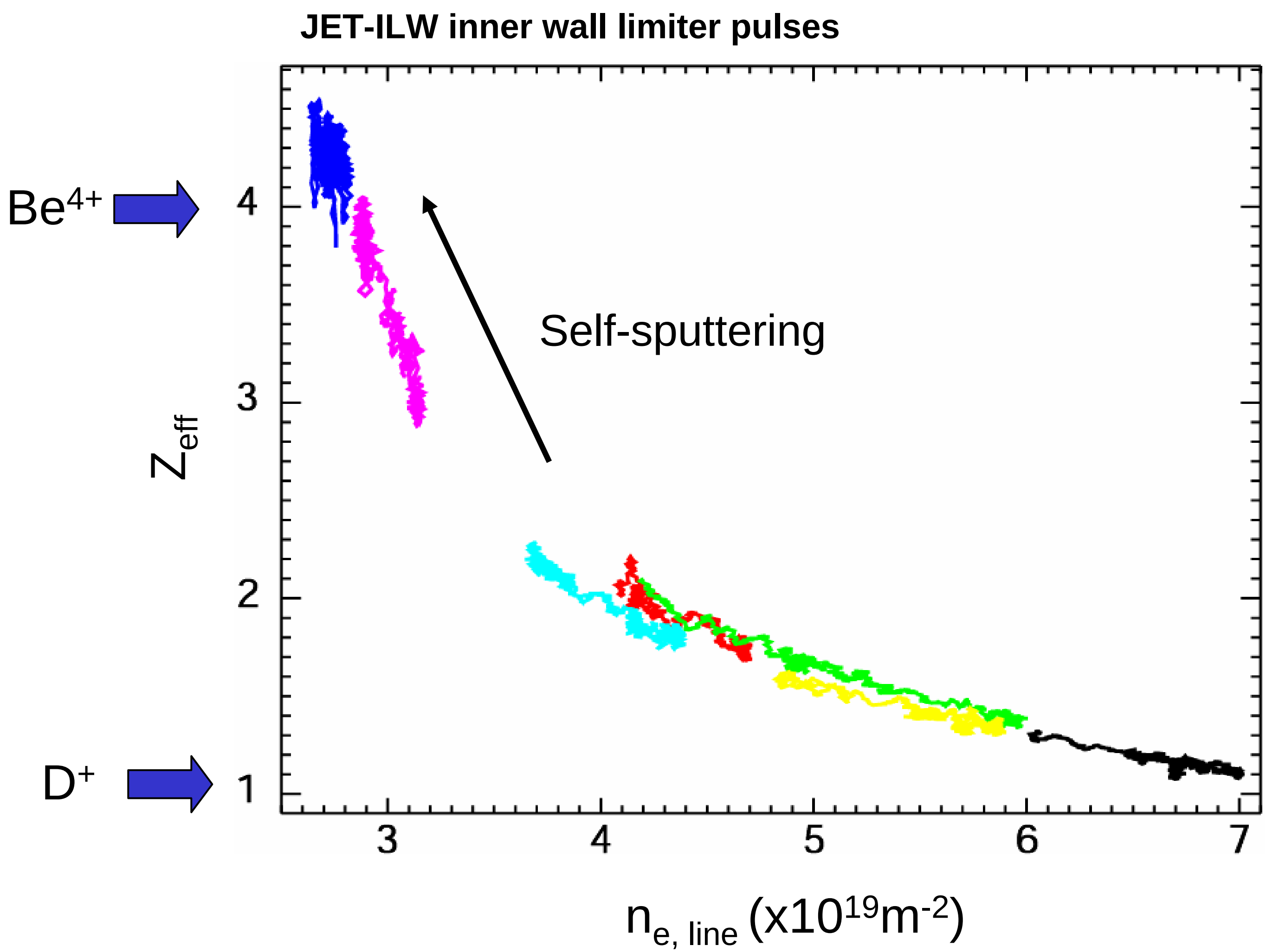
Better screening?

History shows thermal fatigue is not generating W particles (yet)

W-particles ~0.1mm effective diameter

Particles appear as Be/C in the divertor!

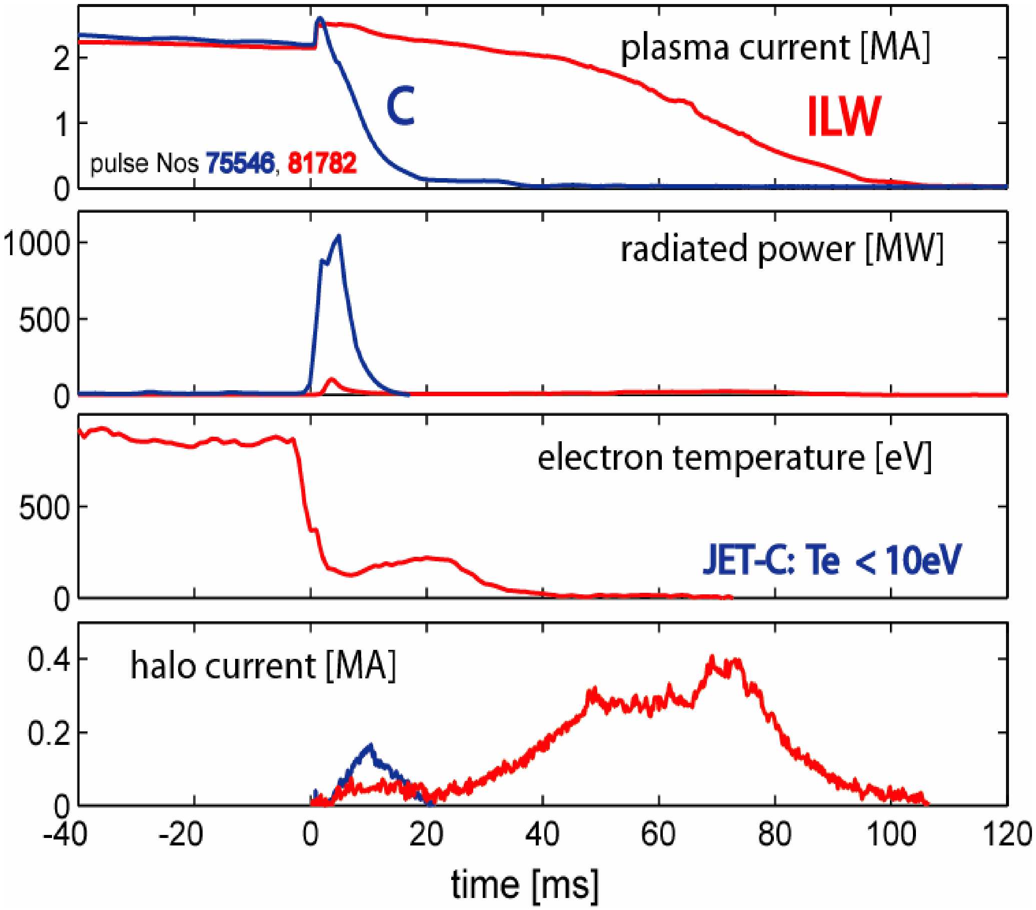
4. Z_{eff} in JET-ILW is dominated by Be



JET-ILW: H-modes typically have Z_{eff}=1.2-1.4 **JETC:** Z_{eff}=1.8-2.5

5. Disruptions: ITER-like Wall compared to C-wall

Ohmic density limit



Typical disruptions with ILW:

Slower current quench

Less energy (W_{mag}+W_{th}) radiated

Higher wall heat load

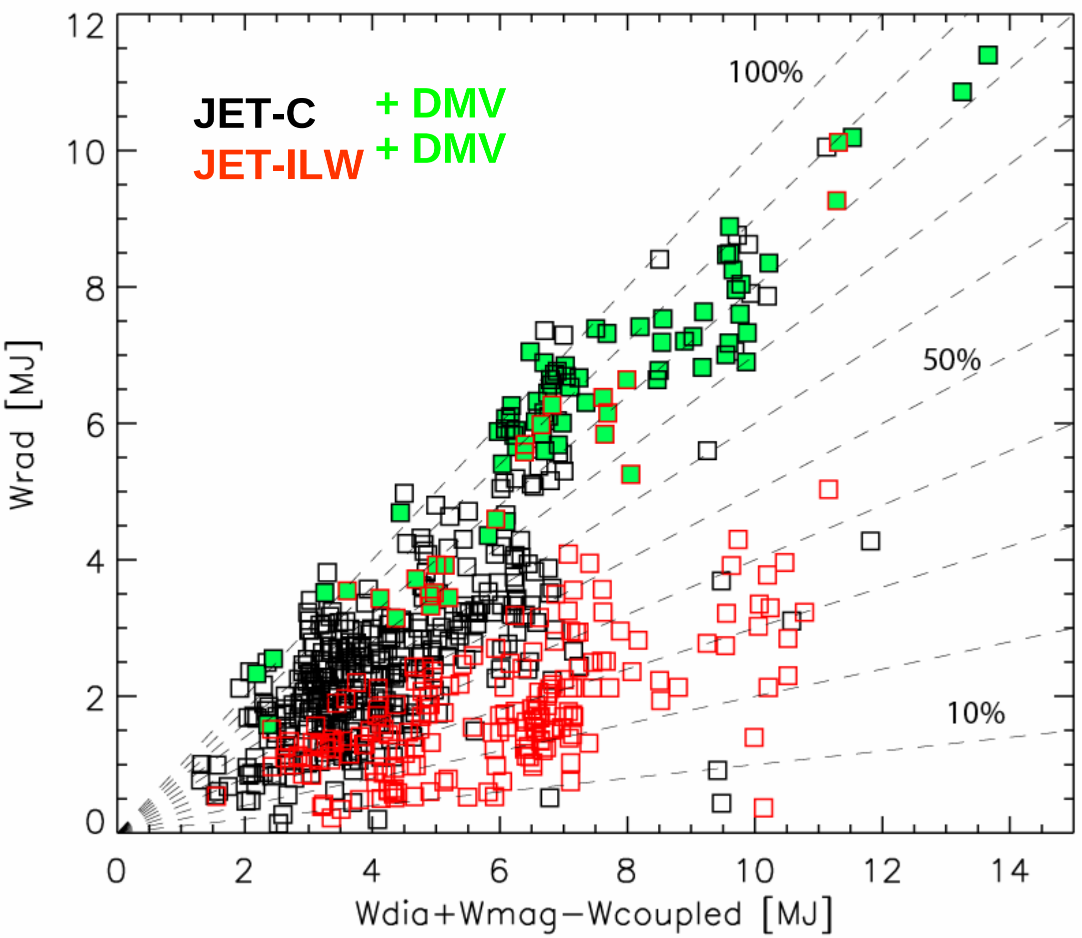
Longer halo current

Larger vessel displacement

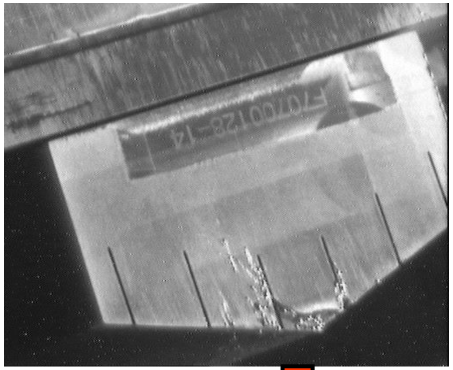
No large runaway electron flux

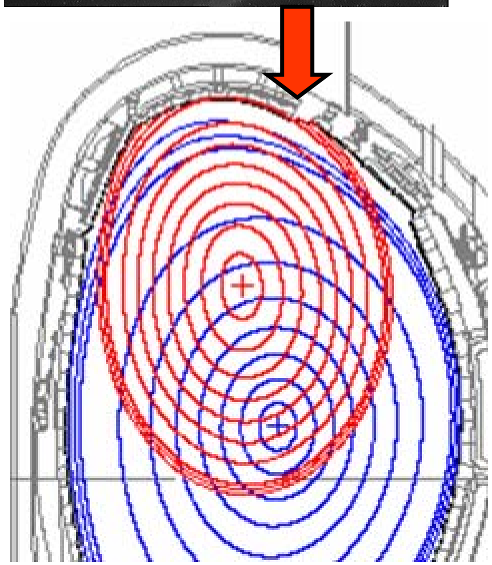
AUG-W: Re-examination of AUG-C data shows similar changes

