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

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[1)] *EFDA JET*

ITER Baseline scenario - Background

ITER baseline scenario, aims:

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

Baseline scenario (BL): **15MA/5.3T, q_{95}=3, f_{GW}=0.85, H_{98}=1, β_N~1.8, high δ**

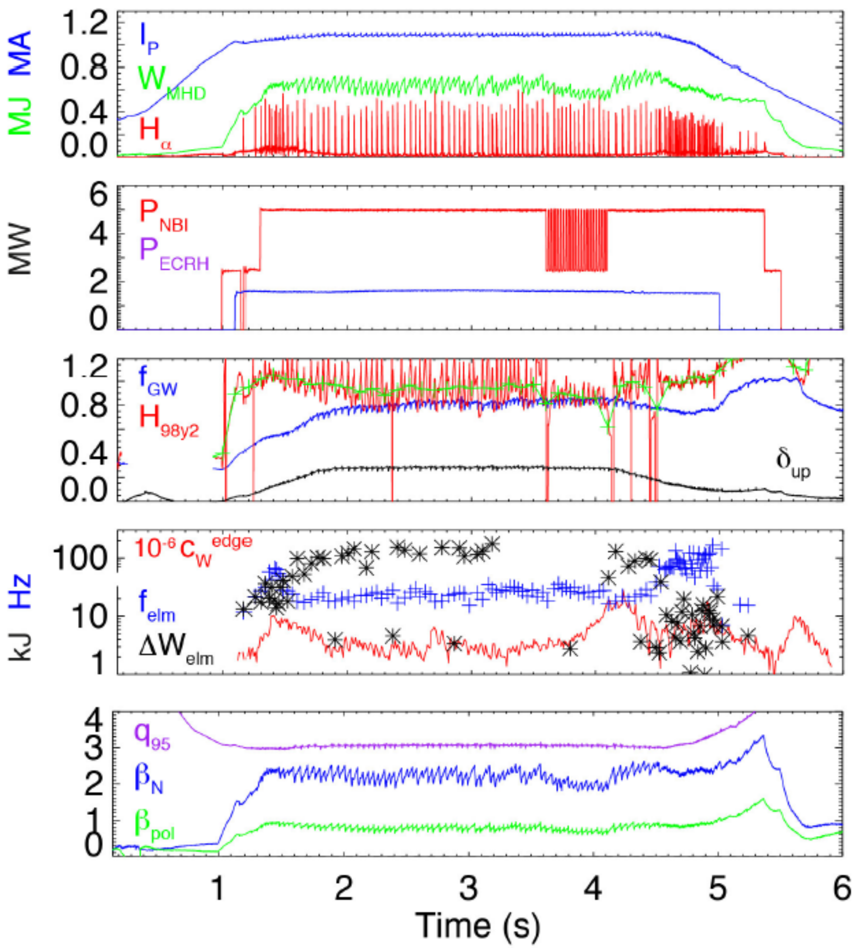
- Working or operation point definded at machines (JET-C, DIII-D, AUG-C) with Carbon wall

- Scenario demonstration at devices with metallic wall like AUG-W (Alcator C-Mod and JET-ILW) required:
  - Main issues observed in ITER BL demonstration discharges at AUG is the topic of this status report:
    - Central (wave) heating beneficial (or even mandatory) to avoid accumulation of high-Z impurities (W)

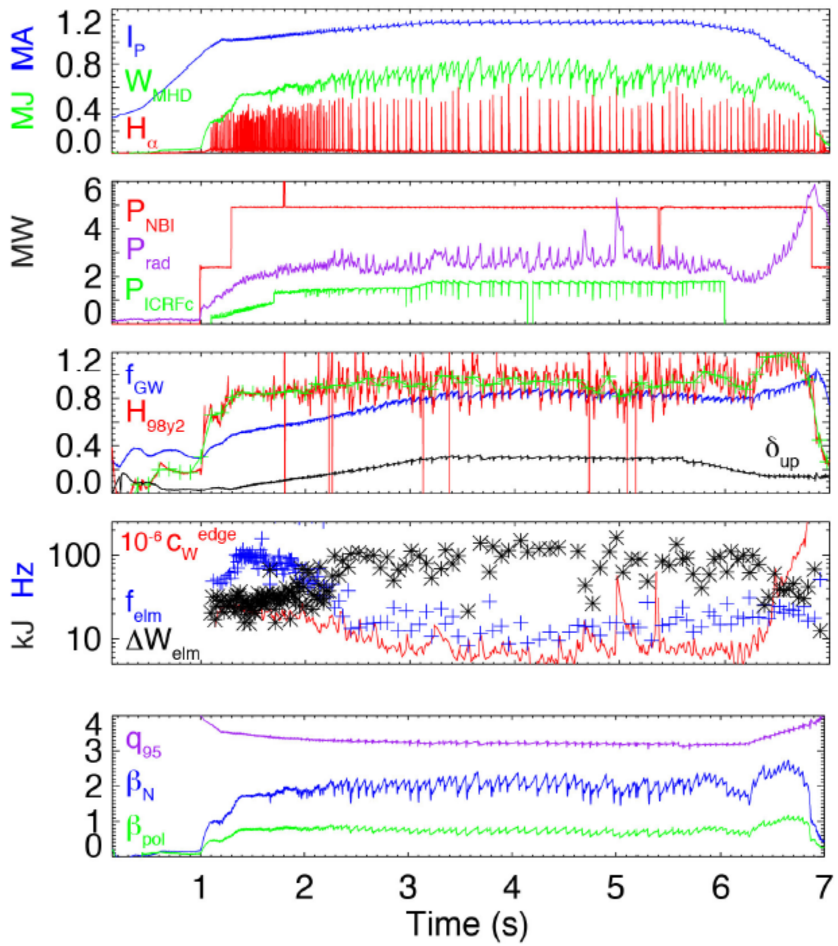
      ➡ only two combinations of I_p / B_t possible for AUG-W

ITER baseline scenario at ASDEX Upgrade (AUG)

