Tungsten Experiences in ASDEX Upgrade and JET

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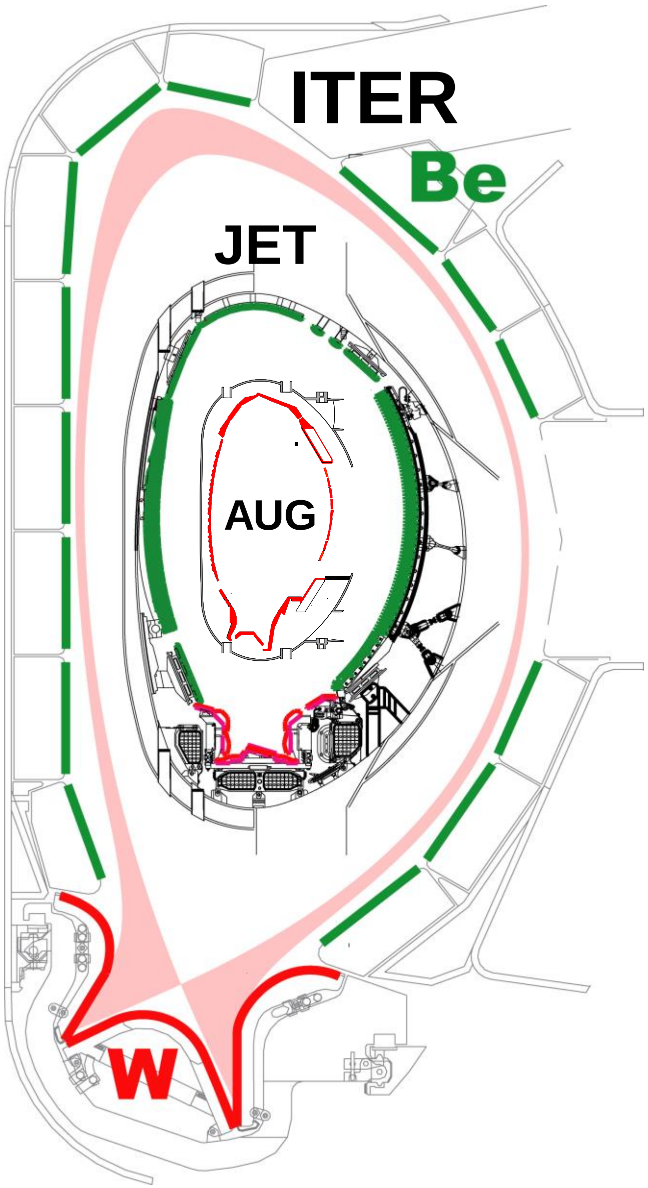
Metal Walls in Support of ITER and DEMO



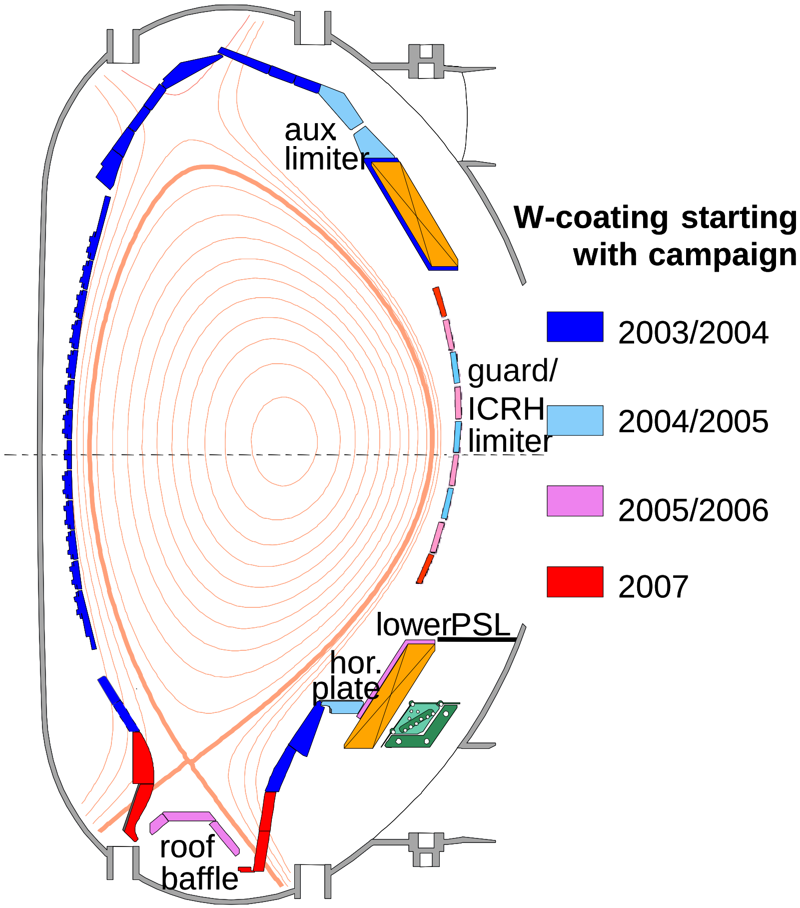
AUG & JET: All Metal PFCs

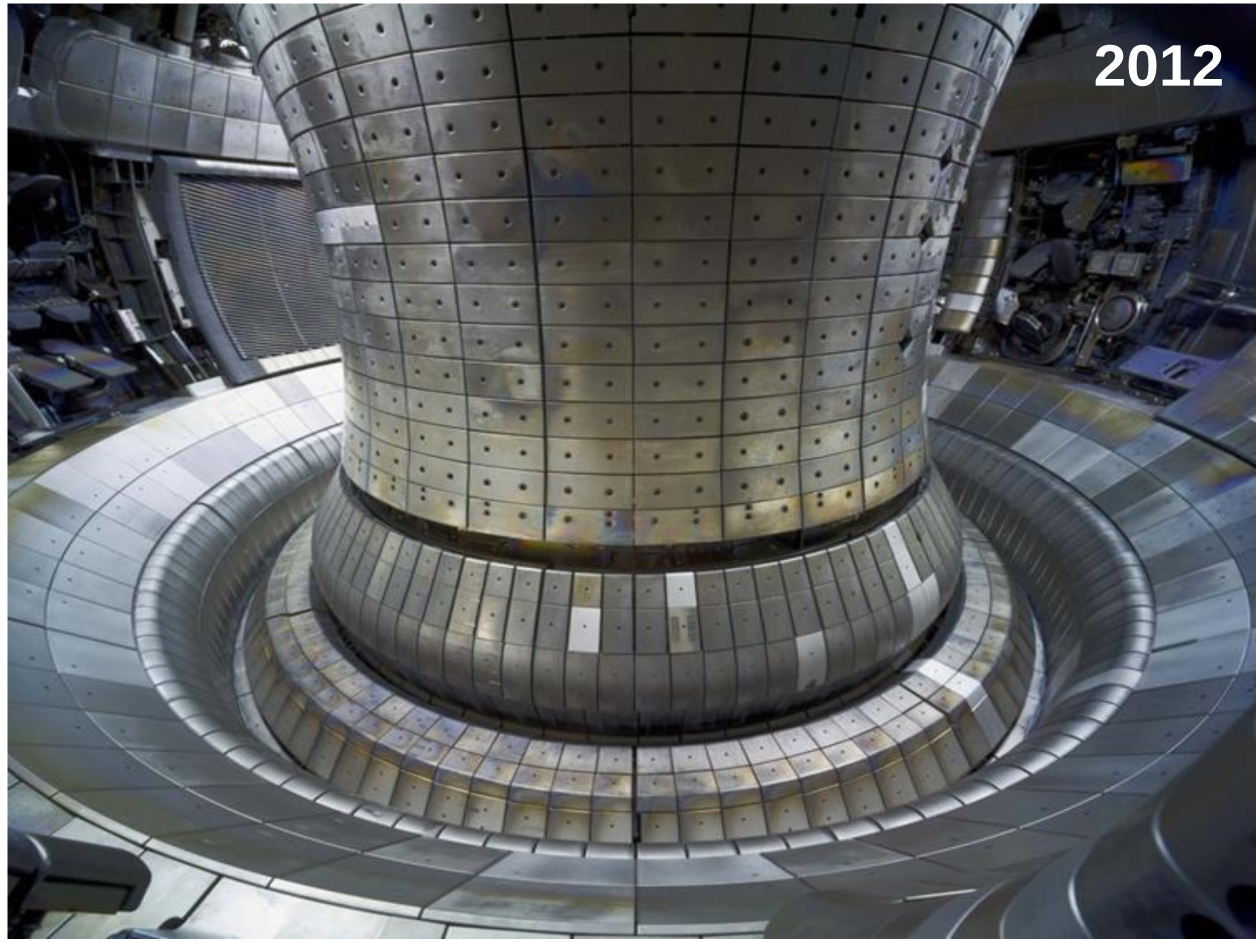
- Demonstrate low fuel retention, migration and possible fuel recovery
- Demonstrate plasma compatibility with metallic walls
- Develop tools for improved plasma control and heat load mitigation
- Provide input to the decision on the first ITER divertor (and DEMO main chamber)