5. Disruptions: ITER-like Wall compared to C-wall



Be upper dump plate tile end



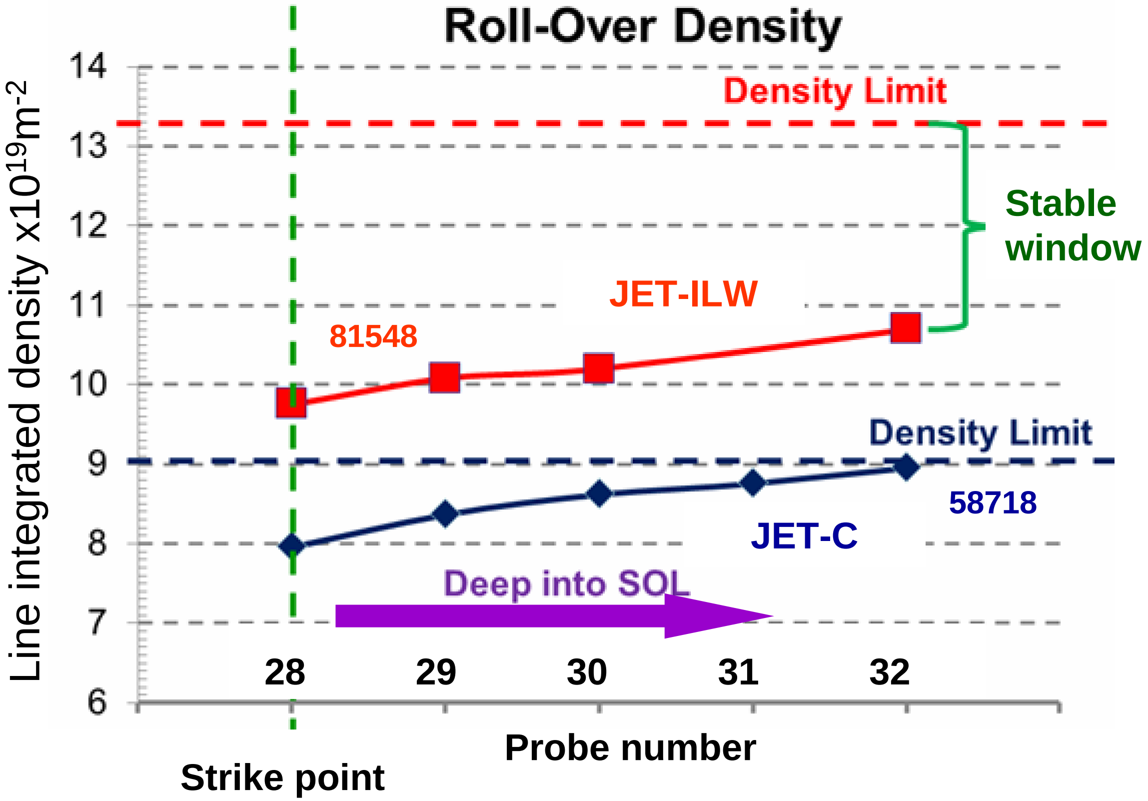


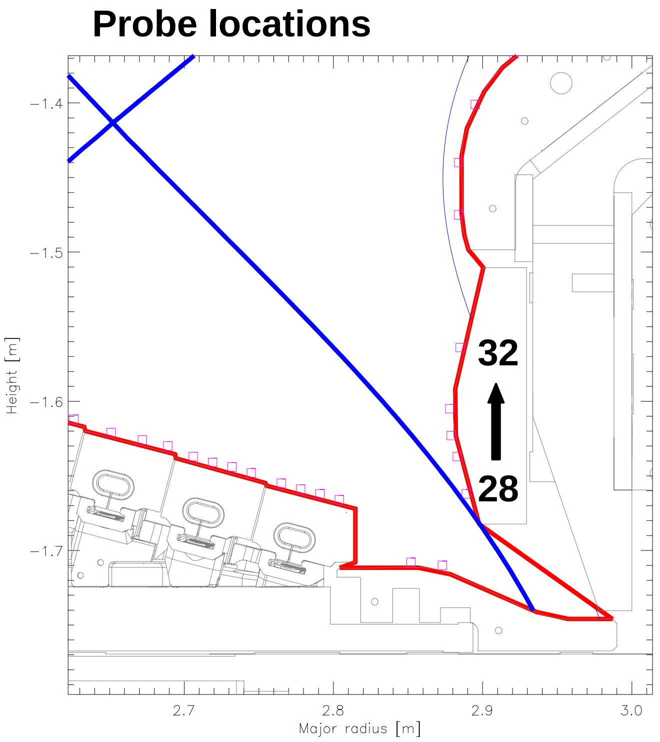
JET-ILW: Massive gas injection ($Ar+D_2$) is now required for I_p>2MA

AUG-W: Massive gas required for I_p>0.9MA due to forces not heat load

No de-conditioning or Ar legacy in JET-ILW or AUG-W

5. Disruptive density limit (vertical target)



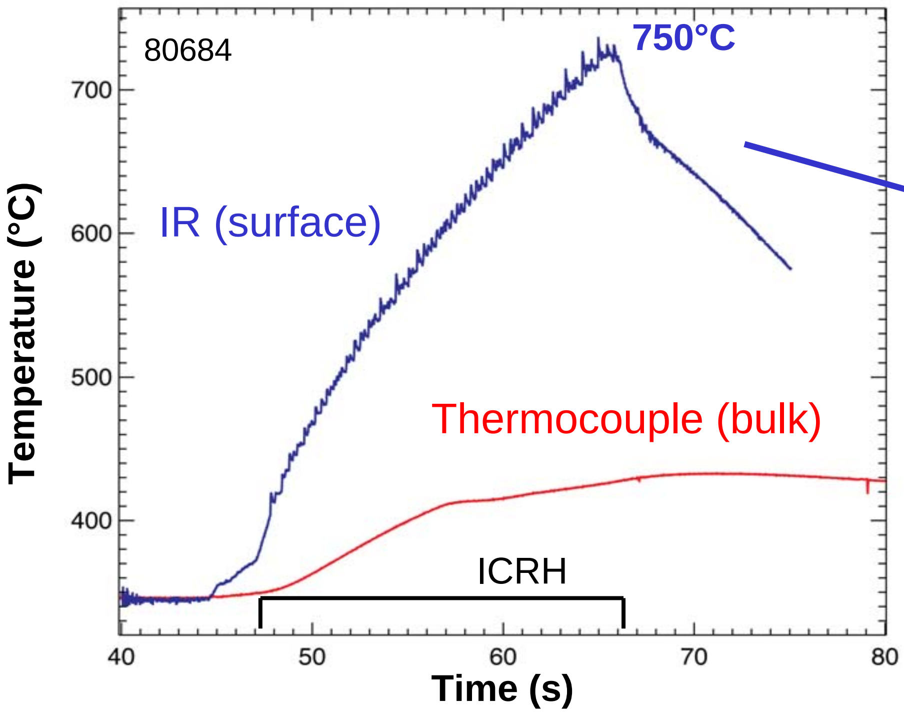


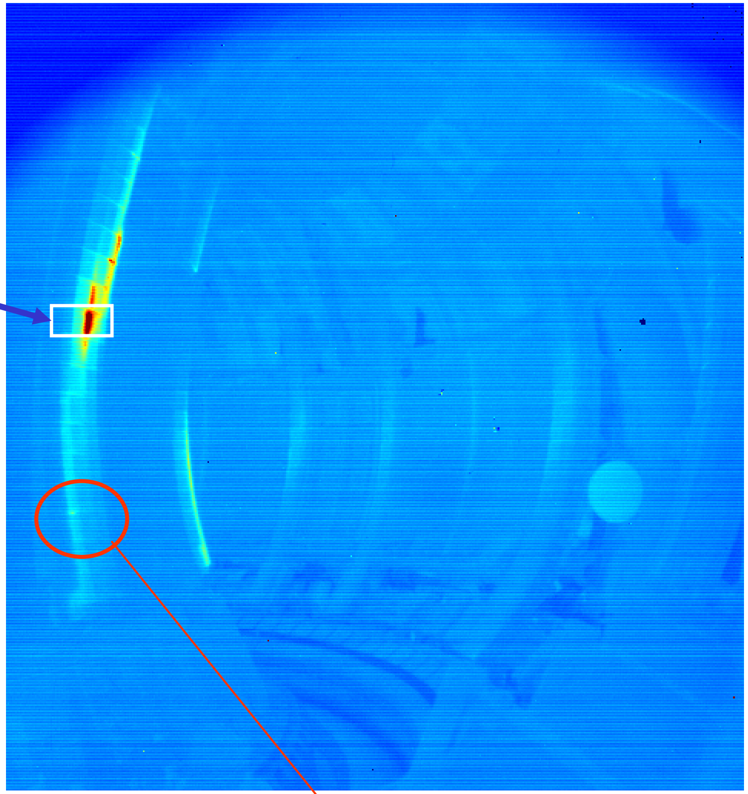
JET-ILW: 40% higher density limit than JET-C & stable detachment at OSP

AUG-W: Not much change due to residual C (not tried after boronisation)