1.1 MA / 1.8T w. X3 ECRH

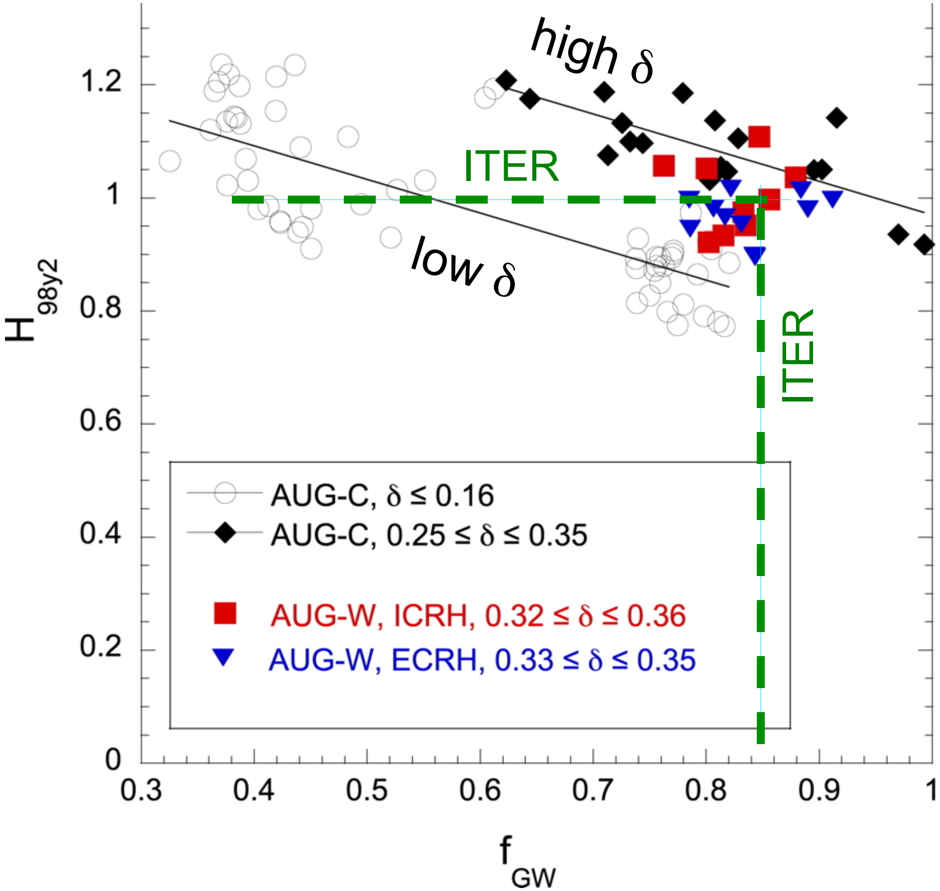


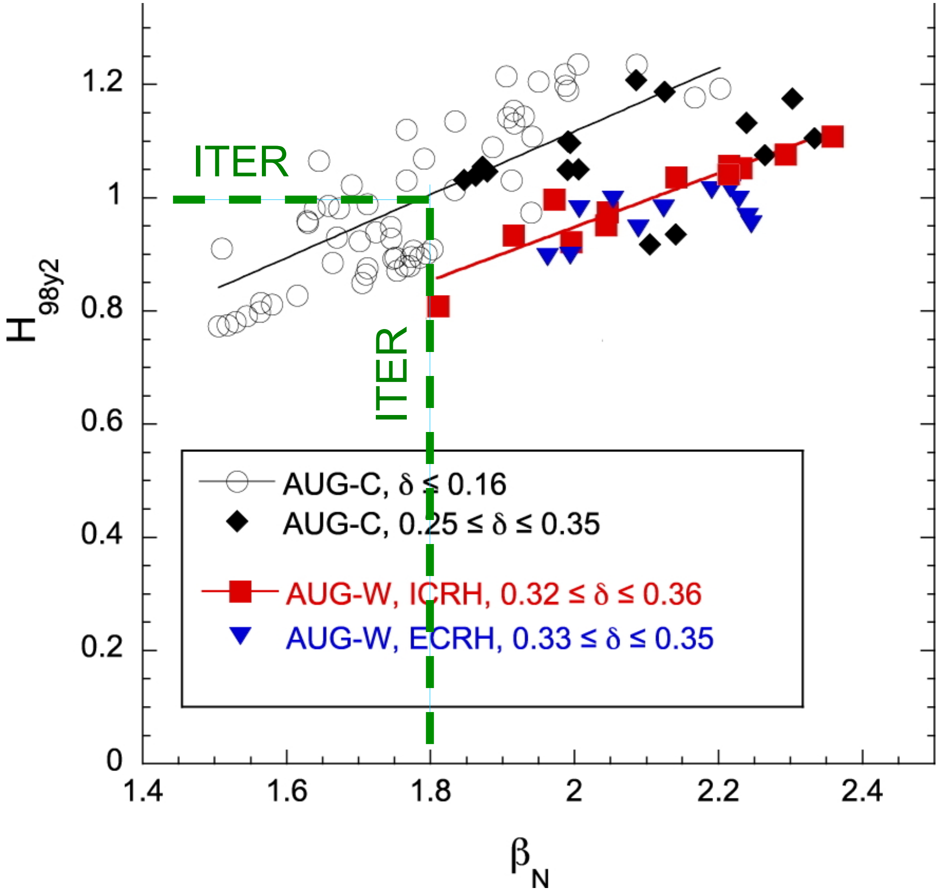
1.2 MA / 2.0T w. ICRH



Stable discharges as long as enough gas puff and central heating

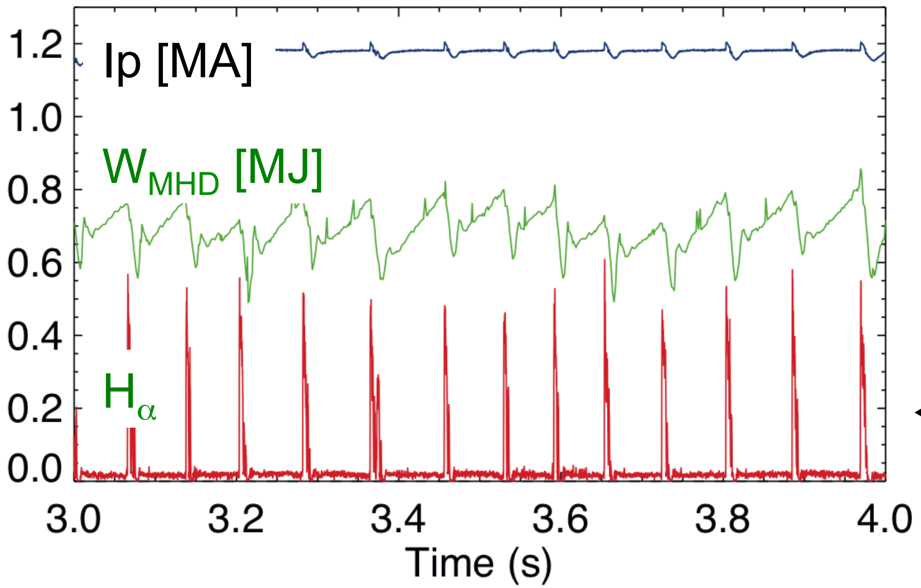
Confinement in ITER BL scenario at AUG
(black = AUG-C, coloured = AUG-W)





- Rising triangularity improves confinement at higher n/n_{GW}
- H_{98} increases with β_N, however: **H_{98}=1 only at β_N > 2**
- **1st major issue: no stable low P_{heat} operation in AUG-W**

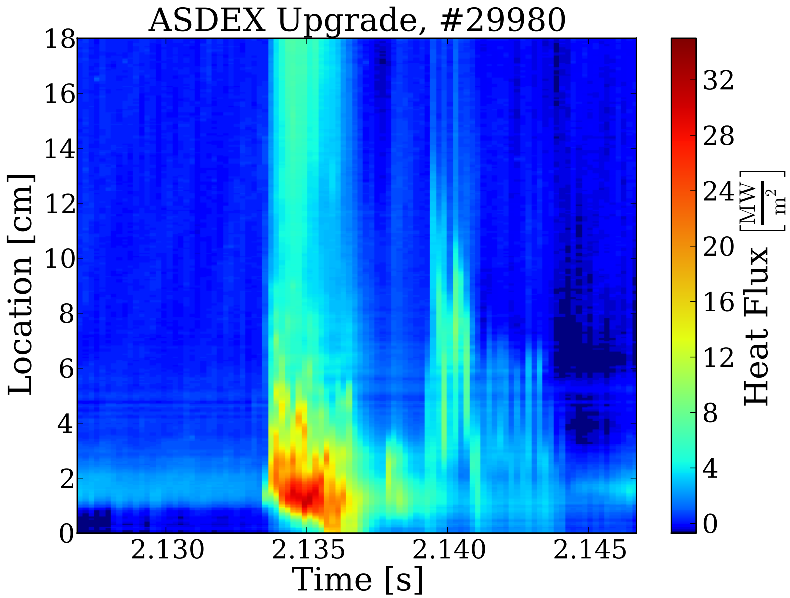
2nd major issue: ELM behaviour



- 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

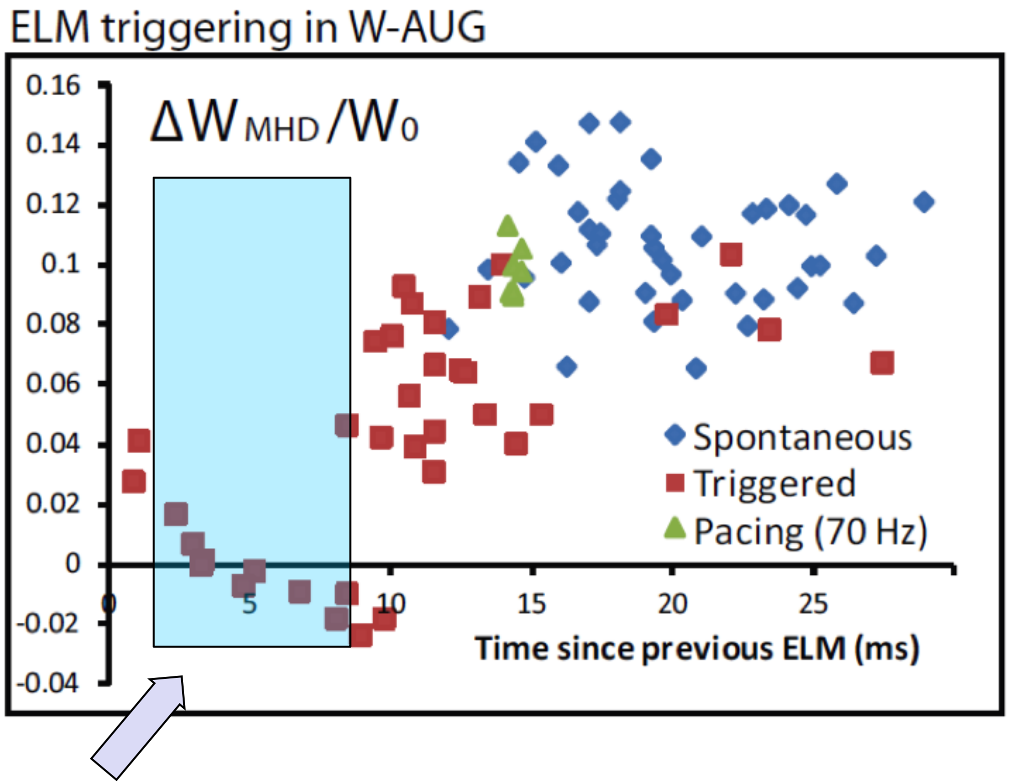


Mitigation of ELMs in the ITER BL scenario

ELM mitigation attemps done using:

- **pellets for ELM pacing**
- **nitrogen seeding** (a few attempts only)
- **magnetic perturbation (MP) fields**

