

Tungsten Experiences in ASDEX Upgrade and JET

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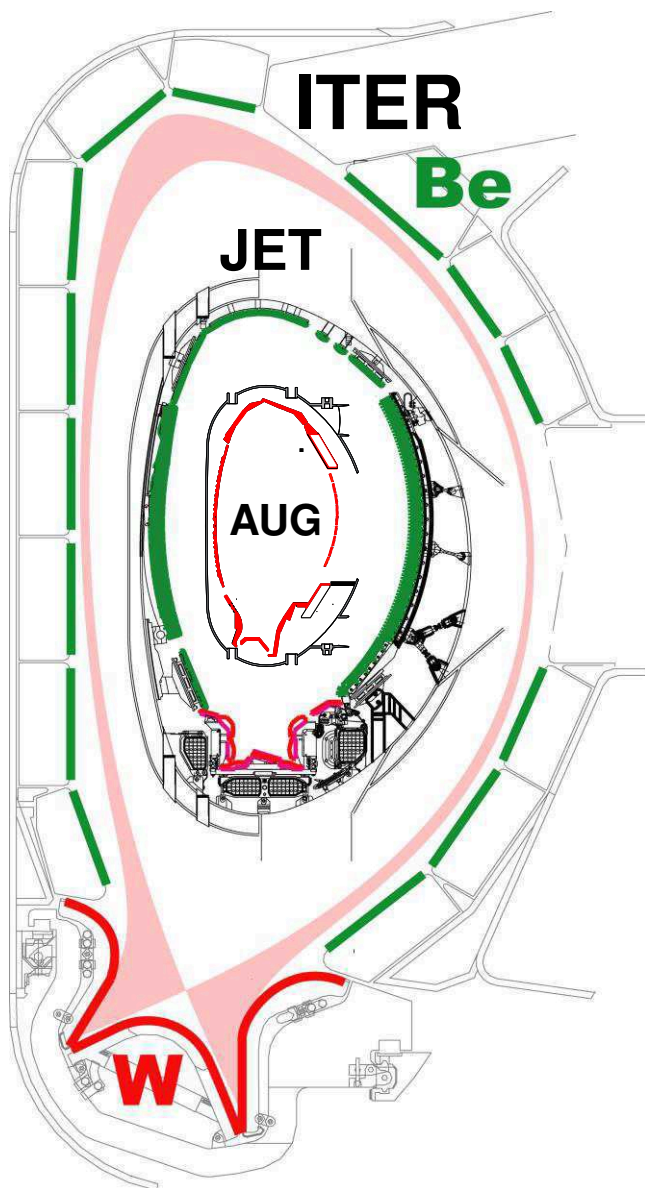
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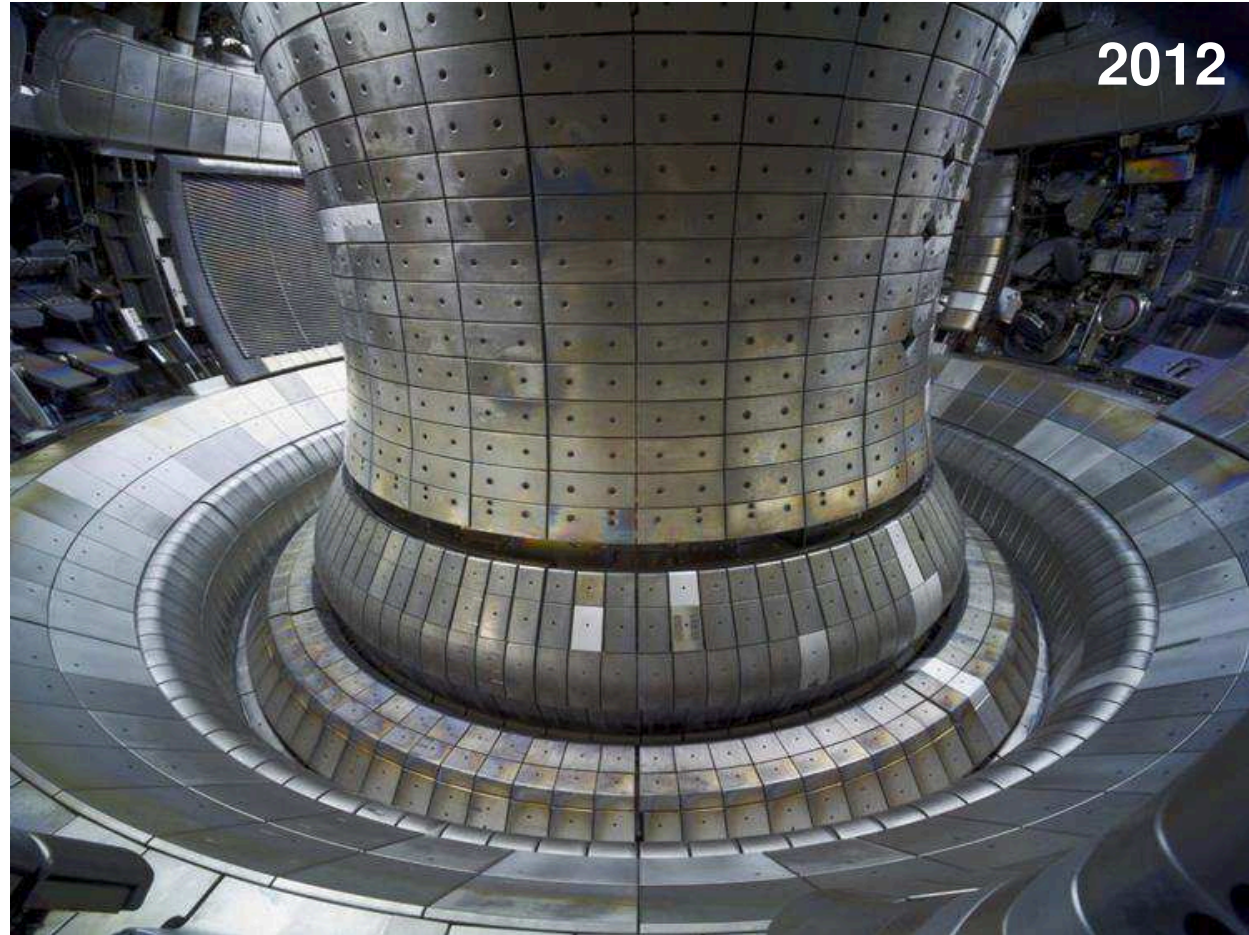
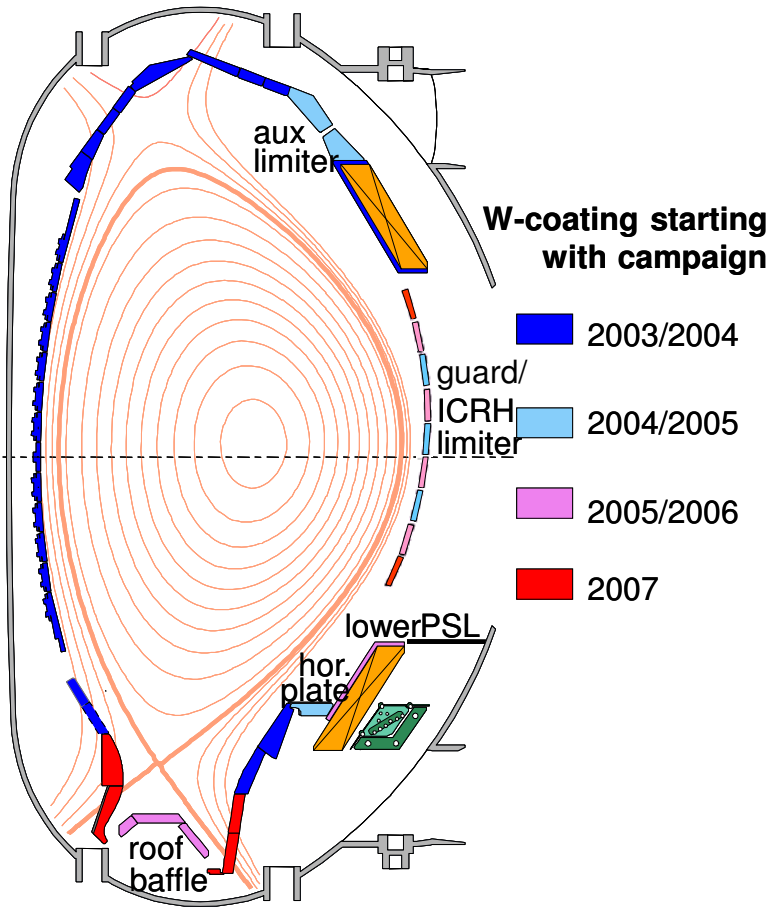
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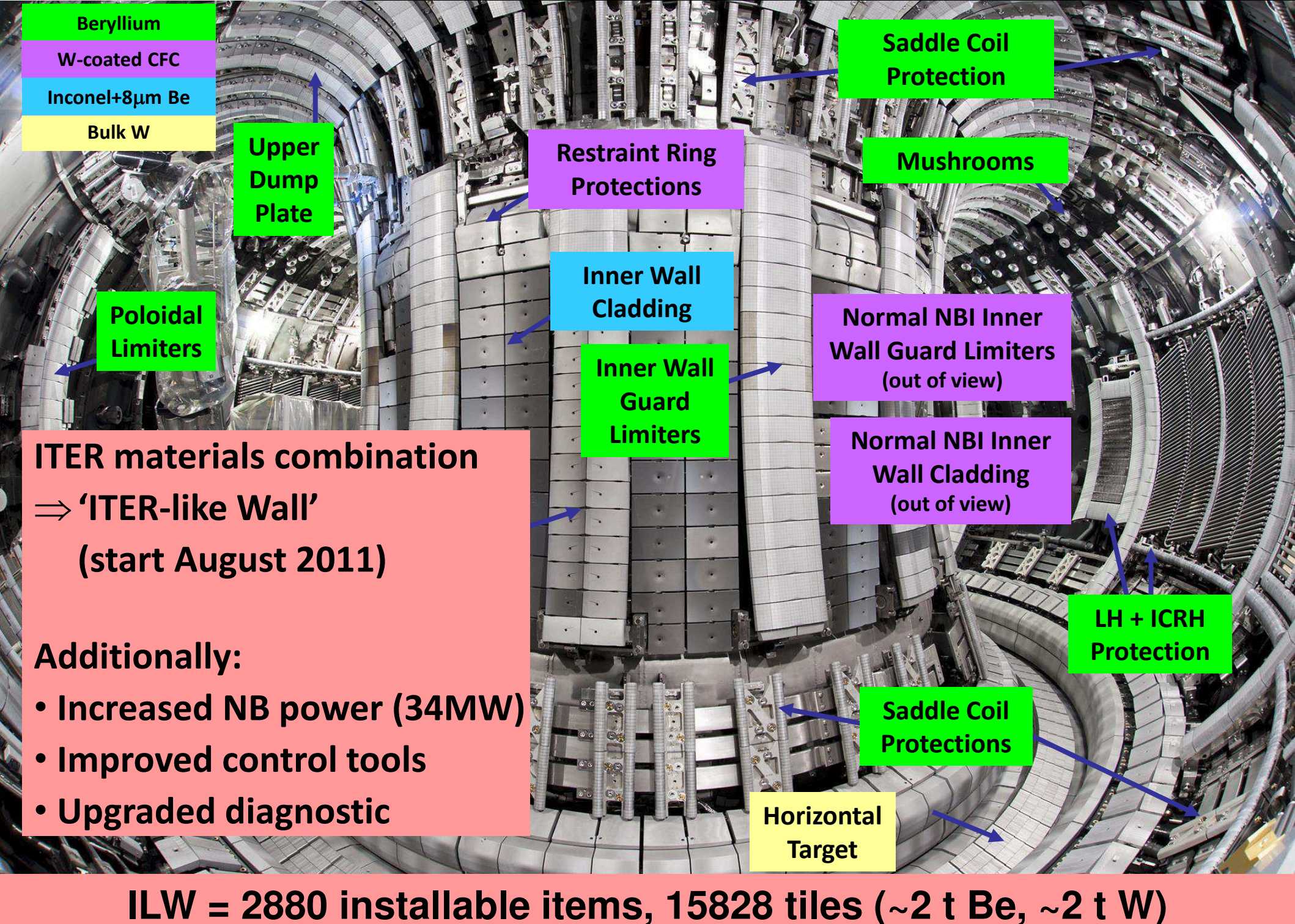
AUG & JET: All Metal PFCs