Outline

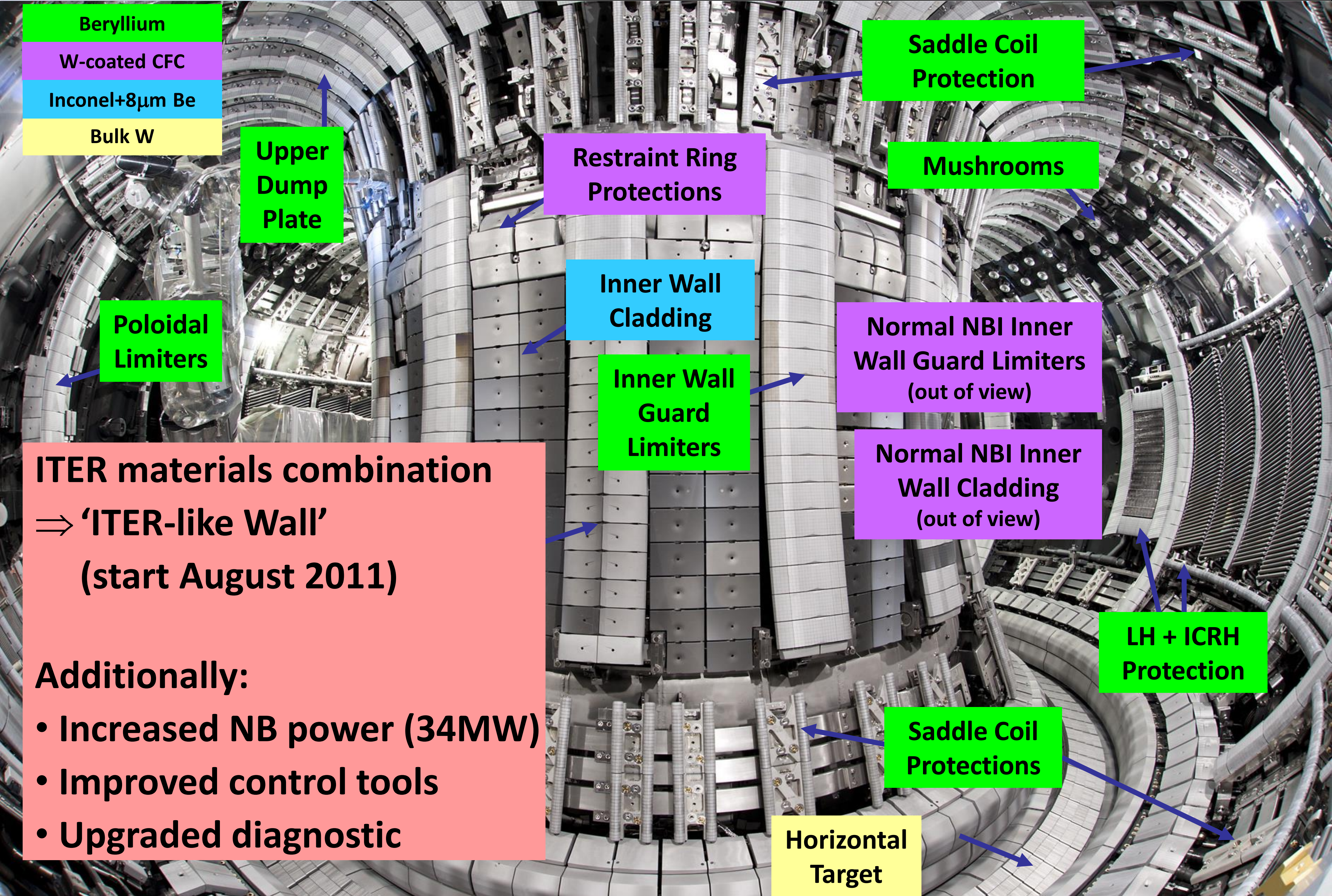
- All Metal Walls in AUG and JET
- Operational Experience
  - Plasma Breakdown
  - Disruptions
  - Fuel Retention
- W Behaviour and H-Mode Properties
  - W Sources
  - W Transport
  - LH-Threshold
  - Confinement Properties
  - Impurity Seeding
- Conclusions

Full W ASDEX Upgrade





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



ITER materials combination

⇒ ‘ITER-like Wall’

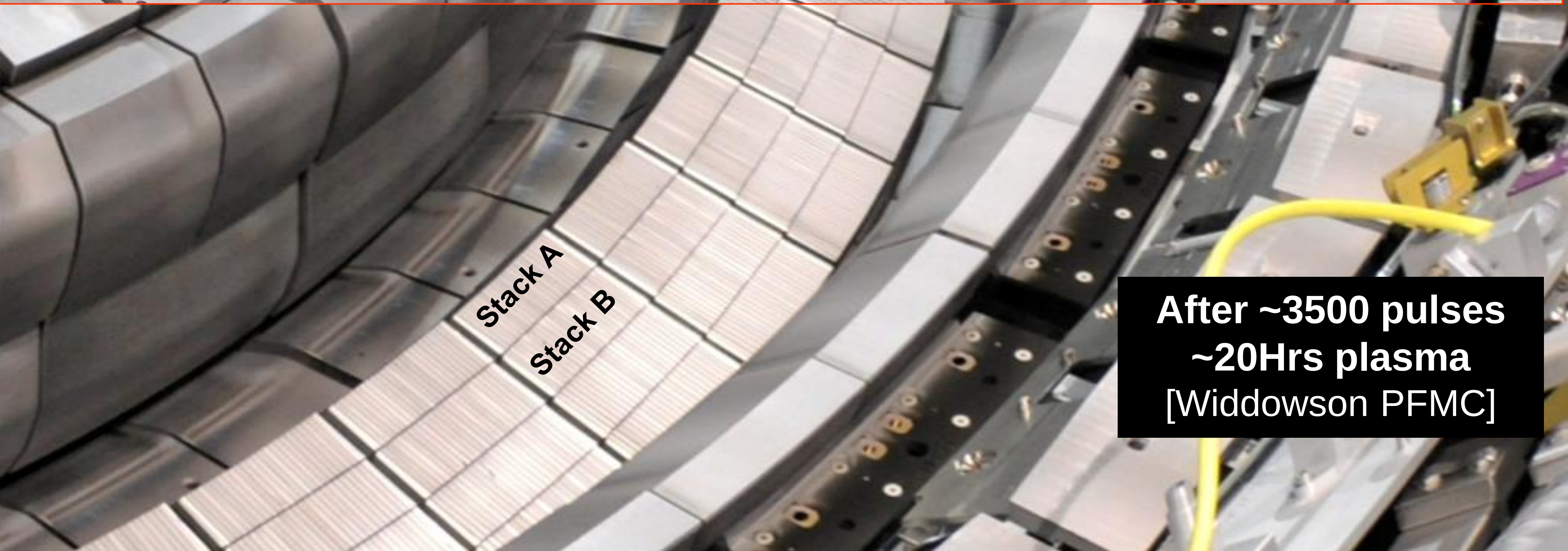
(start August 2011)

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



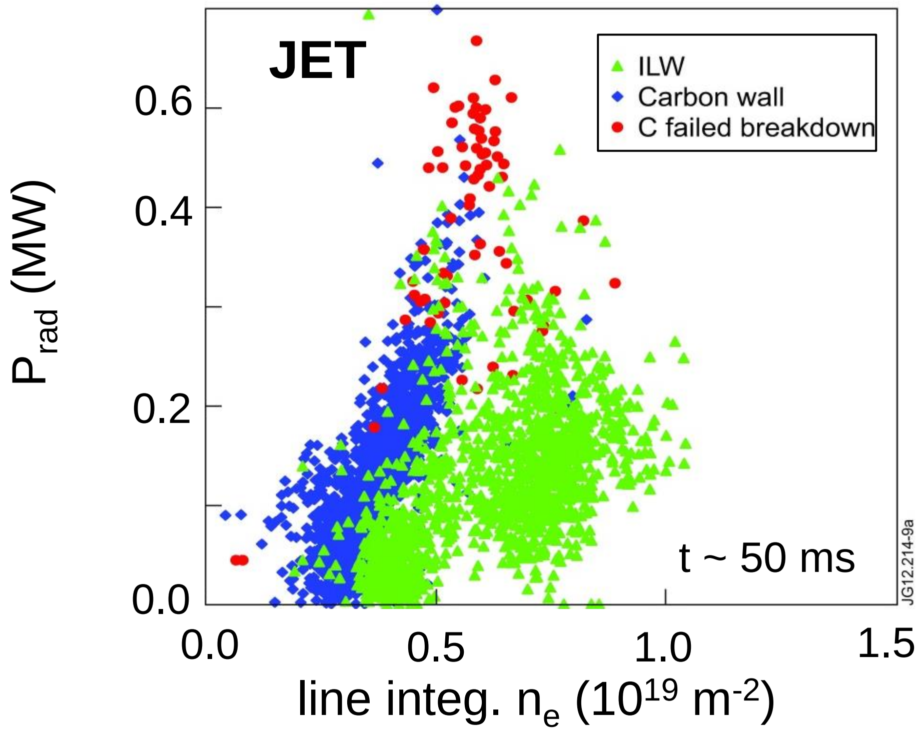
Metal PFCs allow more robust plasma breakdown

