Long pulse operation in JET-ILW

E. Lerche[1,2], D. King[2], X. Litaudon, S. Brezinsek, E. Joffrin, F. Auriemma, M. Beldishevski, N. Balshaw, M. Baruzzo, A. Boboc, P. Card, I. Carvalho, P. Carvalho, I. Coffey, P. Mc Cullen, S. Dalley, E. Delabie, P. Dumortier, R. Felton, N. Fonnesu, S. Gerasimov, Z Ghani, A. Goodyear, N. Hawkes, R. Henriques, S. Hotchin, P. Jacquet, I Jepu, D. Keeling, D. Kinna, D. Kos, E Litherland-Smith, R. Lobel, P. Lomas, C. Lowry, J. Mailloux, M. Maslov, D. Matveev, A. Meigs, S. Menmuir, J. Mitchell, I. Monakhov, C. Noble, M. Poradzinski, F. Rimini, S. Silburn, E. R. Solano, H. Sun, C. Srinivasan, B. Thomas, D. Valcarcel, R. Villari, J. Waterhouse, A. West, I. Young and JET Contributors* and the EUROfusion Tokamak Exploitation Team**

** See the author list of C.F. Maggi et al. 2023 Nucl. Fusion 63 110201*
*** See the author list of E. Joffrin et al. 2024 Nucl. Fusion 64 112019*

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JET

UK Atomic Energy Authority

Special thanks to the JET/UKAEA Engineering, Technician, SL, Pilot ,CODAS and Diagnostics teams

EUROfusion

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Motivation

- Long pulse performance in H-mode in a large full-metal machine (CICLOP)

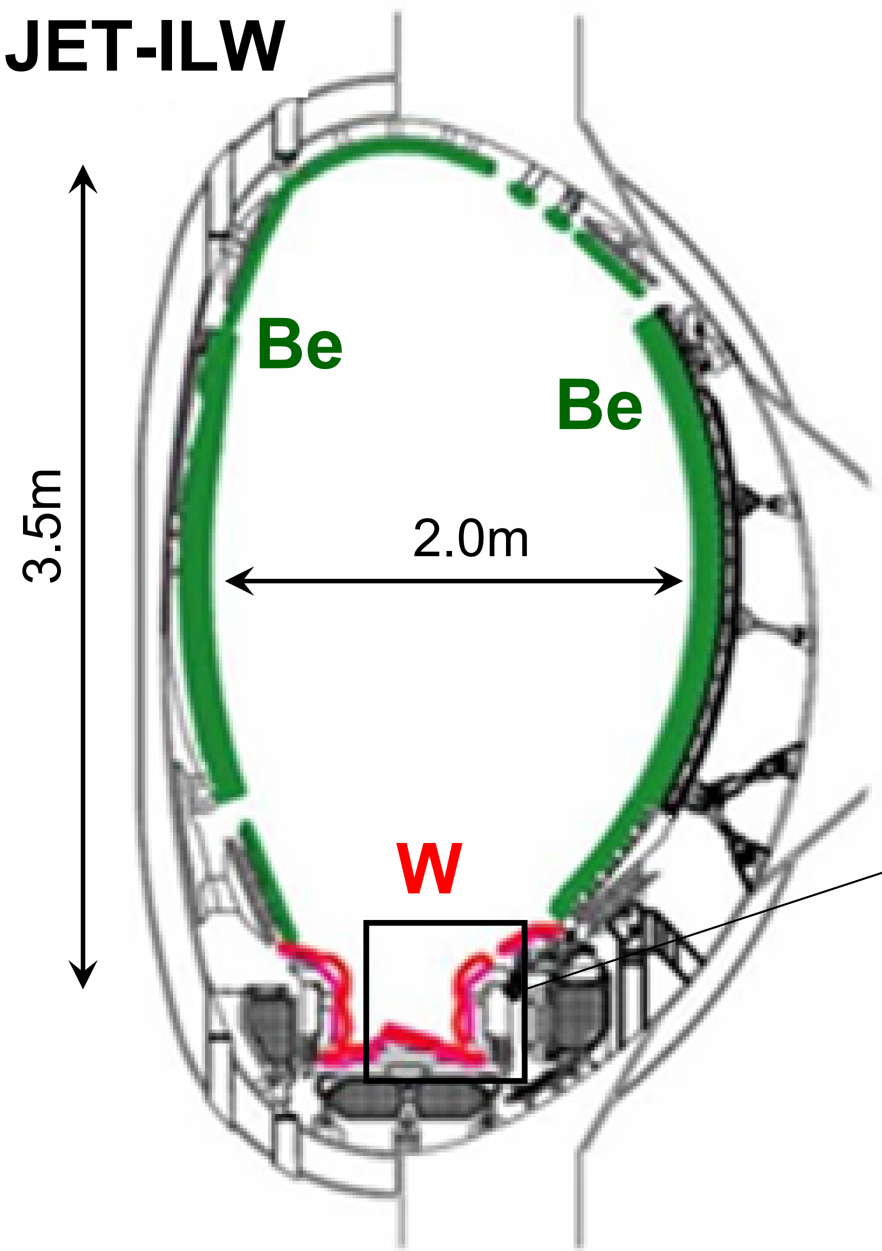
- Impurity behaviour (source and transport) & discharge stationarity

- Heat loads with non-actively cooled PFC's (Be-wall / W-divertor)

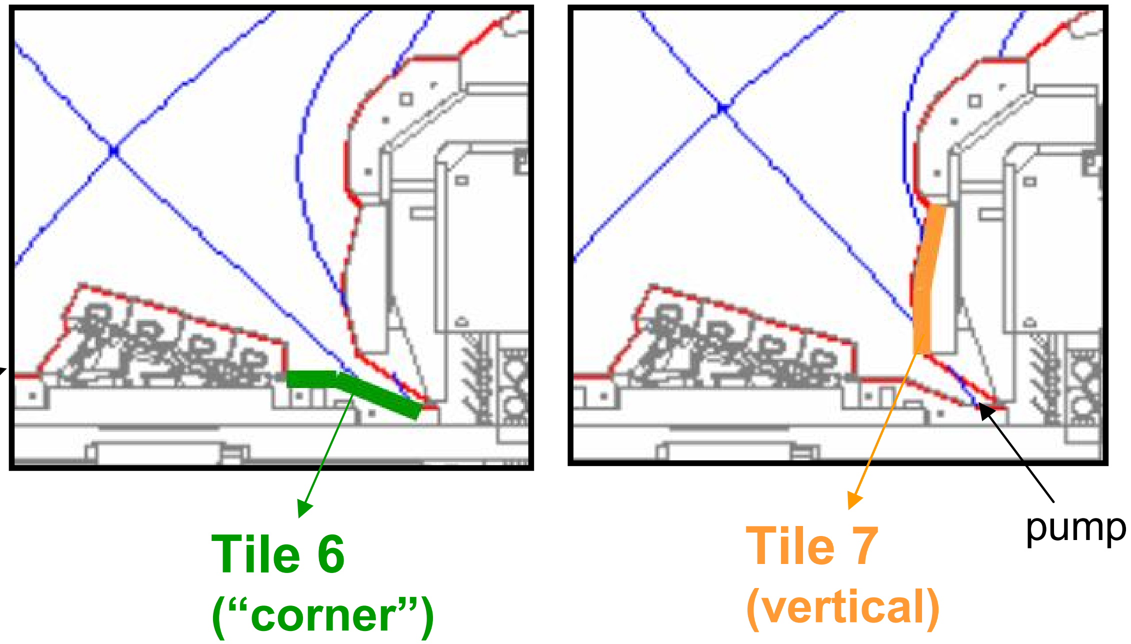
- Plasma wall interaction in long time scales (thermal equil.) (D. Matveev)