- Demonstrate low fuel retention, migration and possible fuel recovery
- Demonstrate plasma compatibility with metallic walls
- Develop tools for improved plasma control and heat load mitigation
- Provide input to the decision on the first ITER divertor (and DEMO main chamber)

- All Metal Walls in AUG and JET
- Operational Experience
 - Plasma Breakdown
 - Disruptions
 - Fuel Retention
- W Behaviour and H-Mode Properties
 - W Sources
 - W Transport
 - LH-Threshold
 - Confinement Properties
 - Impurity Seeding
- Conclusions



W coatings (3-10 μm) on fine grain graphite



- Beryllium
- W-coated CFC
- Inconel+8µm Be
- Bulk W

Upper Dump Plate

Poloidal Limiters

Restraint Ring Protections

Inner Wall Cladding

Inner Wall Guard Limiters

Saddle Coil Protection

Mushrooms

Normal NBI Inner Wall Guard Limiters (out of view)

Normal NBI Inner Wall Cladding (out of view)

LH + ICRH Protection

Saddle Coil Protections

Horizontal Target

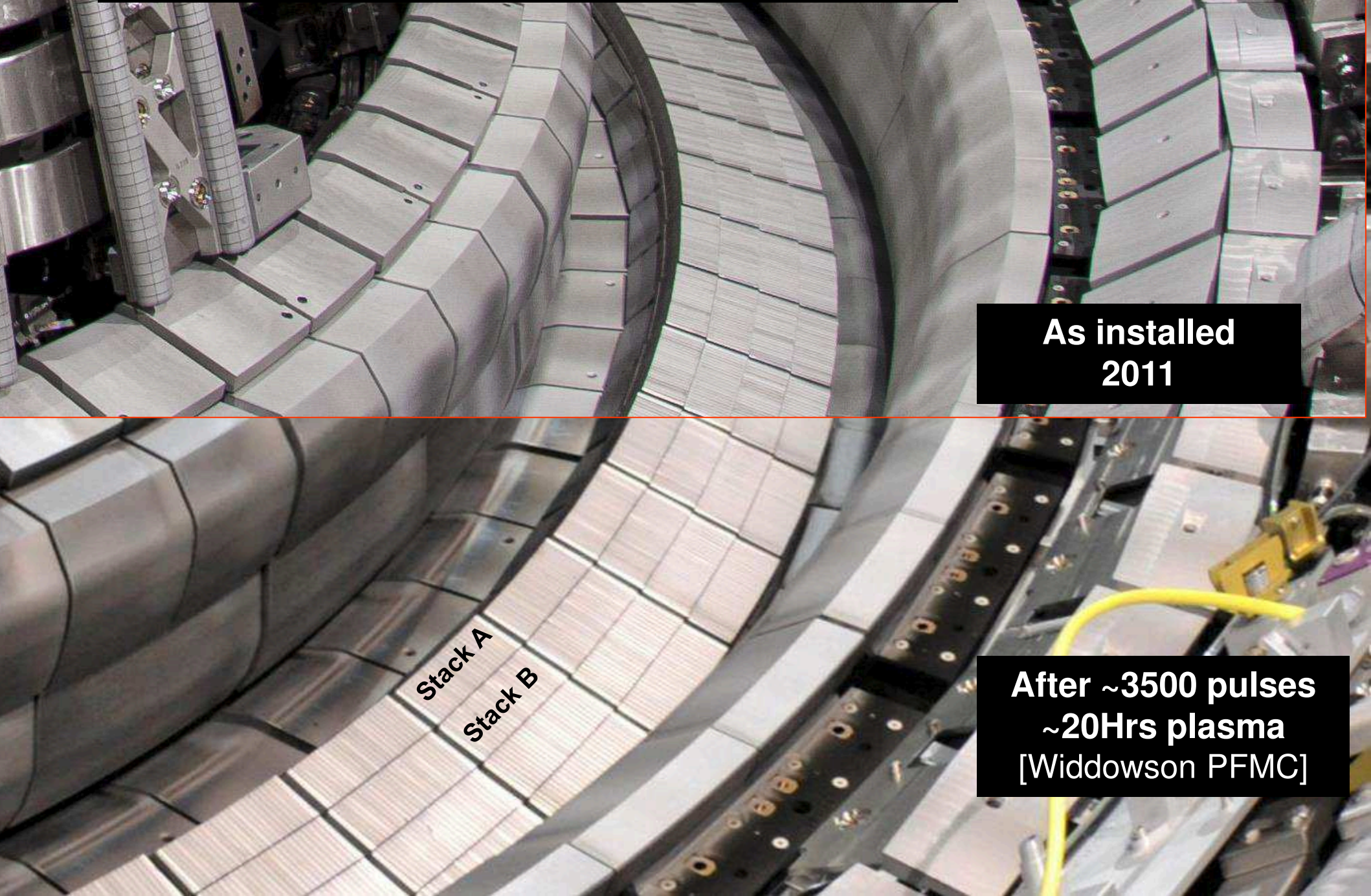
ITER materials combination
 ⇒ 'ITER-like Wall'
 (start August 2011)

Additionally:

- Increased NB power (34MW)
- Improved control tools
- Upgraded diagnostic

ILW = 2880 installable items, 15828 tiles (~2 t Be, ~2 t W)