JET ILW

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

- **lower radiation level** at higher density (except after N_2 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**

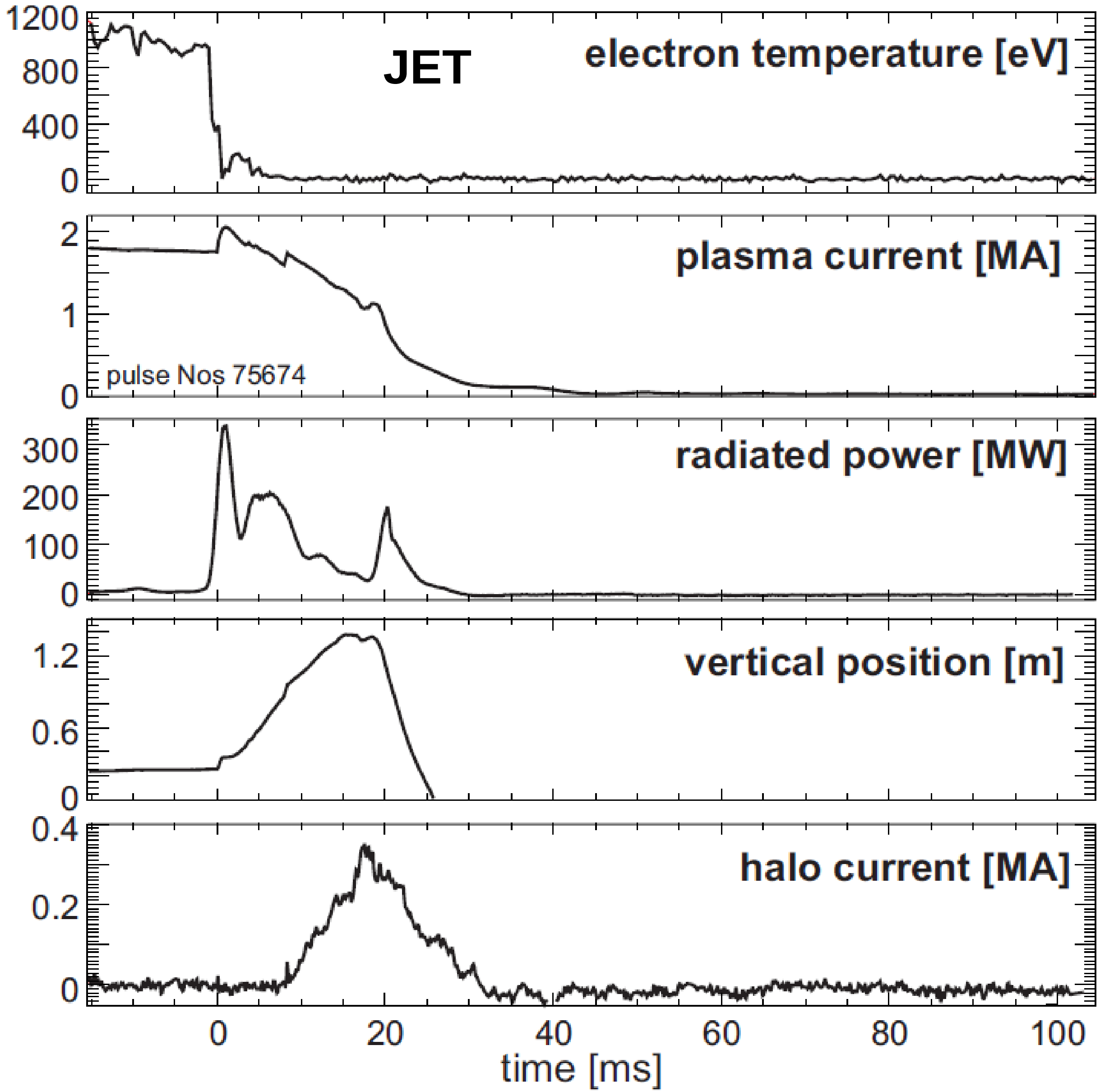


[de Vries, NF2013]

AUG:

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

Disruption Dynamics Completely Changed



CFC wall

fast thermal quench

fast current decay

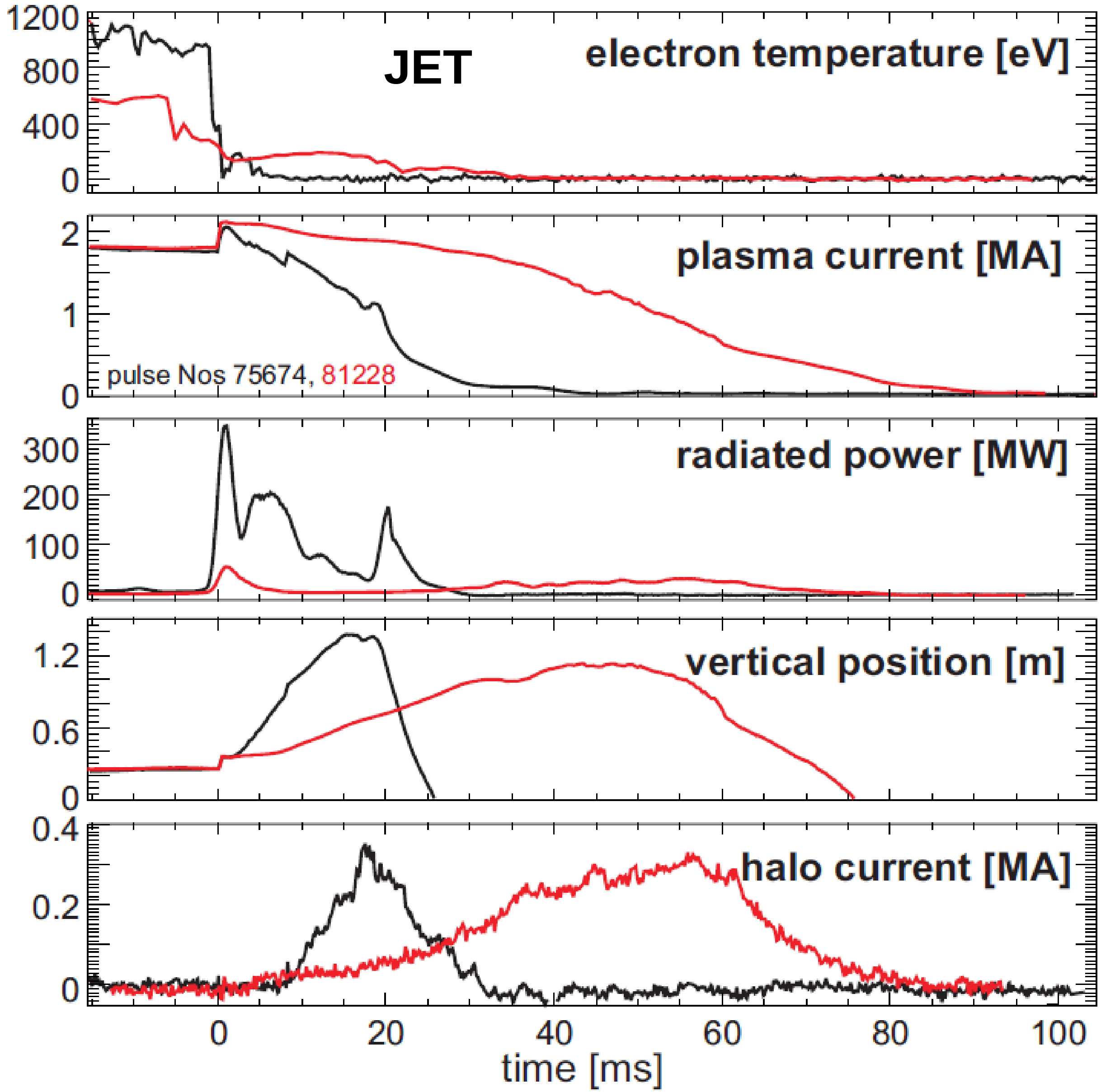
high radiation up to GW range

vertical displacement

halo currents

[Lehnen, IAEA EX/9-1]