6. Power handling: Beryllium limiters perform well

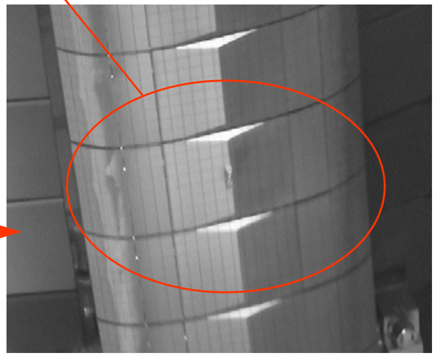
Inner Wall Limiter Plasma: P_{ICRH} = 2.4MW for 19s





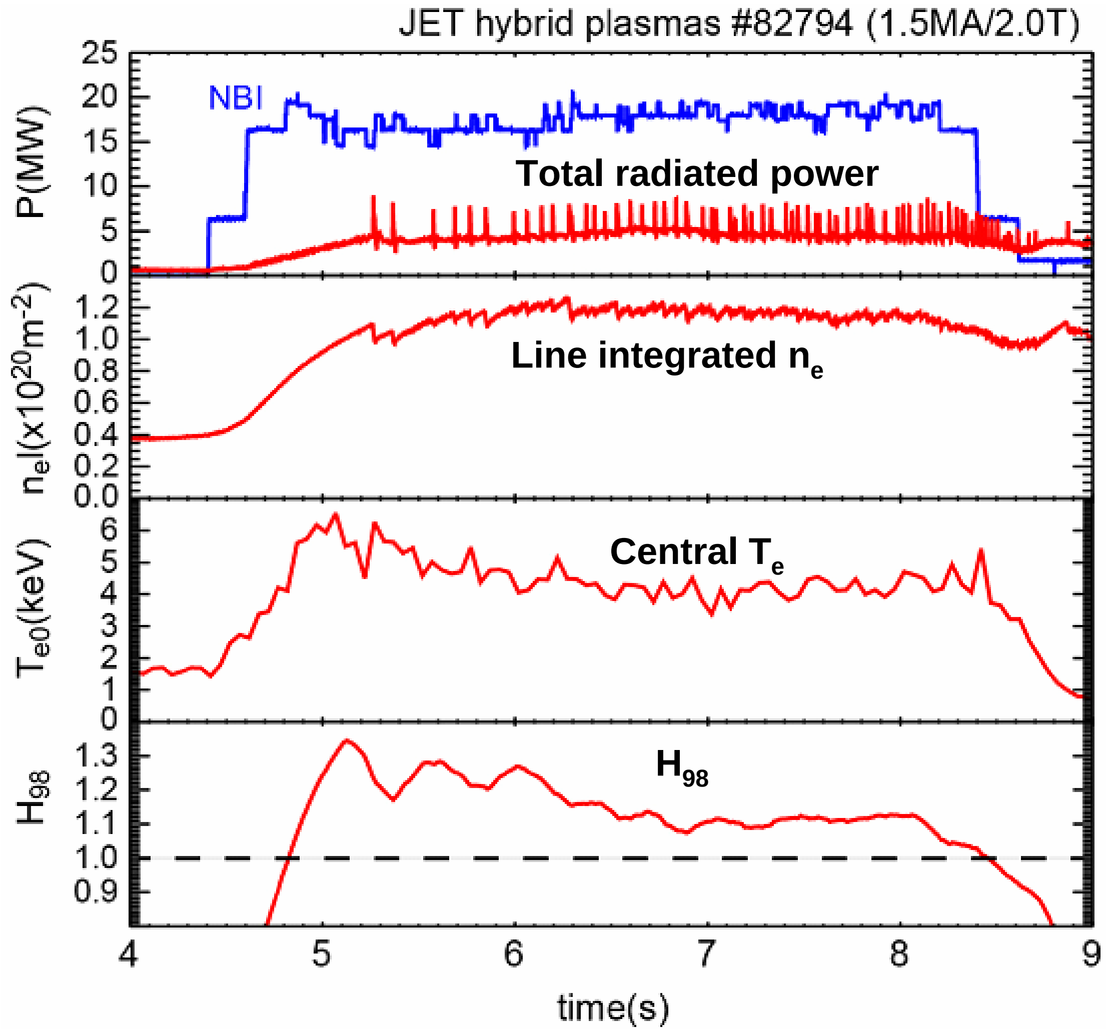
Effective shadowing of Be tile edges – no hot spots

Only one small melt spot on limiters:
emergency shutdown ⇨ runaway e-beam



IVIS survey view

7. Scenarios: Hybrid plasma example



Z_{eff}~1.2

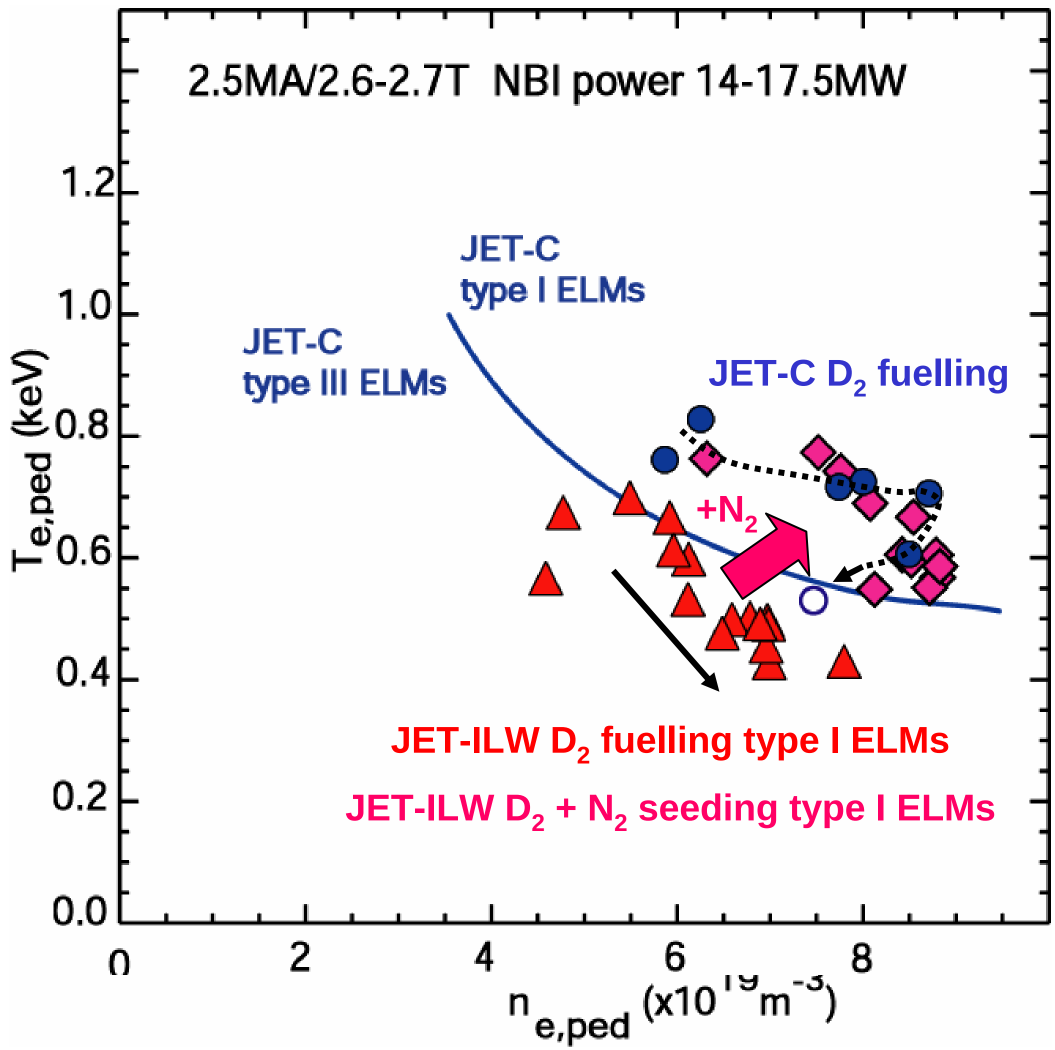
$n/n_{Greenwald}$~80%

β_N~2.8±10%

JET-ILW: H_{98}~1 also achieved in low and high shape inductive scenarios

⇨ H_{98} ~1 requires low fuelling but W control restricts operating window

⇨ Next: Higher power, ELM pacing and central heating (as AUG-W)



JET-ILW: type I ELMs below type III boundary for JET-C

N_2 seeding improves pedestal parameters

9. Conclusions

The ITER-like Wall has shown

Anticipated benefits and risks of a W/Be wall:

⇨Large reduction in fuel retention and very clean/reproducible plasmas

⇨ITER scenarios constrained by W-accumulation but still achievable

⇨Good power handling and protection of the Be/W wall

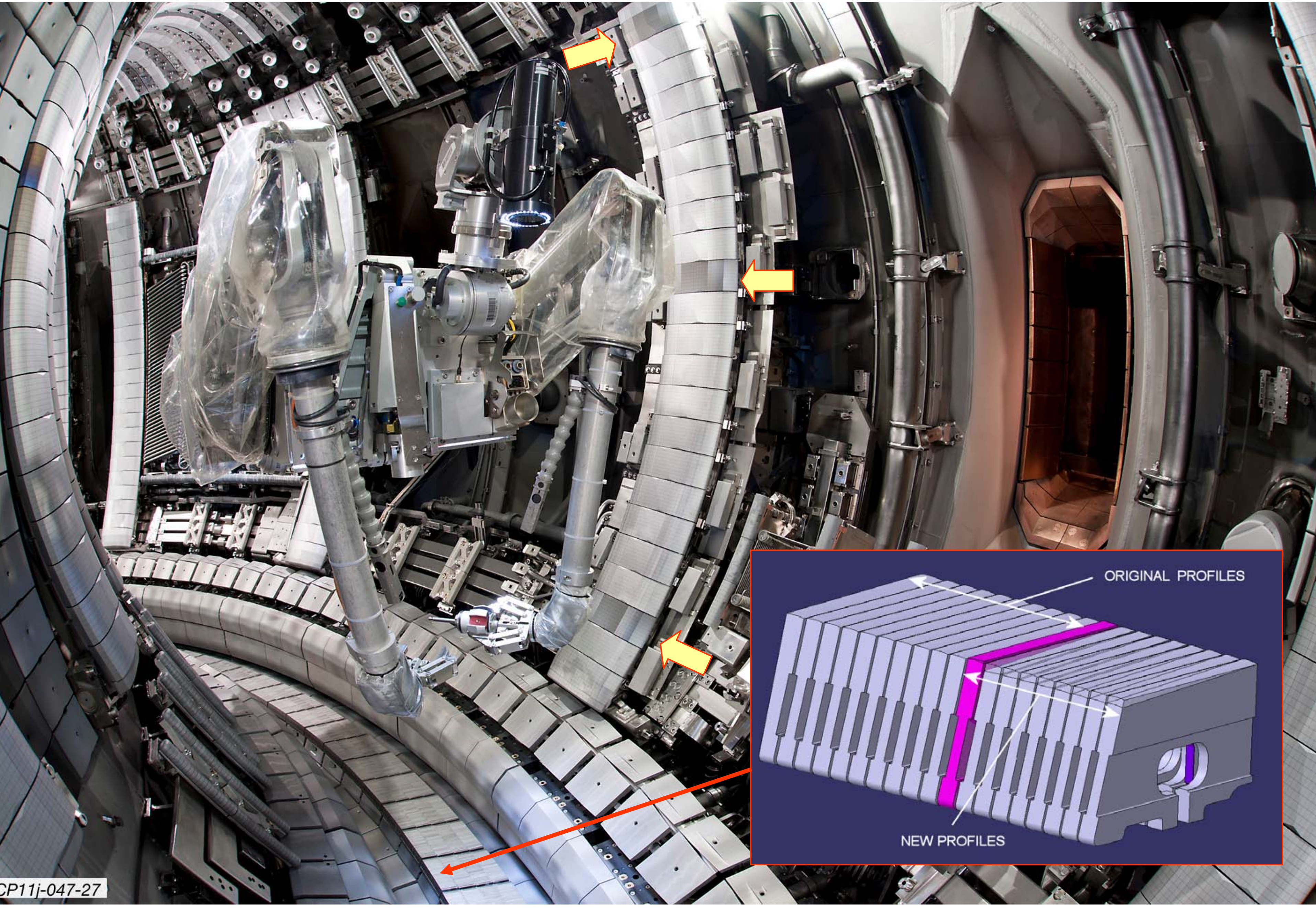
An unpredicted strong effect on pedestal and ELM behaviour