Looking down into the tungsten divertor



**As installed
2011**

**Stack A
Stack B**

**After ~3500 pulses
~20Hrs plasma
[Widdowson PFMC]**

JET ILW

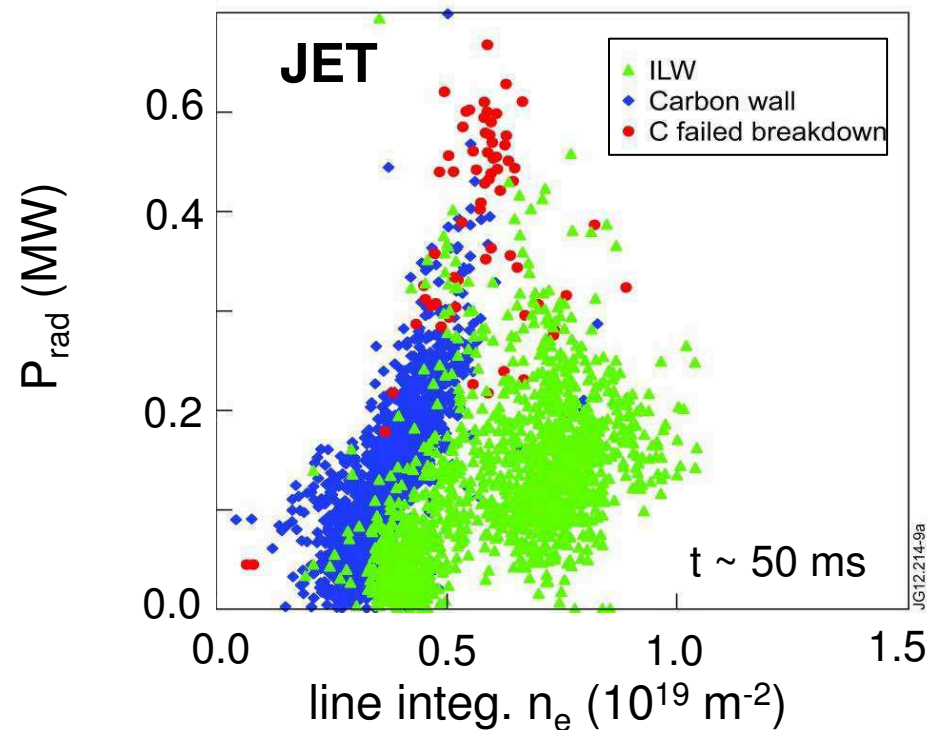
1MA/15s plasmas established at the **first attempt** during the 2011 restart

- **lower radiation level** at higher density (except after N₂ seeding) making the breakdown more robust
- unlike the C-wall, **no de-conditioning** following disruptions (even when using massive gas injection)

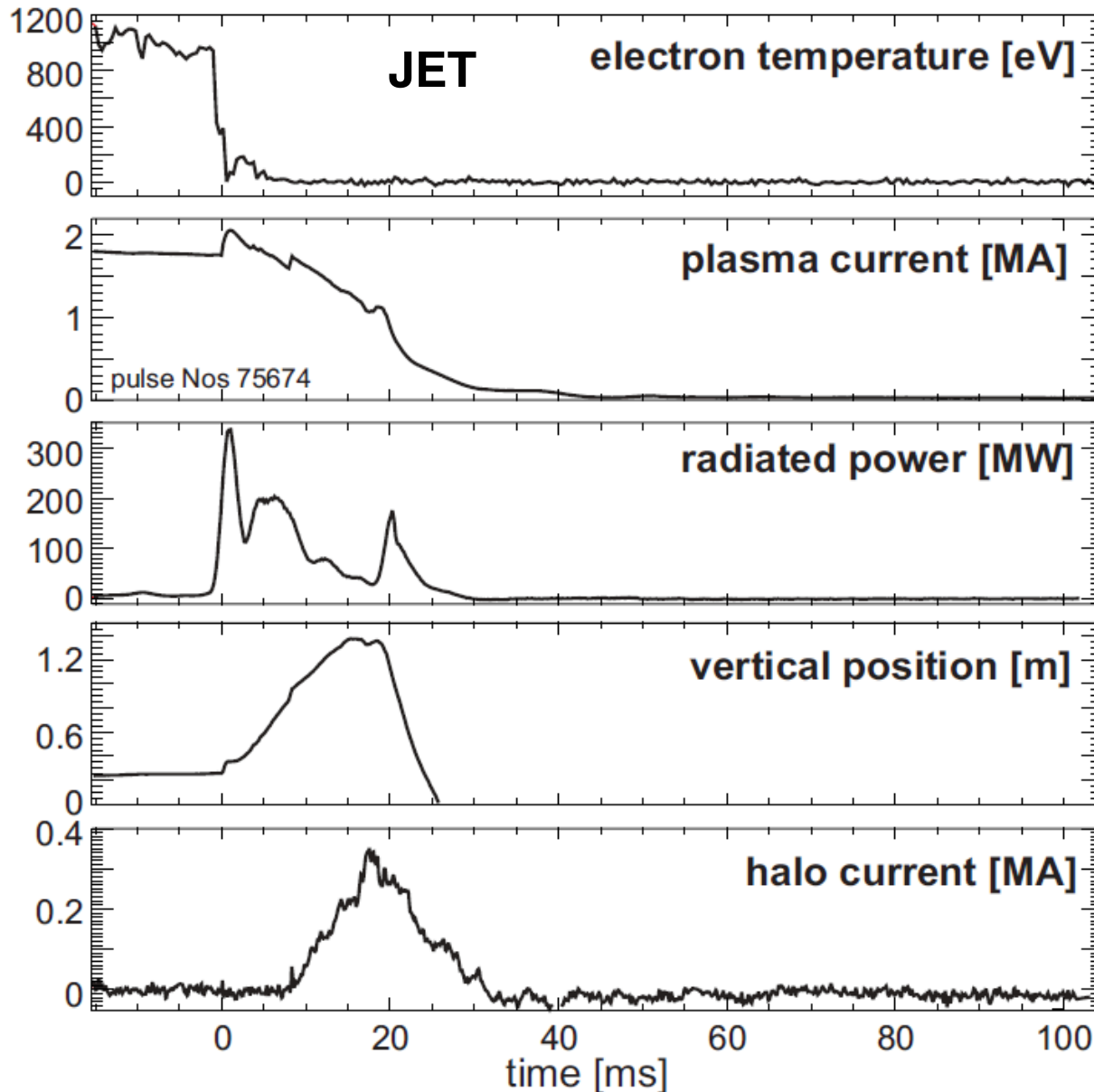
⇒ **no need for GDC or Be evaporation during operation**

AUG:

- facilitated start-up even without boronisation
- no need for GDC during normal operation



[de Vries, NF2013]



CFC wall

fast thermal quench

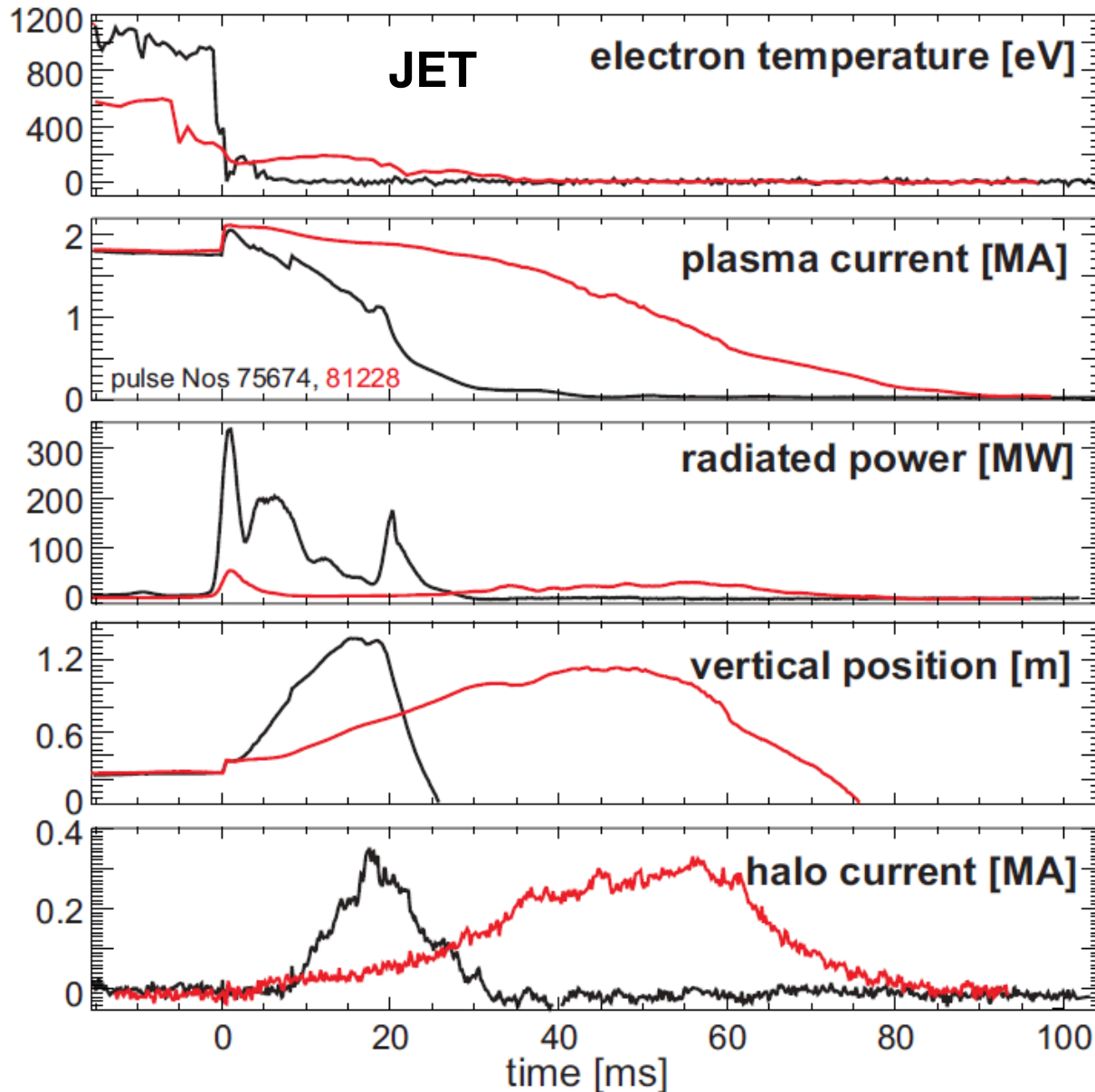
fast current decay

*high radiation
up to GW range*

vertical displacement

halo currents

[Lehnen, IAEA EX/9-1]