Disruption Dynamics Completely Changed



<u>**ITER-like wall**</u>

hot CQ plasma

slow current decay

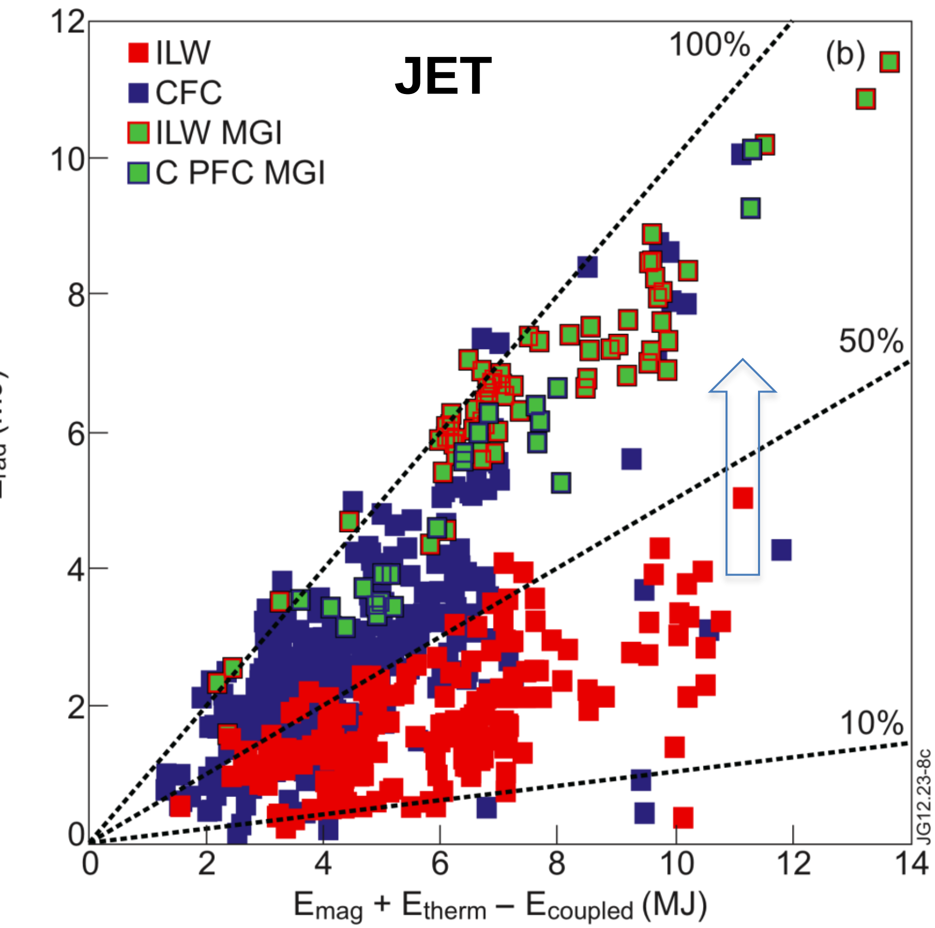
low radiation several 10MW only

slower vertical displacement

longer halo current phase

[Lehnen, IAEA EX/9-1]

Massive Gas Injection Required to Mitigate Disruptions



[Lehnen, IAEA EX/9-1]

JET-ILW

- massive gas injection (D_2+Ar) for disruption mitigation mandatory for Ip ≥ 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

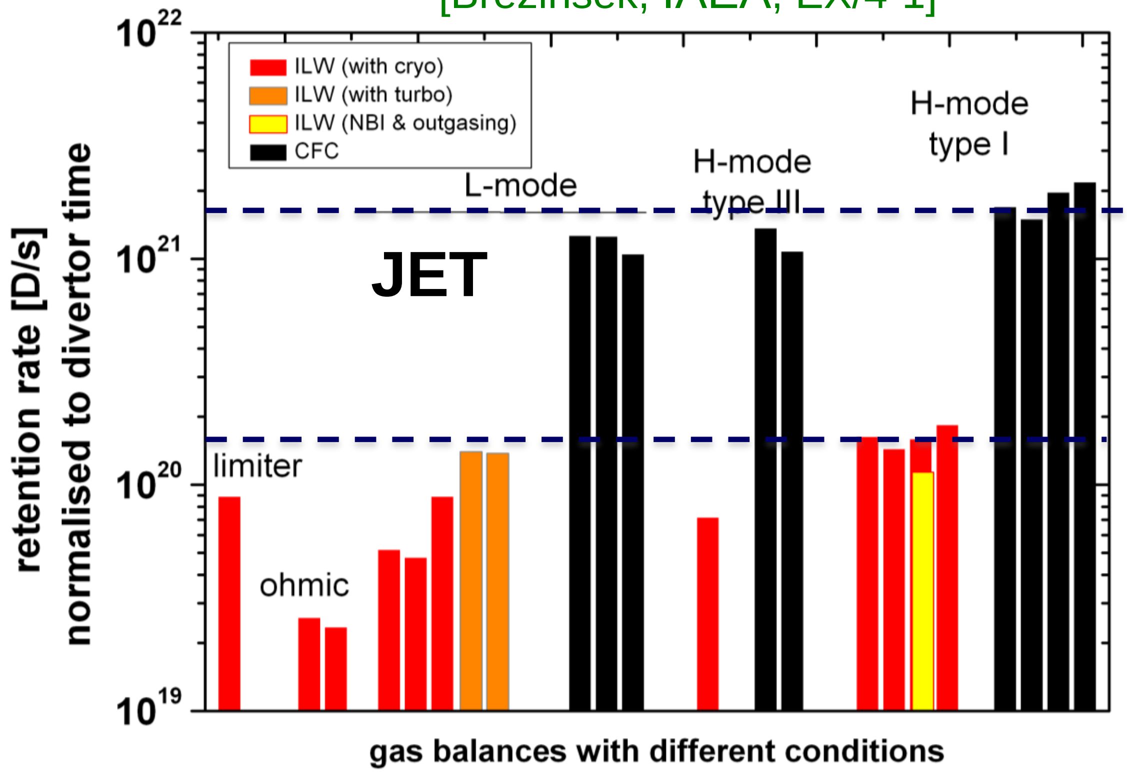
Fuel Retention in Line With ITER Requirements

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

[Brezinsek, IAEA, EX/4-1]