Many similarities to the AUG-C to AUG-W transition ⇨ synergy

ITER/DEMO scenario development needs relevant PWI
i.e. PWI issues and H-mode physics are not separable

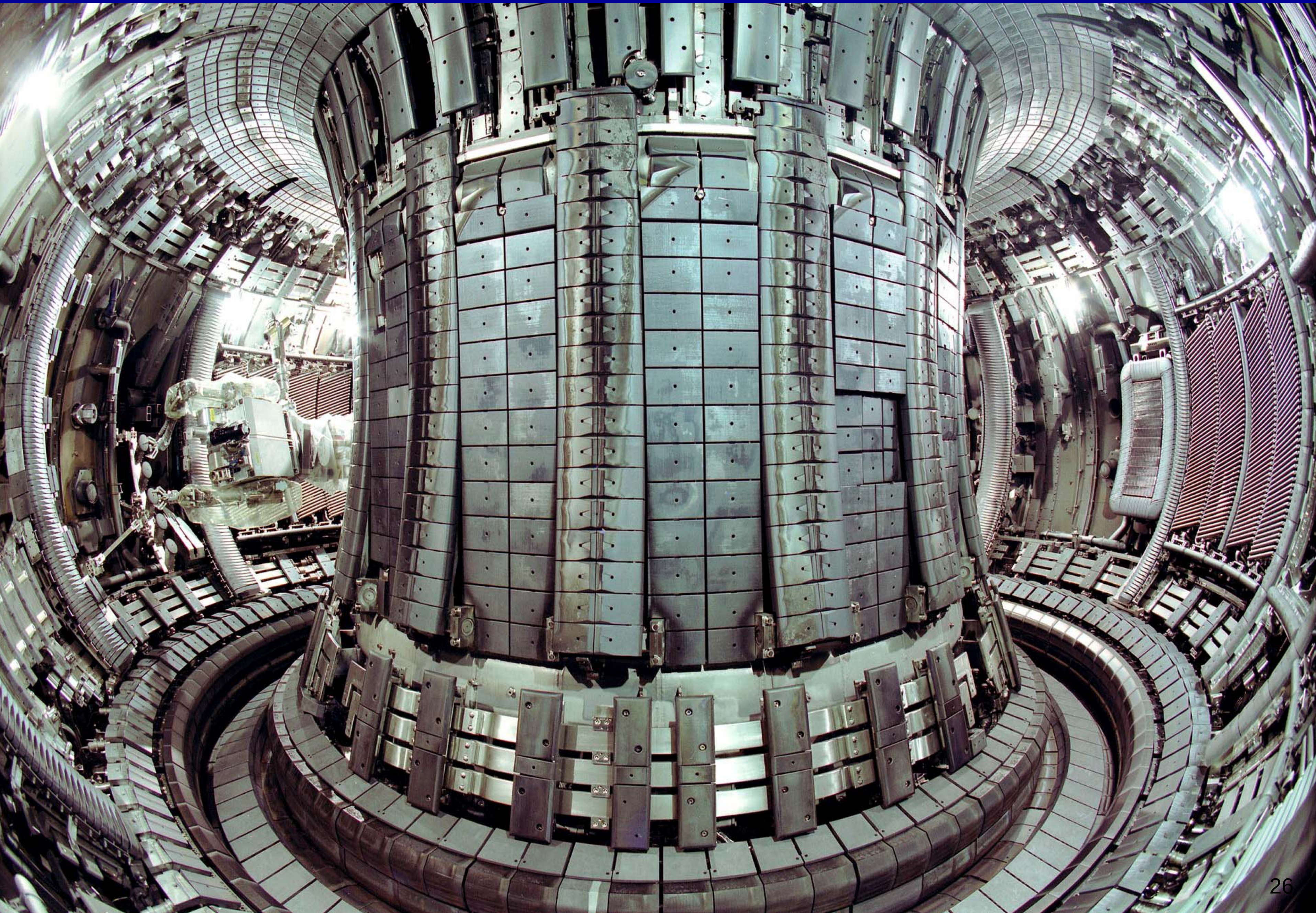
Exploitation & analysis of the ITER-like Wall has only just begun