ITER-like wall

hot CQ plasma

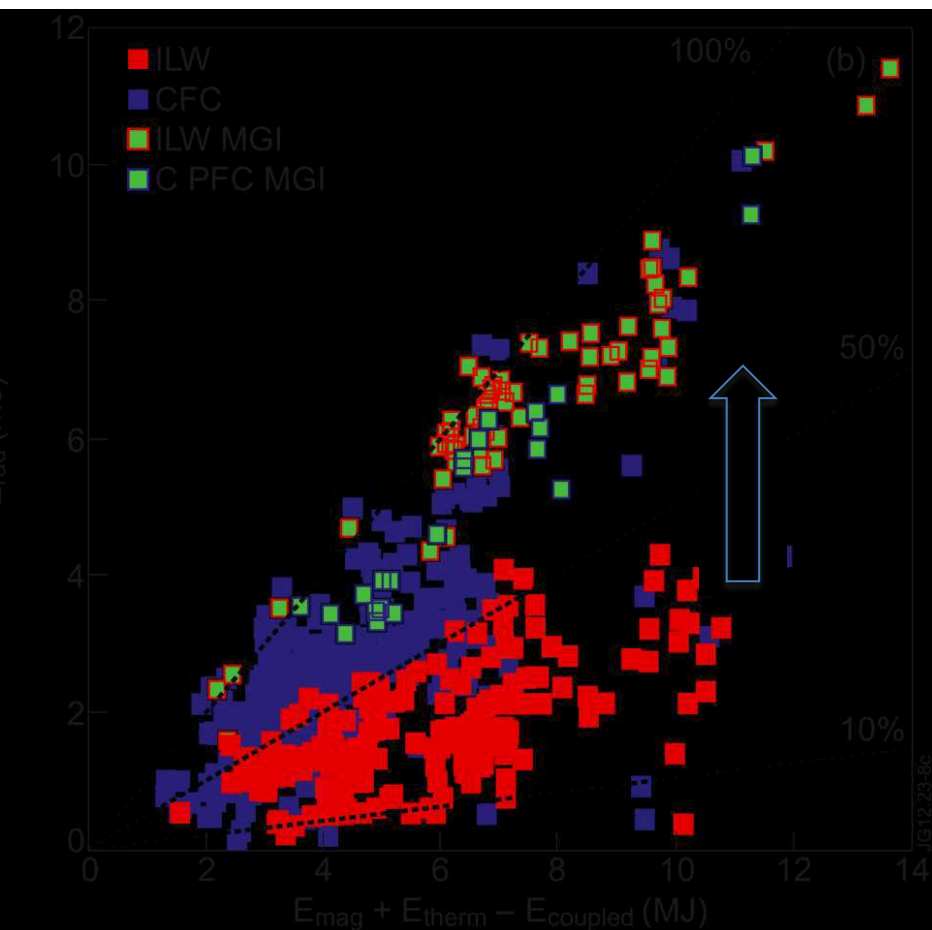
slow current decay

*low radiation
several 10MW only*

slower vertical displacement

longer halo current phase

[Lehnen, IAEA EX/9-1]



[Lehnen, IAEA EX/9-1]

JET-ILW

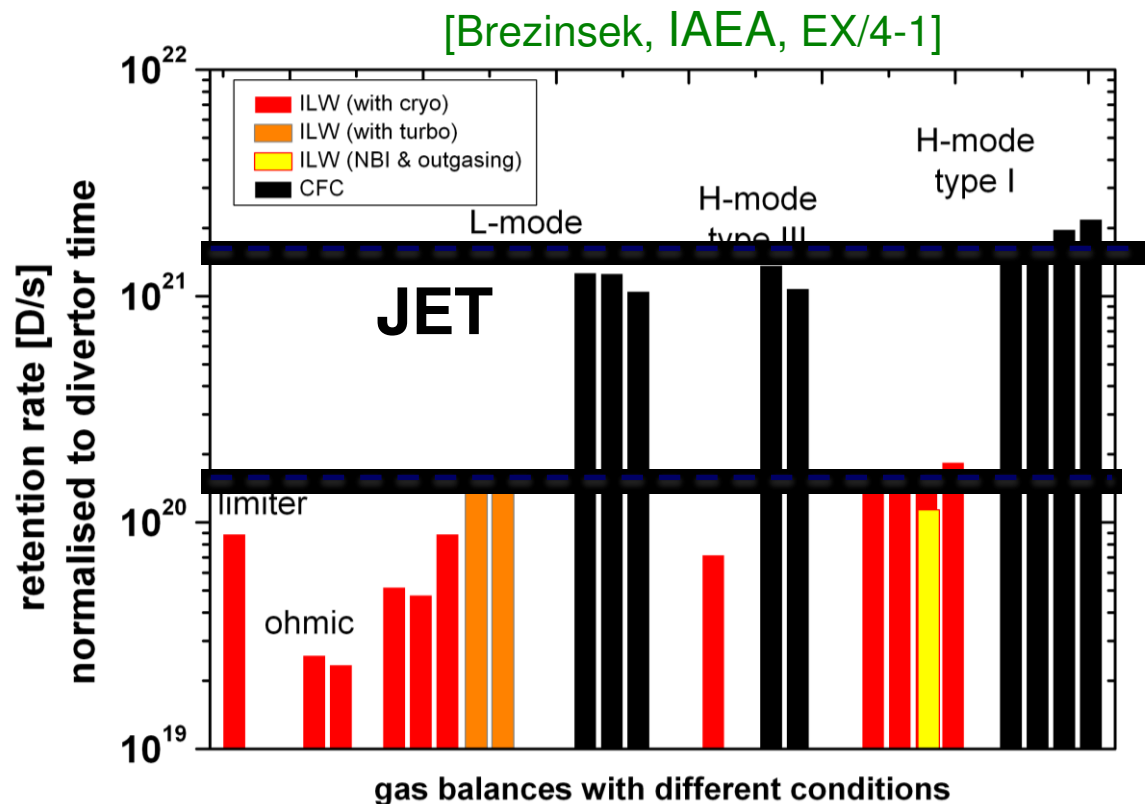
- massive gas injection (D_2+Ar) for disruption mitigation mandatory for $I_p \geq 2.5$ MA
- mitigated disruptions with ILW: forces and power loads are return to the level observed with C wall

AUG:

- similar behaviour but less pronounced
- disruption mitigation is standard procedure

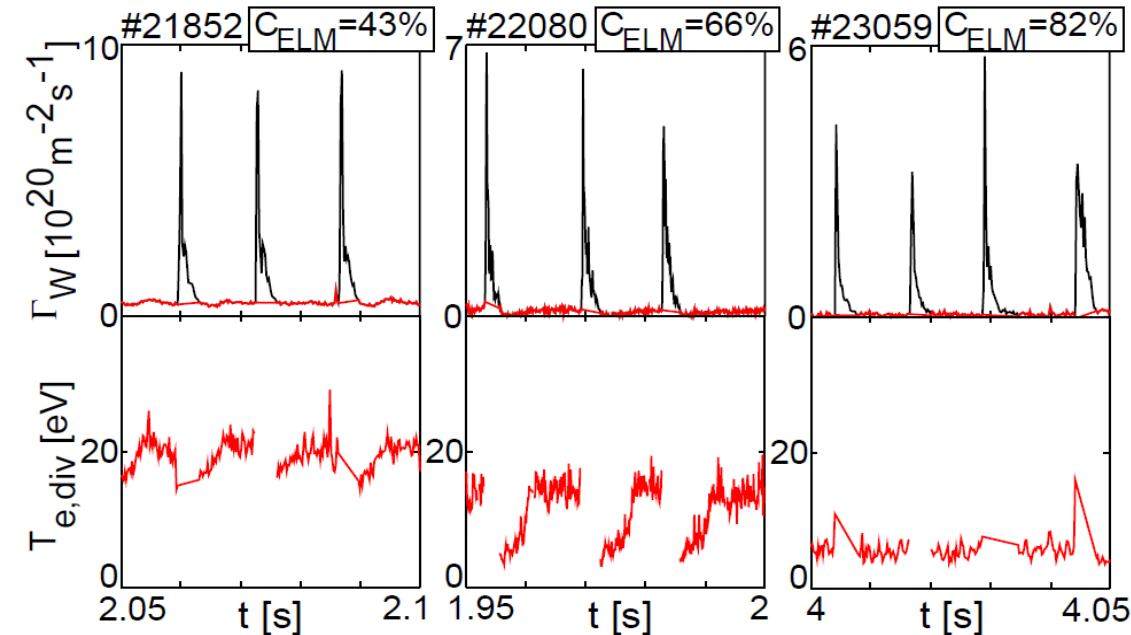
JET ILW

- global gas balances show **reduced retention (factor 10) in all scenarios**
 - co-deposition with Be should dominate
 - even larger reduction expected from “long term outgasing”
- ⇒ both qualitatively confirmed by first post mortem analysis



