Development of the Q=10 Scenario for ITER on ASDEX Upgrade (AUG)

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Introduction / Motivation

ITER baseline scenario, aims:

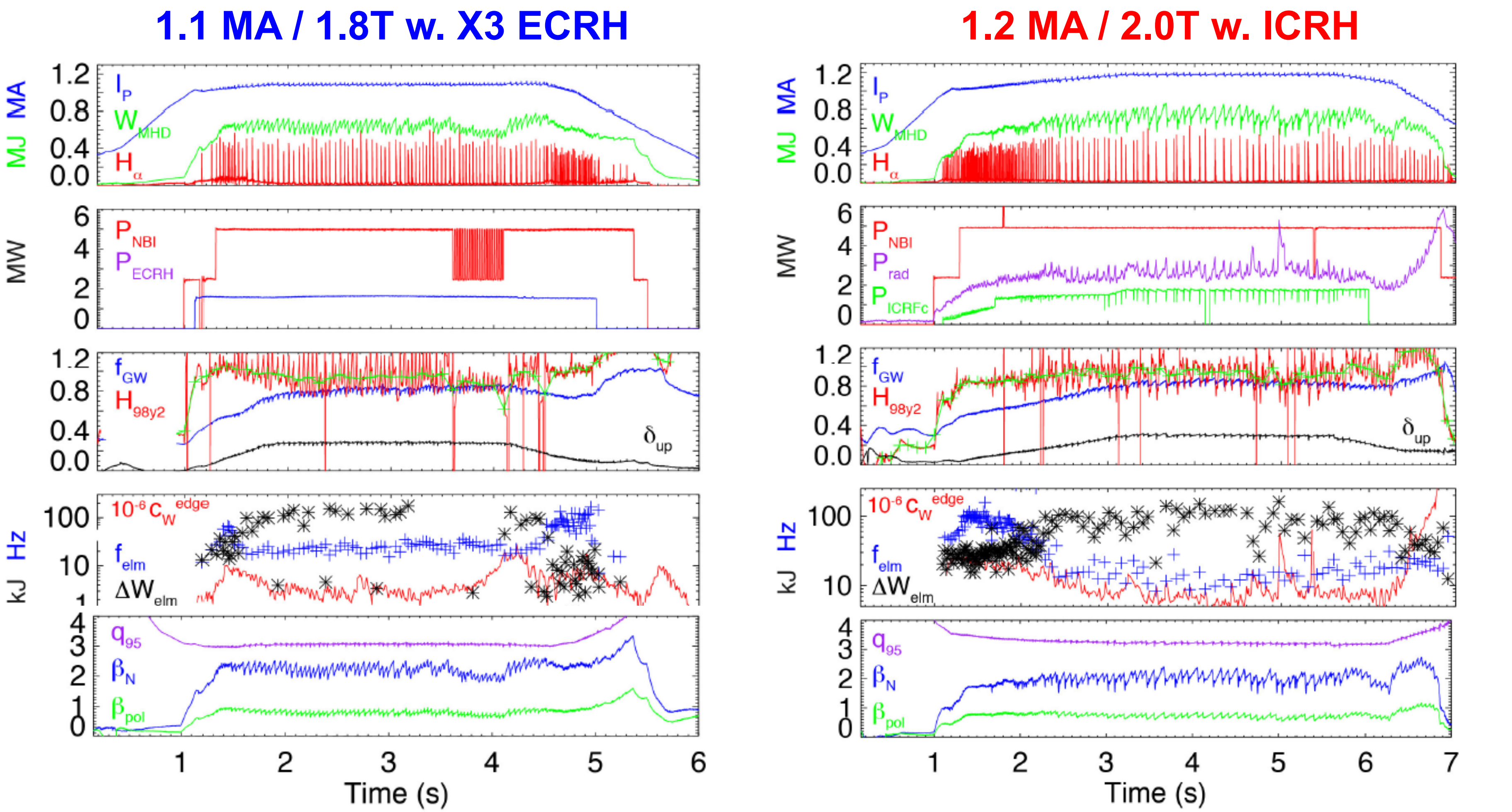
- Q~10, producing 500MW of fusion power for 300-500s.

Baseline scenario (BL):

15MA/5.3T, q_{95}=3, $n_e/n_{GW}=f_{GW}$=0.85, H_{98}=1, β_N~1.8, high δ

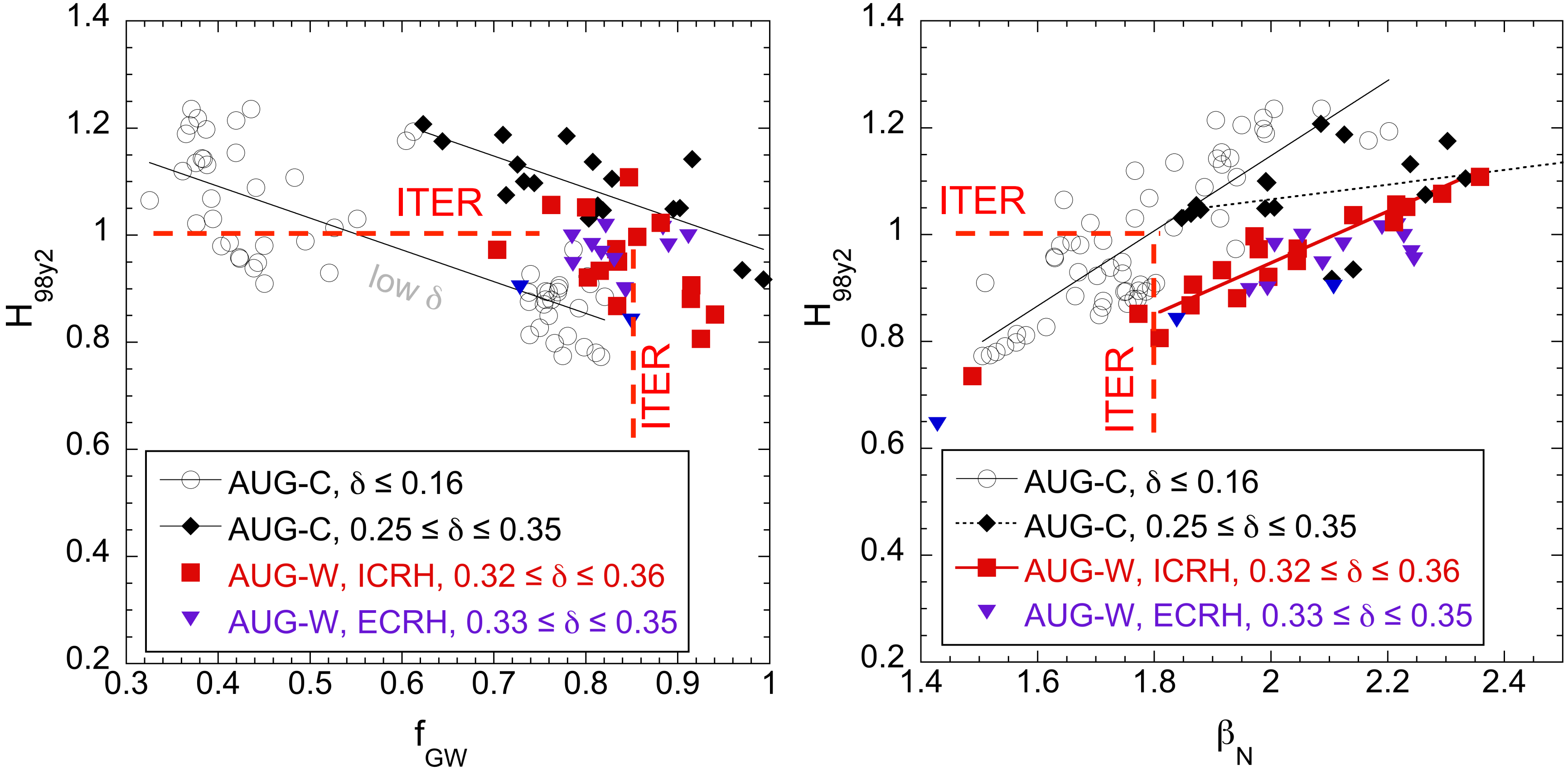
- Working or operation **point defined on machines with Carbon wall**
- Scenario demonstration at devices with **metallic wall like AUG-W** (Alcator C-Mod and JET-ILW) in view of ITER is required
- Matching parameters **for demonstration on AUG** are: **q_{95}, f_{GW}, H_{98}, β_N** (or P_{heat}/P_{L-H}), δ and hence **NOT ν^*, ρ^***

ITER baseline scenario on ASDEX Upgrade (AUG-W)



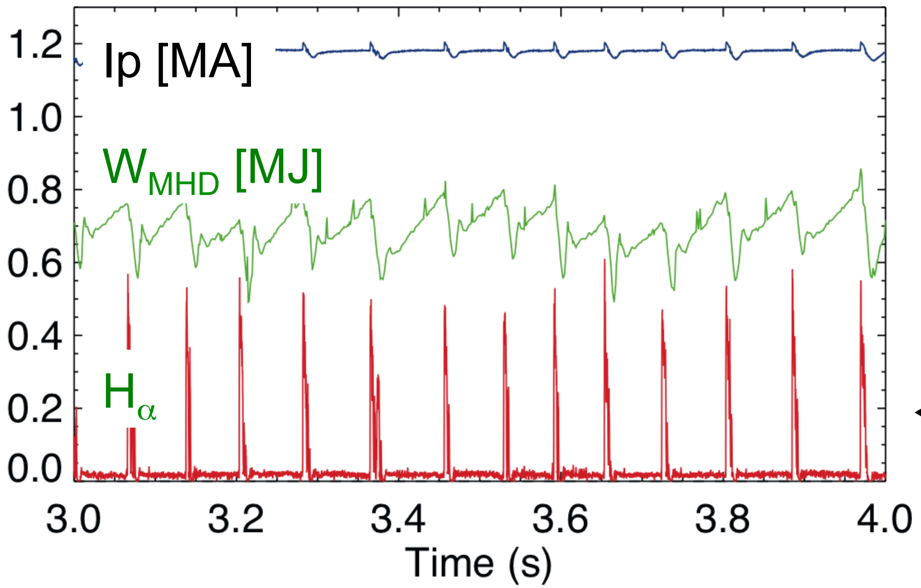
- Ramp-up in low δ configuration
- Stationary discharges as long as **enough gas puff** and **central heating**