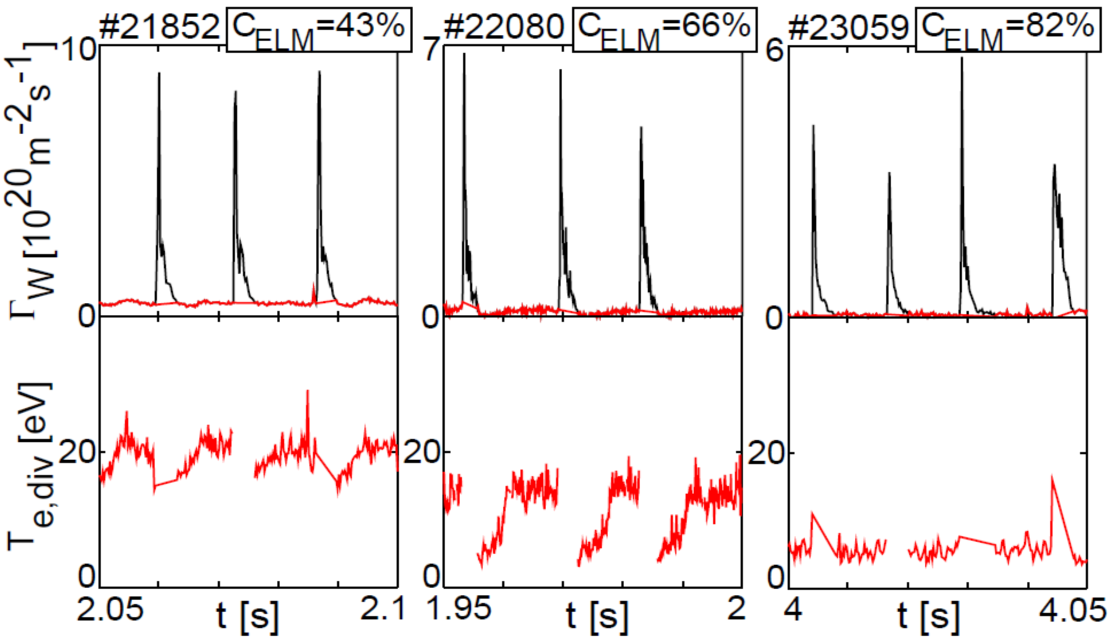
AUG

- 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 Sputter Yields

ASDEX Upgrade

IPP

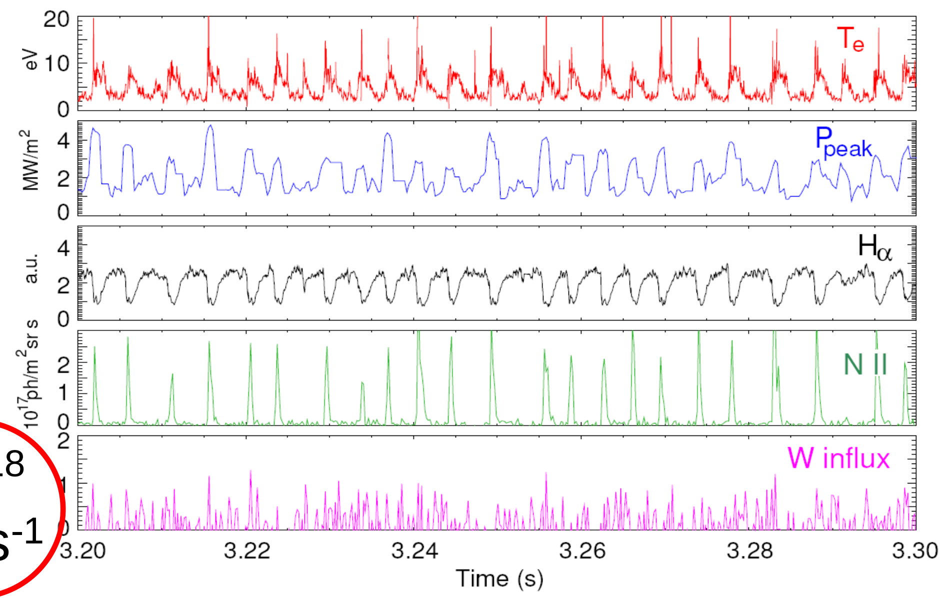


- W erosion in the AUG divertor strongly depends on plasma temperature
- ELMs can dominate total erosion

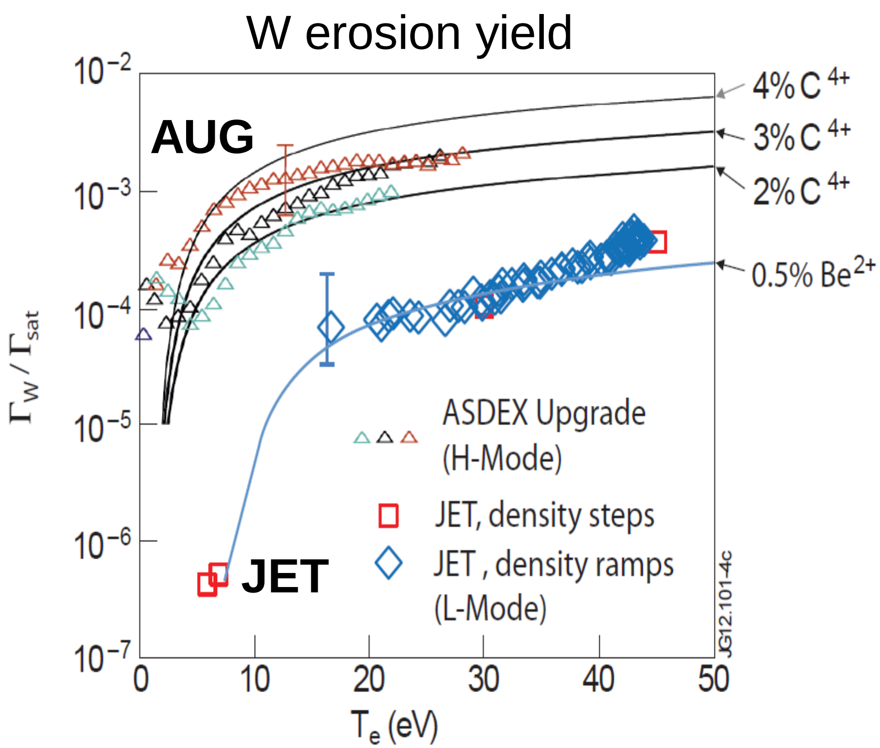
[R. Dux, JNM 2009]

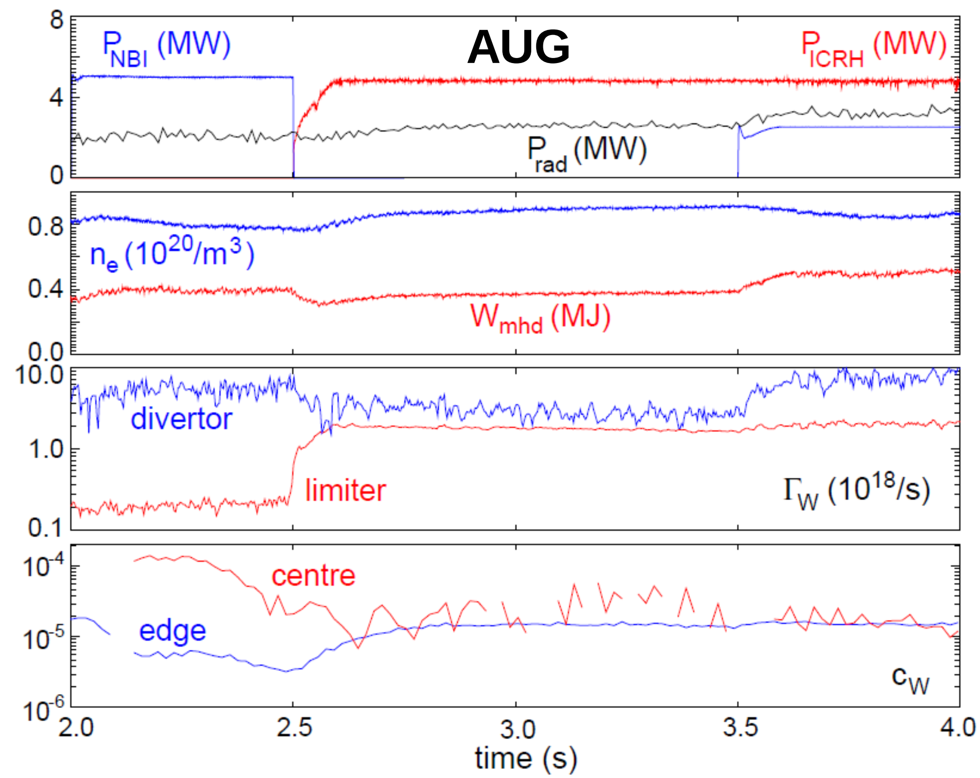
- vanishes for Te < 5 eV (Type III ELMs)
- much larger as in pure D plasmas

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



W sources





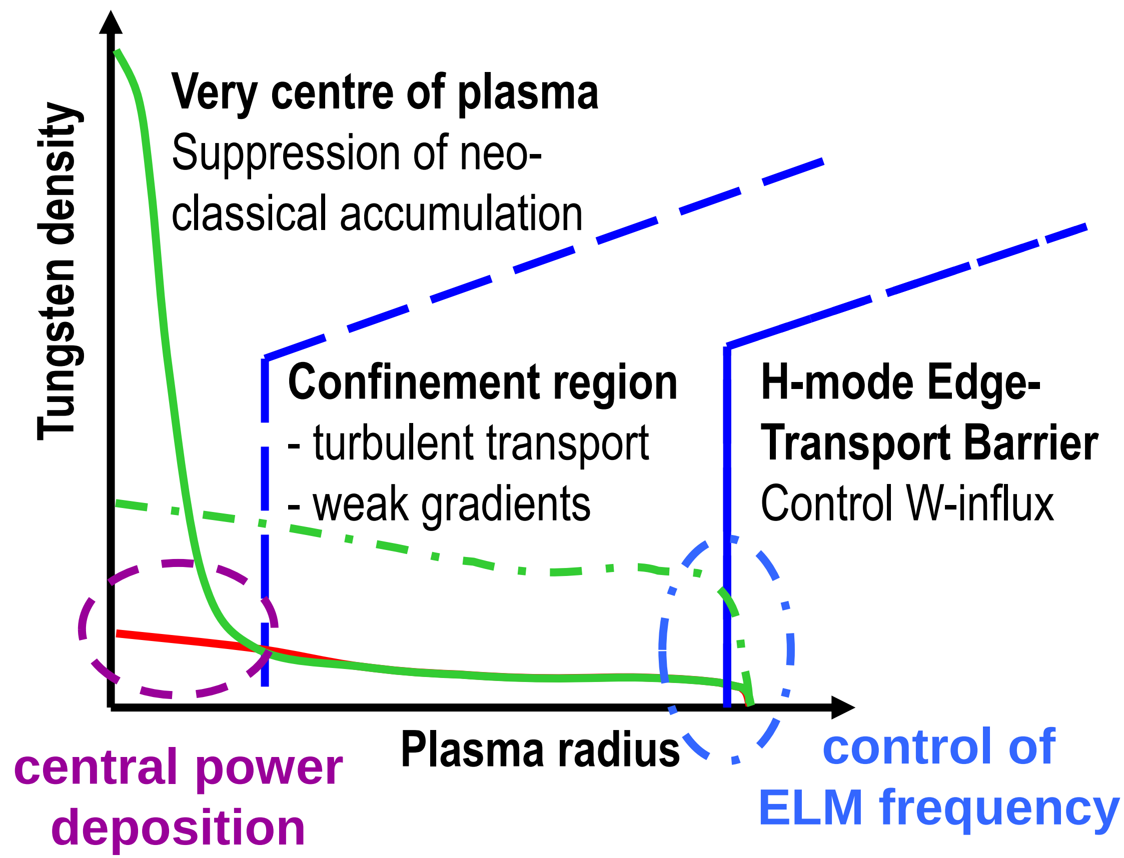
[G.v.Rooij, IAEA 2012, EX/P5-5]