2012 Shutdown: Replace samples & install W melt test module

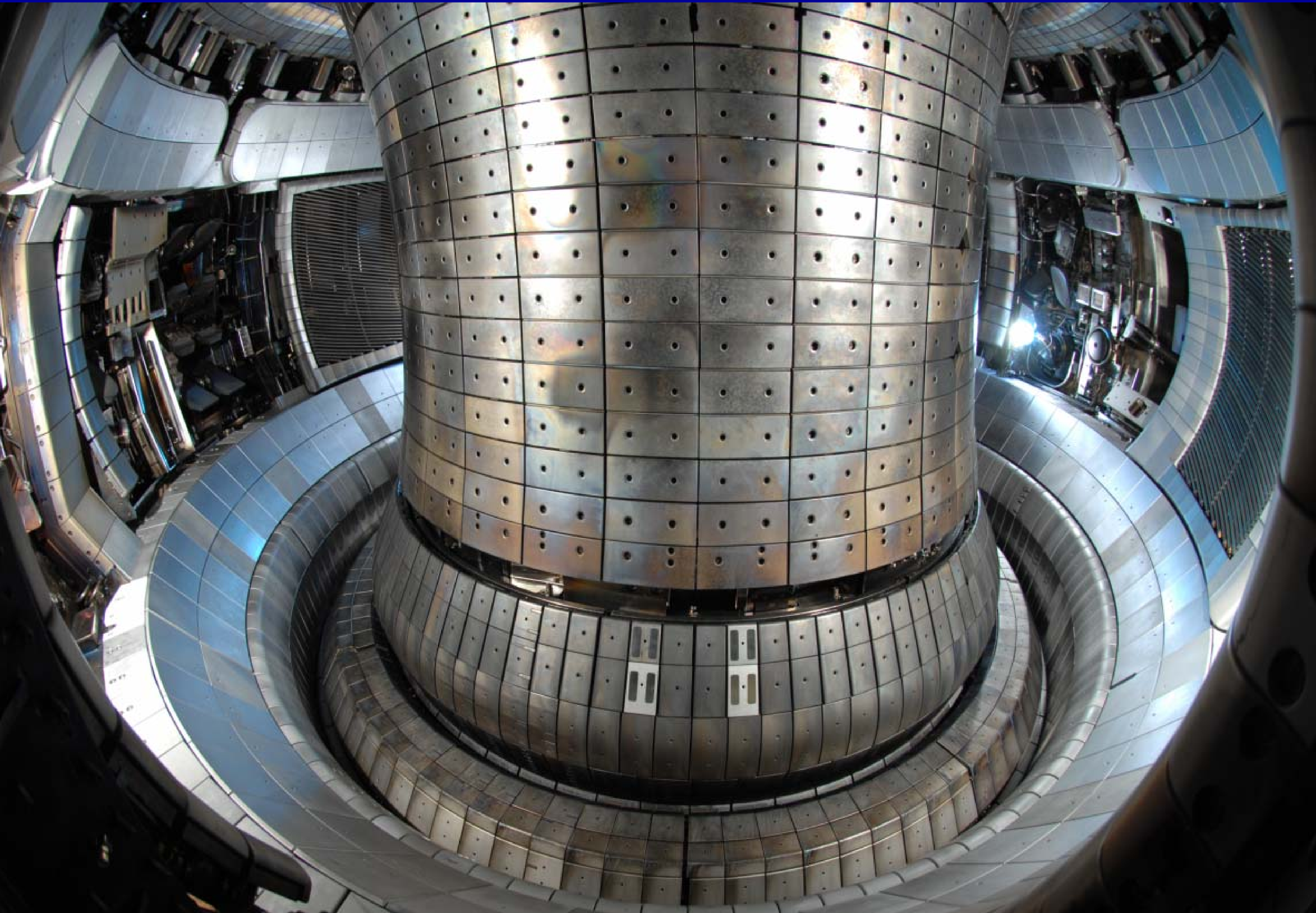


SPARE SLIDES FOLLOW

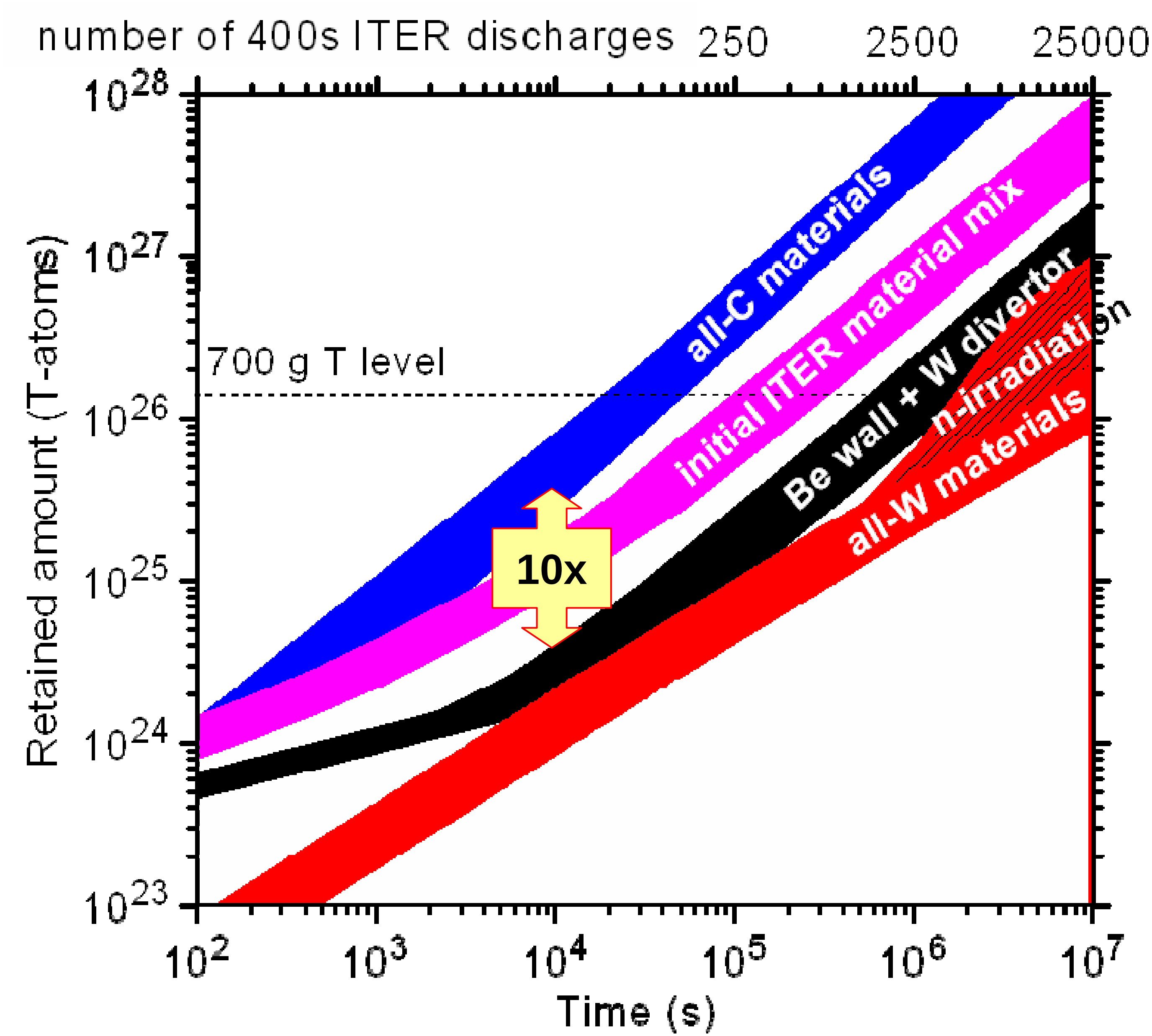
1. JET-C Carbon era of JET ended in Nov. 2009



1. ASDEX-Upgrade tungsten wall (AUG-W)



3. Long Term Fuel Retention Predicted for ITER



(4 months)

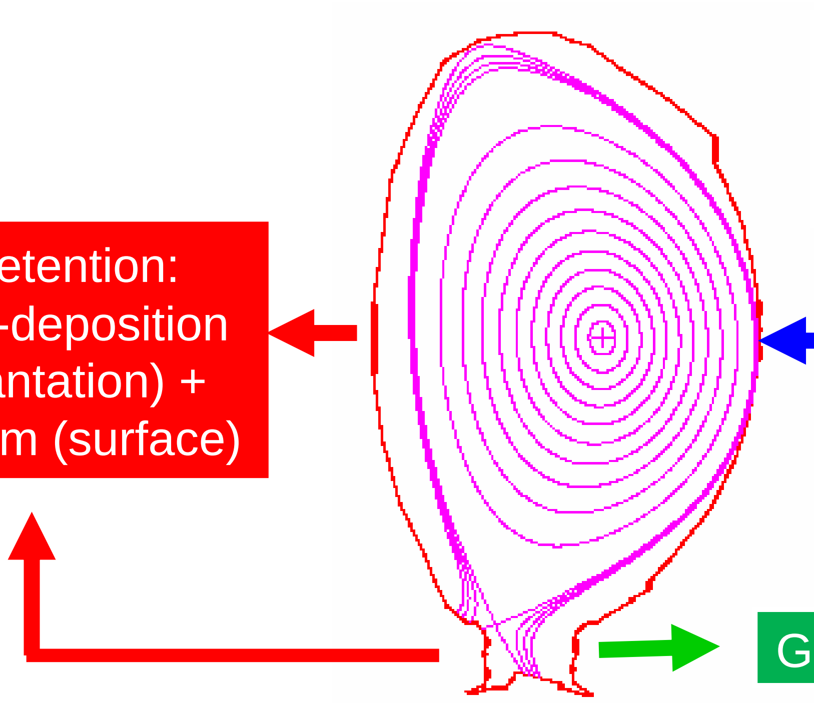
Roth NF

3. Fuel retention: JET Gas Balance Experiments

Regeneration of cryogenic pumps before and after experiment

Repeat sets identical discharges

Fuel retention: long (co-deposition & implantation) + short term (surface)



Calibrated particle source (gas injection modules)

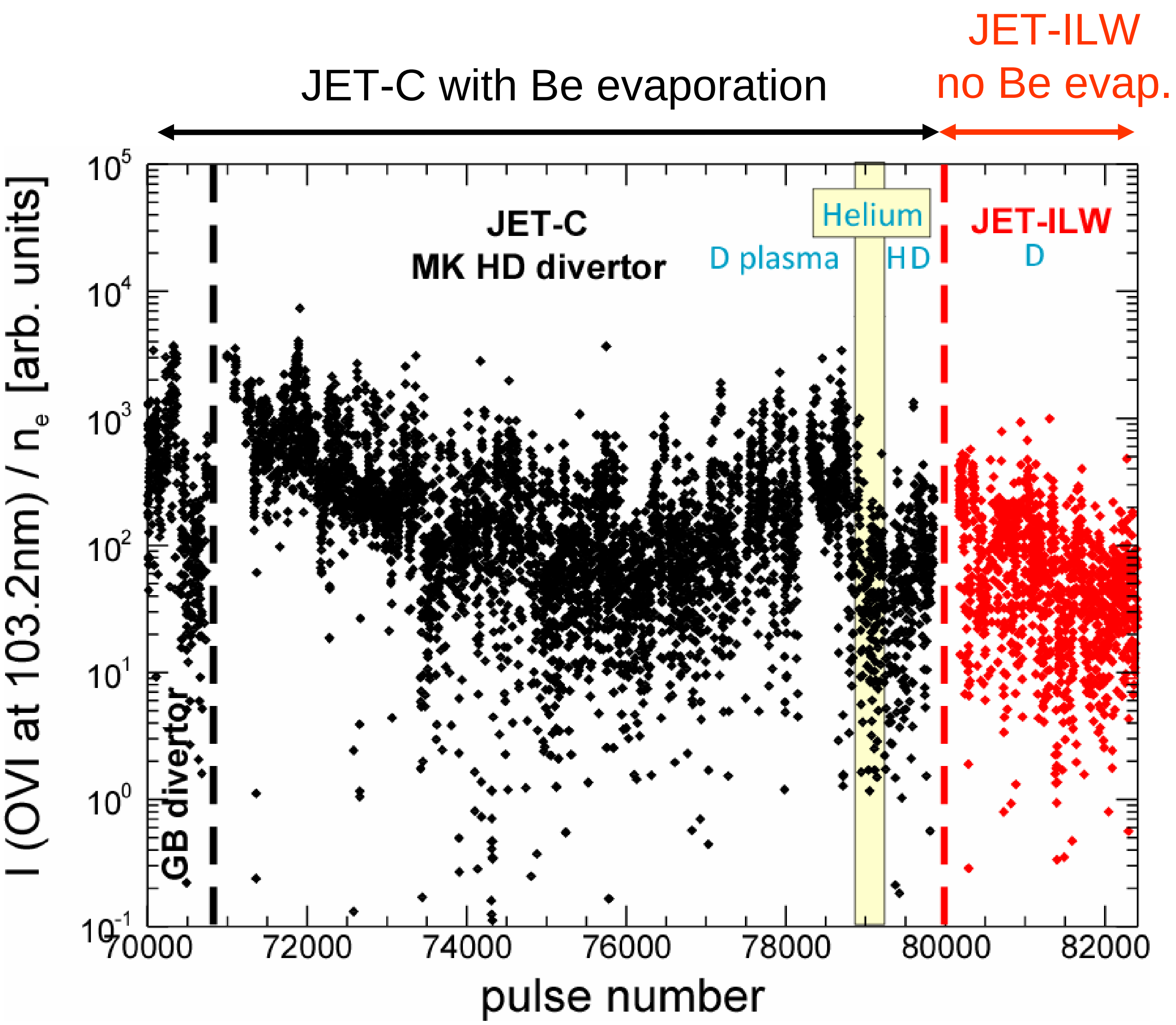
Gas collection on divertor cryo pumps

Injected gas = Pumped gas+ Short term retention + Long term retention

1. Stronger gas consumption during limiter phase with ILW ≈ 2x
2. Lower gas consumption during divertor phase w.r.t. CFC walls
3. Stronger outgasing after the discharge compared to CFC walls

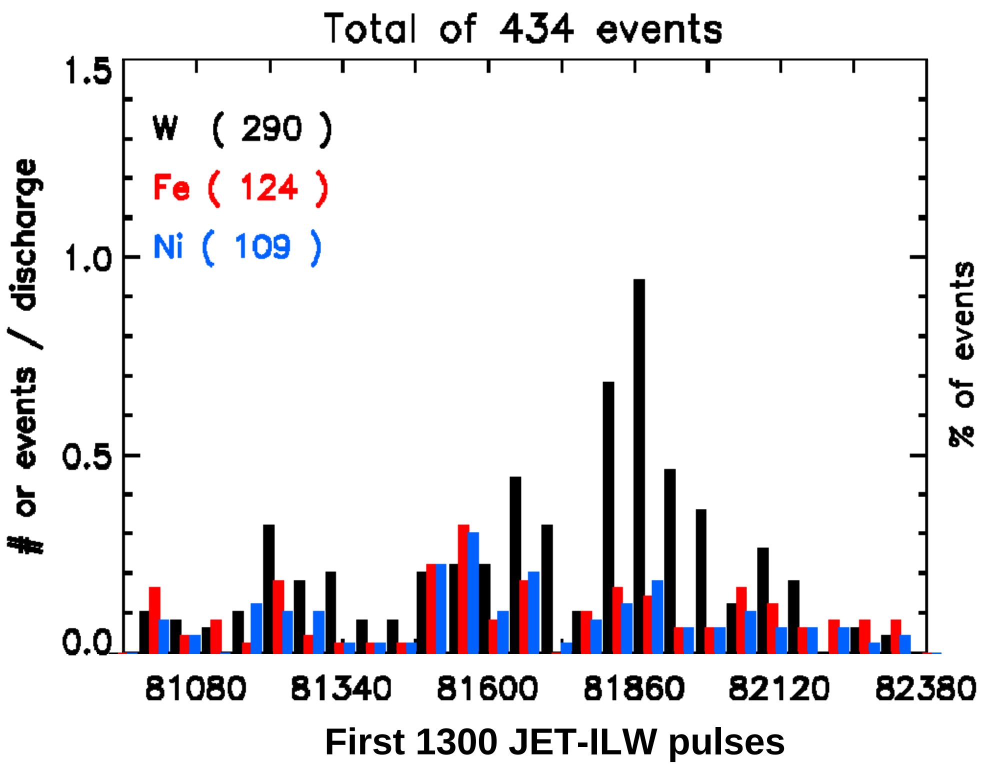
Note: C-wall long term retention from surface analysis << gas balance