Confinement in ITER BL scenario at AUG
(black = AUG-C, low & high δ, coloured = AUG-W, high δ only)



- Existence diagrams for H_{98y2} vs. f_{GW} (left) and H_{98y2} vs. β_N (right)
- Rising triangularity improves confinement at higher n/n_{GW}
- **At low P_{heat} ($\beta_N \leq 1.8$) confinement $H_{98y2} \leq$ 0.85 in AUG-W**

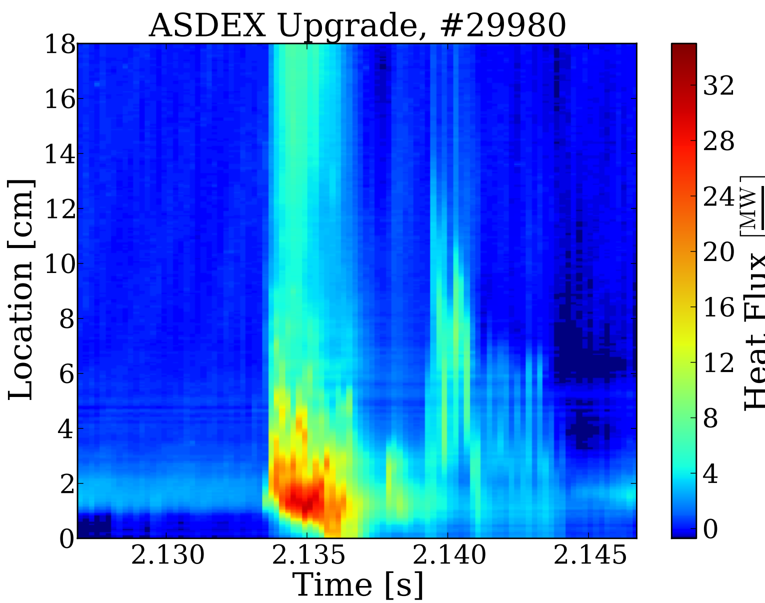
Major issue: ELM behaviour



- although significant D_2 puff, low f_{ELM} = 13 Hz
- W_{ELM} up to 200kJ or 25% of W_{MHD}

IR Thermography:

- high heat flux on outer target plate during ELM



Mitigation of ELMs in the ITER BL scenario

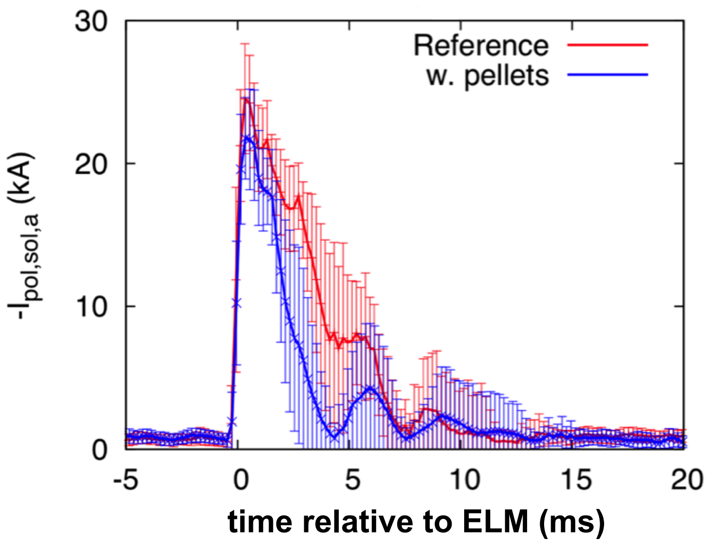
ELM mitigation attempts done using:

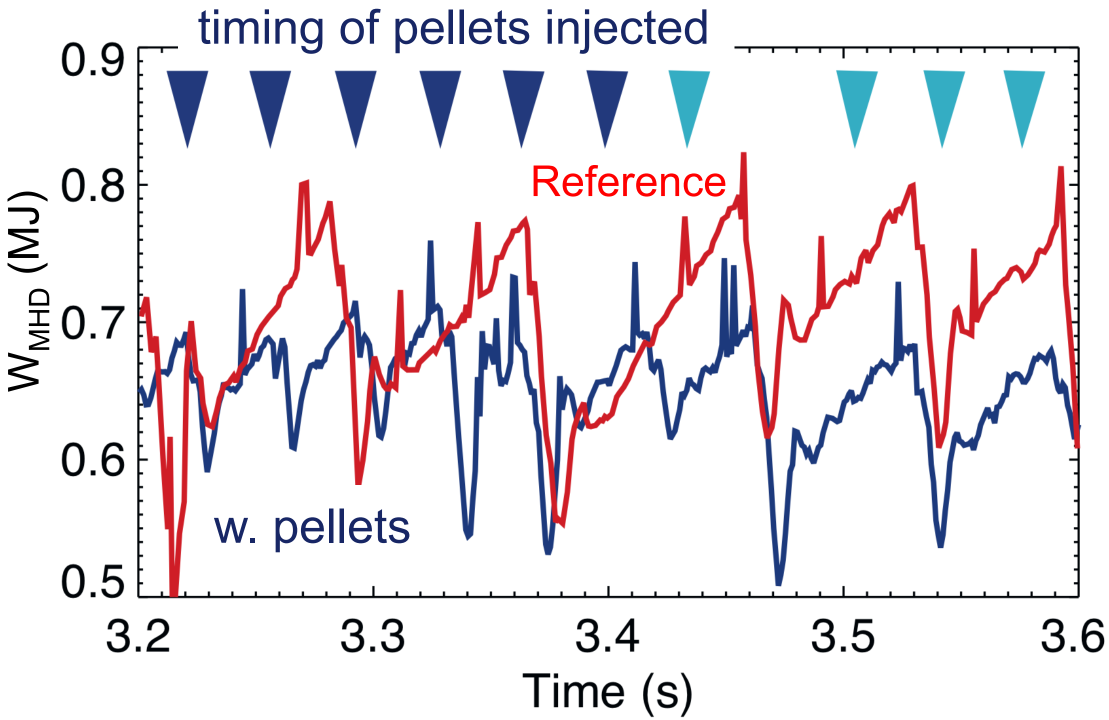
- **pellets for ELM pacing**
- **nitrogen seeding**
- **magnetic perturbation (MP) fields**

ELM pacing w. pellets in ITER BL scenario in AUG-W

ELM frequency not always elevated by pellets:

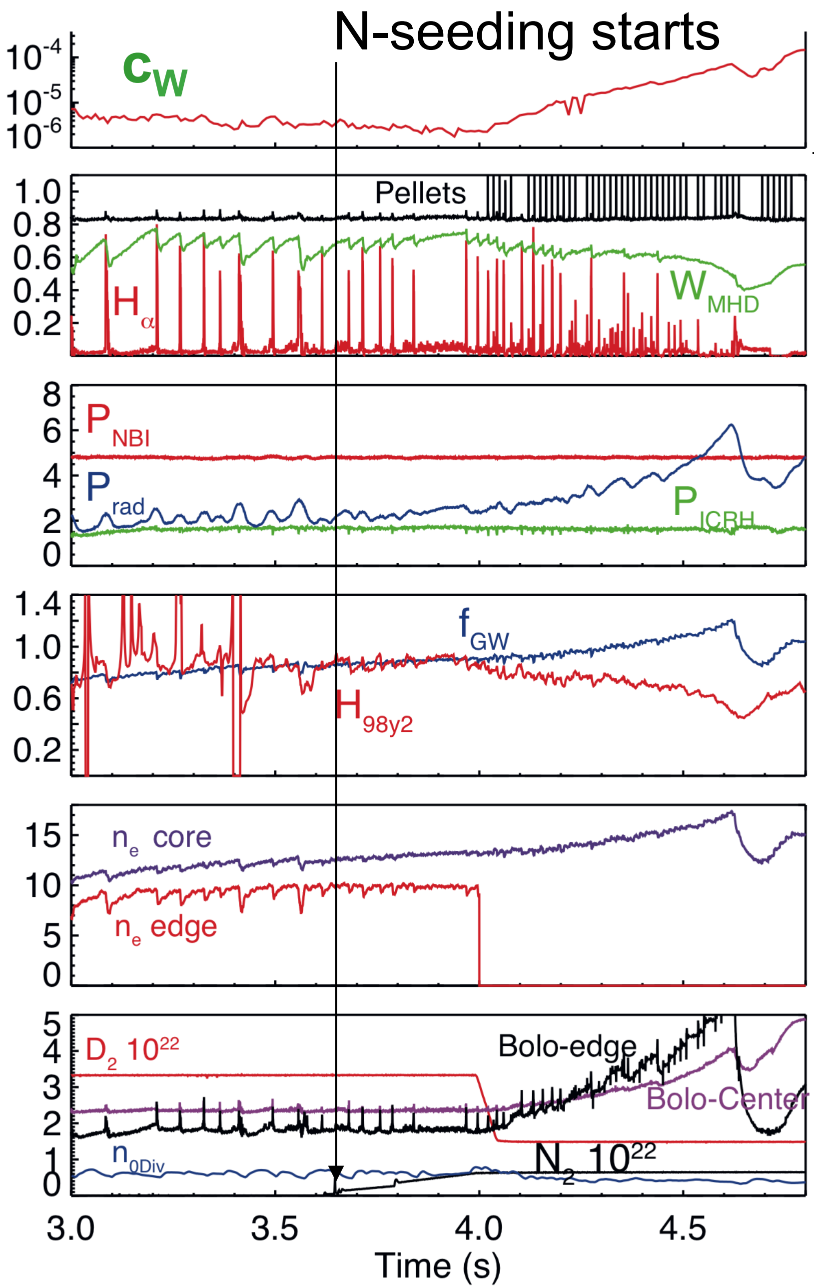
- ELM not **reliably triggered**
- ELM size **still very large**
- ELM duration decreased (though 'loss tail' still present)