- Engineering challenges for Long Pulses in JET (D. King)

The ‘ITER-like’ wall (ILW)



- **JET-ILW:** Be main chamber, W divertor
- Divertor tiles not actively cooled (but some heat exchange with neighbouring structures)
- Enhanced set of diagnostics (core and edge)
- Two strike-point positions used:

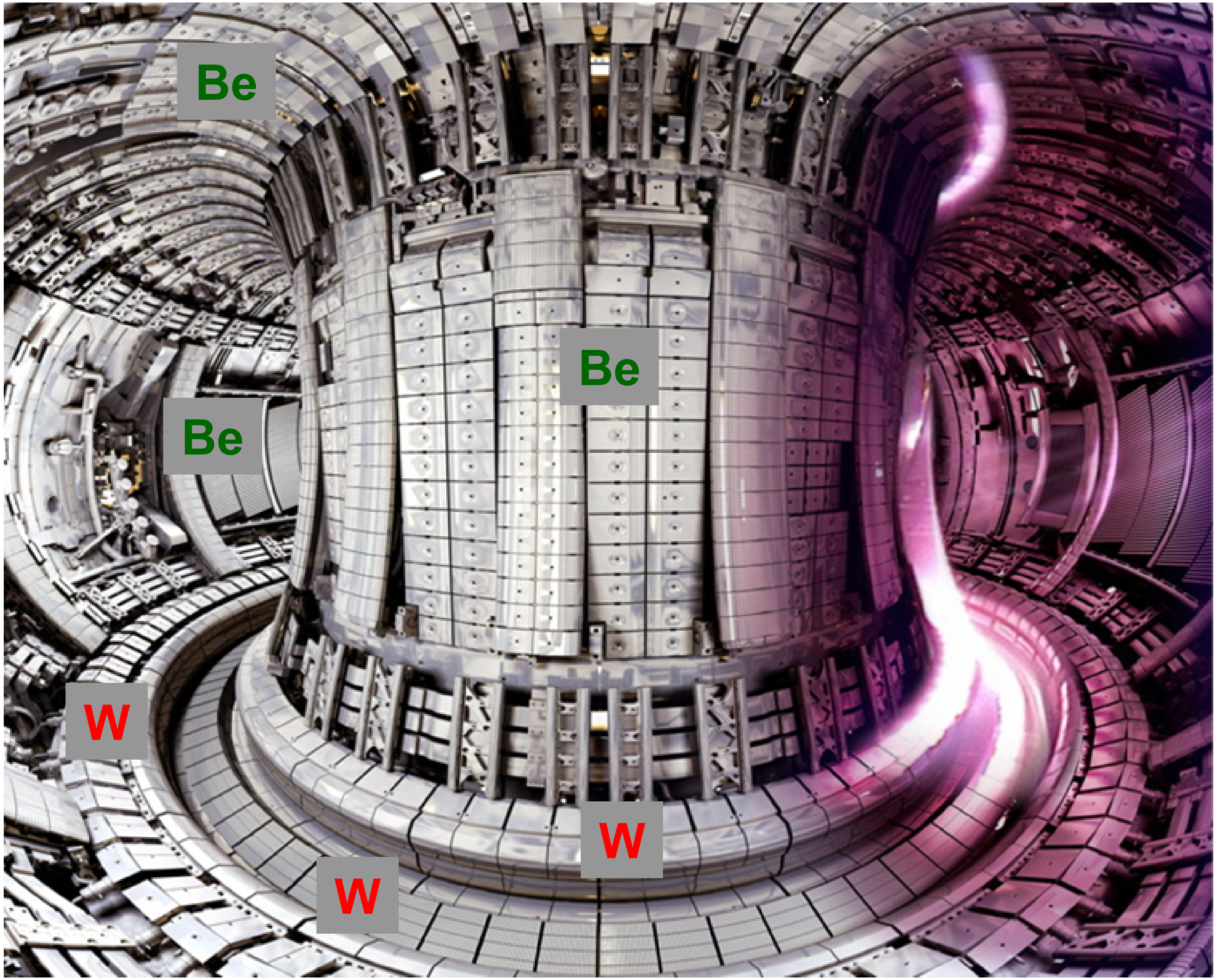


→ Tile 6 known to have better performance

[Pamela, JNM2007]
[Matthews, Phys.Scr. 2007]

[C.F. Maggi et al., Nucl. Fusion 55 (2015) 113031]