ELM triggering via pellets on AUG-W, in general



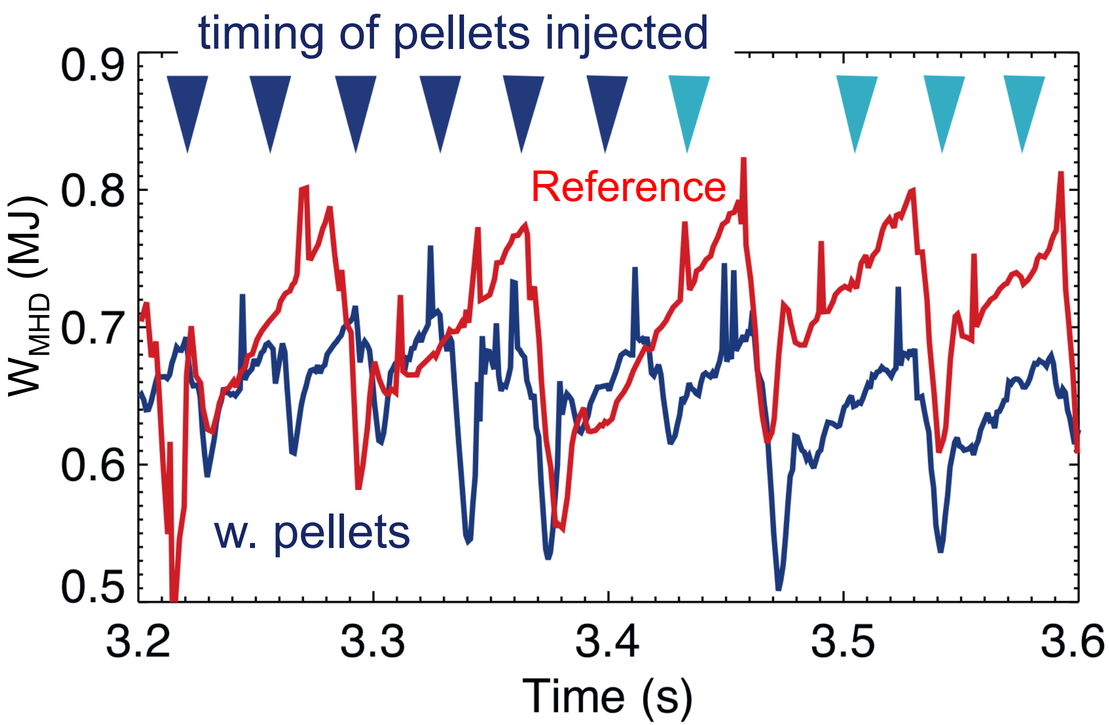
With W-wall: ‚dead time' after previous ELM until triggering can be effective

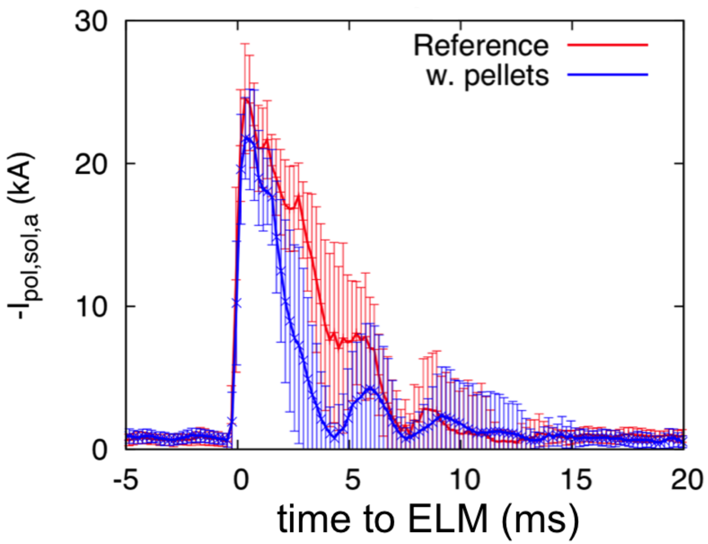
- for significant part of ELM cycle, pellet triggering not possible
- sets an upper limit for pacing frequency under these conditions

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)





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

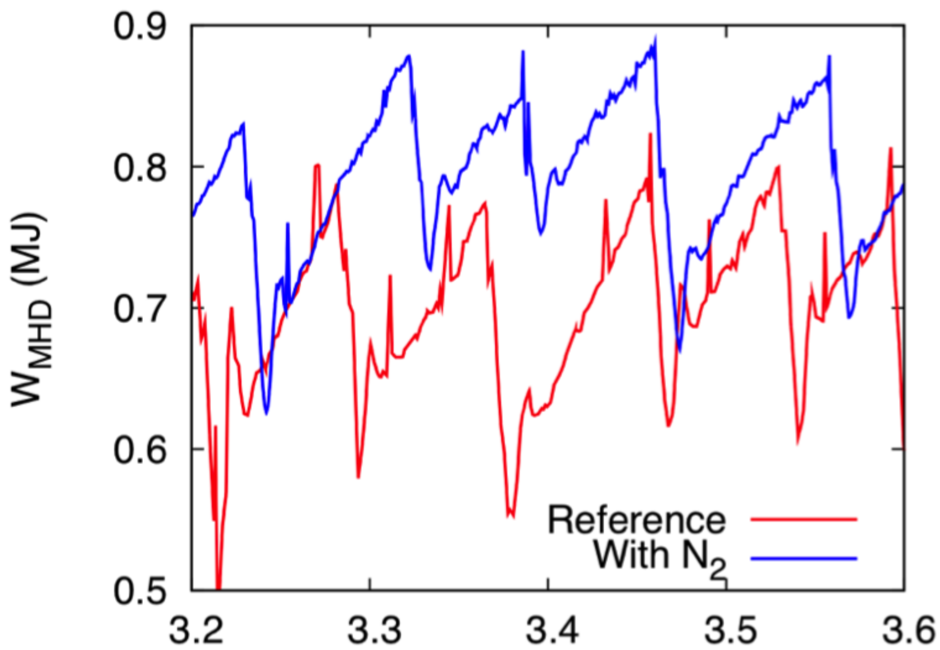
First attempt of nitrogen seeding in ITER BL scenario

ELM size:

- ELMs not majorly affected by nitrogen seeding, but so far only low N puff rates tried

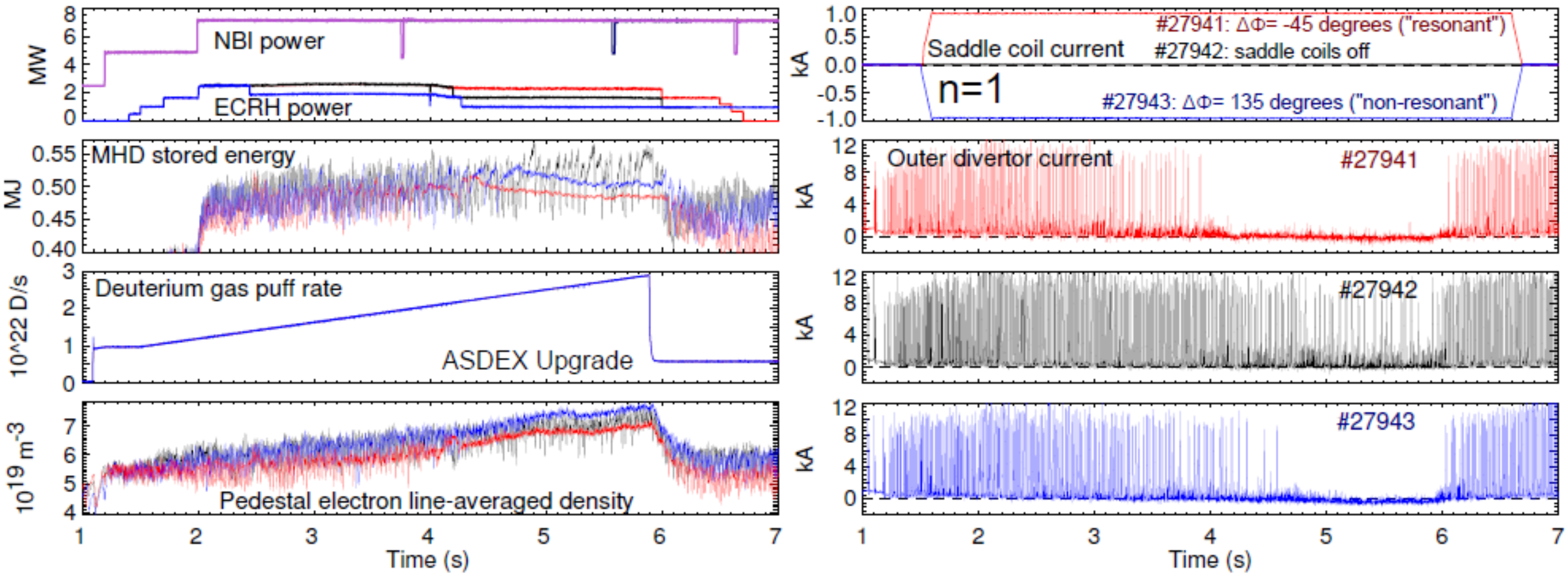
Impact on confinement:

- Confinement improves by a few %



Much stronger effect in other AUG scenarios found -> More studies needed in ITER BL