Next step: in combination with N-seeding the trigger probablity should go up

Attempt of ELM pacing, with pellets + N-seeding

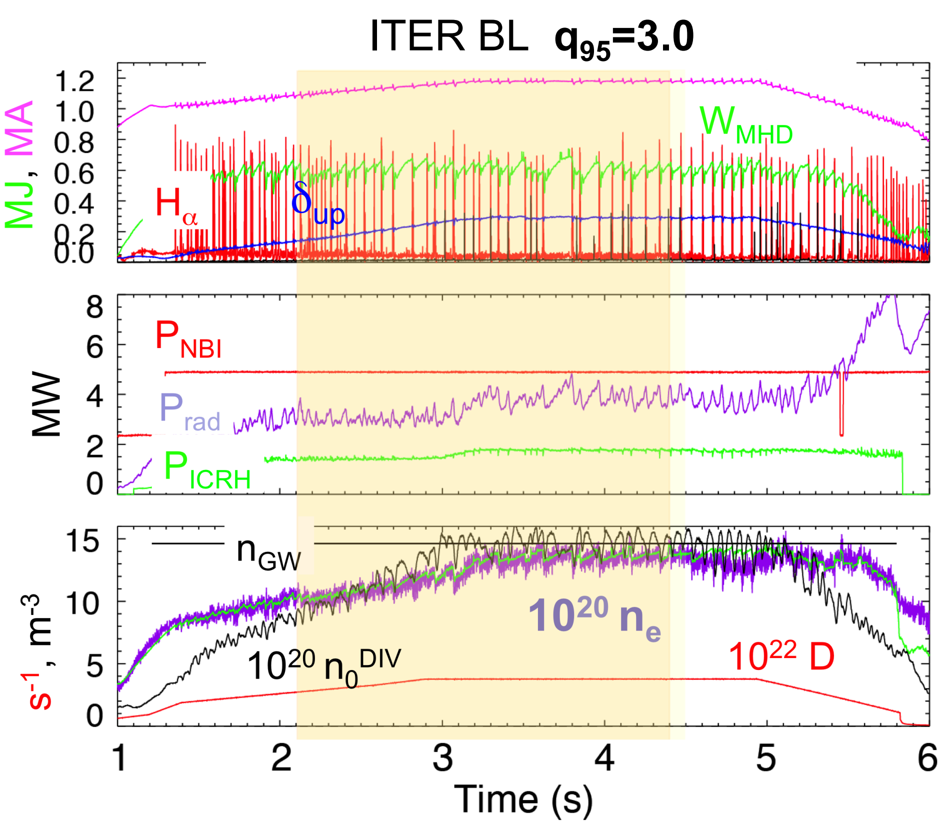


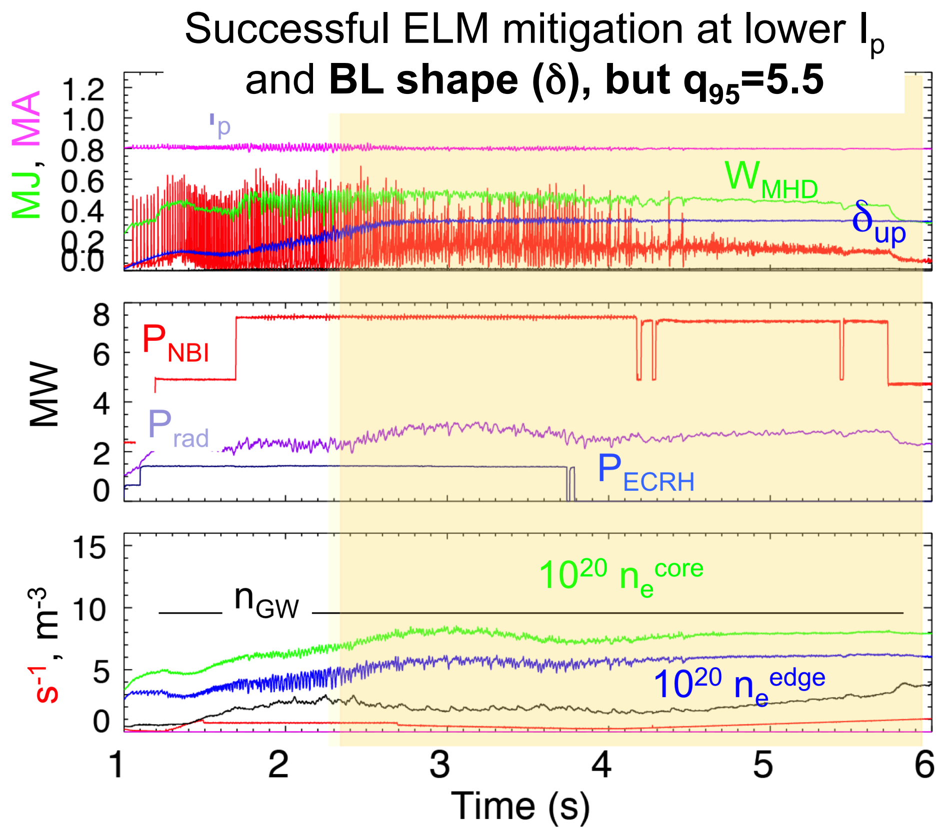
- N-puff slowly ramped up (t>3.6s) max. level $8 \bullet 10^{21}$ e^-/s
- 70 Hz Pellets from 4s with reduced D-puff level
- ΔW_{ELM} smaller with N
- Pellets increase f_{ELM}
- c_W increase with pellet onset
- Pellets drive discharge towards density limit f_{GW} -> 1

-> **scenario not stationary yet**

Attempt at (R)MP mitigation in ITER Baseline

(MP-coils active in the shaded area)





- ITER BL, MP mitigation not achieved, although $f_{GW} \sim 1$
- low q_{95} reduces collisionality

ELM mitigation at high density using n=2, MPs:

- threshold of pedestal top density (or collisionality) has to be exceeded

Demonstration of ITER BL scenario at AUG difficult

Achieved:

- Operation at $\mathbf{q_{95}=3}$ demonstrated at $H_{98}=1$, β_N **> 2**, f_{GW} ~0.85

BUT:

- Large ELMs (also observed at JET both JET-C & JET-ILW) - integration of ELM mitigation not achieved until now
- At relevant P_{heat} (~1.3 $P_{L\text{-}H}$) confinement $\mathbf{H_{98} \leq 0.85}$

q_{95} = 3 seems to be a difficult corner in the operational space ->

try to find alternative operational point for Q=10

Proposal: Operation could move to higher q_{95} (lower I_p)

For scaling (at similar density), **keeping P_{fus} and G constant:**
(**Peeters et al**., Nucl. Fusion **47 (2007)** 1341–1345)

$$P_{fus} = 2.77\left(\frac{\beta_N}{q_{95}}\right)^2$$

Fusion power normalized to the ITER value

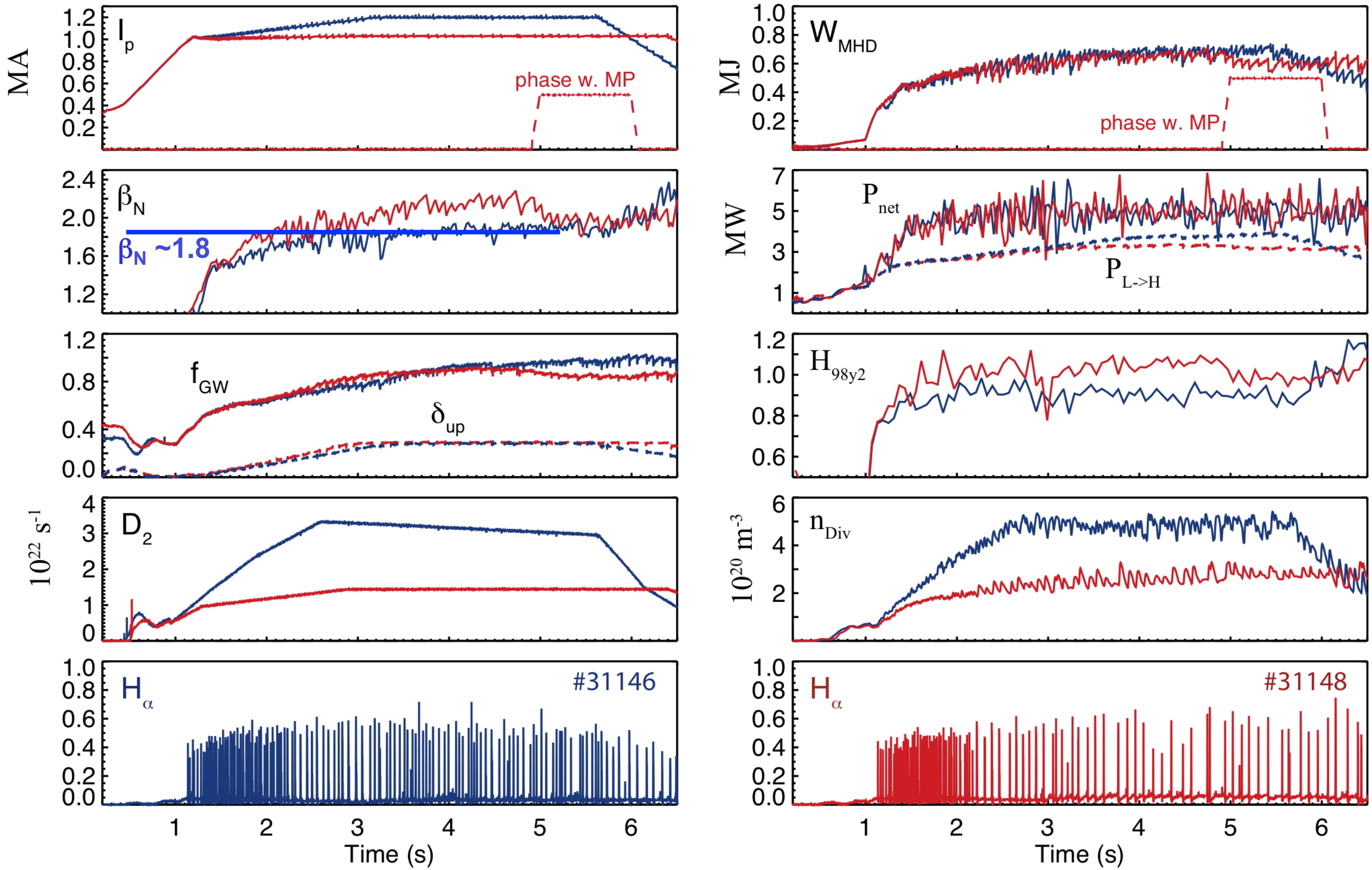
$$G = \frac{Q}{Q+5} = 10.8\,\frac{H_{98}^3}{\beta_N\, q_{95}^2}$$