W yield consistent with physical sputtering through low-Z impurities

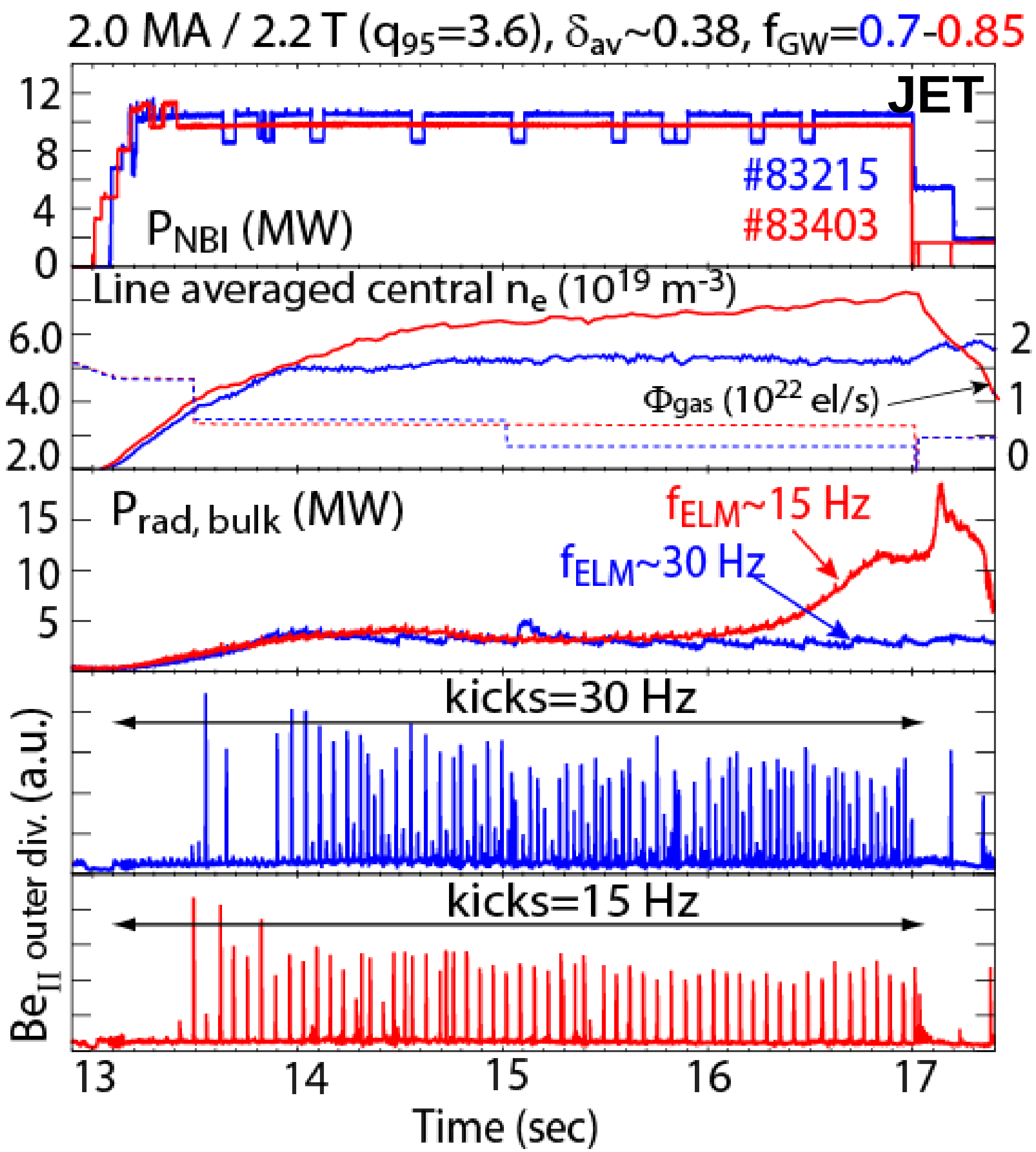
- ICRH strongly increases W influxes
  - AUG: mostly limiter source
  - JET: unidentified main chamber source
- increased W sputtering by rectified sheath

Control of W transport

- 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



ELM Pacing for W Flushing



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

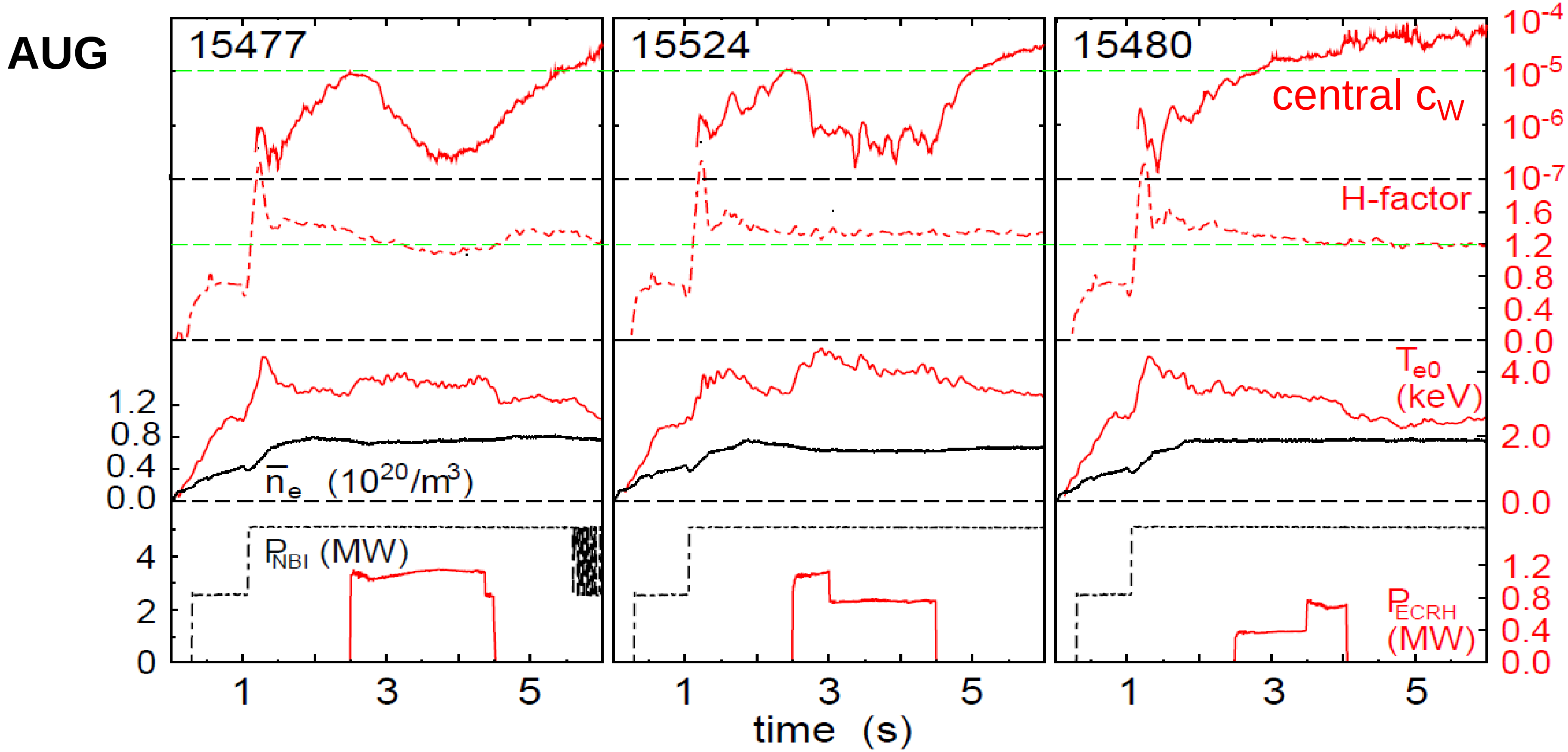
JET-ILW

- **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

Efficient suppression of W accumulation by central heating



- 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?)