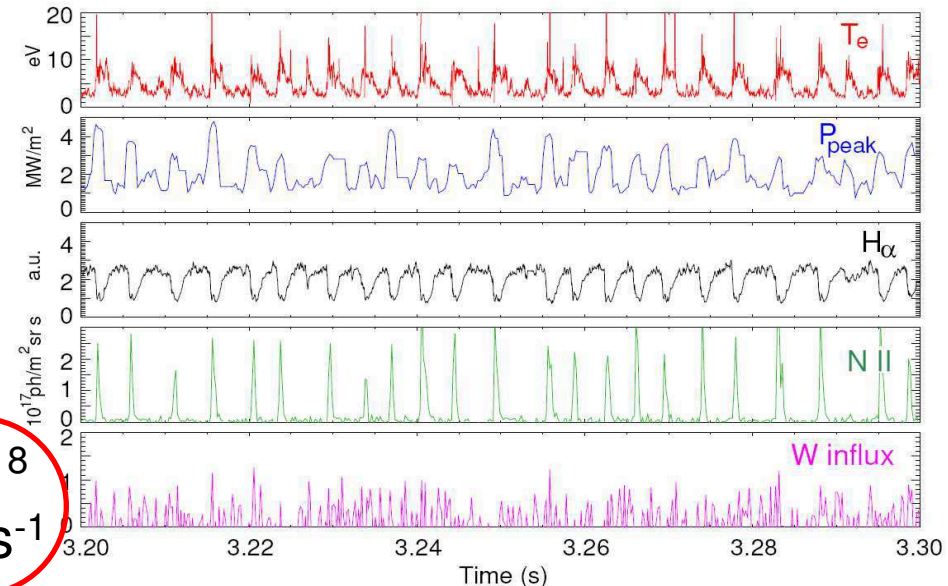
AUG

- reduction by factor 5-10, dominated by co-deposits with residual C and B
- H-retention in W bulk close to values from laboratory experiments
- retention in blisters low in technical W surfaces

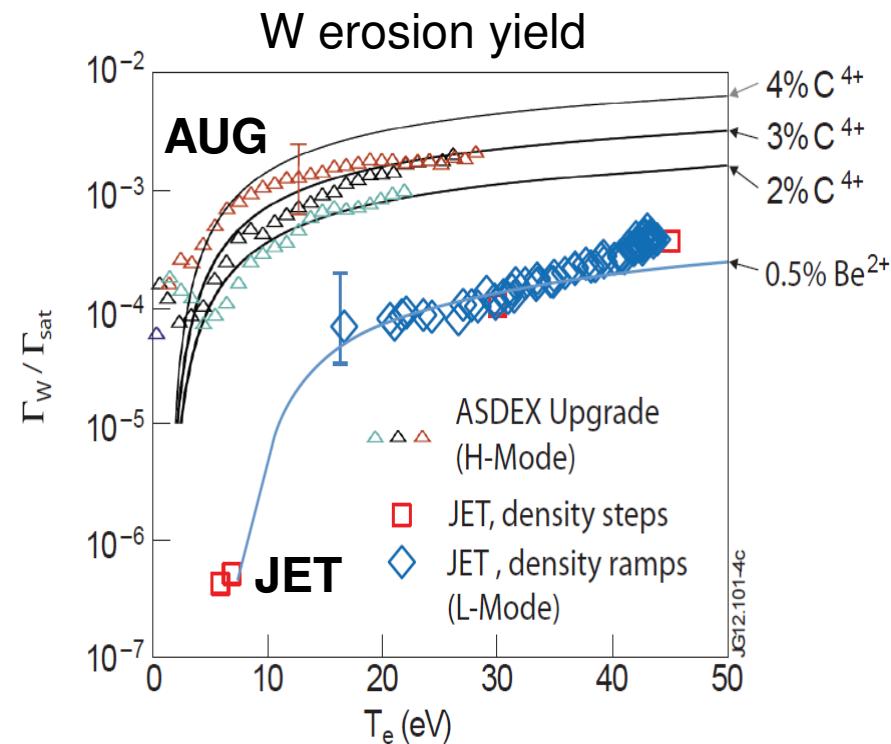


- W erosion in the AUG divertor strongly depends on plasma temperature
- ELMs can dominate total erosion
[R. Dux, JNM 2009]

- vanishes for $T_e < 5$ eV (Type III ELMs)
- much larger as in pure D plasmas

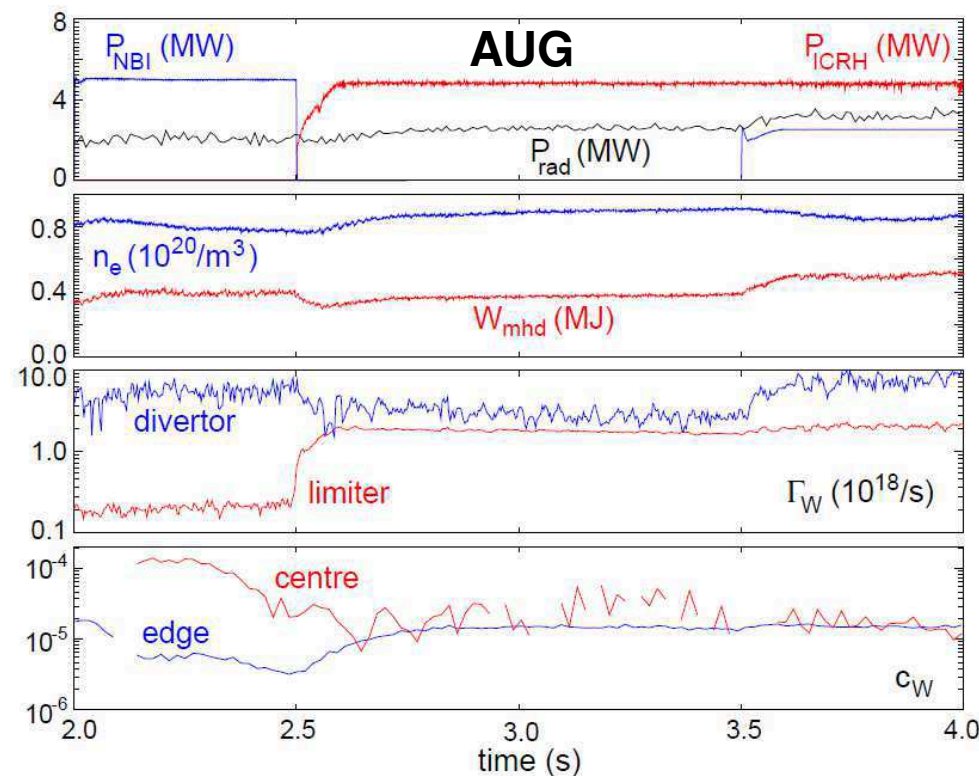


$10^{18} m^{-2} s^{-1}$



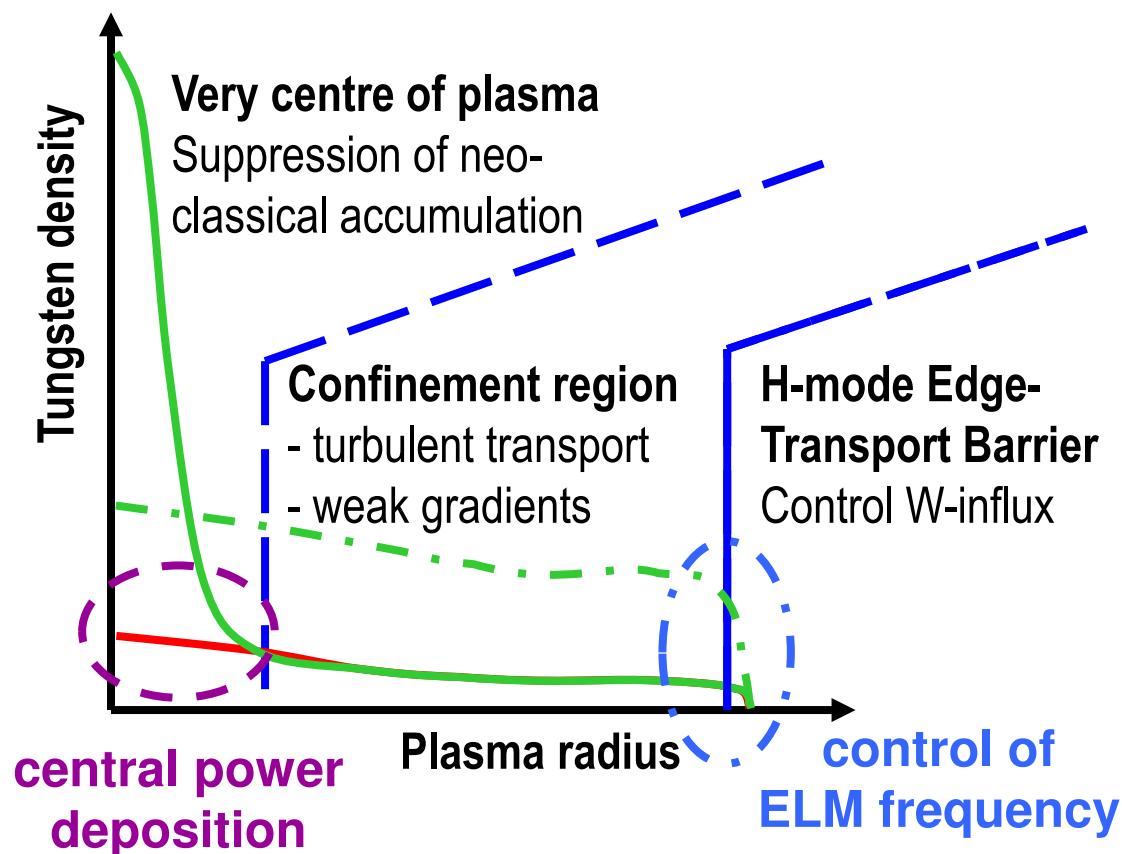
[G.v.Rooij, IAEA 2012, EX/P5-5]