ELM mitigation by (R)MPs on AUG in general



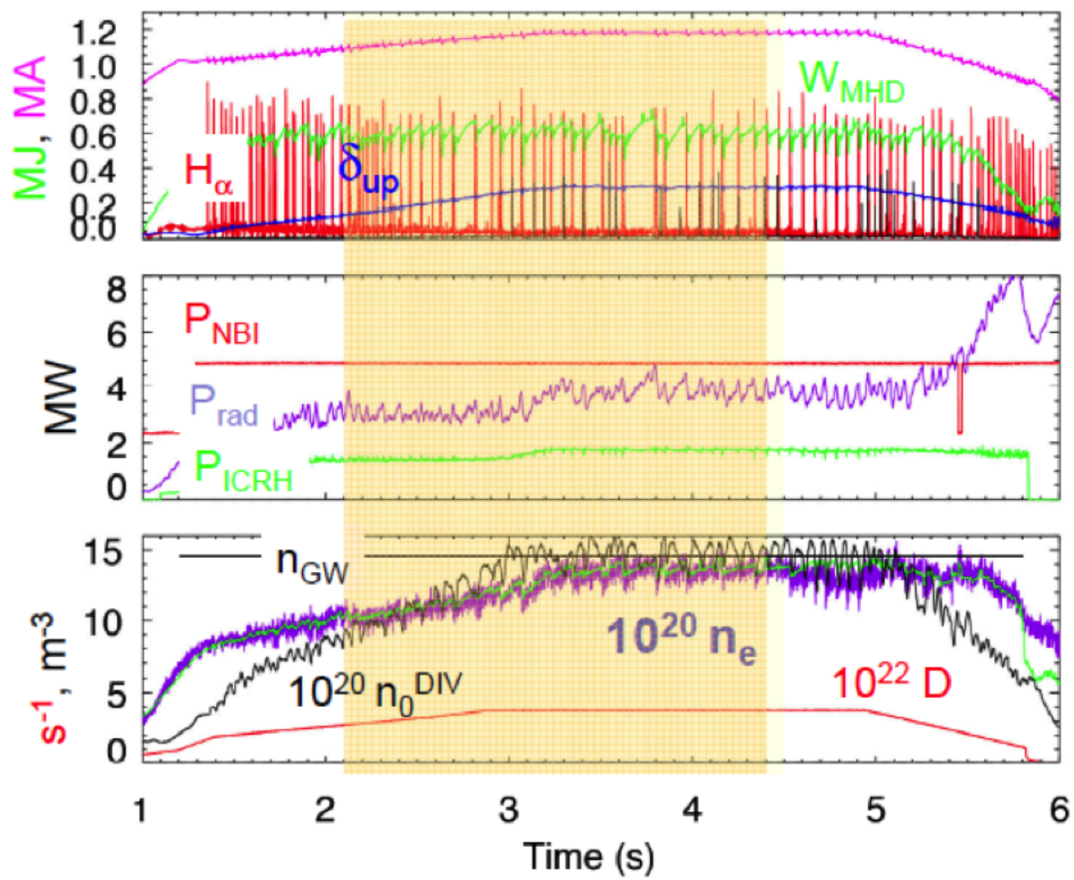
ELM mitigation at high density at AUG using n=1, n=2, n=4 MPs:

- have to **exceed certain pedestal top density** (or collisionallity ?)
- ELMs turn into small, high frequency, periodic events
- largely independent of MP configuration and edge q (non-resonant)
- stored energy stays constant, W content does not rise

Initial attempt at (R)MP mitigation in ITER Baseline

ELM **mitigation attempt w. MP-coils** (#29964)

(MP-coils active in the shaded area)



…at ITER BL, MP mitigation not achieved using the standard recipe!

Demonstration of ITER BL scenario at AUG difficult

Achieved:

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

BUT:

- **Integration of ELM mitigation not achieved**
- No stable operation at low P_{heat}

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

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

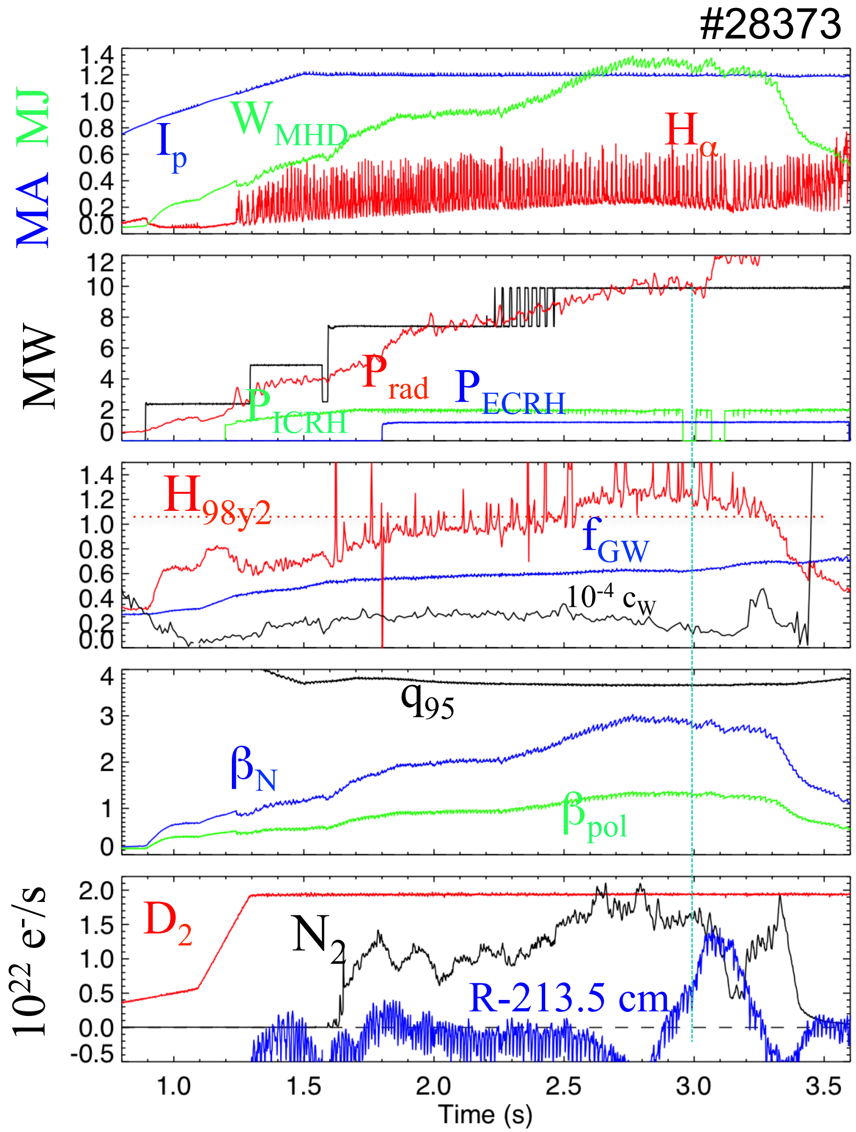
Alternative operation point for Q = 10, keeping P_{fus} and G constant

for **q_{95} = 3.6: β_N ~ 2.2, H_{98} = 1.2** **(ITER I_p ~ 12 MA)**

- Implications for required target density:
  - pedestal n_e below f_{GW} & as high as possible (for exhaust)
  - higher n_{e0} / <n_e> (w. pellets) to reach **f_{GW} ~ 1**

- Keep high triangularity to reach simultaneously high confinement at high f_{GW}

Starting point for development of alternative Q=10 scenario at AUG: Hybrid plasma at q_{95} = 3.7



- N-seeded Hybrid Scenario 2.5T / 1.2MA achieved so far:
  - low-delta shape, δ=0.27
  - β_N = 2.8, H_{98y2} = 1.27, f_{GW} = 0.63, f_{ELM}=68Hz

- **Target values of** alternative Q=10 scenario **NOT reached, but** seems realistic to be achieved in the future **with less P_{heat} at higher δ and higher f_{GW}.**

Outlook

ASDEX Upgrade will work in future campaigns on:

- **solving the issues of the q_{95} = 3 scenario** (in particular ELM mitigation)
- and in parallel try to **port the Hybrid scenario** from the q_{95} ~ 4-5 domain **to lower q_{95} ~ 3.6** with the aim to **qualify it for an alternative Q=10 scenario** for ITER

BACKUP Slides

ITER BL scenario demonstration in JET-C

JET data with the Carbon wall at 2MA/2T

- P_{in}/P_{LH}=1.07
- q_{95}=3.25, H_{98} = 1.11
- β_N = 1.52, f_{GW} = 0.71

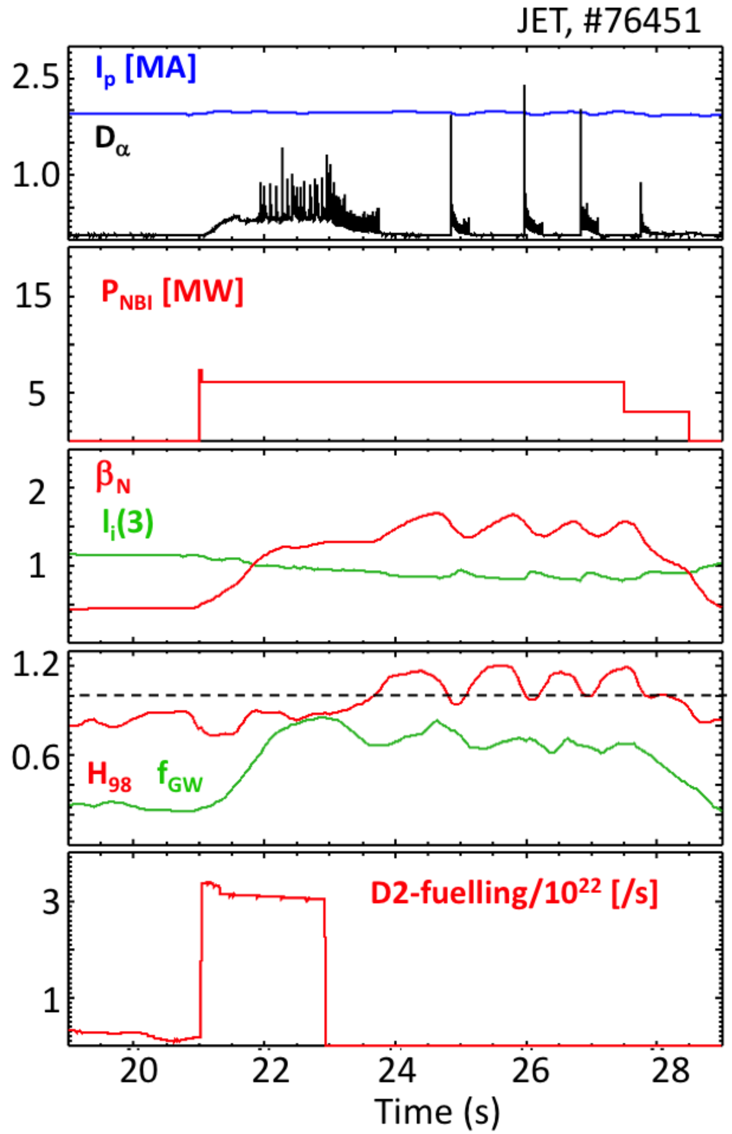
These results can not be repeated with the ILW at JET (W accumulation)