Non-disruptive H-L cycle due to central radiation

too large W influx and/or

too low central transport

can cause W accumulation

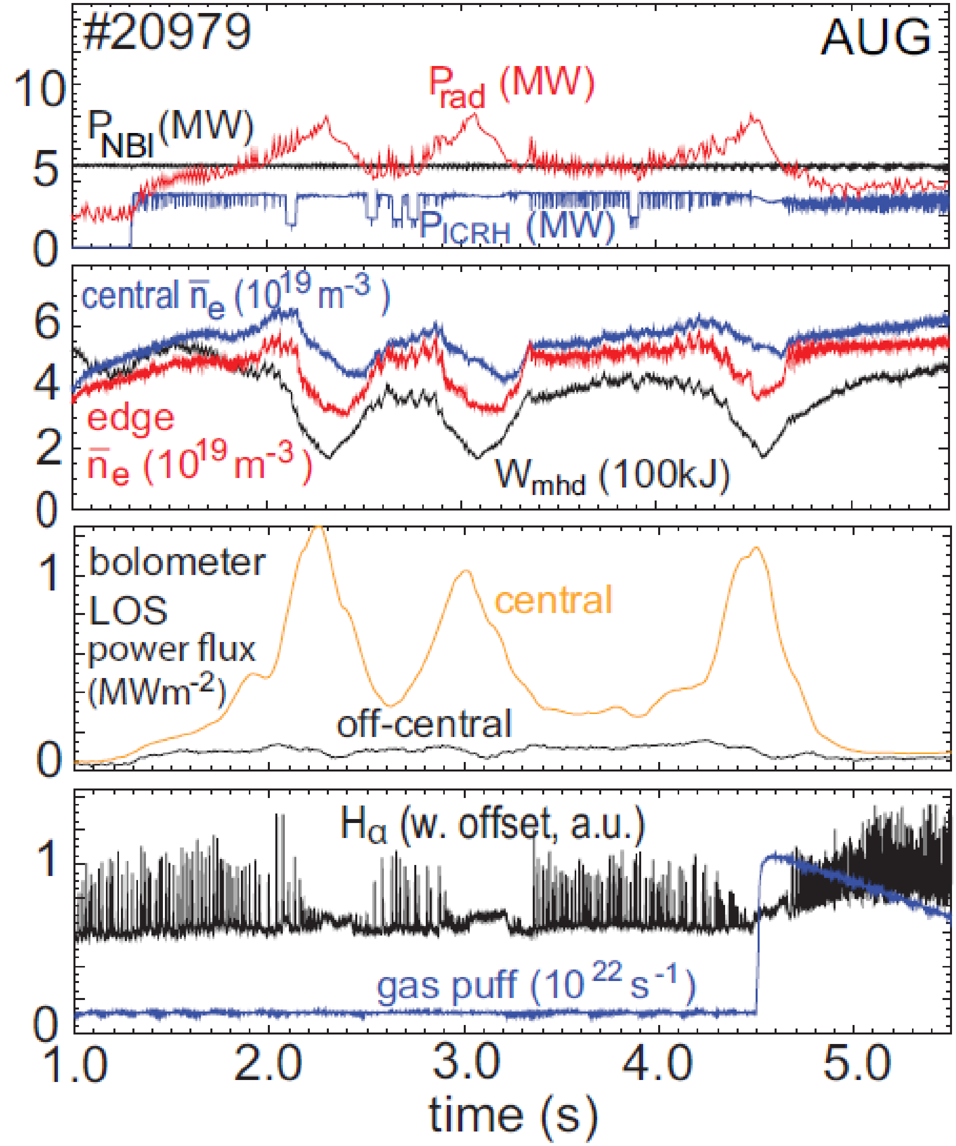
⇒ large central radiation

⇒ back transition to L-Mode

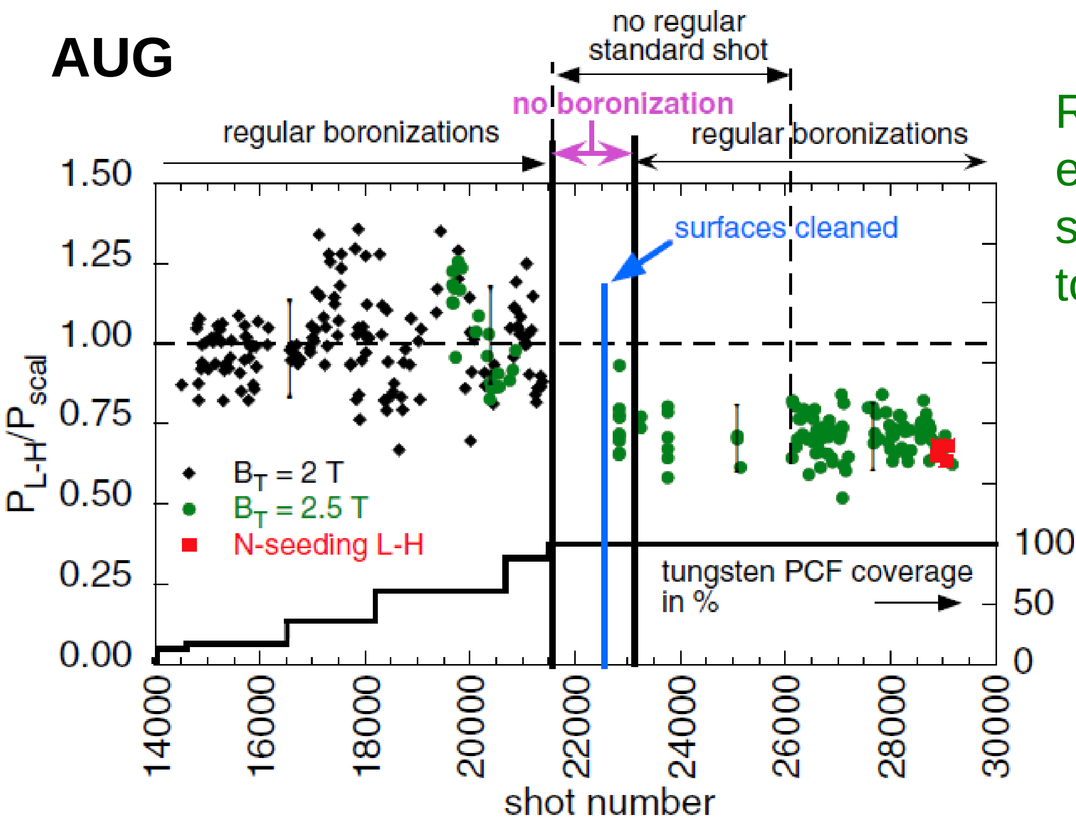
⇒ expulsion of W

⇒ no disruption if heating is maintained

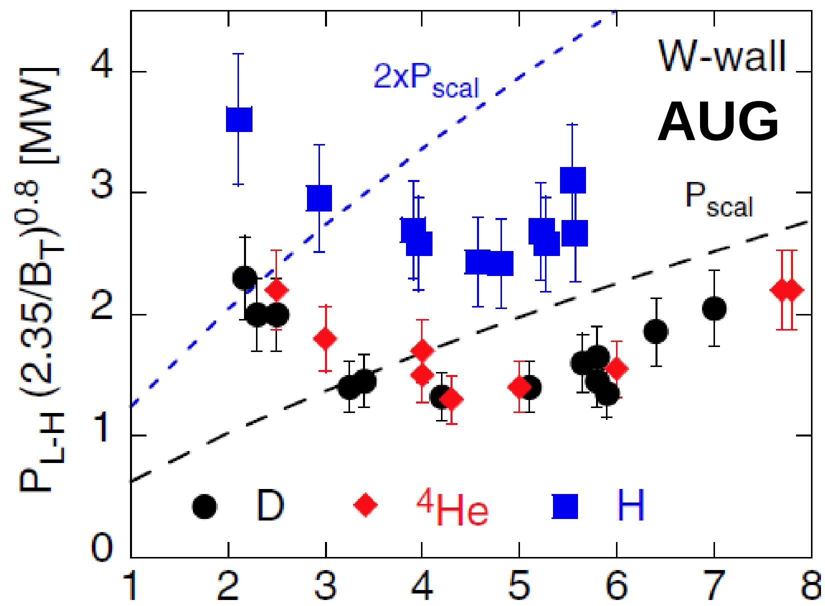
discharge can recover completely if W influx is reduced