W yield consistent with physical sputtering through low-Z impurities

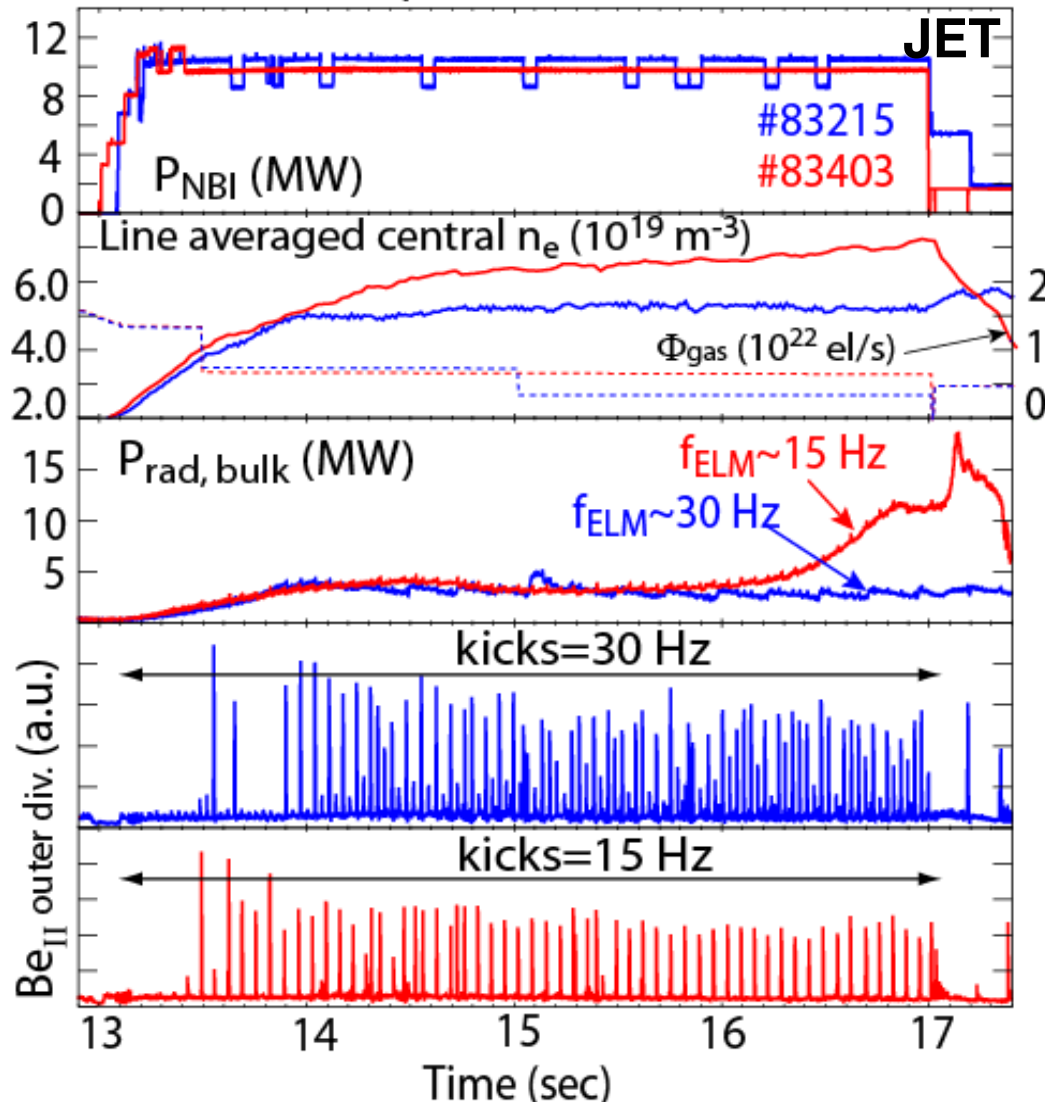


- ICRH strongly increases W influxes
 - AUG: mostly limiter source
 - JET: unidentified main chamber source
- increased W sputtering by rectified sheath

- central deposition of heating power suppresses W peaking
- NBI only heated discharges usually show peaked W profile
- ICRH & ECRH mitigate central accumulation (critical power density needed)
- additional W-influx during ICRH may outweigh beneficial effect on central transport
- pellet ELM pace-making helps to keep edge c_W low



2.0 MA / 2.2 T ($q_{95}=3.6$), $\delta_{av}\sim 0.38$, $f_{GW}=0.7-0.85$



[de la Luna, IAEA EX/6-1]

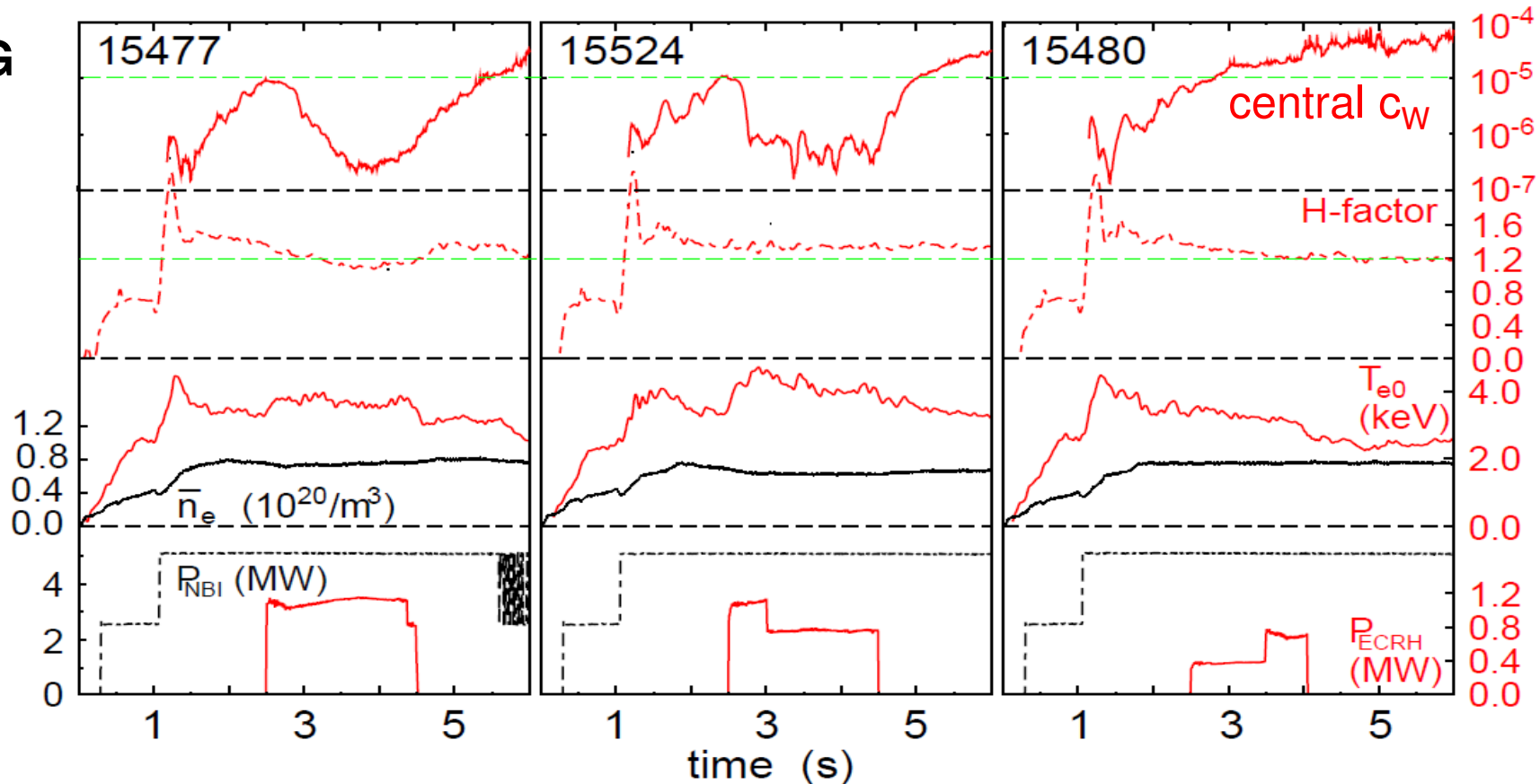
JET-ILW

- **Vertical kicks:** increase in f_{ELM} reduces W accumulation in gas fuelled H-mode plasmas
- **Pellets:** ELM frequency increased by factor 4.5 stabilises W content

AUG

- **Pellets ELM pace-making** successfully flushes W
- ELM mitigation by **magnetic perturbation** compatible with W suppression

AUG



- tailoring of ECRH results in **strong reduction of peaking of c_W** and moderate confinement degradation
- **threshold for mitigation of peaking** seems to depend on central radiation (transport reacts on local power balance?)