2. Residual impurities JET-C to JET-ILW: Oxygen

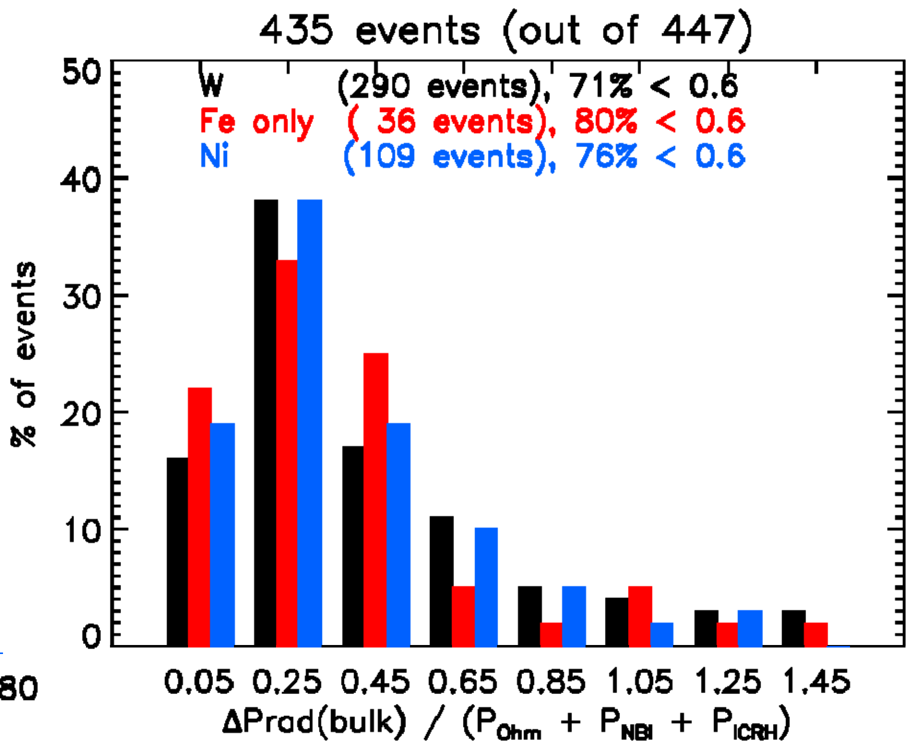


4. Particle Analysis JET-ILW: Not all are tungsten

VUV spectroscopy identifies type



Majority are tolerable

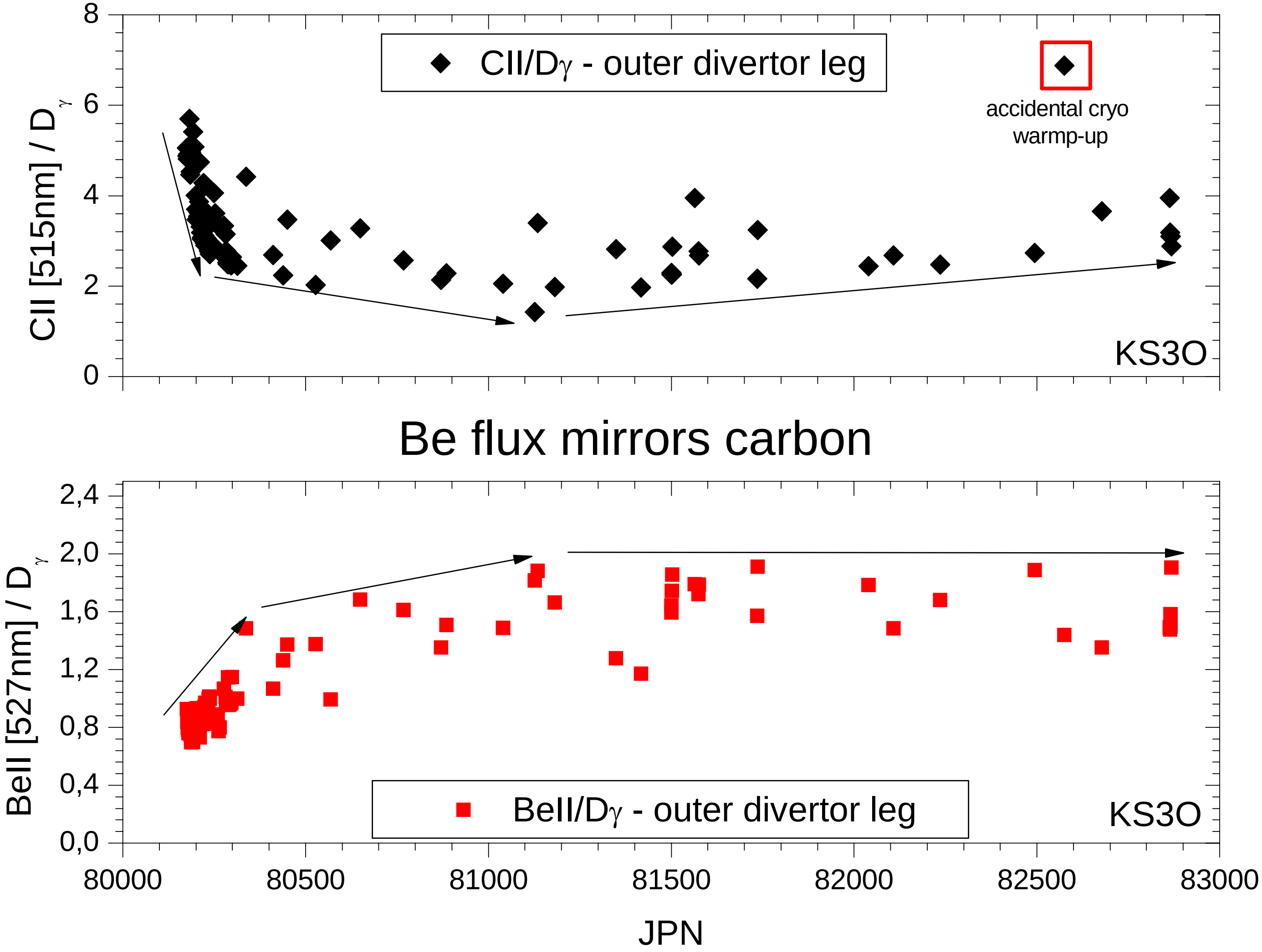


History shows thermal fatigue is not generating W particles (yet)

W-particles ~0.1mm effective diameter

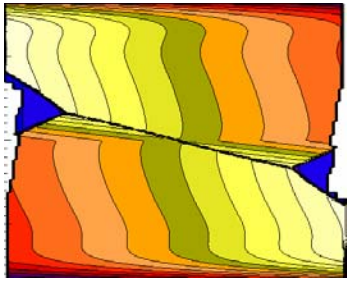
Particles appear as Be/C in the divertor!

JET-ILW: Monitoring pulses



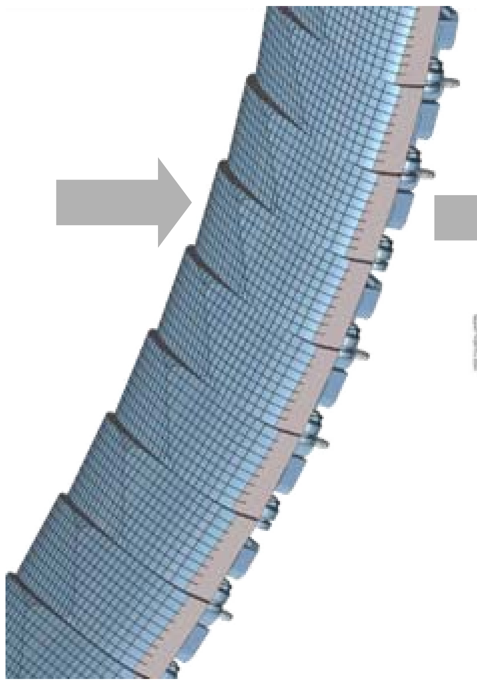
6. Power handling: shape optimised for edge exposure < 40μm

Local
Analytical Profile
Optimisation



JET Plasma
Operations Group

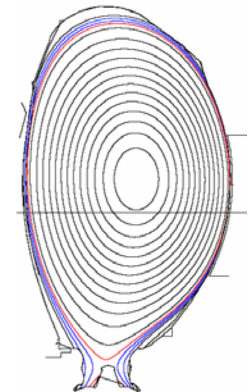
CATIA V5 Model



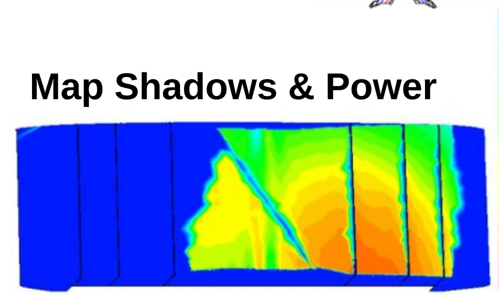
Limiter scale mesh
+ shadows from other limiters
+ installation tolerances