Alternative operation point for Q = 10, keeping P_{fus} and G constant

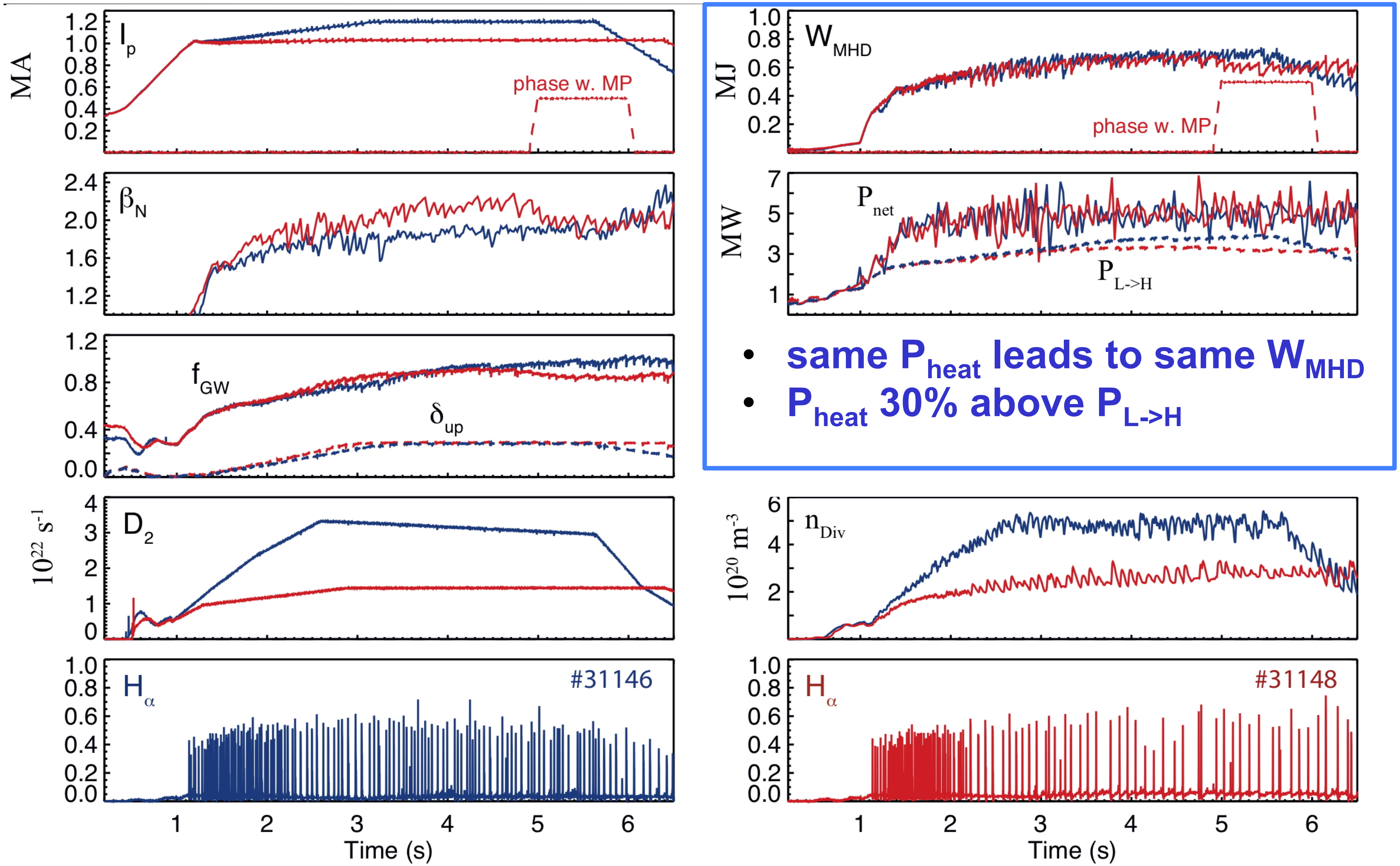
for **q_{95} = 3.6: $\beta_N \sim 2.2$, $H_{98} = 1.2$** **(ITER $I_p \sim 12$ MA)**

- Implications for required target density:
  - pedestal n_e as high as possible (for exhaust)
  - higher n_{e0} / $\langle n_e \rangle$ (w. pellets) to reach **$f_{GW} \sim 1$**
- Keep high triangularity to reach simultaneously good confinement at high f_{GW}

Comparison q_{95} = 3 to q_{95}=3.6 at same P_{heat}
(P_{heat} chosen to get β_N ~1.8 for q_{95} = 3 case)

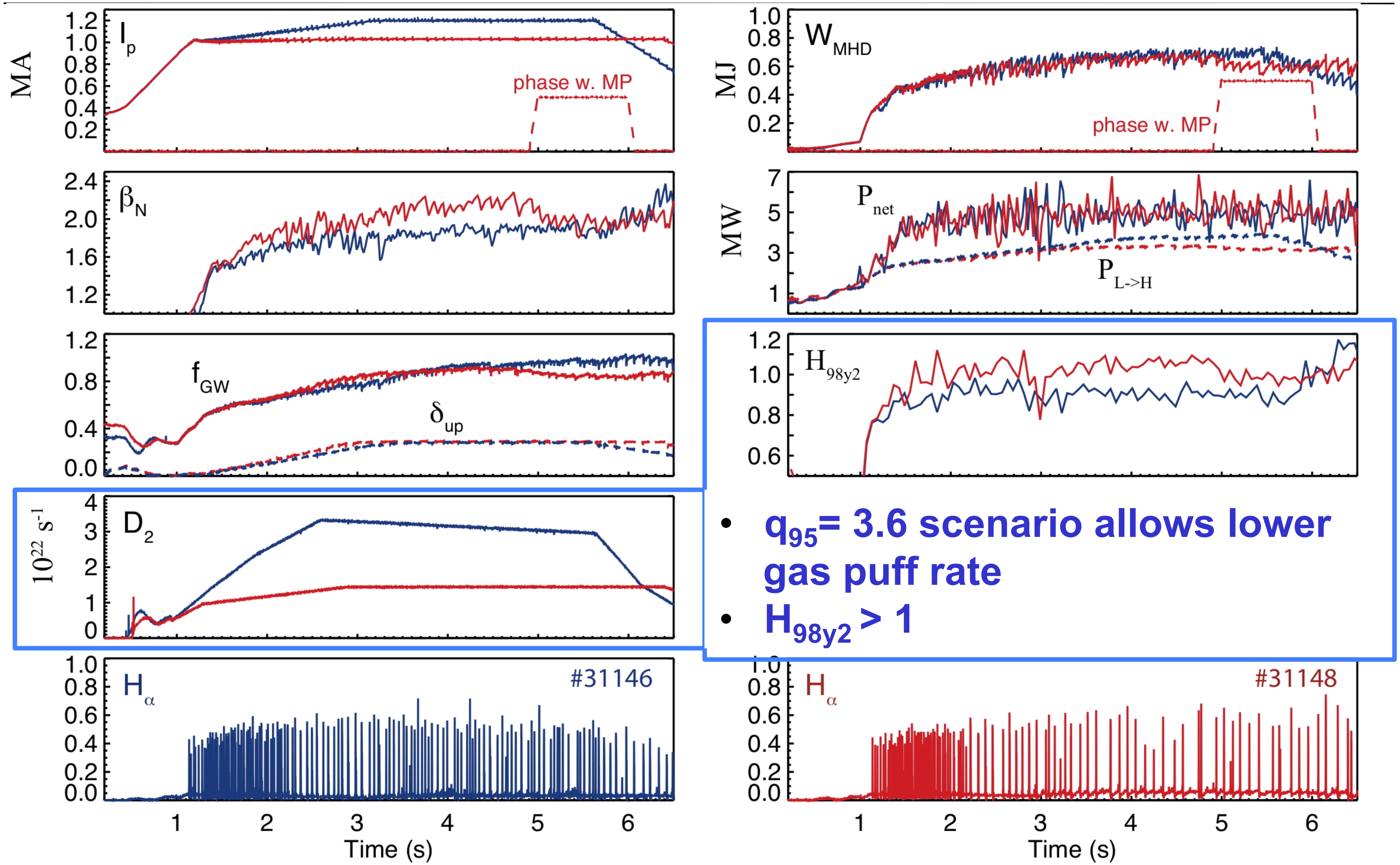


Comparison $q_{95} = 3$ to $q_{95}=3.6$ at same P_{heat} (P_{heat} chosen to get β_N ~1.8 for $q_{95} = 3$ case)