Also not relvant for ITER:

- Infrequent large ELMs
- Impurity accumulation (seeded and W)

2014: Demonstrate baseline with the ILW

Sips et al. IAEA FEC 2012



ITER BL scenario demonstration in DIII-D

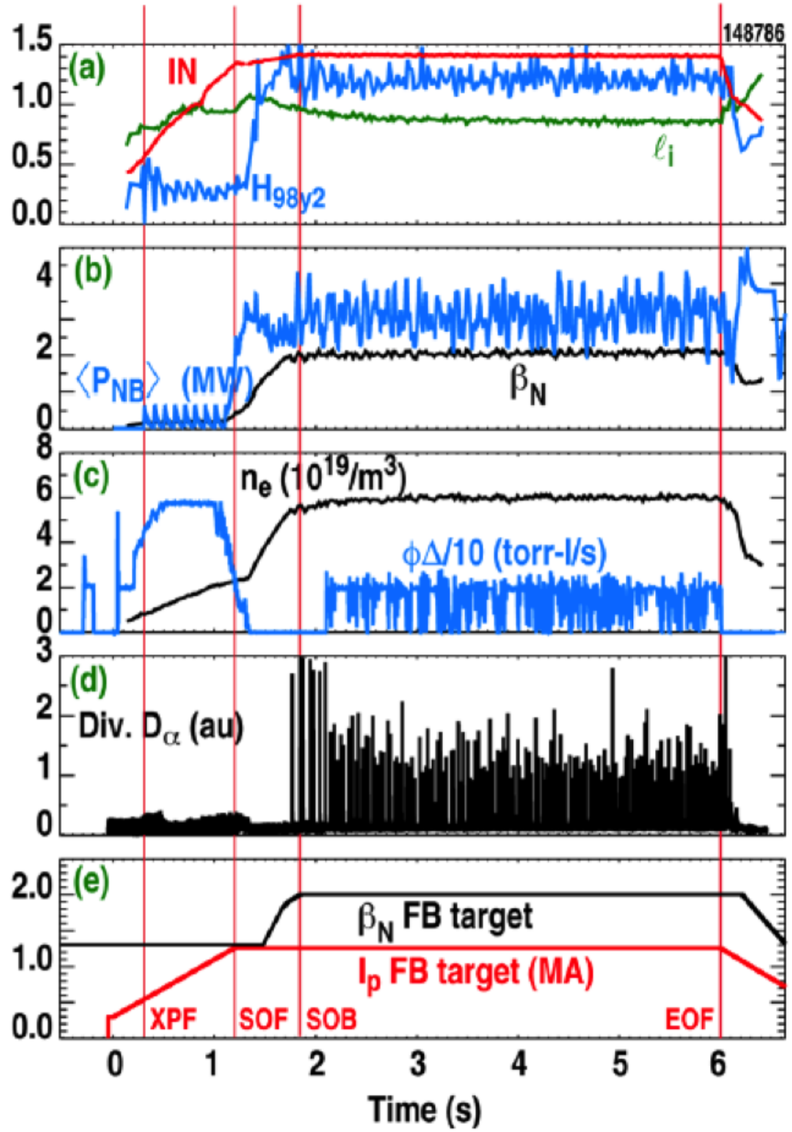
DIII-D data with a Carbon wall

- q_{95}=3, H_{98} = 1.2
- β_N = 2, f_{GW} ~ 0.5-0.6
- Long pulse operation

Infrequent ELMs: Need to operate at β_N =2 and some gas dosing.

ELM mitigation not effective at q_{95}=3 (ELM pacing or RMPs)

Experiments started with dominant ECRH and low net torque from balanced NBI.



Luce et al. ITPA, 2013

ITER BL scenario demonstration in AUG-C (2002)

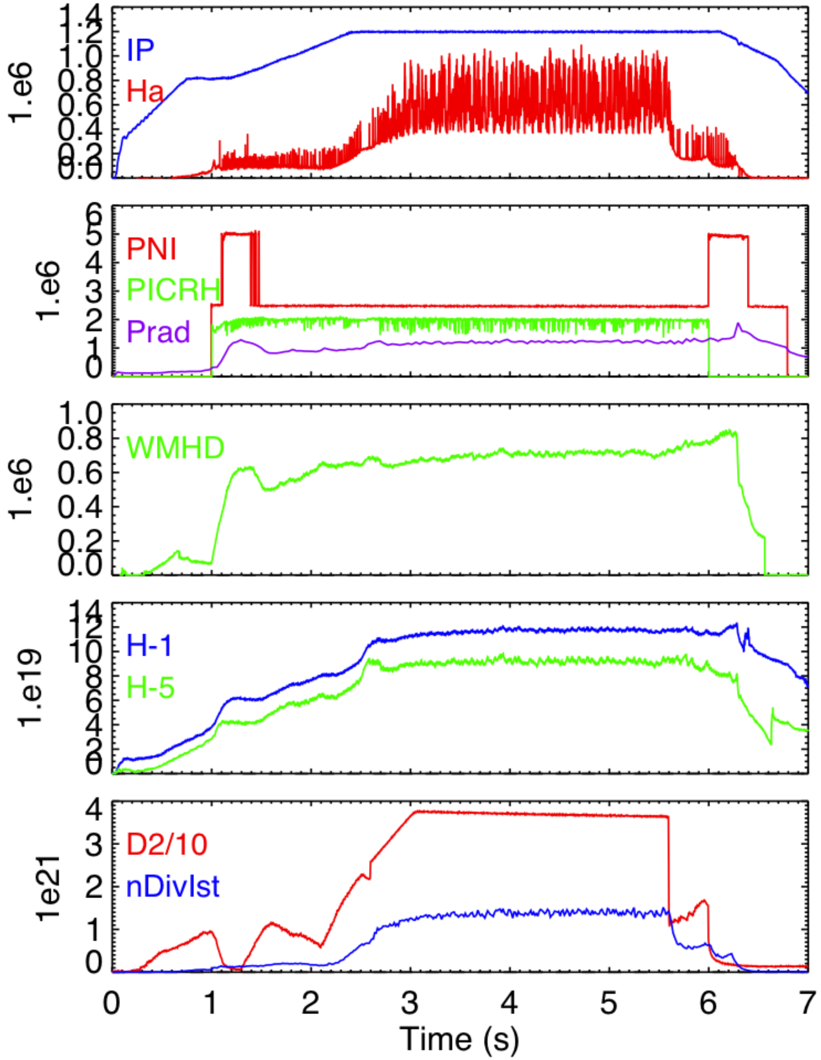
C-dominated AUG (2002):

- δ=0.27, β_N=1.87
- H_{98}=1, f_{GW}=0.82
- ITER BL 1.2 MA / 2.0T

- early H-mode transition at high q_{95} / β_N with high P_{NBI} important for stability?