CEA

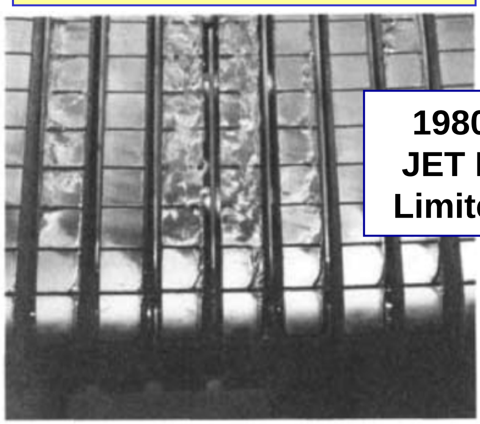
Library of
Equilibria
+ Off Normal



Map Shadows & Power

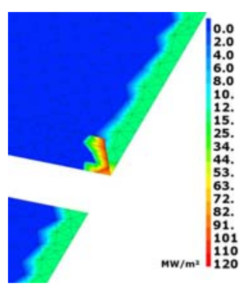


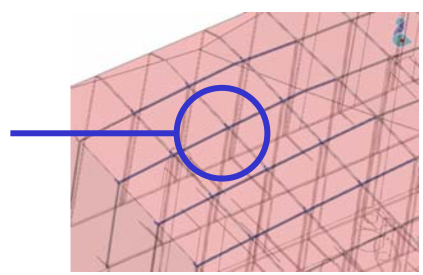
Poor local geometry



1980s
JET Be
Limiters

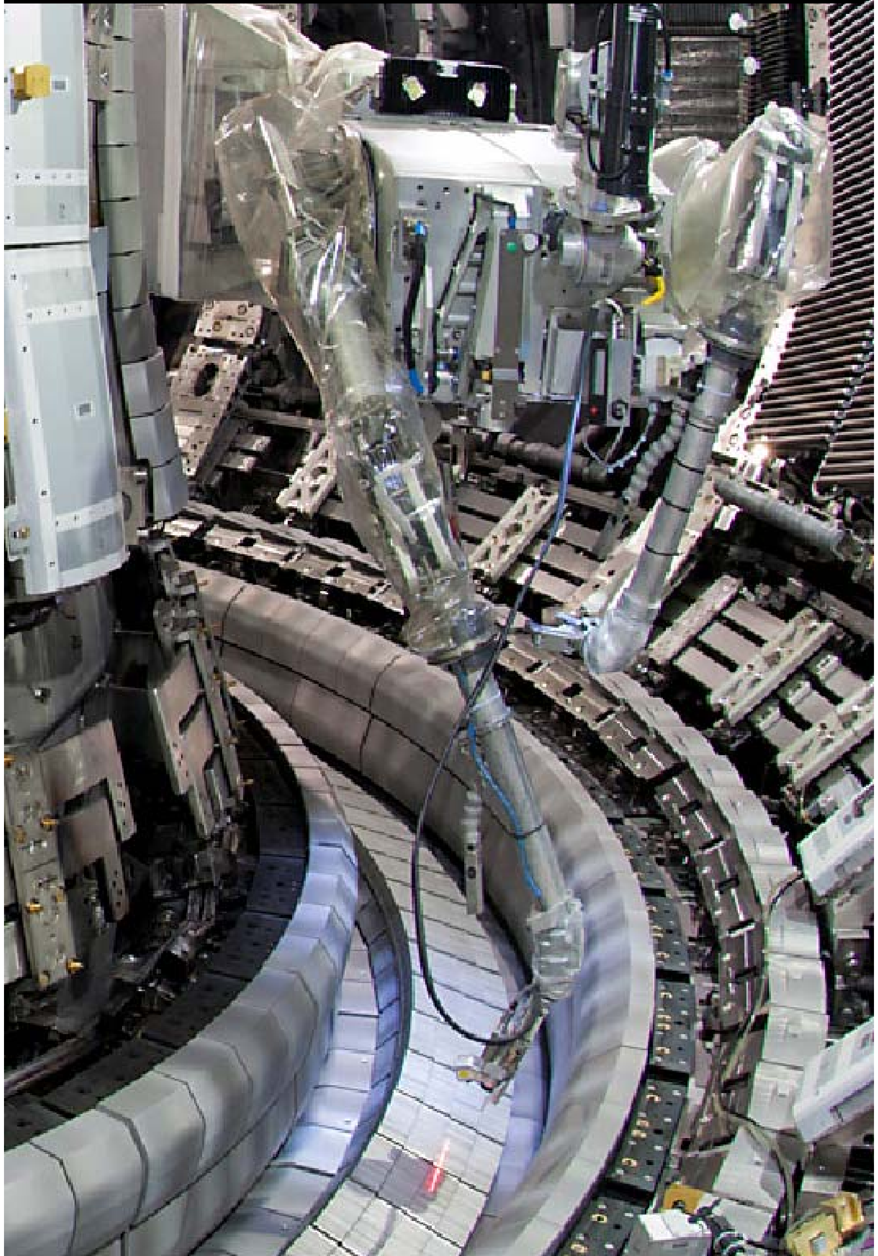
Castellation scale meshes
⇨ Edge heating