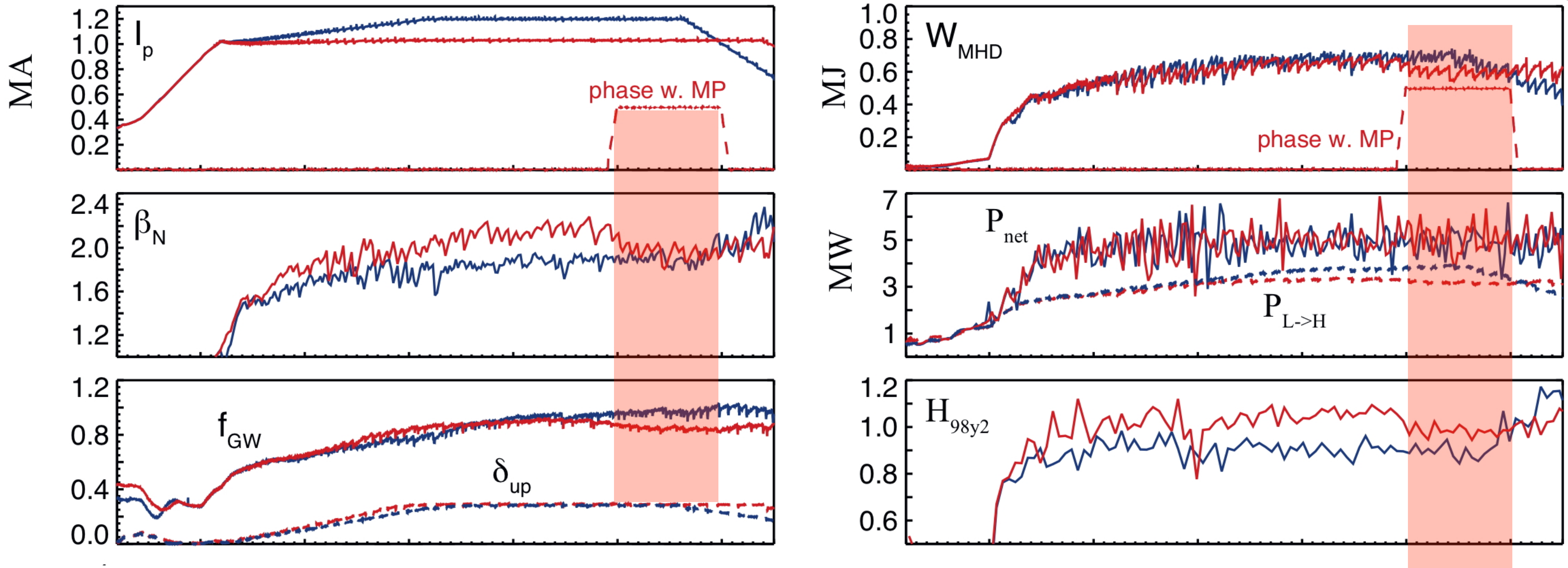
- **same P_{heat} leads to same W_{MHD}**
- **P_{heat} 30% above $P_{L\text{->}H}$**

Comparison q_{95} = 3 to q_{95}=3.6 at same P_{heat}
(P_{heat} chosen to get β_N ~1.8 for q_{95} = 3 case)

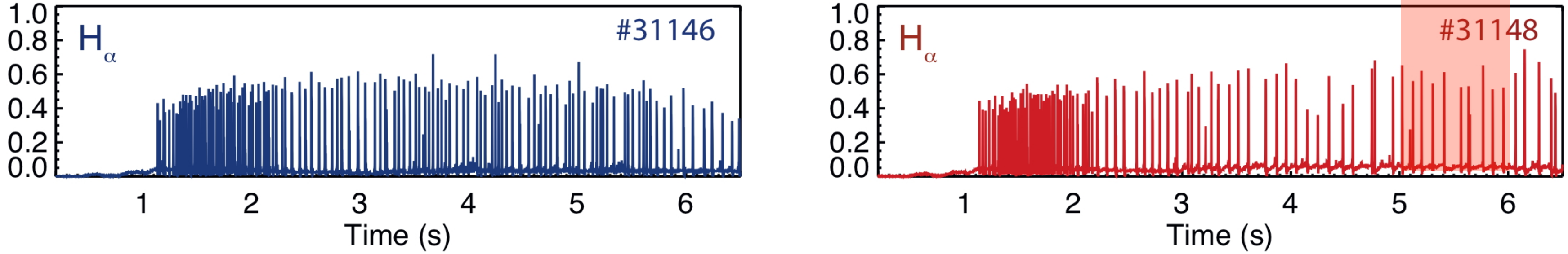


- **q_{95}= 3.6 scenario allows lower gas puff rate**
- **H_{98y2} > 1**

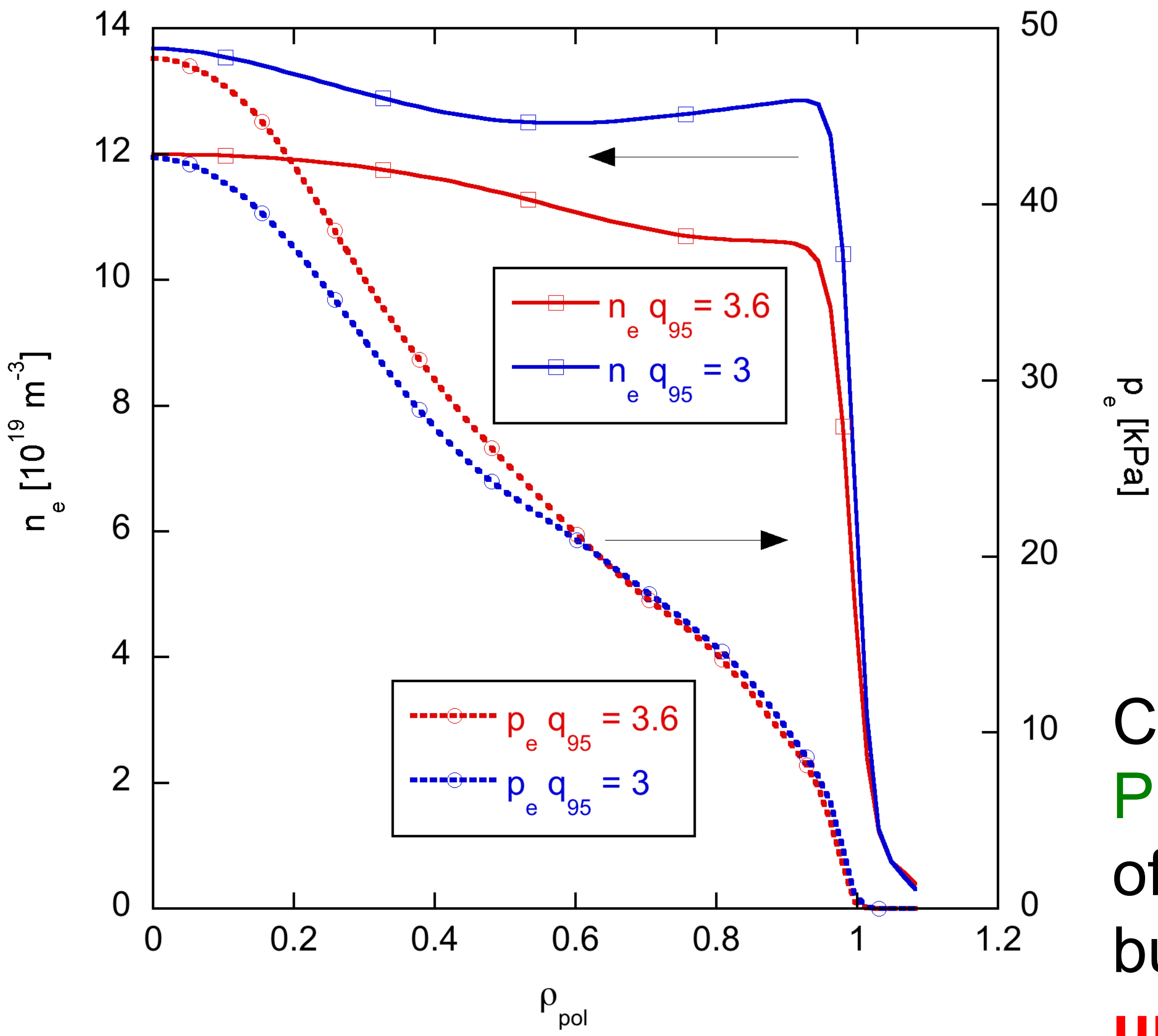
Comparison q_{95} = 3 to q_{95}=3.6 at same P_{heat}
(P_{heat} chosen to get β_N ~1.8 for q_{95} = 3 case)



- **ELM signature similar in both scenarios**
- **Phase with MP reduces confinement, but does not affect ELMs**



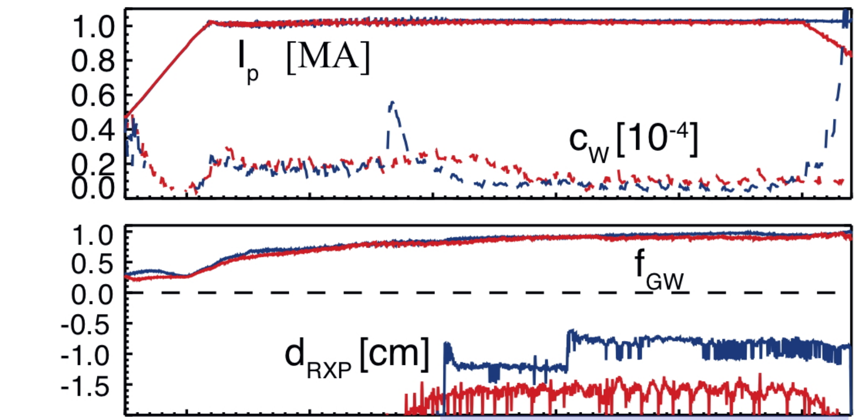
Comparison q_{95} = 3 to q_{95}=3.6 at same P_{heat}
(P$_{heat}$ chosen to get β_N ~1.8 for q_{95} = 3 case)



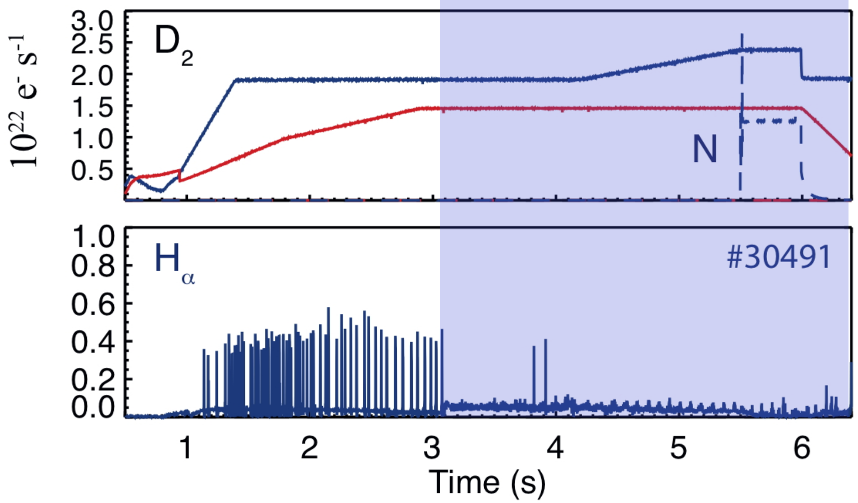
- Same W_{MHD} confirmed by kinetic profiles
- Same f_{GW}, less absolute n_e in q_{95}=3.6 case
- Edge n_e rather similar