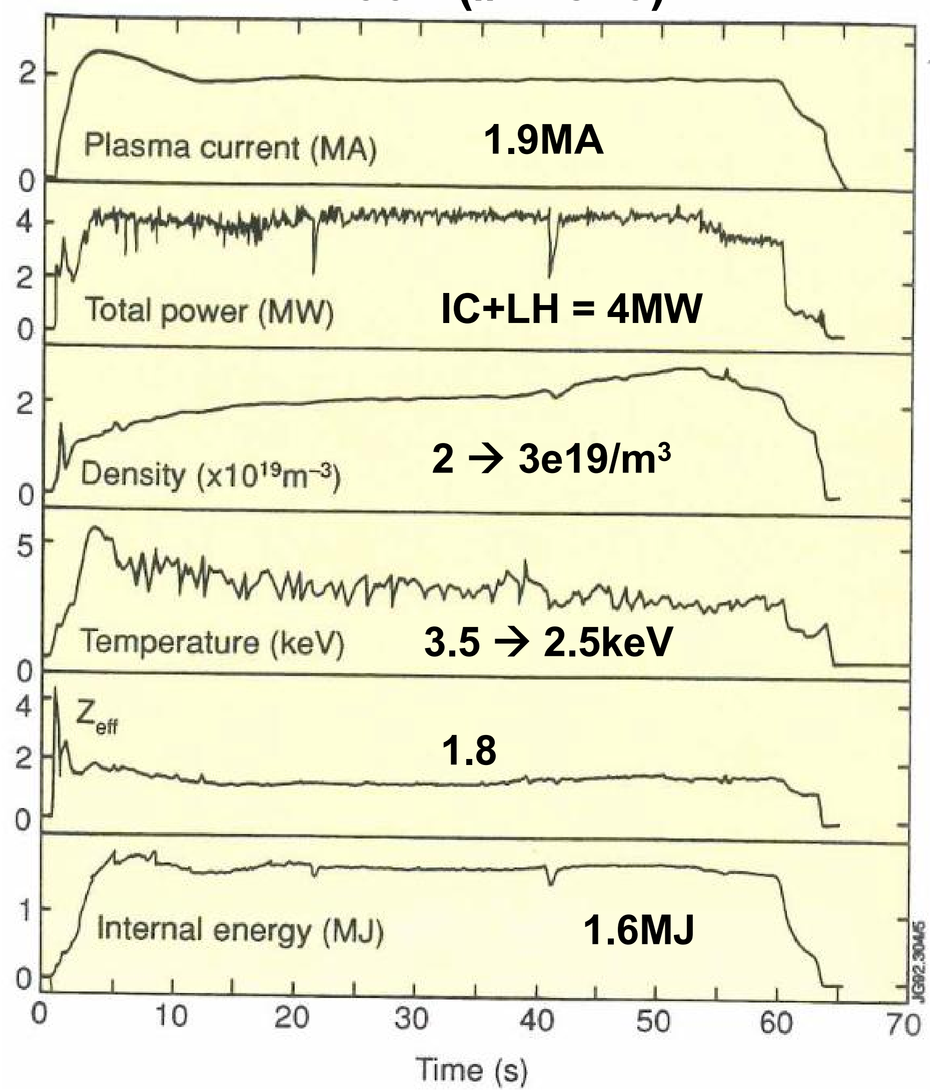
The 'ITER-like' wall (ILW)



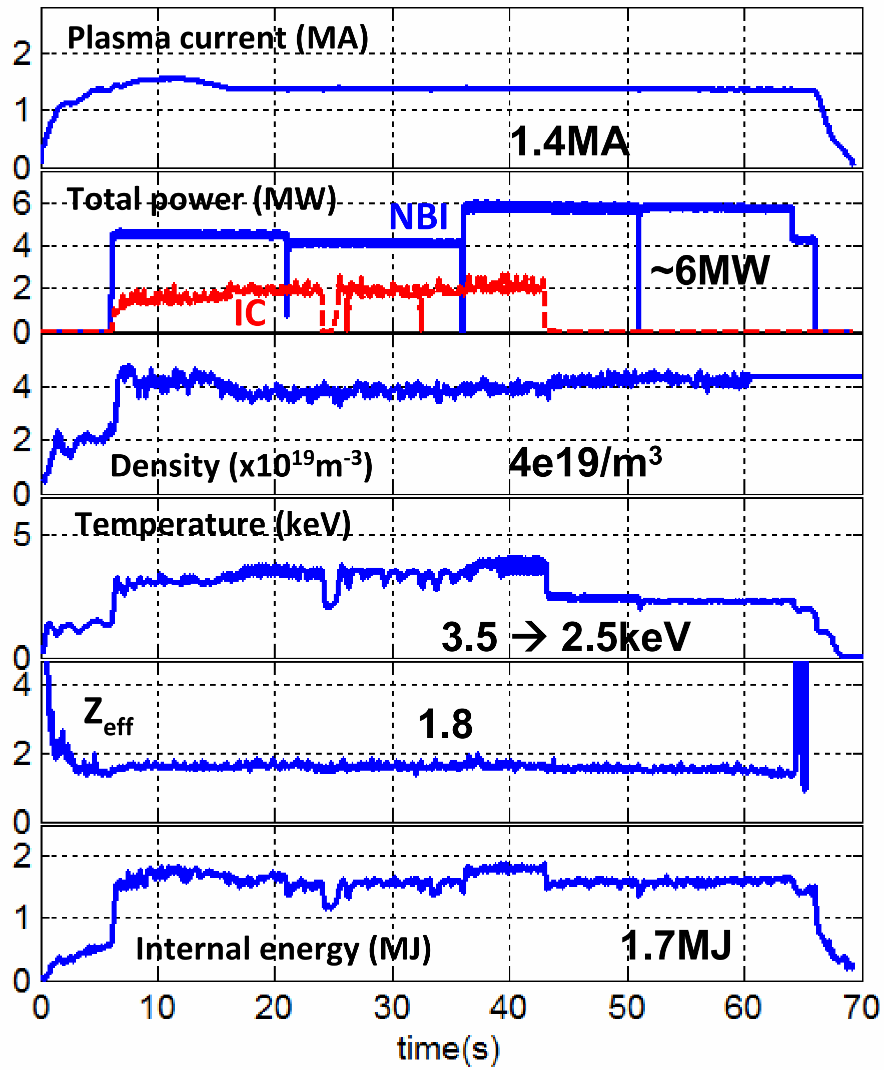
[Pamela, JNM2007]
[Matthews, Phys.Scr. 2007]

Historical background

1991 (#24875)



2023 (#105750)



- 60 sec pulses with similar performance obtained in JET-ILW <u>30 years after</u> JET-C experiments but with type-I ELMs and dominant ion heating ($T_i \sim T_e$)
- Some ~30s pulses also performed in JET-C in early 2000

[E. Joffrin et al., NF 2005, IAEA 2007]

Machine constrains for long pulses

- Various engineering challenges:

Toroidal field (I^2T), ohmic flux (resistivity), PFC power handling (not actively cooled), plasma control & diagnostics, ….