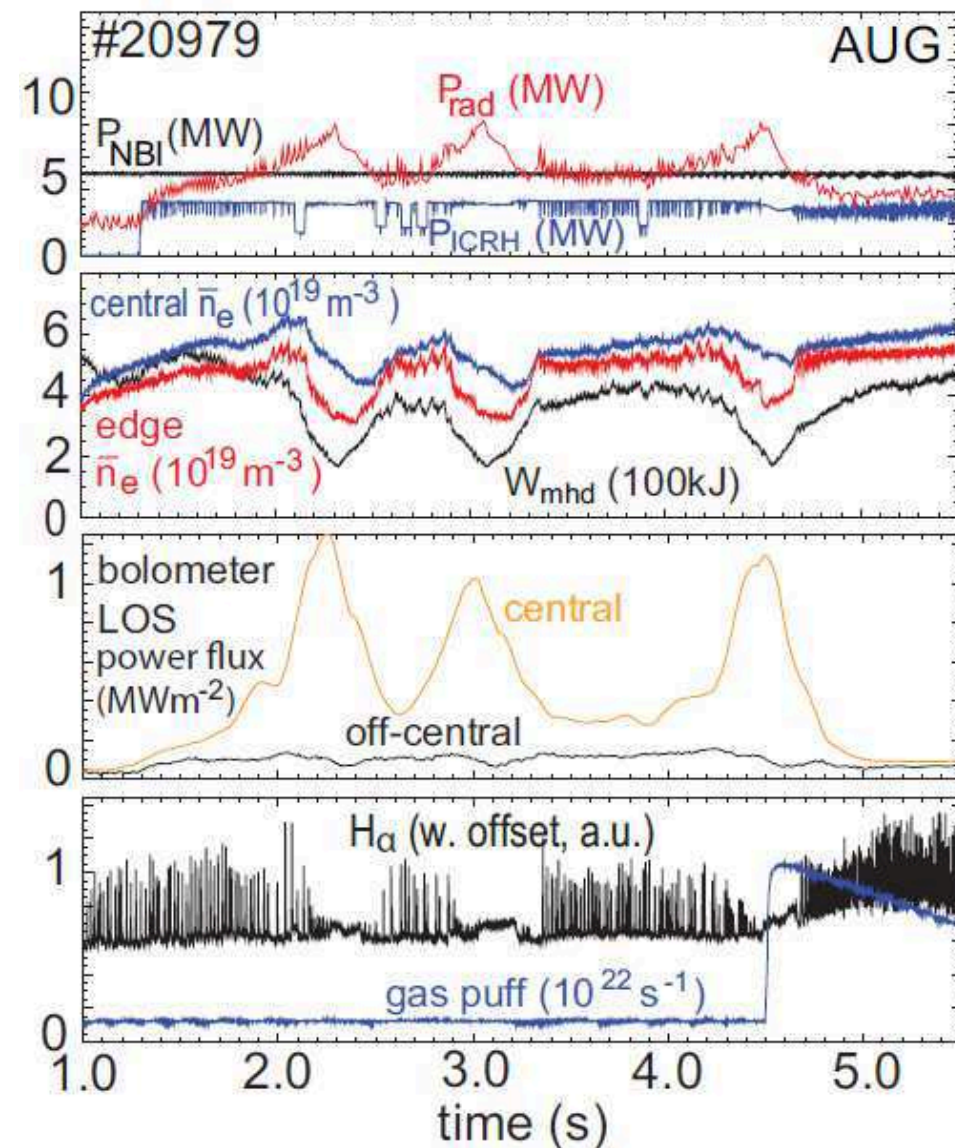
too large W influx and/or
too low central transport
can cause W accumulation

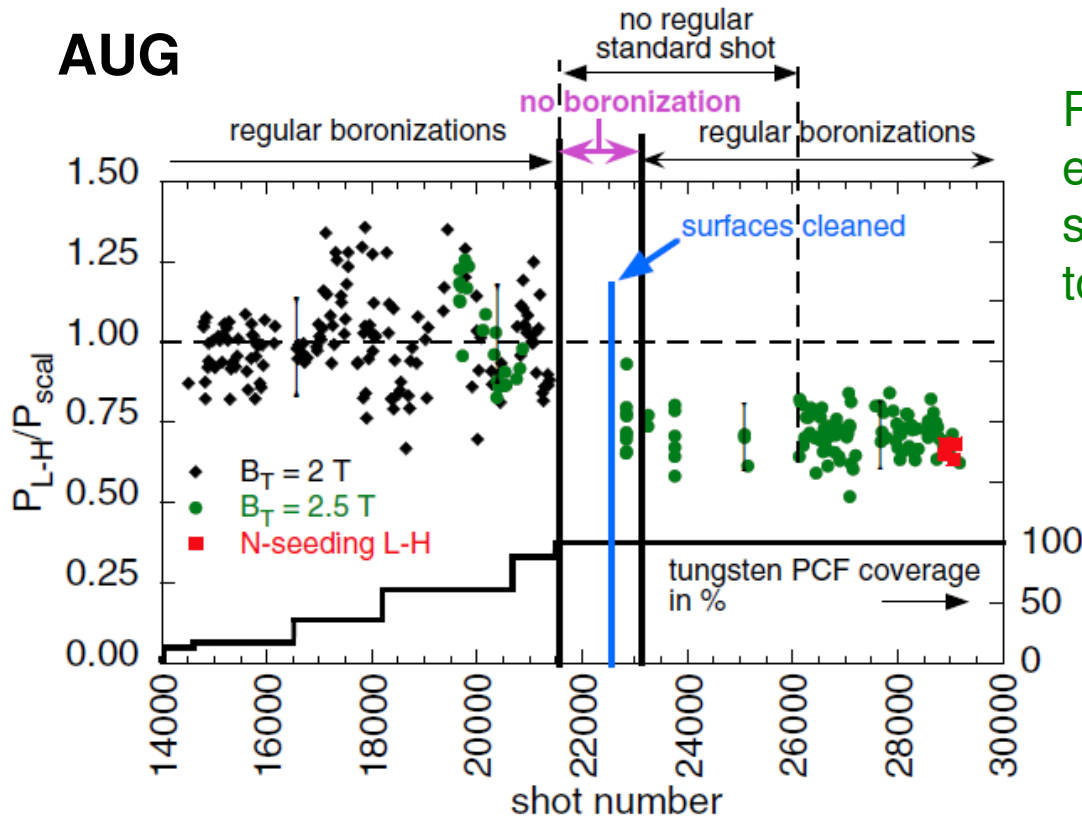
⇒ large central radiation
⇒ back transition to L-Mode

⇒ expulsion of W

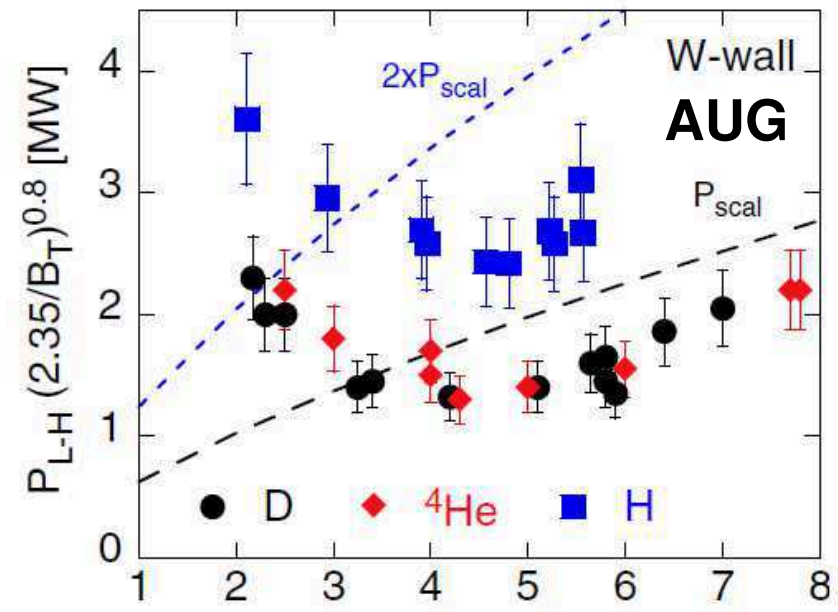
⇒ no disruption if heating
is maintained