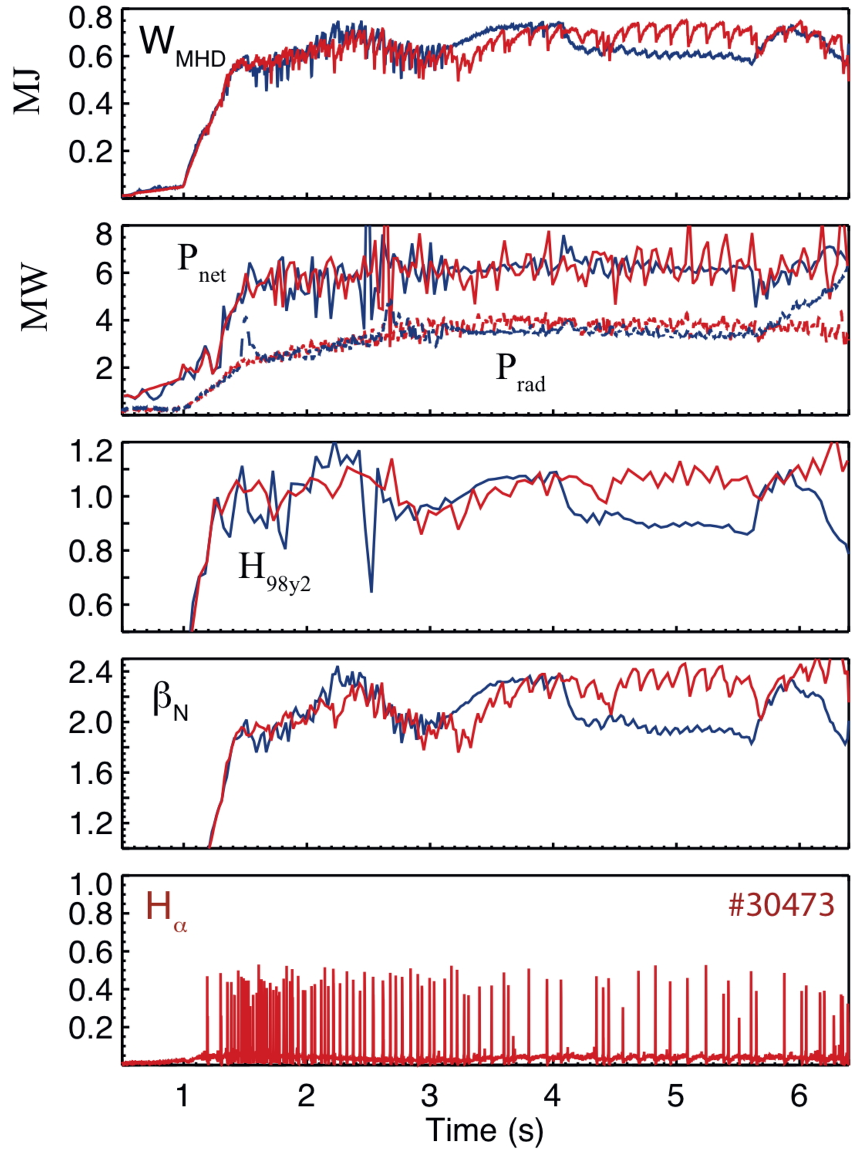
Conclusion:
Promising performance of ‚alternative ITER BL‘, but **ELM behaviour unchanged**.

‚Alternative ITER BL‘ plasmas (q_{95}=3.6) with and without type-II ELMs

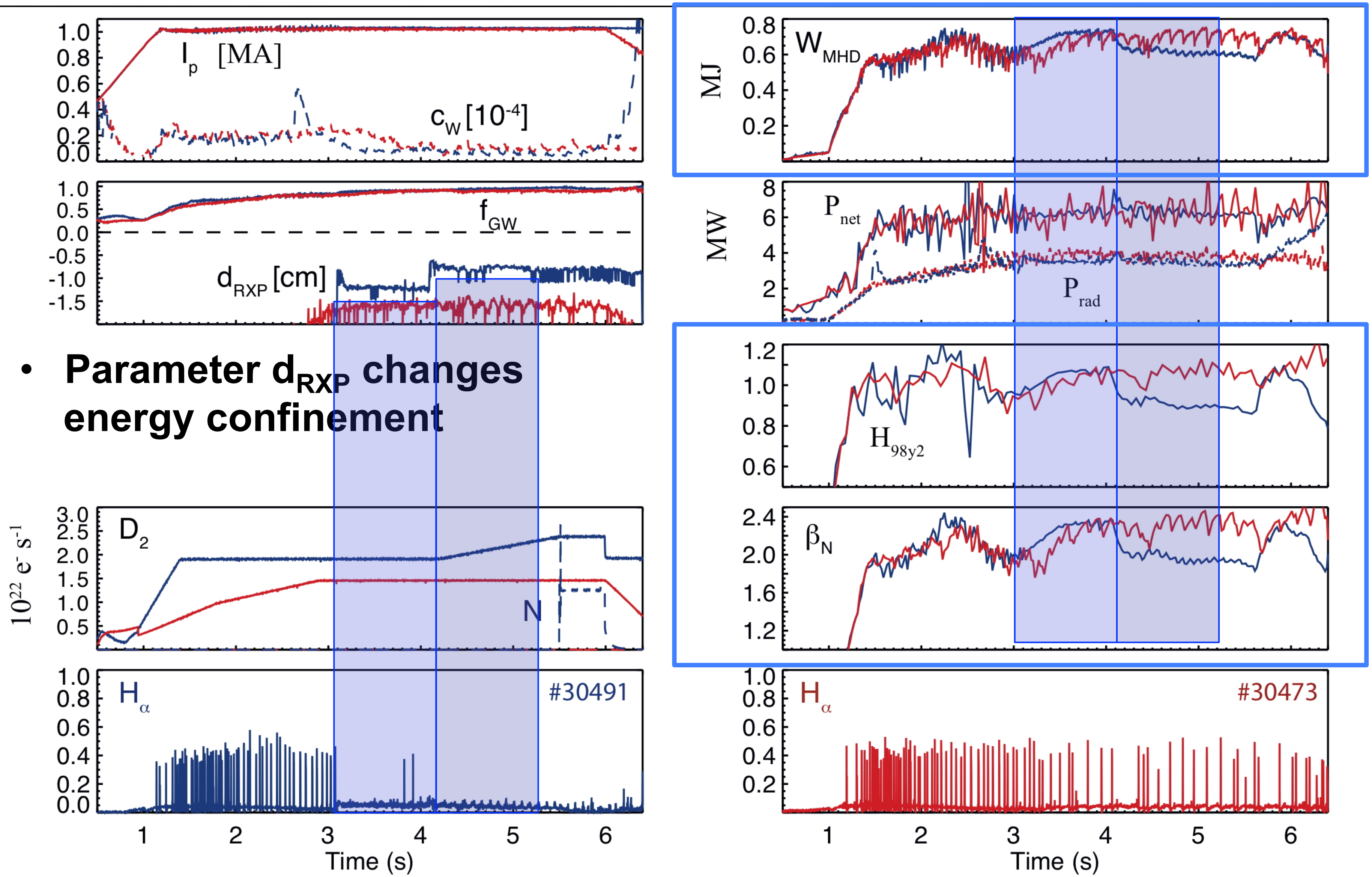


- **Closeness to DN configuration (parameter d_{RXP}) decisive for switch to type-II ELMs**