- large ELMs

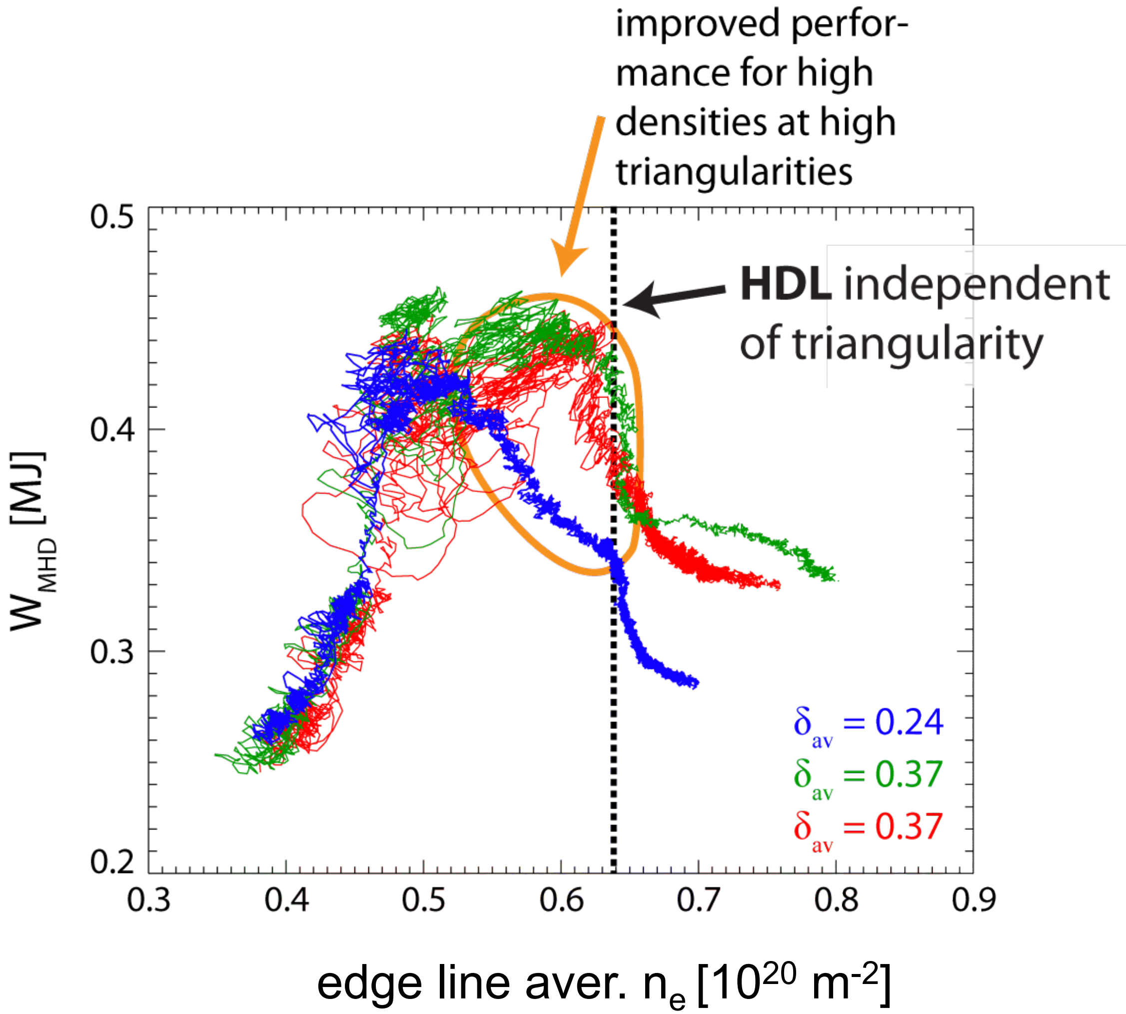
#15617



δ dependence of confinement close to f_{GW}=1

- Triangularity (δ) has **no influence** on density limit of H-modes
- **BUT**: phase with degradation of confinement starts at higher densities for high triangularity

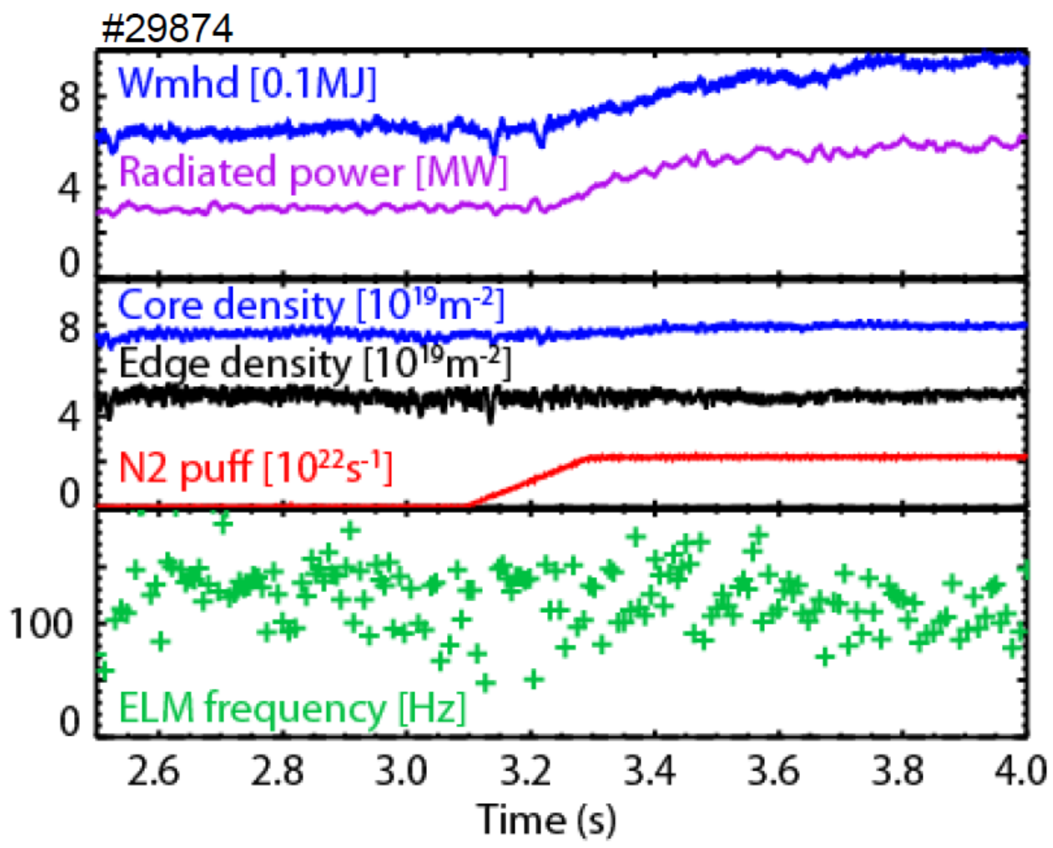
➡ **Higher performance at high densities**

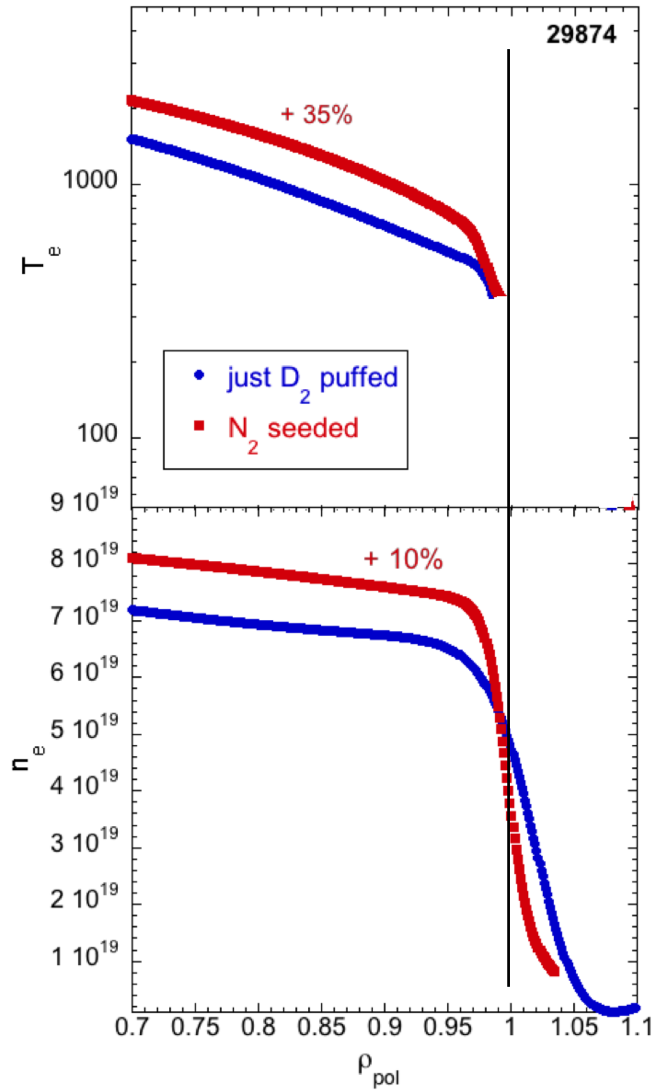


Strong confinement improvement with N seeding

- Wmhd increases when seeding N into the divertor

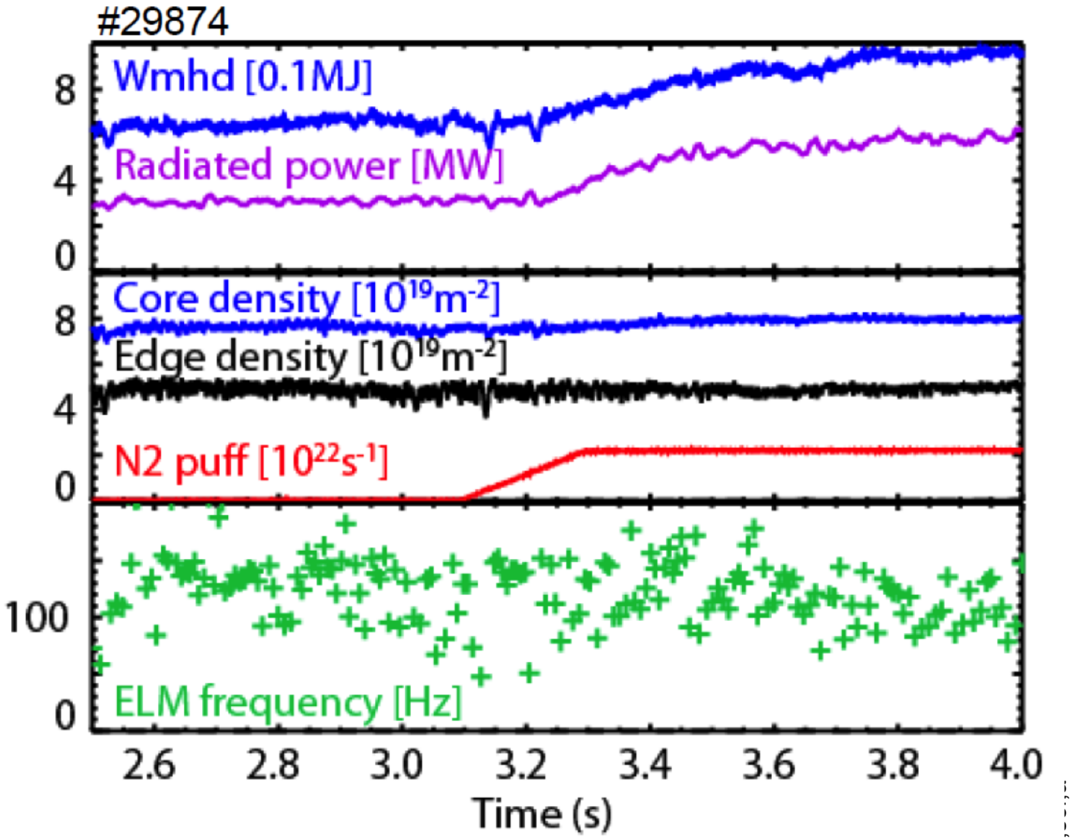
40% increase in this case!