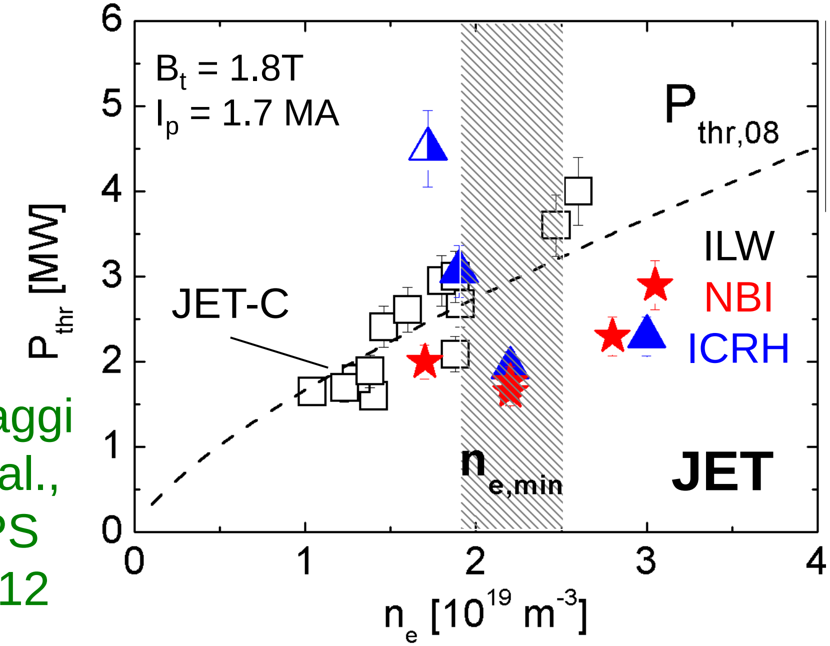


LH Threshold Reduced by 25-30%



Ryter et al., subm. to NF





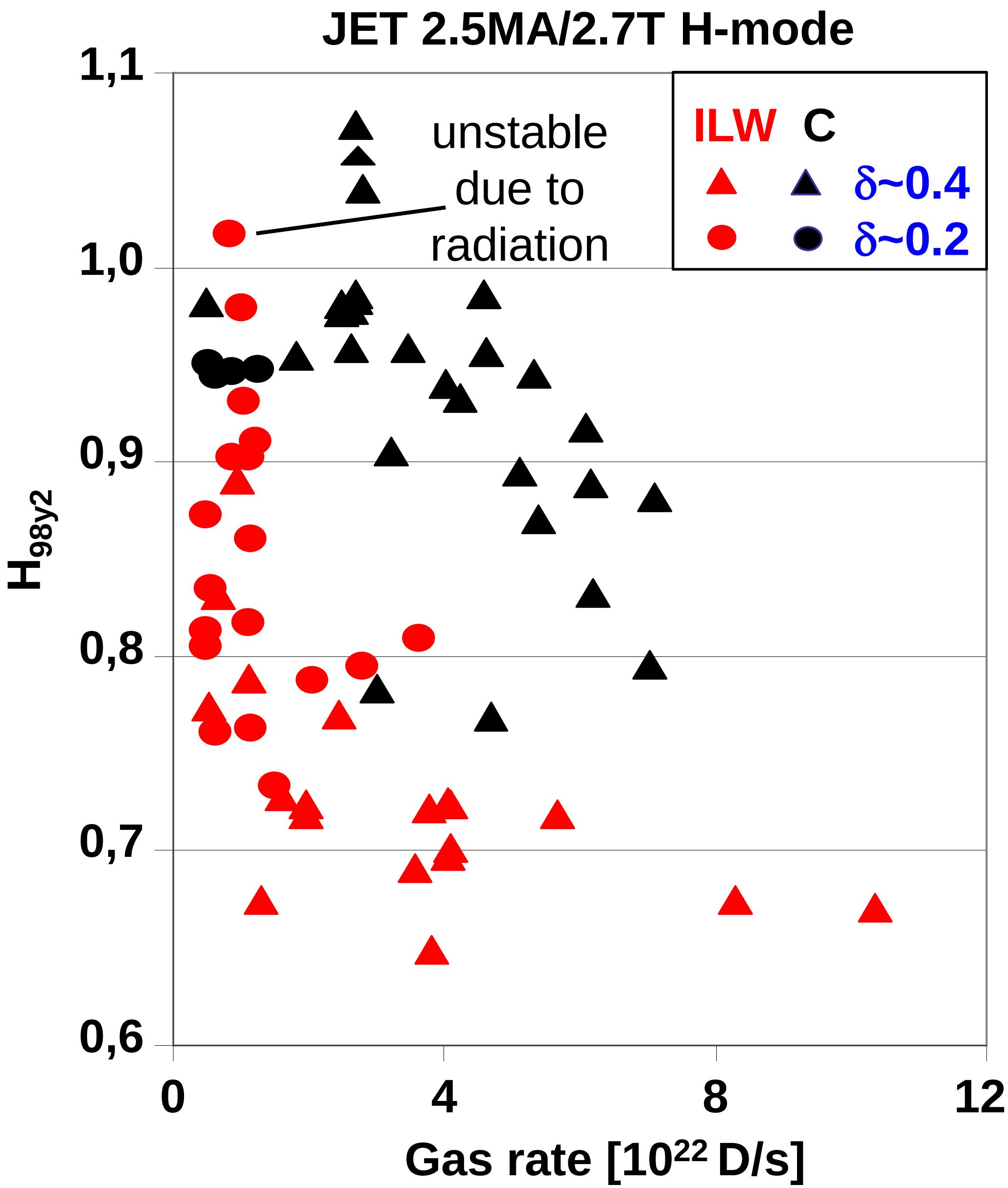
C dominated AUG/JET: $P_{th}/P_{scal08} \approx 1$,

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

Gas fuelling strongly impacts on confinement in JET

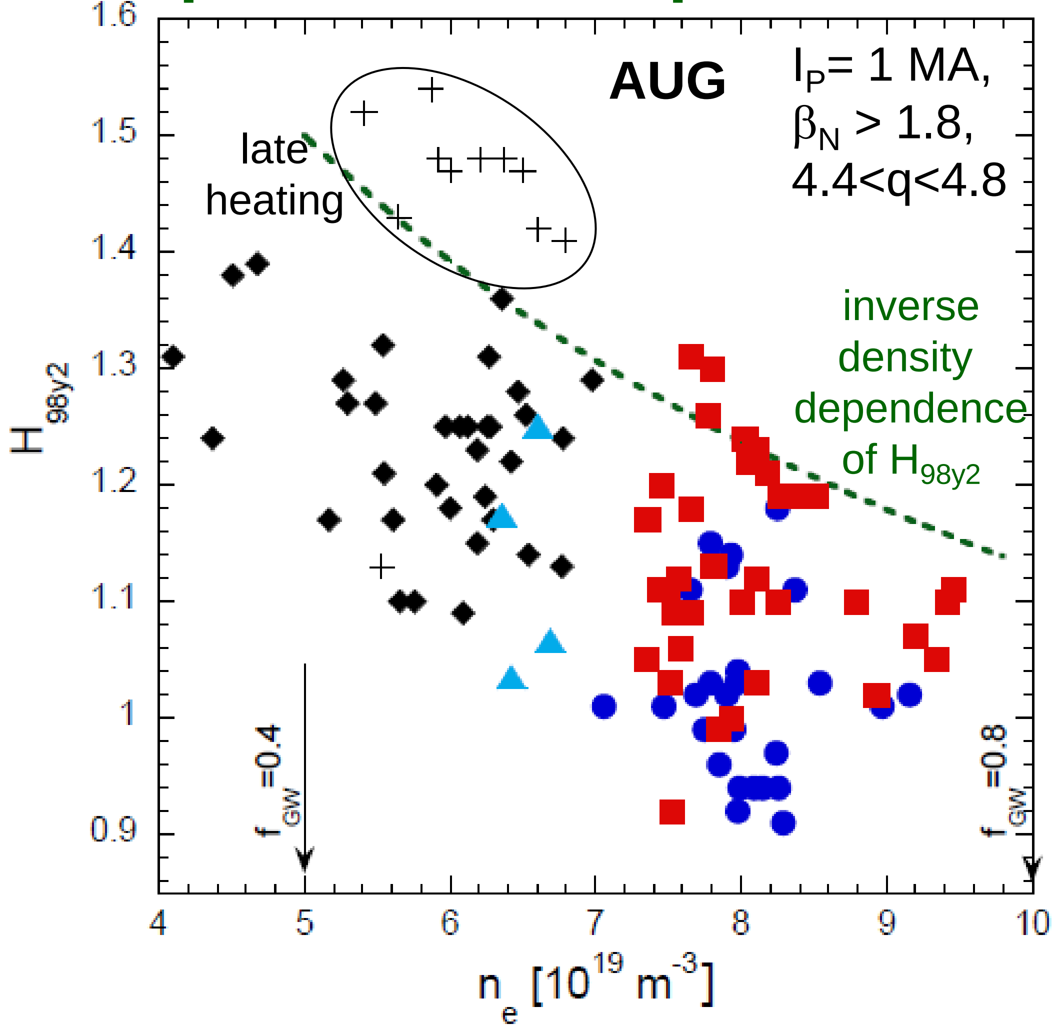


- ELMy H-mode achieved at low and high δ with up to 26 MW of injected power (Ip ≤ 3.5 MA)
- Confinement is lower than with the carbon wall under similar conditions: I_p, B_t, shape (high δ), fuelling
- But at high input power $P_{net}/P_{thr}>2$ confinement can be recovered

[Joffrin, IAEA, EX/1-1]

Increased Confinement with Impurity Seeding

[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

Summary and Conclusions

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

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

But also

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

  ↔ new physics insights (correlation with edge radiation/dilution?)