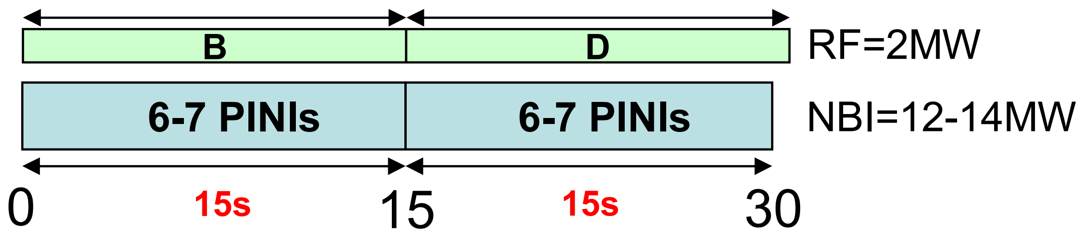
D. King

- Auxiliary heating power limitations:

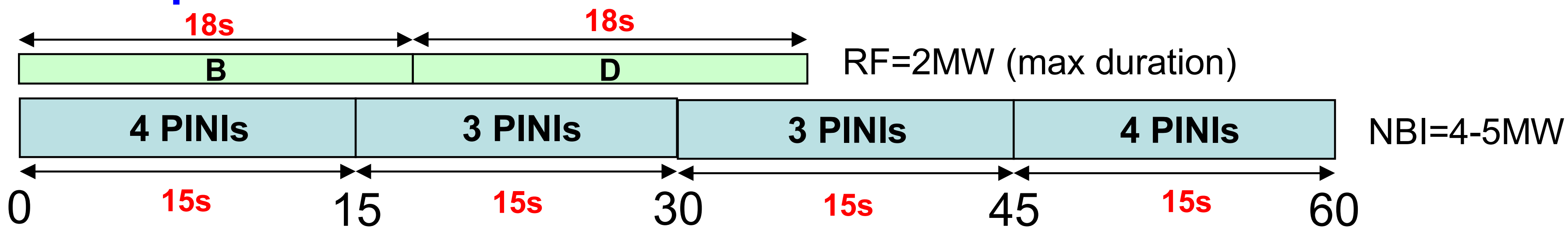
→ **NBI:** **Max 15sec** per injector, 15 injectors (1.5-2.0MW), shine-through limits (Energy)

→ **ICRH: Max 18sec** per antenna, 2 antennas (2MW)

High power 30s:



Medium power 60s:



Outline

- Overview of **30s** and **60s** pulses
  - B_0=1.9T, I_P=1.4MA
  - **30s:** $<P_{IN}>$=14-16MW
  - **60s:** $<P_{IN}>$=6-7MW

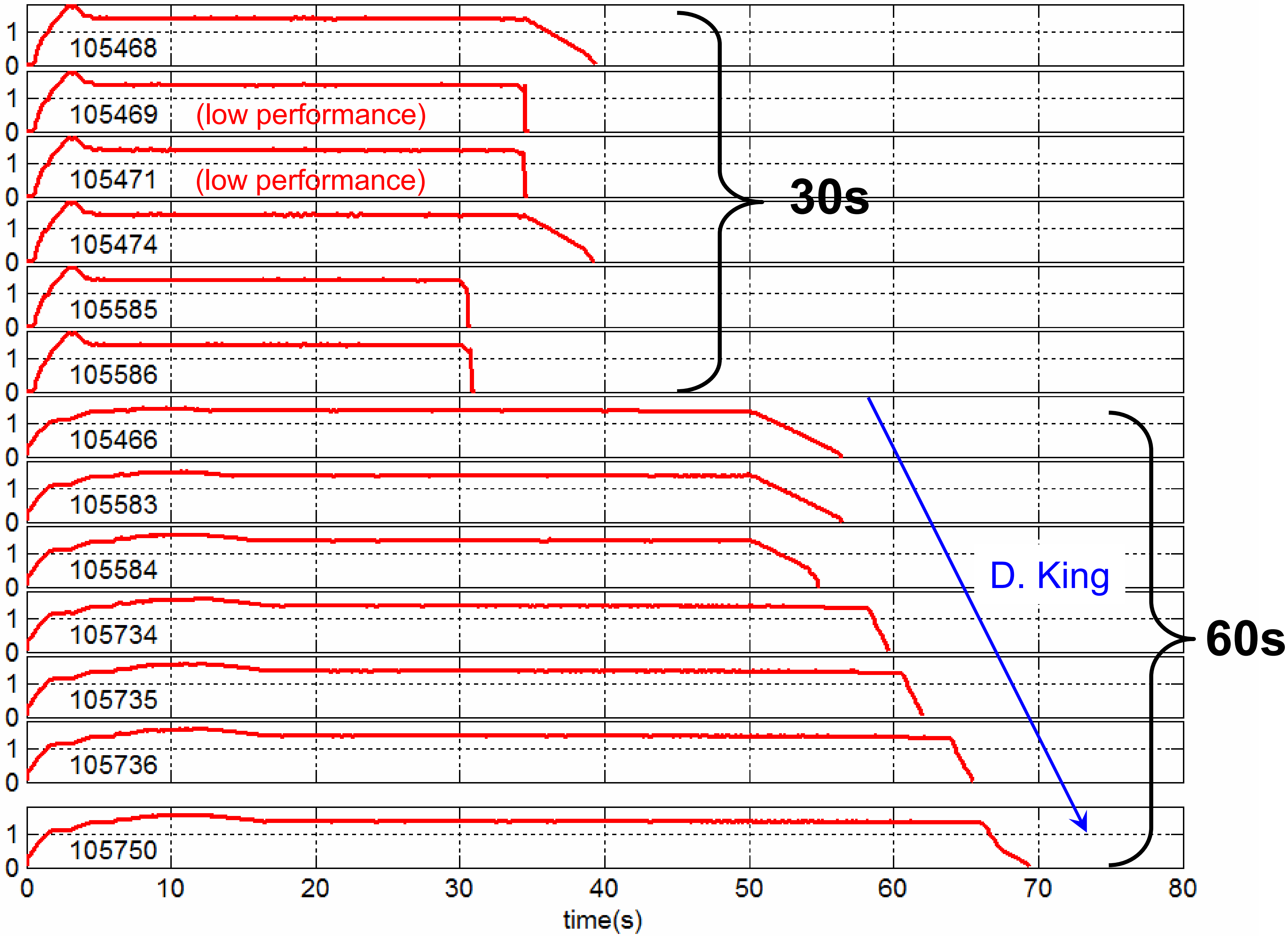
  - Performance
  - Stationarity
  - ELM behaviour

  - (PWI) – D. Matveev
  - Wall / divertor heat loads (quick glance)
  - WACT Neutron activation measurements for PrIO (R. Villari)

- Extension to the inter-machine CICLOP database (X. Litaudon)