discharge can recover completely
if W influx is reduced



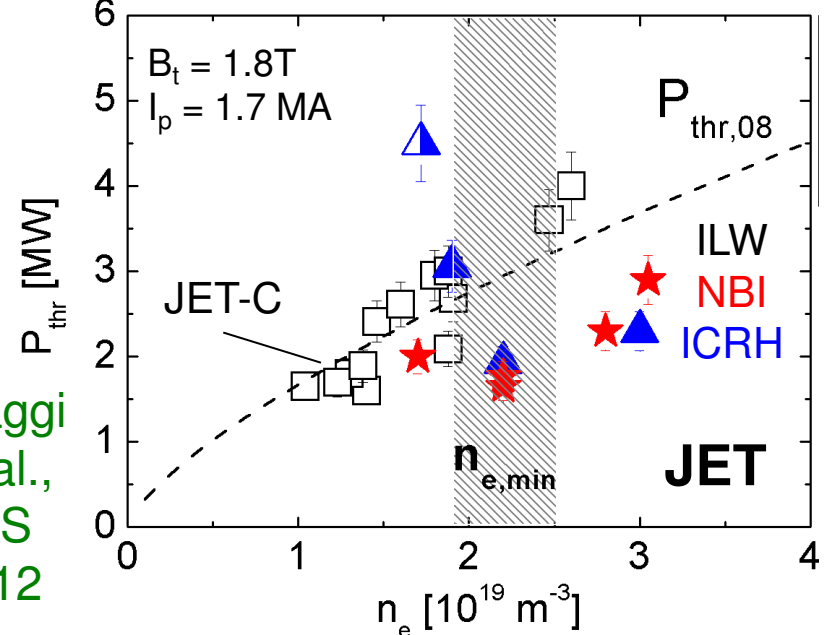


Ryter et al.,
 subm.
 to NF

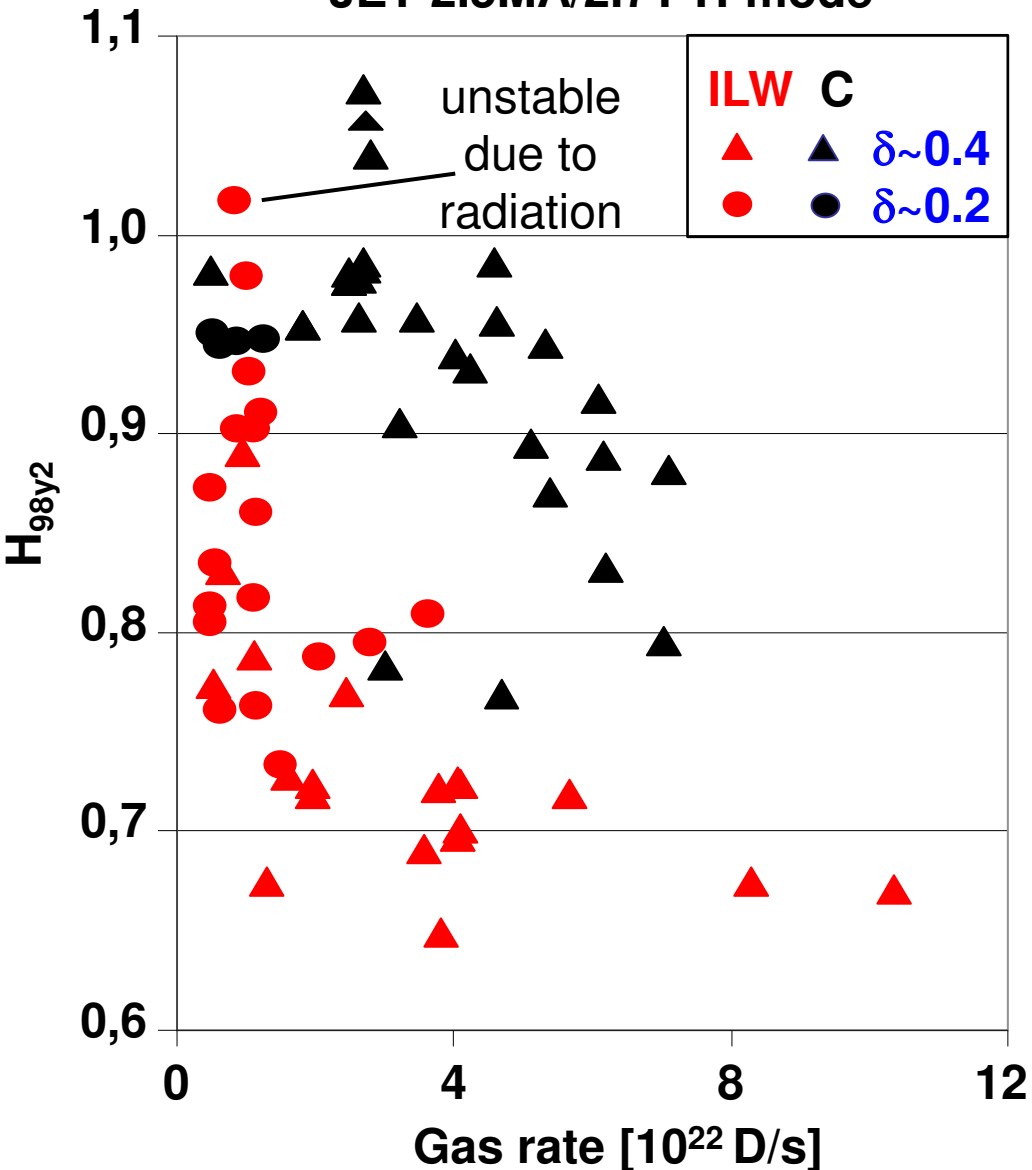


C dominated AUG/JET: $P_{th}/P_{scal08} \approx 1$,
 AUG with full W PFCs: $P_{th}/P_{scal08} \approx 0.75$
 JET ILW: $P_{th}/P_{scal08} \approx 0.70$

Maggi et al.,
 EPS
 2012



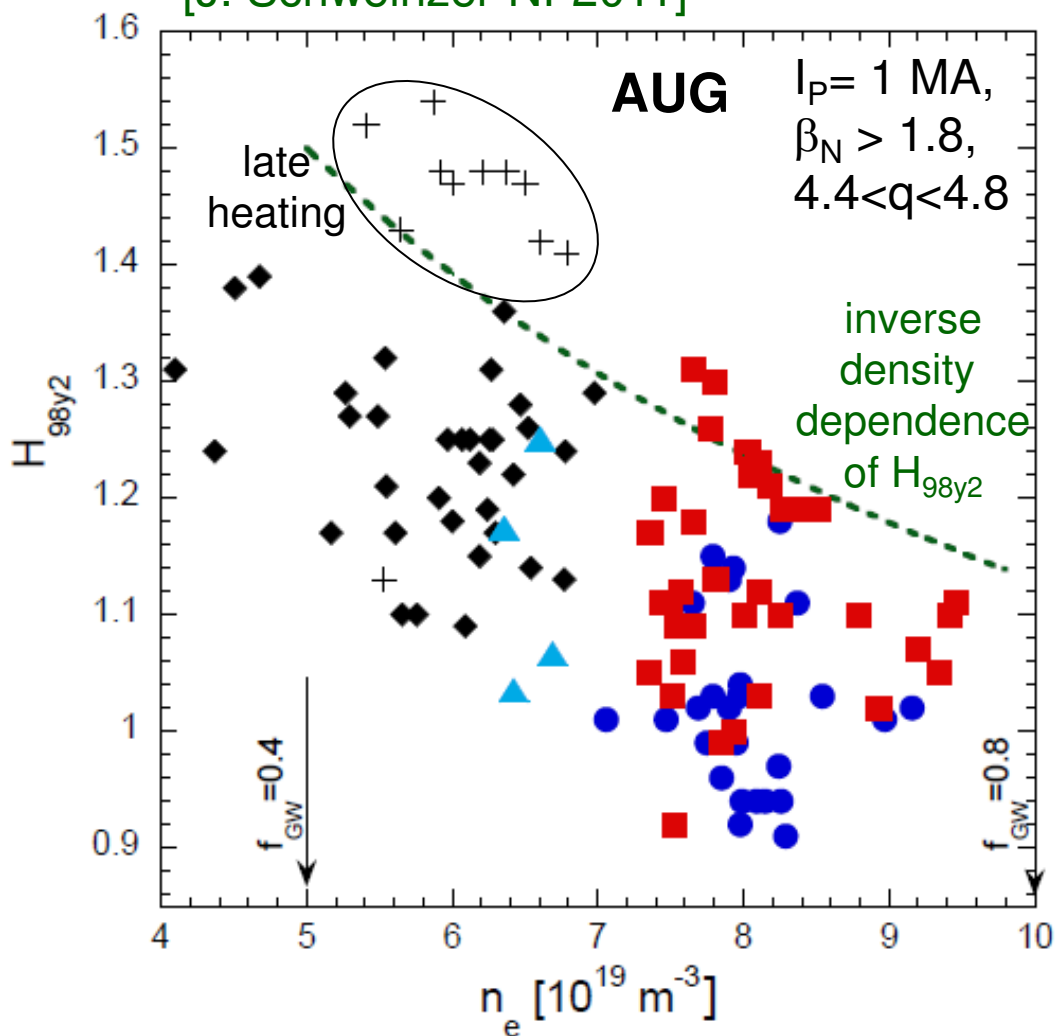
JET 2.5MA/2.7T H-mode



- ELMy H-mode achieved at **low and high δ** with up to 26 MW of injected power ($I_p \leq 3.5$ MA)
- **Confinement is lower** than with the carbon wall under similar conditions: I_p , B_t , shape (high δ), fuelling
- But at high input power $P_{net}/P_{thr} > 2$ confinement can be recovered

[Joffrin, IAEA, EX/1-1]

[J. Schweinzer NF2011]



black C dominated AUG
(light) blue all W AUG
red all W AUG & N-seeding

AUG

- Considerable improvement of confinement (with N_2 and CH_4 seeding)
- mainly at high β_N discharges

JET

- edge transport barrier almost re-established by N_2 radiative cooling

but

- not observed in low δ ,
- plasmas still prone to W accumulation

AUG and JET show very similar results concerning plasma operation and W behavior

- **facilitated conditioning** \Rightarrow highly beneficial during (ITER) operation
- **low C and O content** \Rightarrow high plasma purity (low Z_{eff} - Be plays major role in JET)
- **large reduction of D retention** \Rightarrow consistent with extrapolations to ITER
- significantly **lower L-H threshold** \Rightarrow easier H-Mode access

But also

- strongly **reduced radiation during disruptions** \Rightarrow mitigation necessary/relevant
- **efficient ICRH but increased W influx** \Rightarrow important for antenna optimisation
- **reduced operational space** (no zero gas-puff!) \Rightarrow focus on ITER relevant operation schemes
- observation of **W accumulation** \Rightarrow confirmation/development of counter measures
- **lower pedestal confinement (in JET)** \Rightarrow no effect of W radiation!
 \leftrightarrow new physics insights (correlation with edge radiation/dilution?)