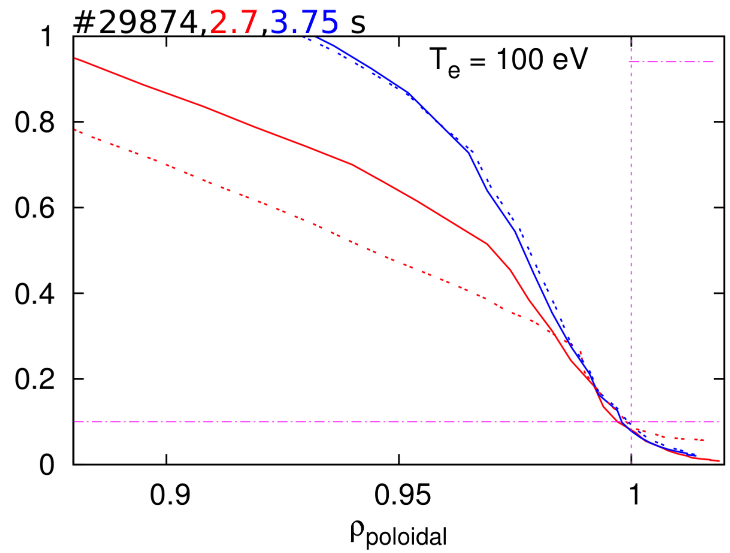


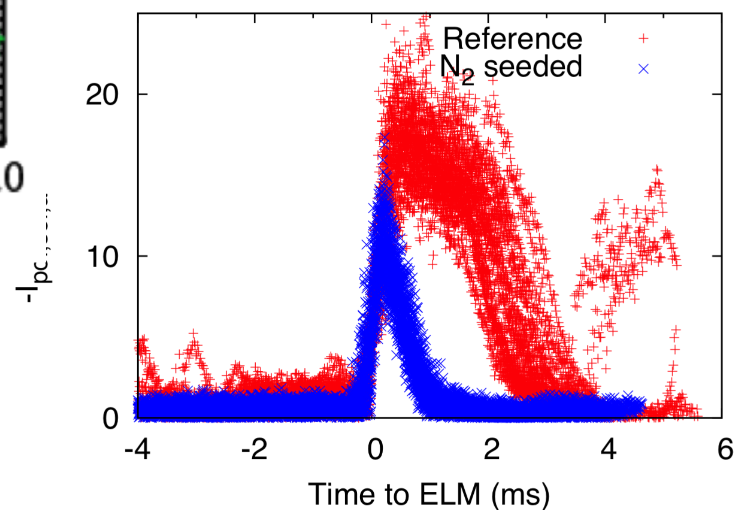


- **Clear effect of pedestal**

ELM size reduction with N seeding

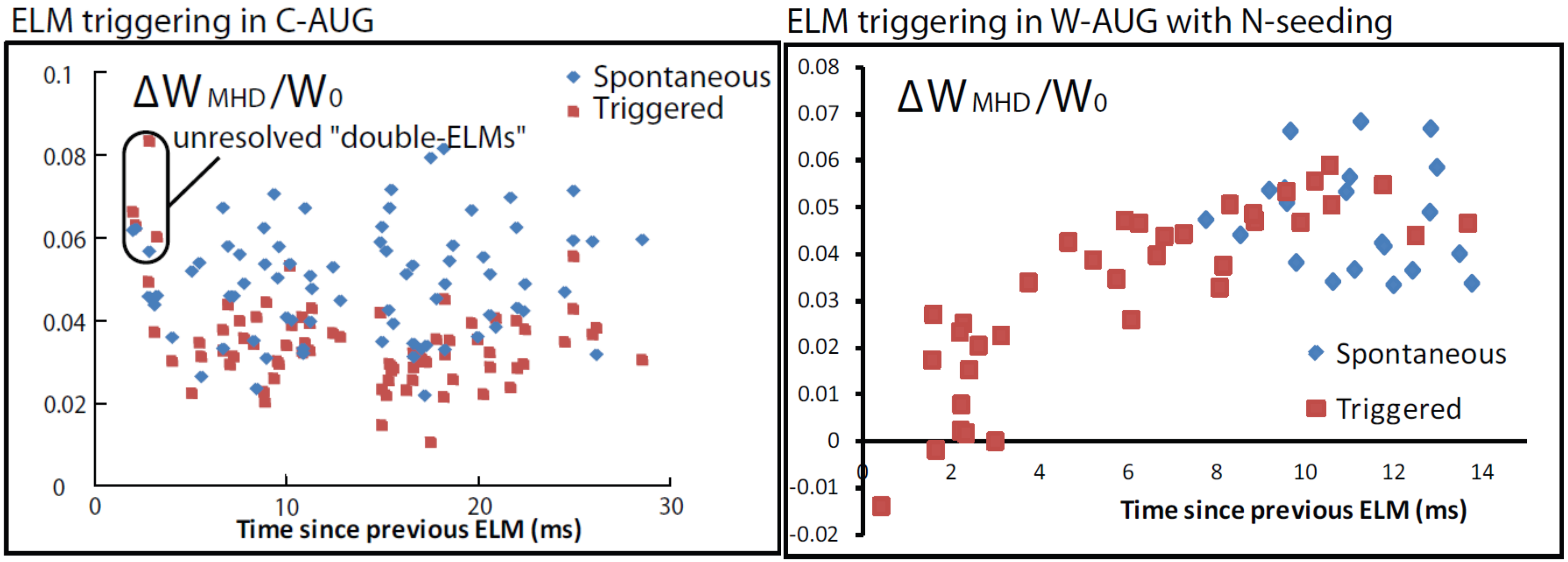






- typically ELMs are **shorter and have smaller peak power load**
- possibly due to second phase of ELM crash being blocked by nitrogen

ELM triggering via pellets with N seeding in AUG-W

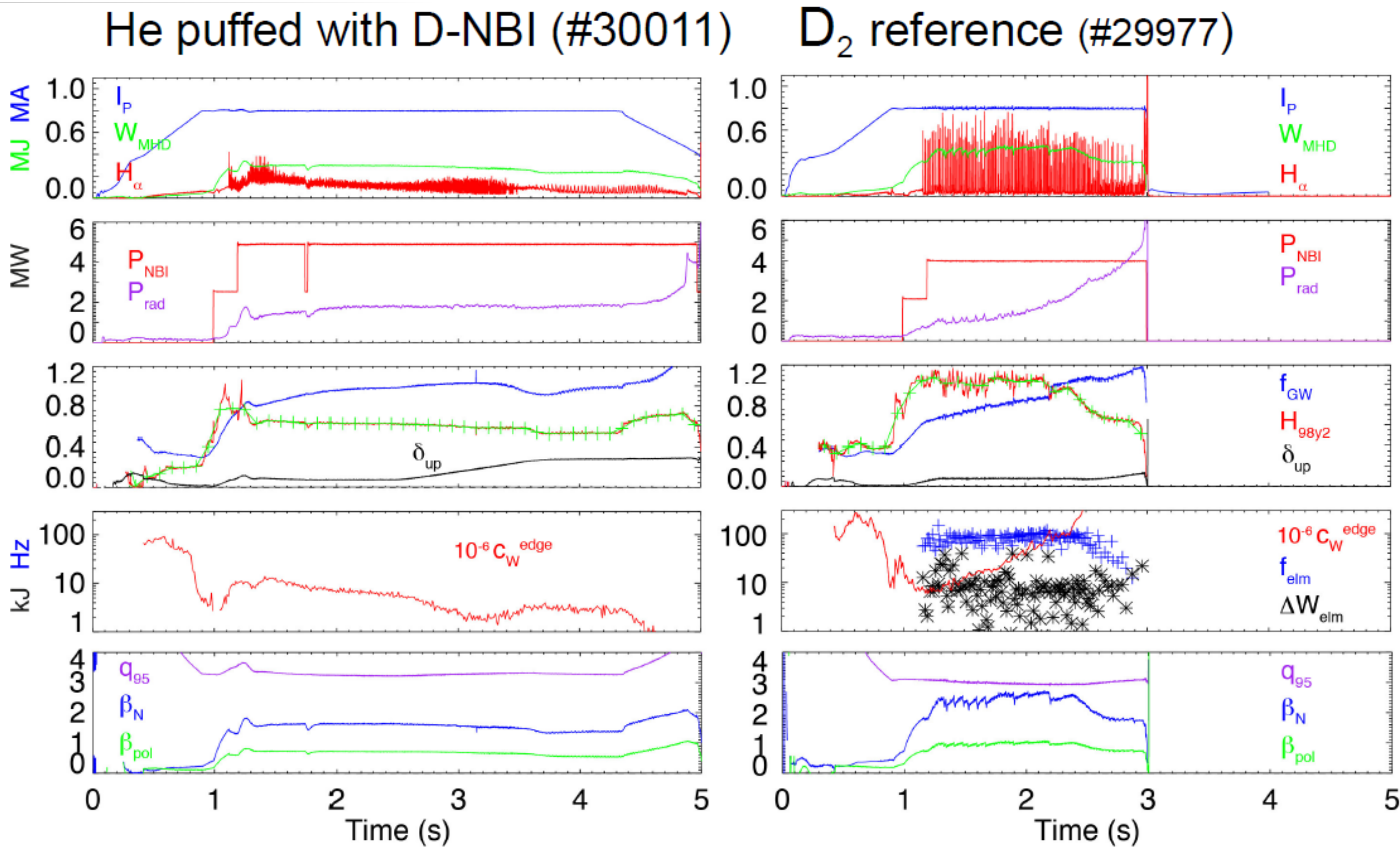


With higher heating power and N-seeding in W-device, ELM duration returns to C-like value and ‚dead time‘ becomes shorter