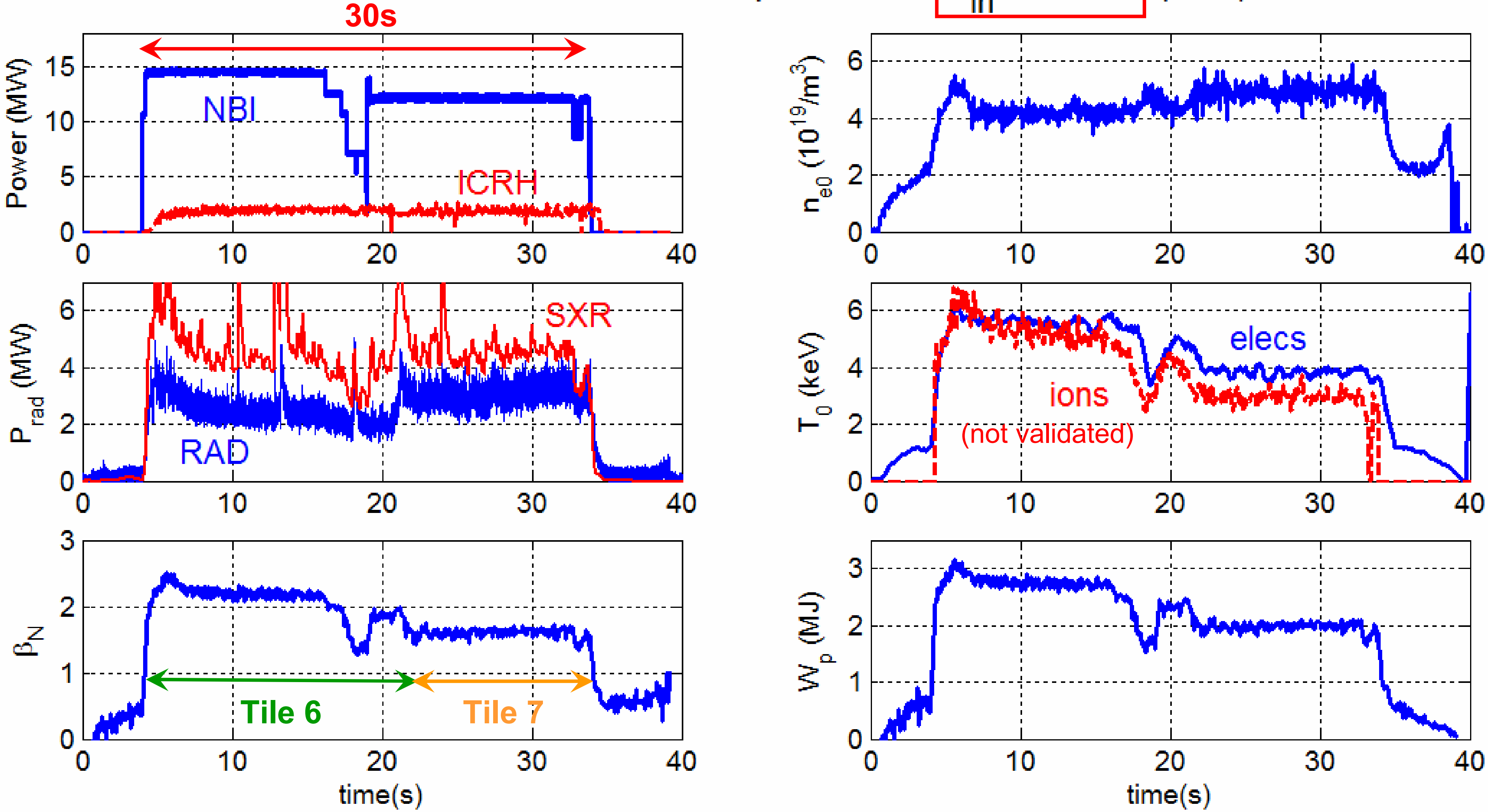
Long Pulse Development

Plasma current = 1.4MA



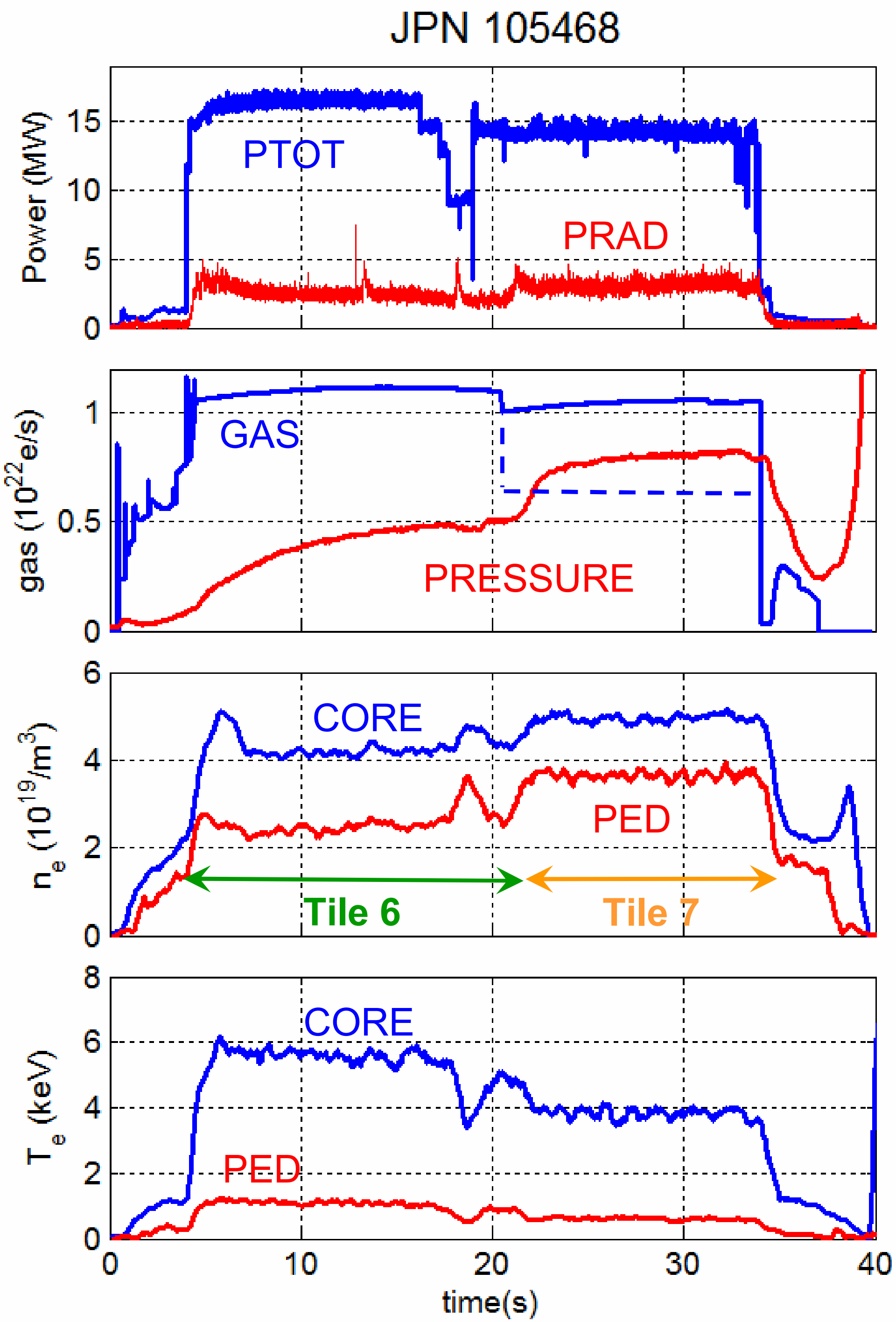
30s: Overview (Energy record)