‚Alternative ITER BL' plasmas (q_{95}=3.6) with and without type-II ELMs

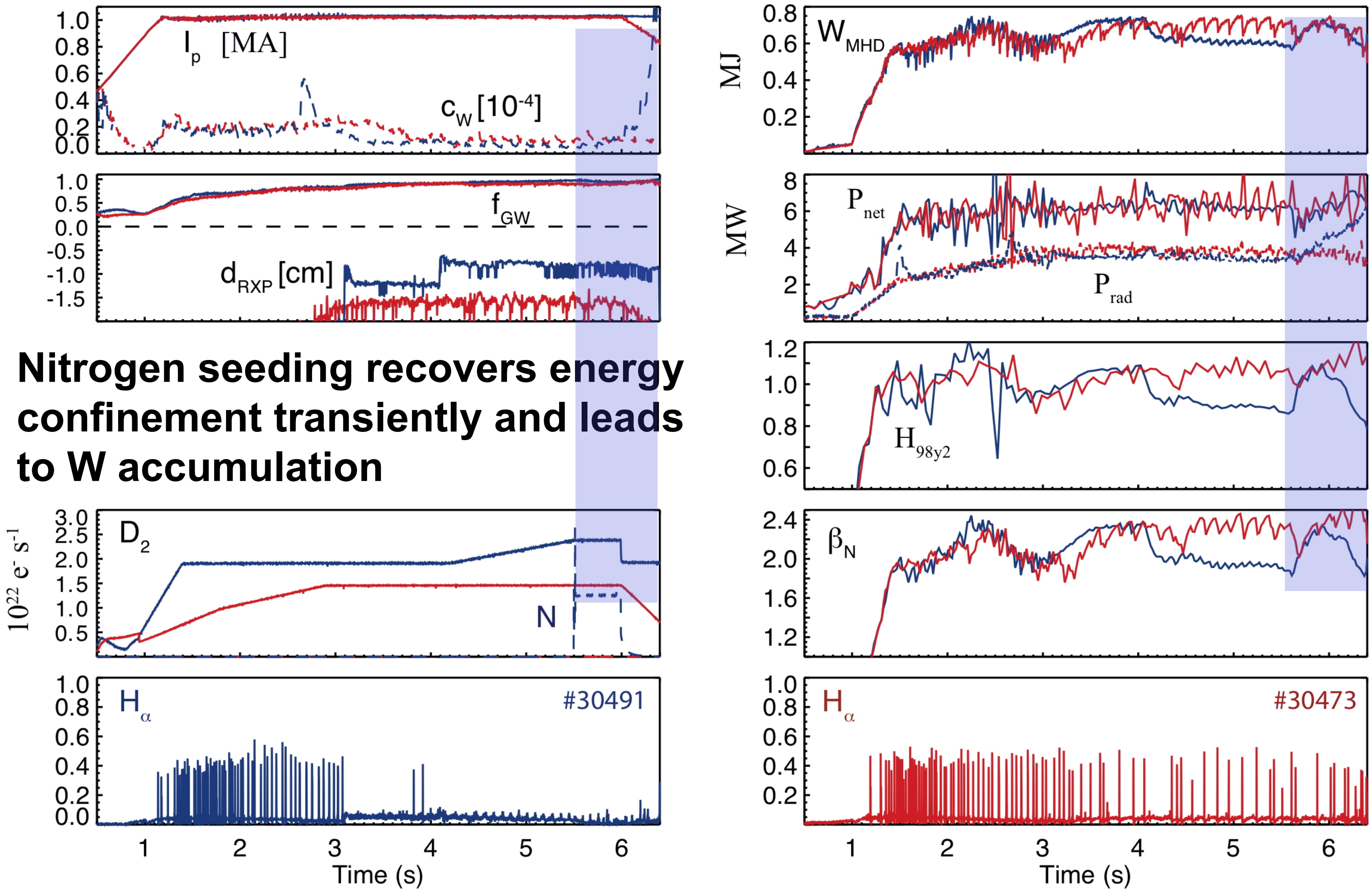


- **Parameter d_{RXP} changes energy confinement**

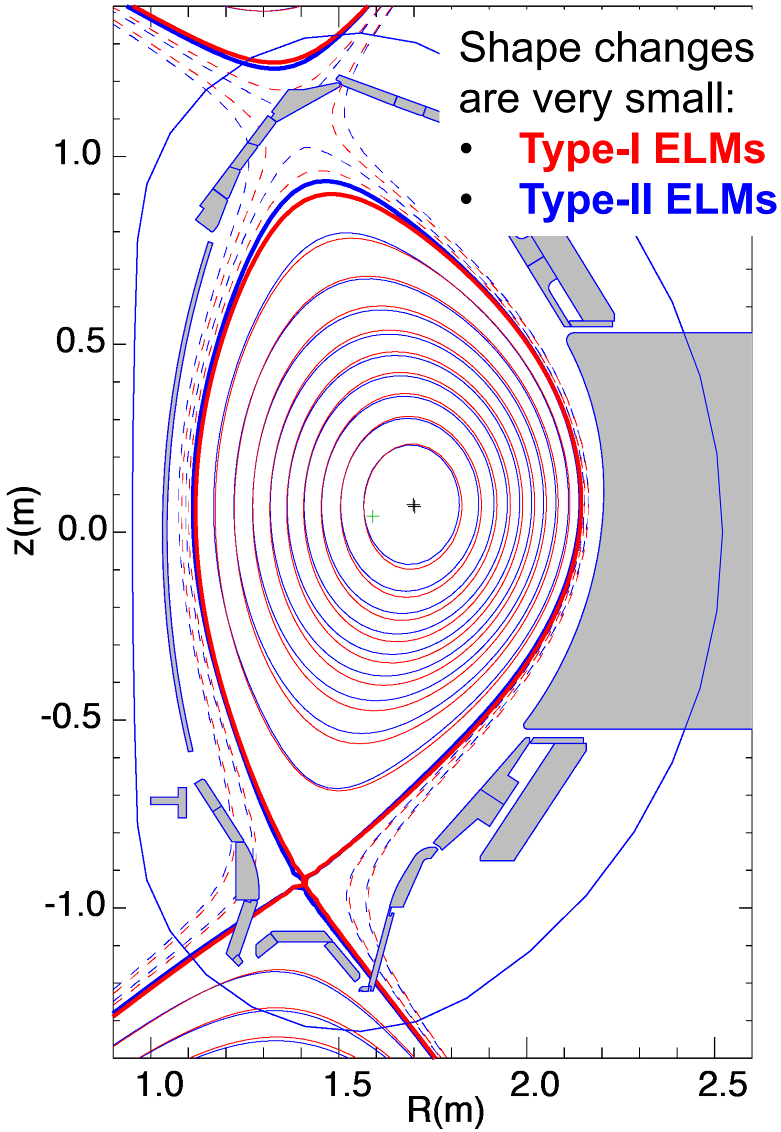
‚Alternative ITER BL‘ plasmas (q_{95}=3.6)

Nitrogen seeding in phase with type-II ELMs

Nitrogen seeding recovers energy confinement transiently and leads to W accumulation

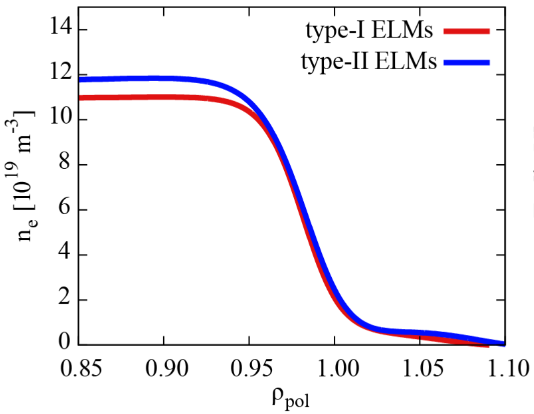


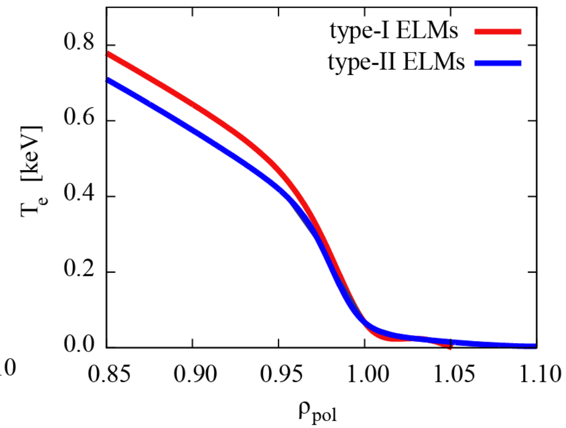
Type-II ELMs observed in ‚alternative ITER BL‘ plasmas (q_{95}=3.6) – typical signature as in the past



- MHD behaviour similar as for the type-II ELMs observed in the past at q_{95}=5.5

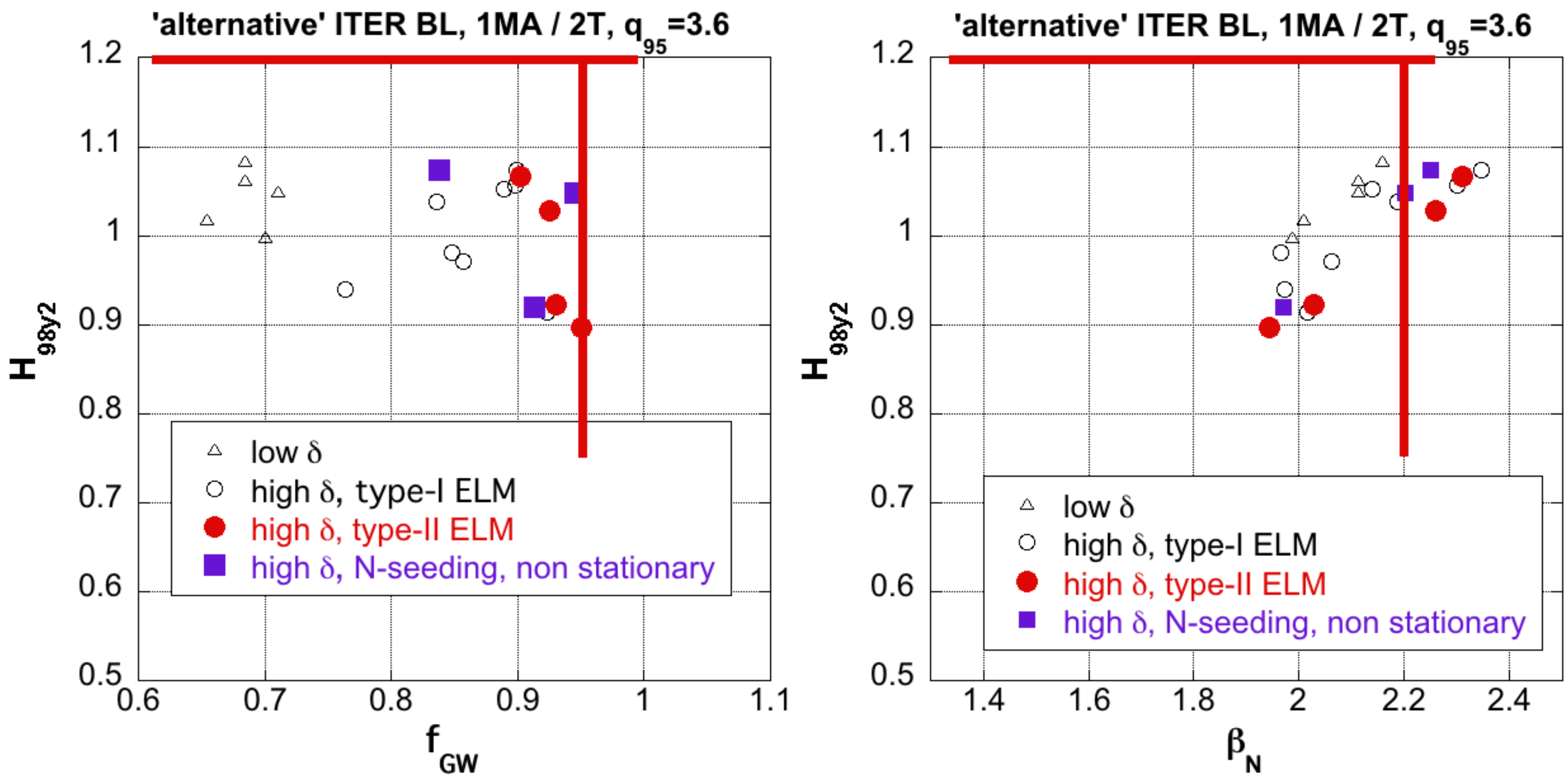
- Profiles show **no** significant change in edge gradient
- Type-II ELM pedestal has slightly lower $T_{e,}^{ped}$ and higher $n_{e,}^{ped}$