Efficiency of pellet pacing depends on nonlinear ELM evolution

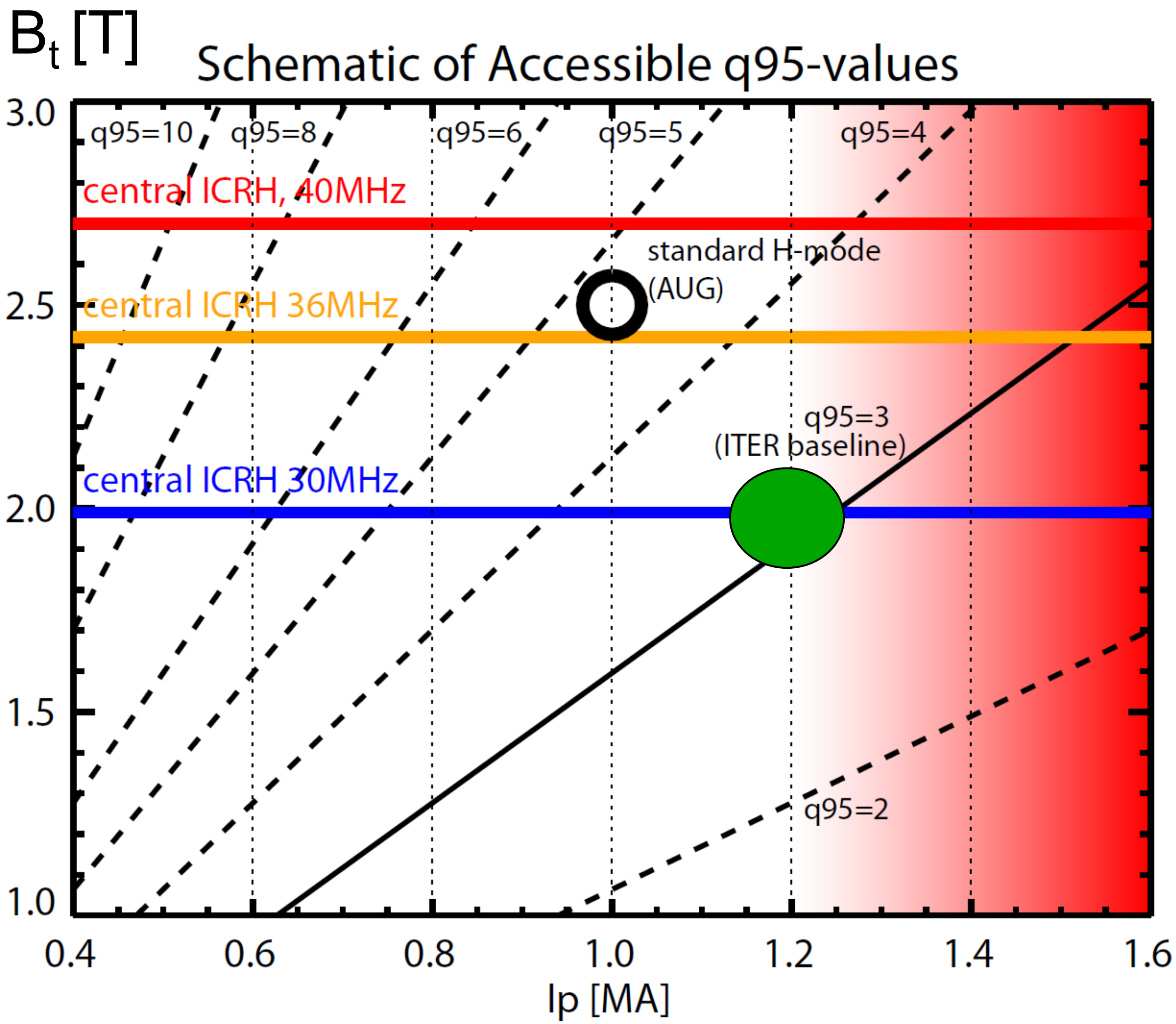
⇒ truly predictive capability only if ELM cylce is understood nonlinearly

ITER baseline scenario in Helium on ASDEX Upgrade



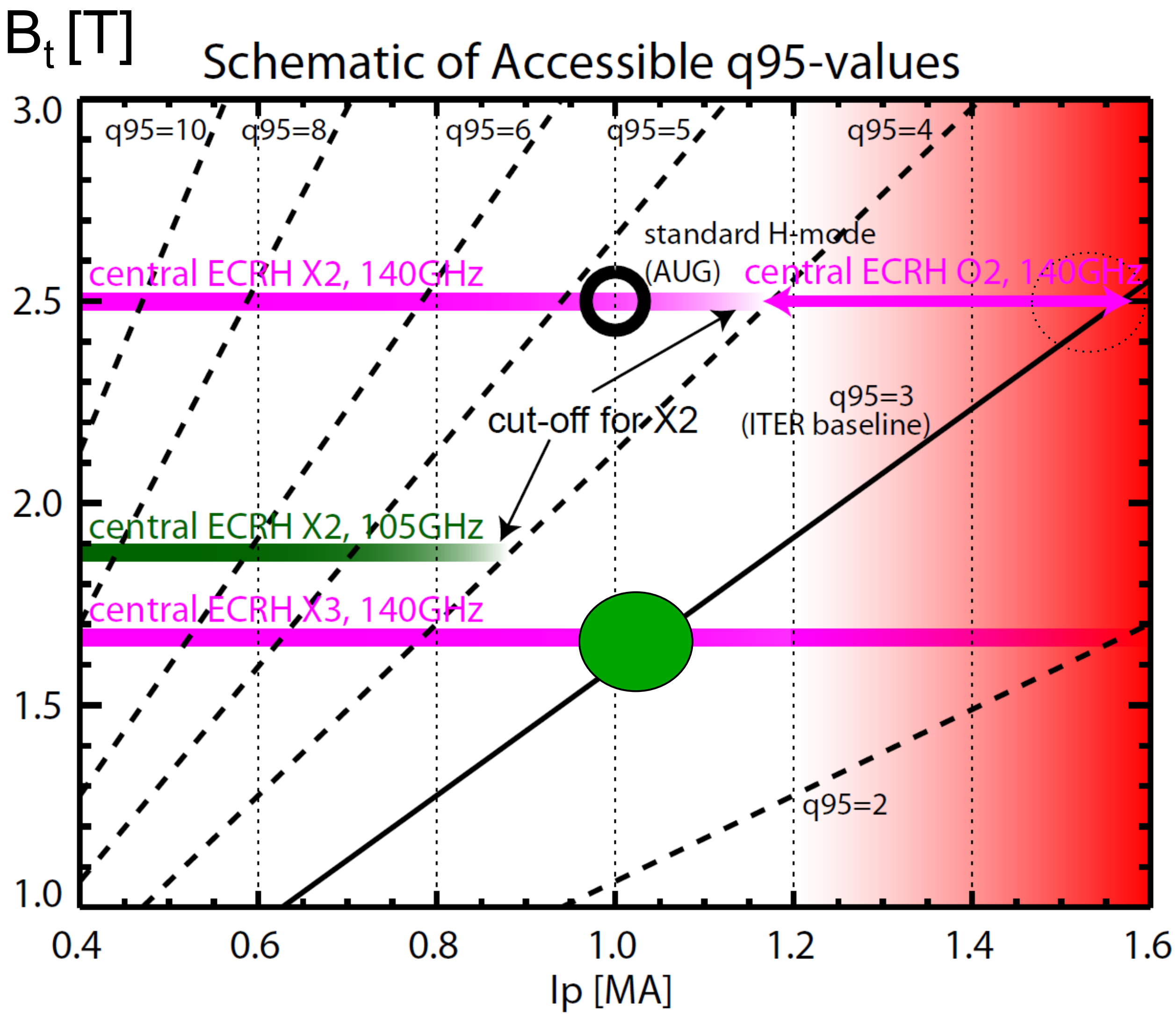
In He, access without central RF, but at lower confinement, smaller ELMs

Access to central ICRH at AUG at q_{95} = 3



- Standard AUG-operation at q_{95} ~ 4.7 i.e. 1MA / 2.5T
- **ITER-baseline: q_{95} = 3 i.e. 1.2 MA / 2.0T**
- **Boundary Condition** Tungsten erosion at limiter close to the antenna due to RF sheath-enhanced sources

Access to central ECRH at AUG at q_{95} = 3



- Standard AUG-operation at q_{95} ~ 4.7 i.e. 1.MA / 2.5T
- **ITER-baseline: q_{95} = 3 i.e. 1.1 MA / 1.8T**
- Boundary Conditions Cut-Off density
- Required for ECRH: X3 (O2) heating schemes => central T_e > 1.5 keV for good absorption