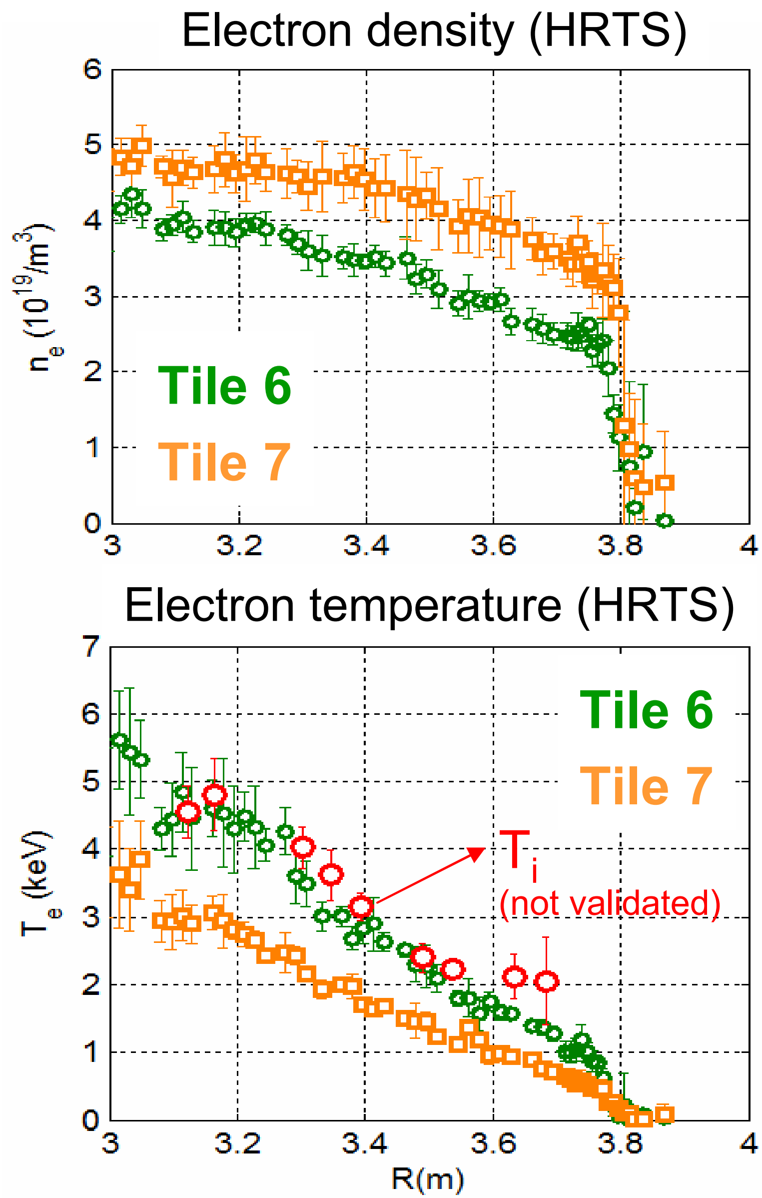
JPN 105468: Bo=1.9T, Ip=1.4MA, E_{in}=449MJ (30s)



- Better performance with strike points on Tile 6
- Deteriorates when switching to Tile 7 (lower energy, higher radiation)
- Discharge in H-mode, stationary throughout (no impurity accumulation)

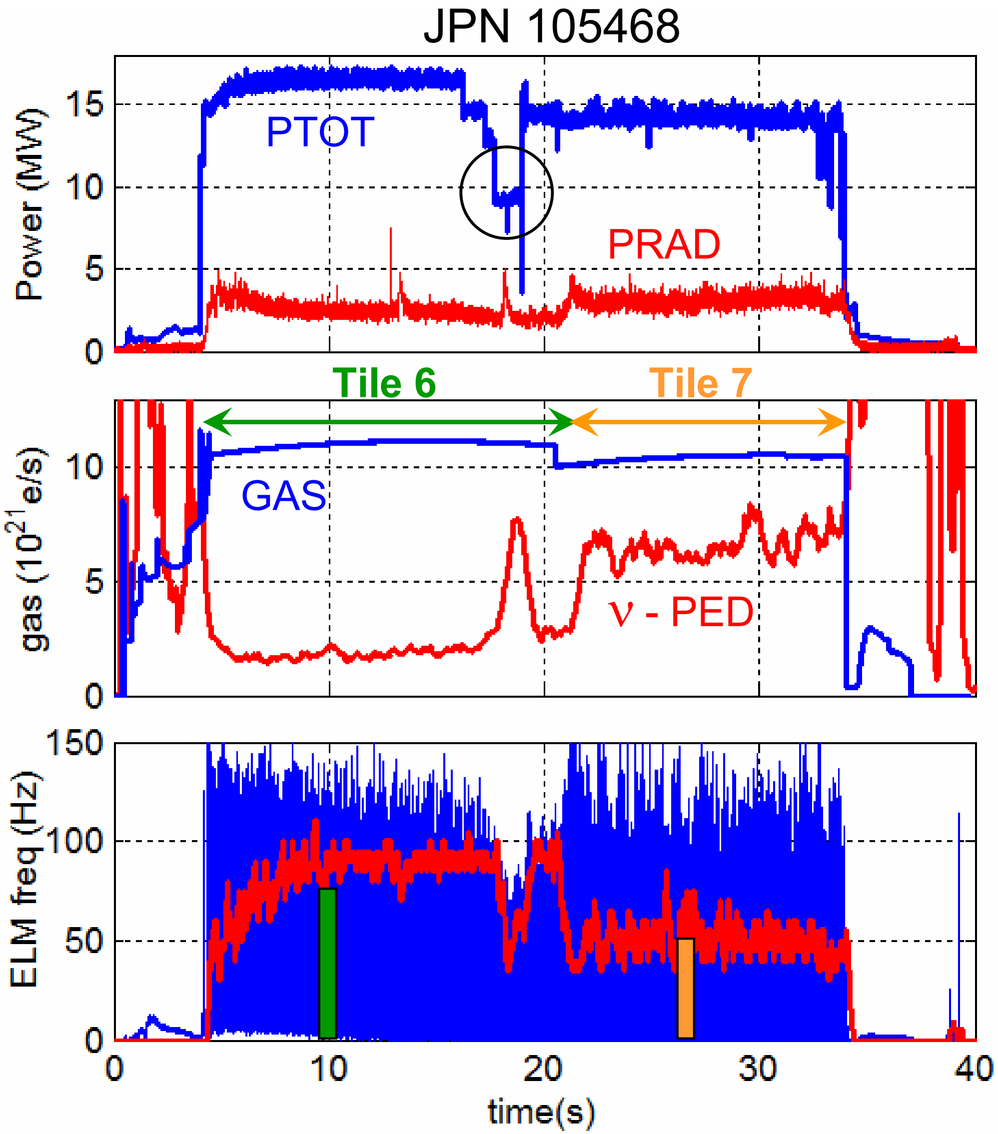
30s pulses: Tile 6 vs. Tile 7 performance