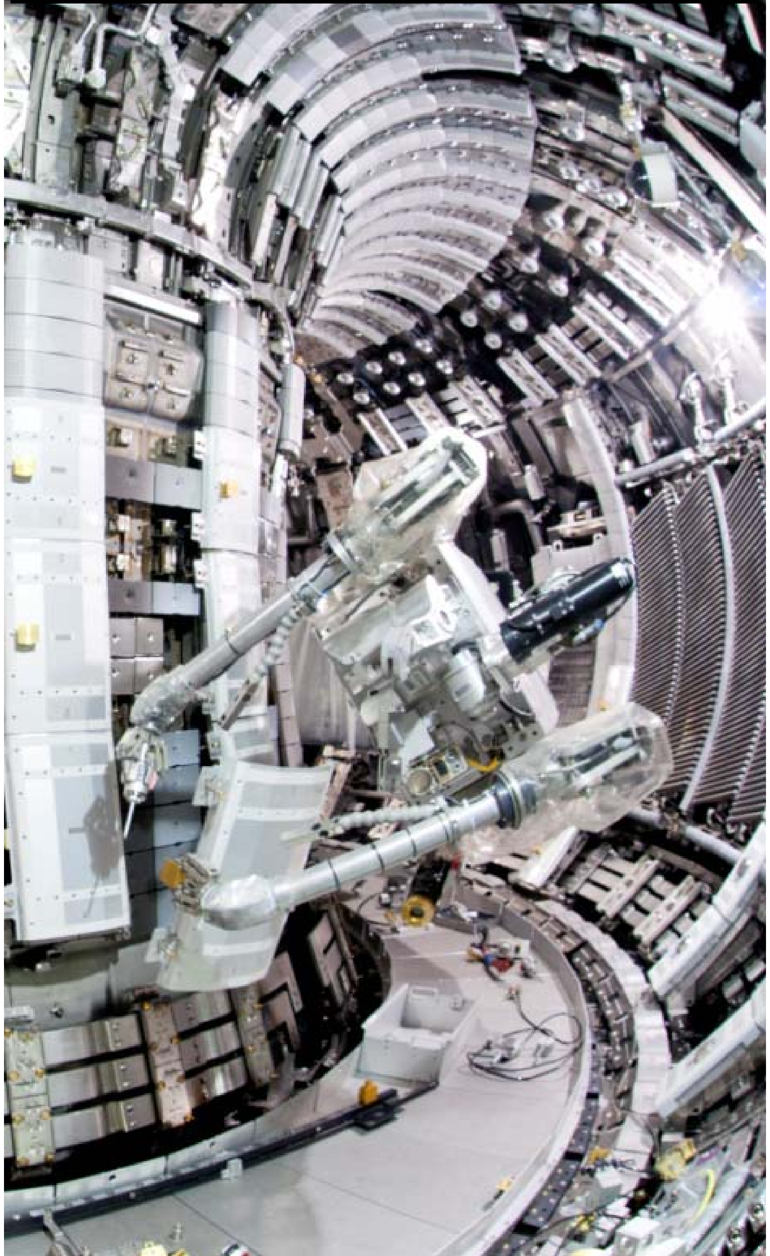


6. Power handling: achieving the tolerances

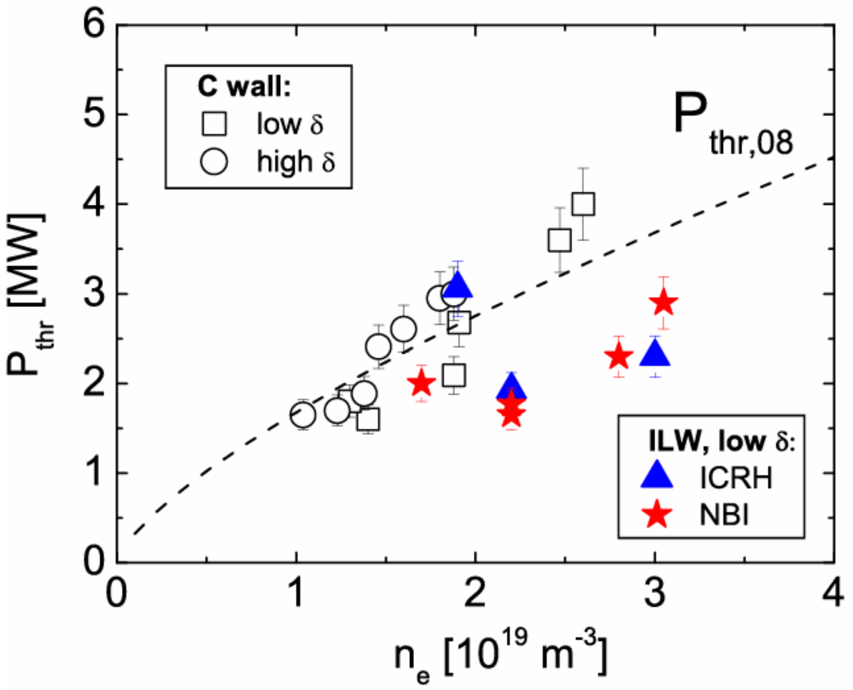
Feb 2011 – Gap gun laser scan



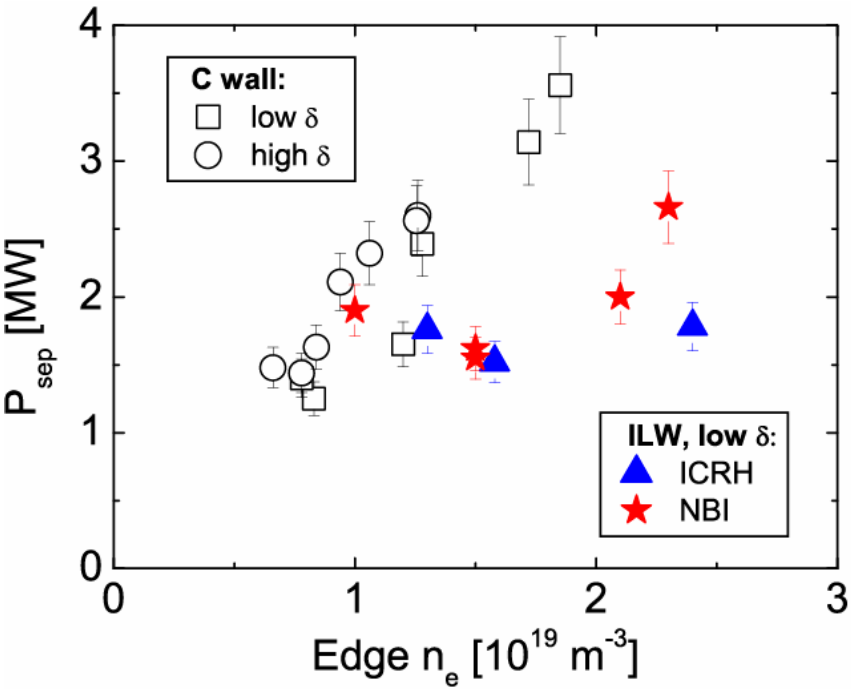
Mar 2011 – installing covers



JET-ILW: Total power threshold

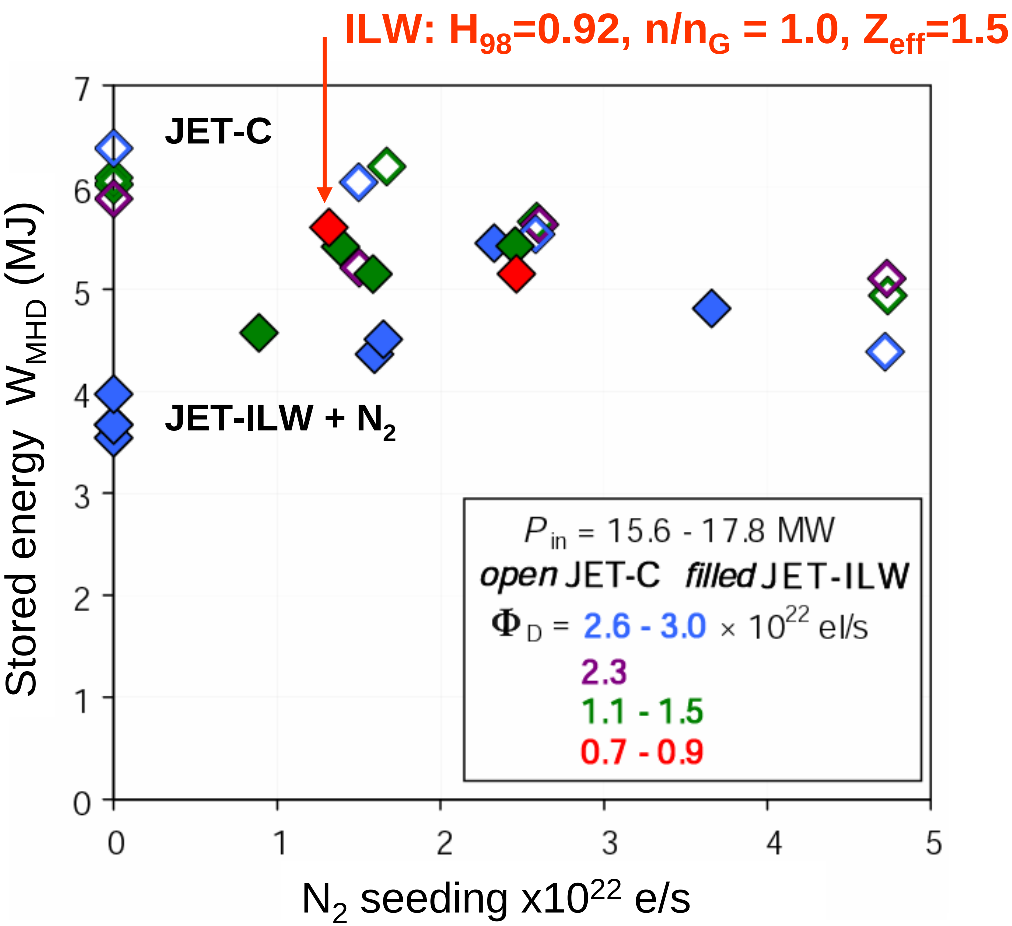


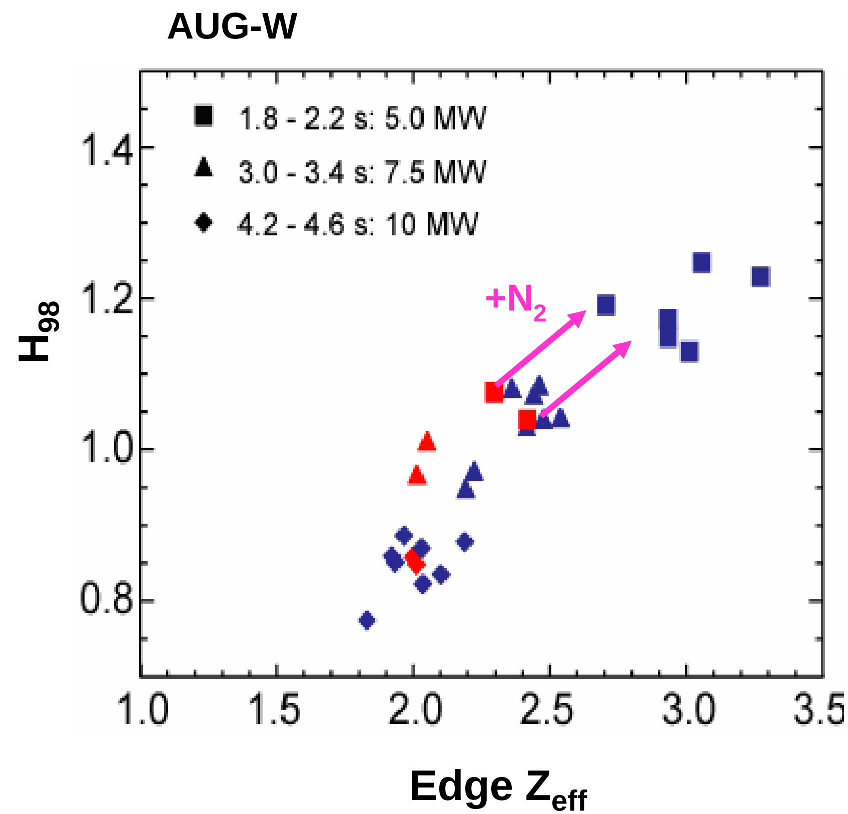
JET-ILW: Separatrix power threshold



AUG-W: P_{thr} reduced by 25%

7. High triangularity inductive scenario: Effect of N_2 seeding



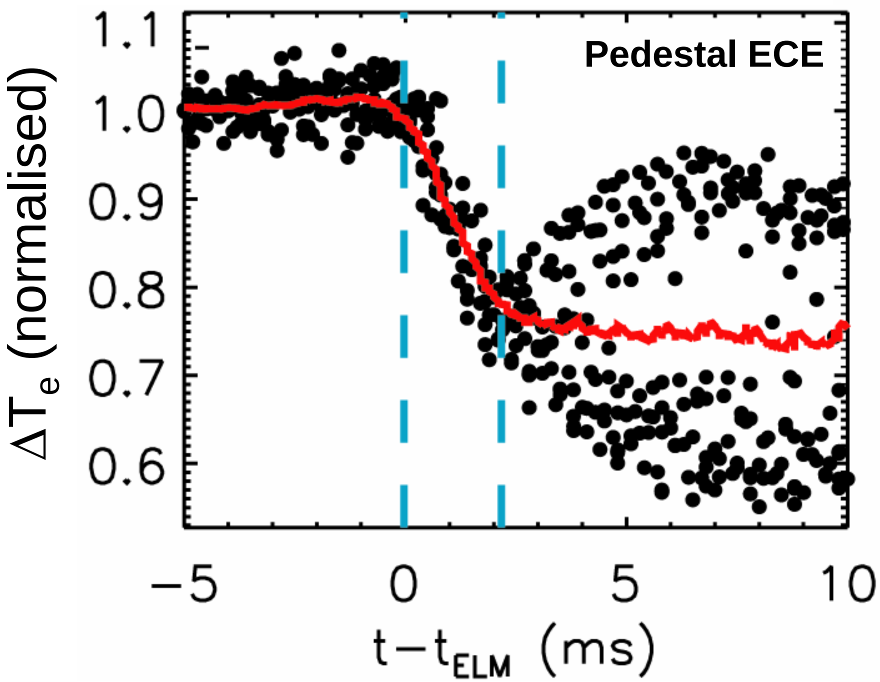


JET-ILW: Link to Z_{eff} is not convincing

⇨ co-linearities make causal interpretation difficult

7. Scenarios: Slow ELMs seen at low $T_{e,ped}$ in JET-ILW

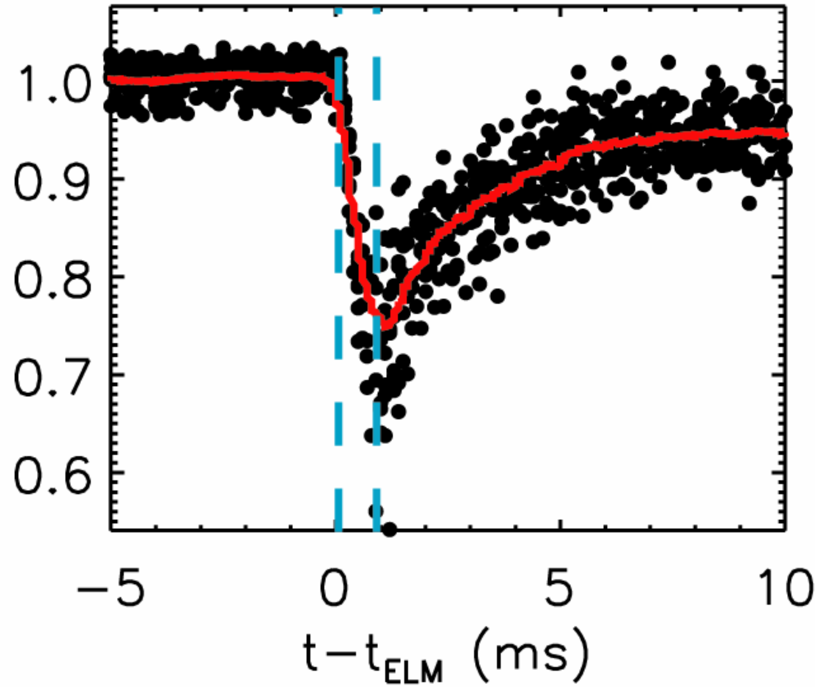
82806 2.5MA/2.7T high delta D_2 only



W_{dia}=4.0MJ, P_{input}=17MW

$T_{e,ped}$=500eV, $n_{e,ped}$=7.0x10^{19}m^{-3}

82817 2.5MA/2.7T high delta D_2+ N_2



W_{dia}=5.9MJ, P_{input}=18MW

$T_{e,ped}$=770eV, $n_{e,ped}$=7.6x10^{19}m^{-3}

AUG-W: review of past data has revealed similar behaviour

ITER requires high T_{ped} so slow ELMs probably not relevant