Existence of type-II ELMs extended to q_{95} = 3.6 in AUG

Summary q_{95}=3.6 ‚alternative BL‘ demonstration



- Operational range (gas puff level, wall conditions) **considerably larger** than in q_{95}=3 scenario, **less prone to W-accumulation**
- First results for ‘alternative’ ITER BL (**target:** H_{98y2}=1.2, β_N=2.2, f_{GW}>0.9) promising, but confinement off target by 10%
- Cold divertor operation by N-seeding not yet stationary

Summary

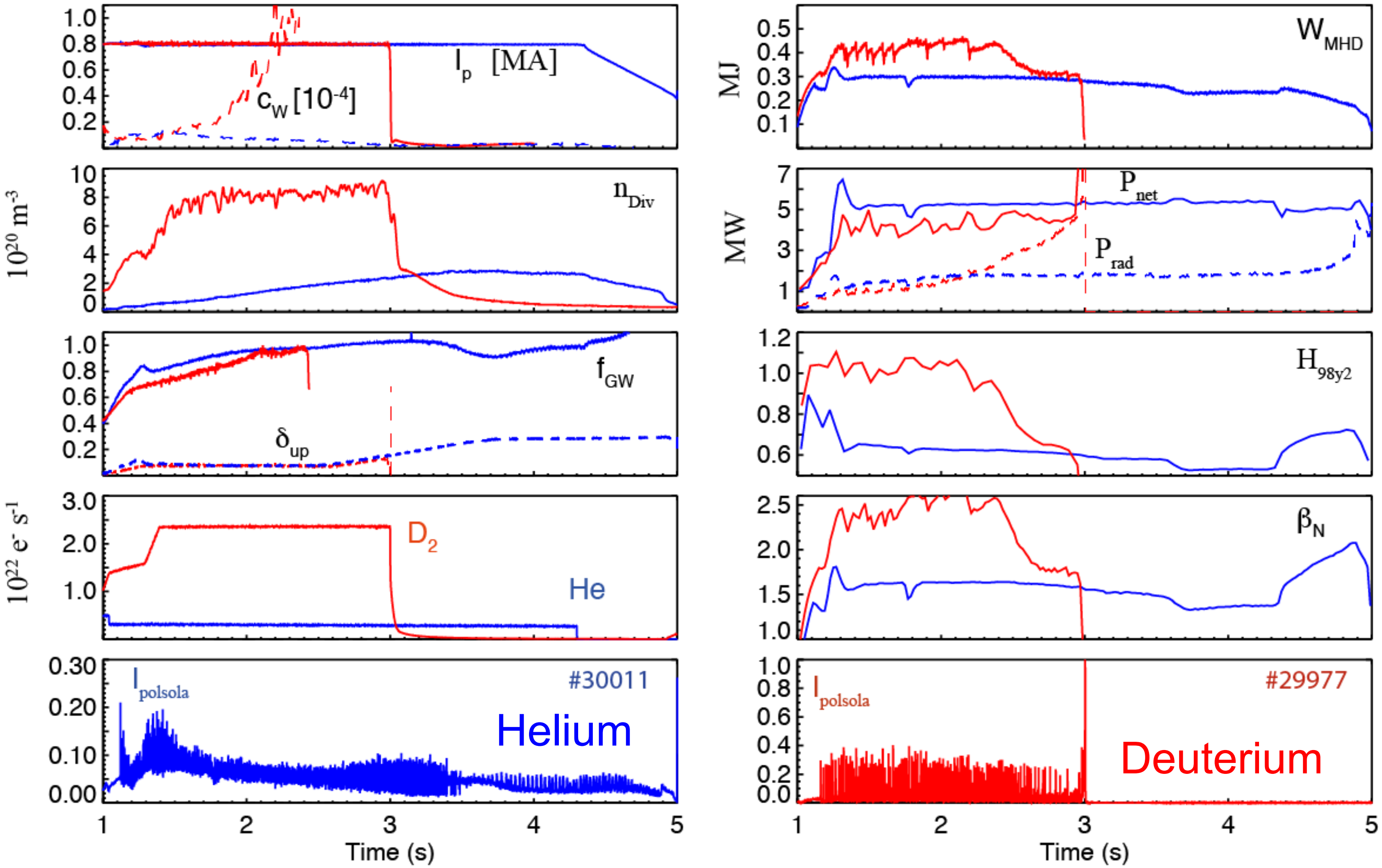
- q_{95} = 3 ITER BL:
  - With 3.8 MW NBI + 1.8 MW ICRH discharge at β_N=1.8 established, but H_{98} below 1.
- q_{95} = 3.6 'alternative ITER BL':
  - At low P_{heat} promising performance achieved
  - Extended operational window compared to q_{95}=3
  - Type-II ELMs rediscovered

For both scenarios:

- ELM mitigation techniques still need to be integrated
- Operation with 'cold divertor' (by N-seeding) in both scenarios not stationary so far. Attempts with higher puff rates for D and N on the agenda for next experiments

Operation in Helium compared with Deuterium

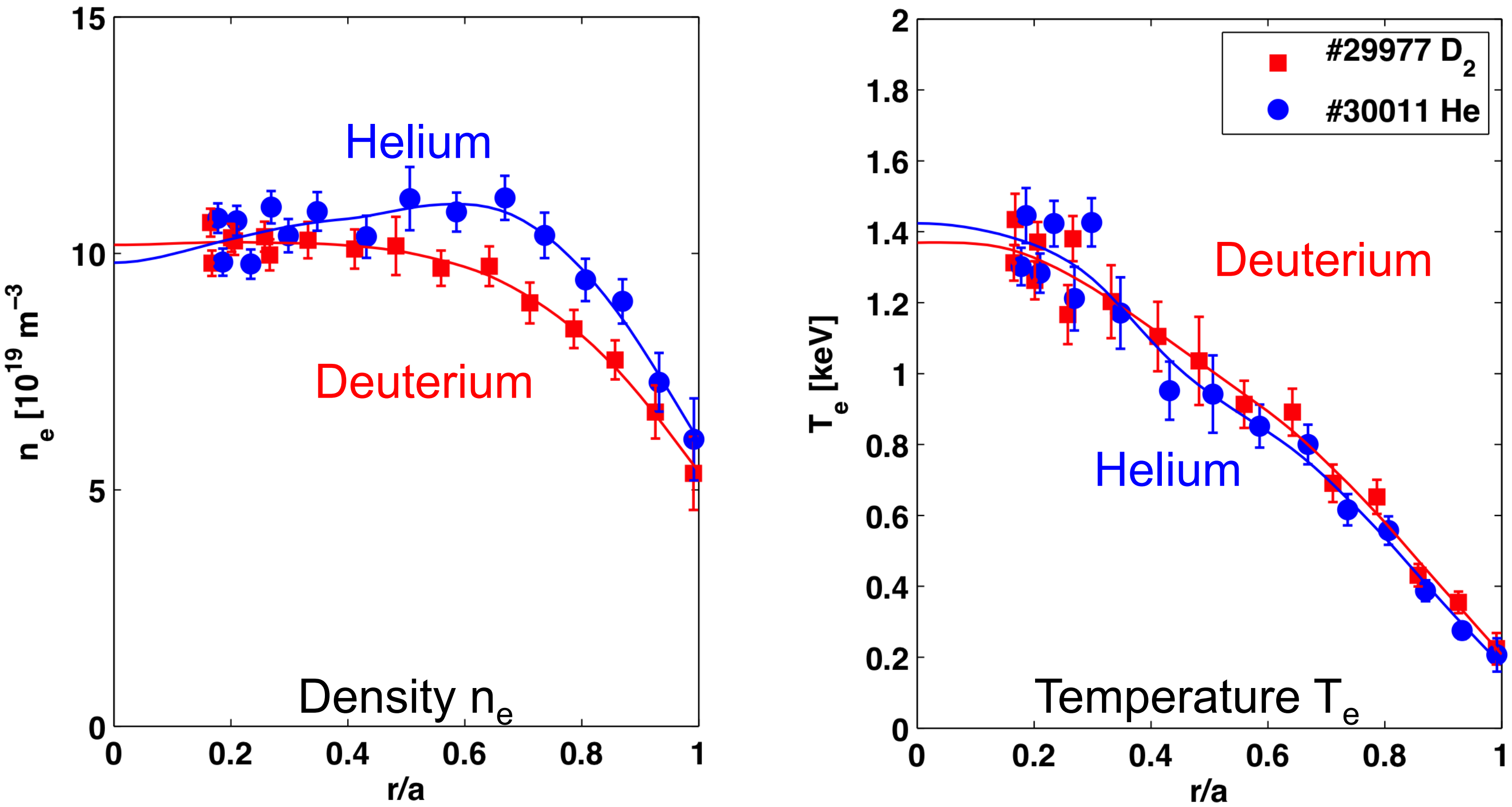
- **0.8 MA /1.4 T**, Both discharges performed ~20 days after boronization
- **Deuterium** reference discharge suffers from W-accumulation



Helium discharge shows stable W behaviour

Operation in Helium compared with Deuterium

- He plasma has same n_e, T_e (and likely same T_i, not measured) as D plasma, with 1.5 less particles (both discharges at **0.8 MA /1.4 T**)
- This is consistent with global stored energy (W_{MHD} in D ~ 1.5 W_{MHD} in He)



Summary: Helium operation

- A few discharges were performed with the following technical boundary conditions:

  - Helium not pumped by AUG cryo-pumps
  - He-NBI not possible -> D_2-NBI used in all discharges
  - Discharges were performed under almost un-boronized wall conditions

- Low current He operation (0.8 MA) even without central wave heating