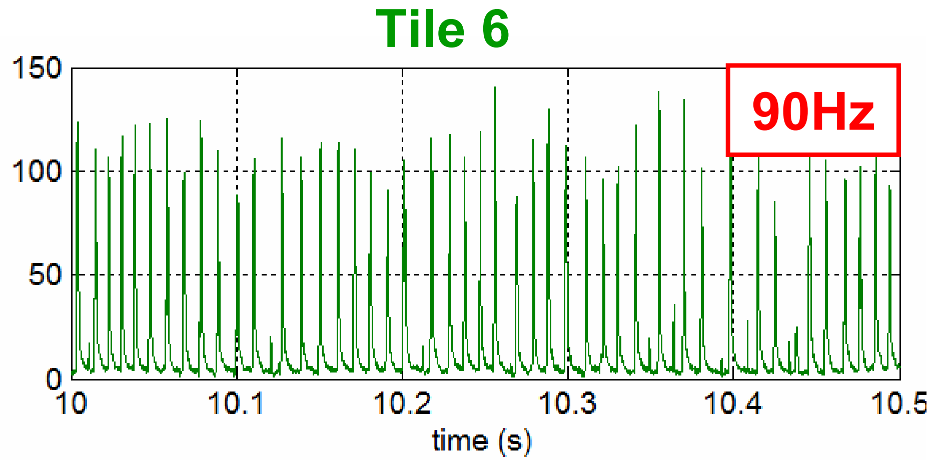


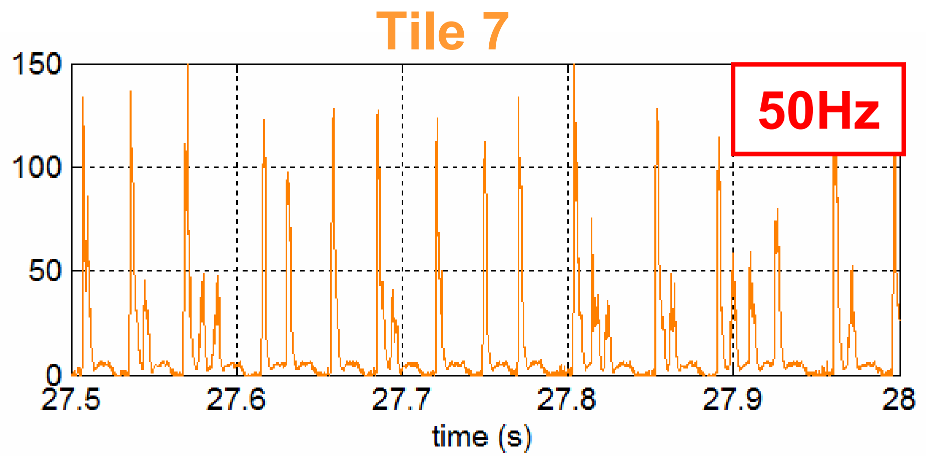


- Larger n_e / lower T_e on Tile 7, both in the core and pedestal (lower pumping)

30s pulses: ELM's

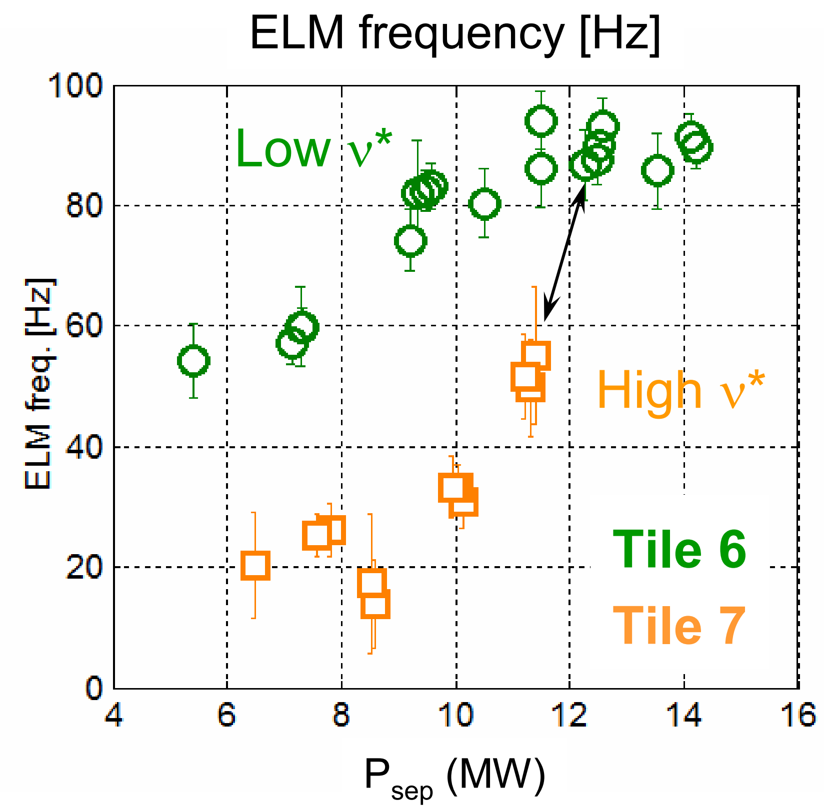


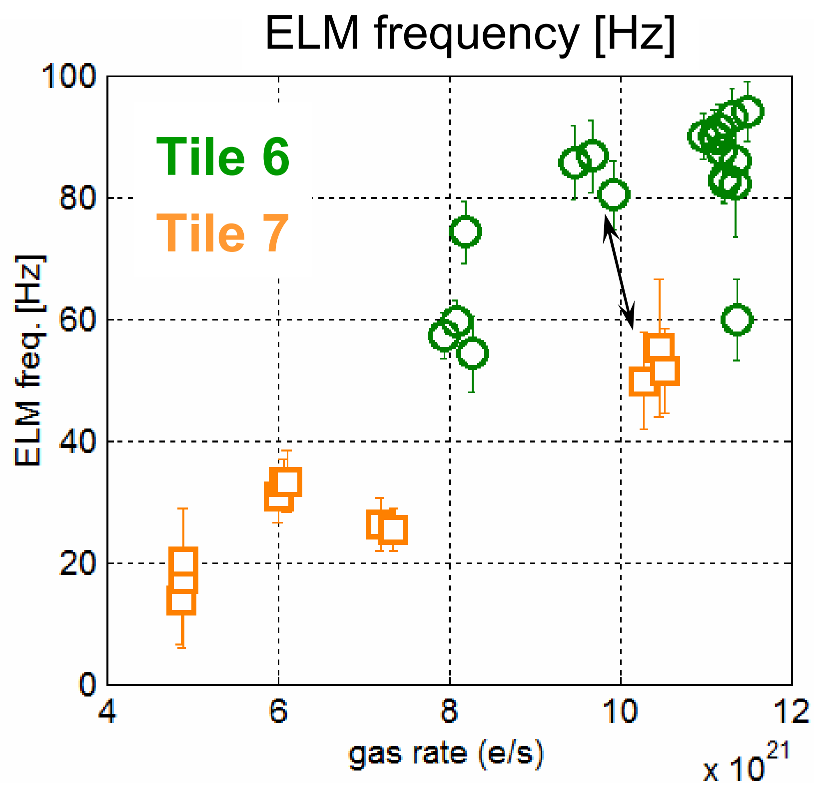




- Type-I ELMs throughout but slower / compound type I/III on Tile 7 (higher pedestal collisionality)
- Mixed P_{sep} / pedestal effect

30s pulses: ELM's





- ELM frequency increases with P_{sep} and with gas rate in both cases
- ELM freq. is always lower on Tile 7, even when P_{sep} and gas are matched

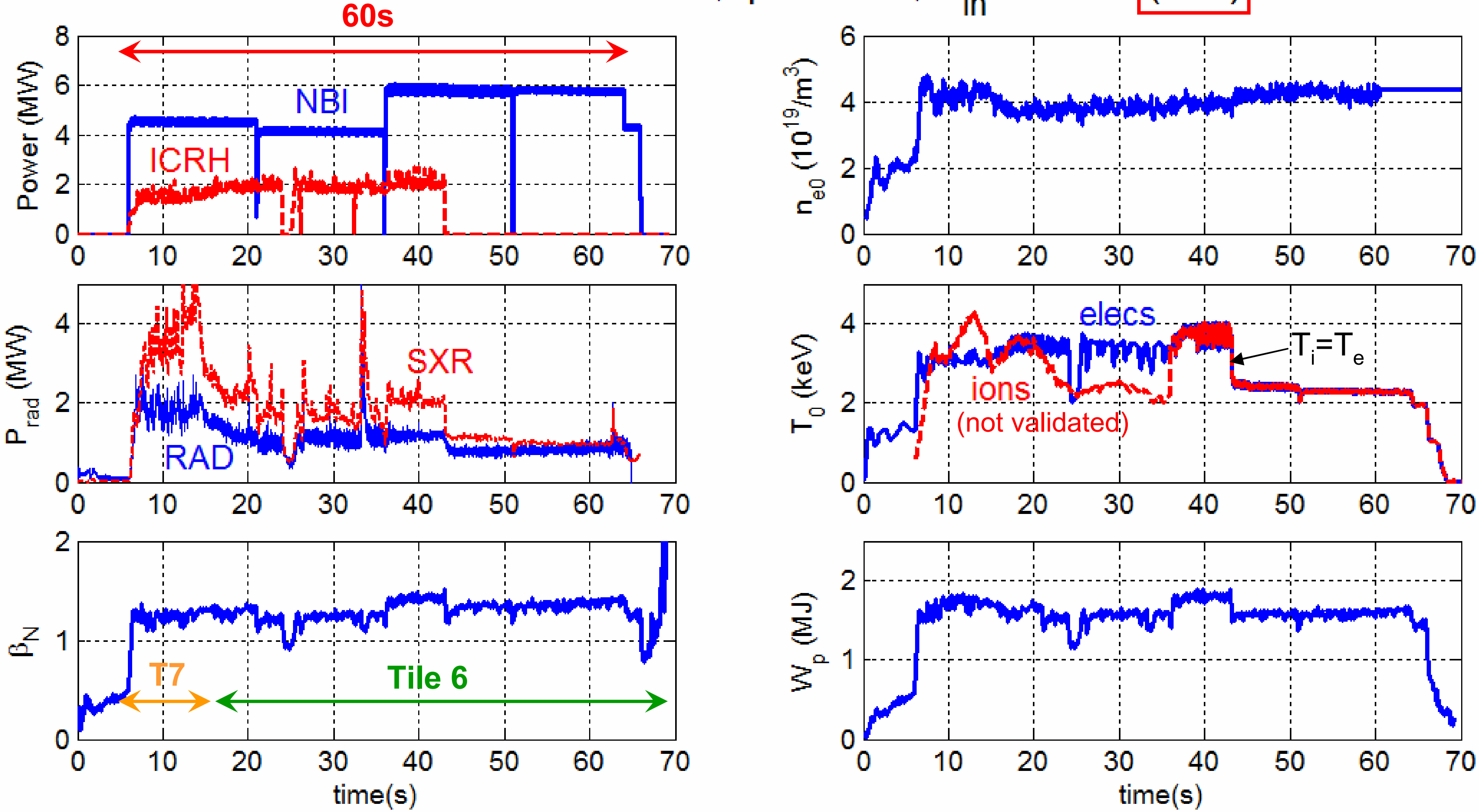
→ Well documented in JET but nice data for pedestal stability modelling

C. Challis et al 2015 Nucl. Fusion 55 053031

Many others

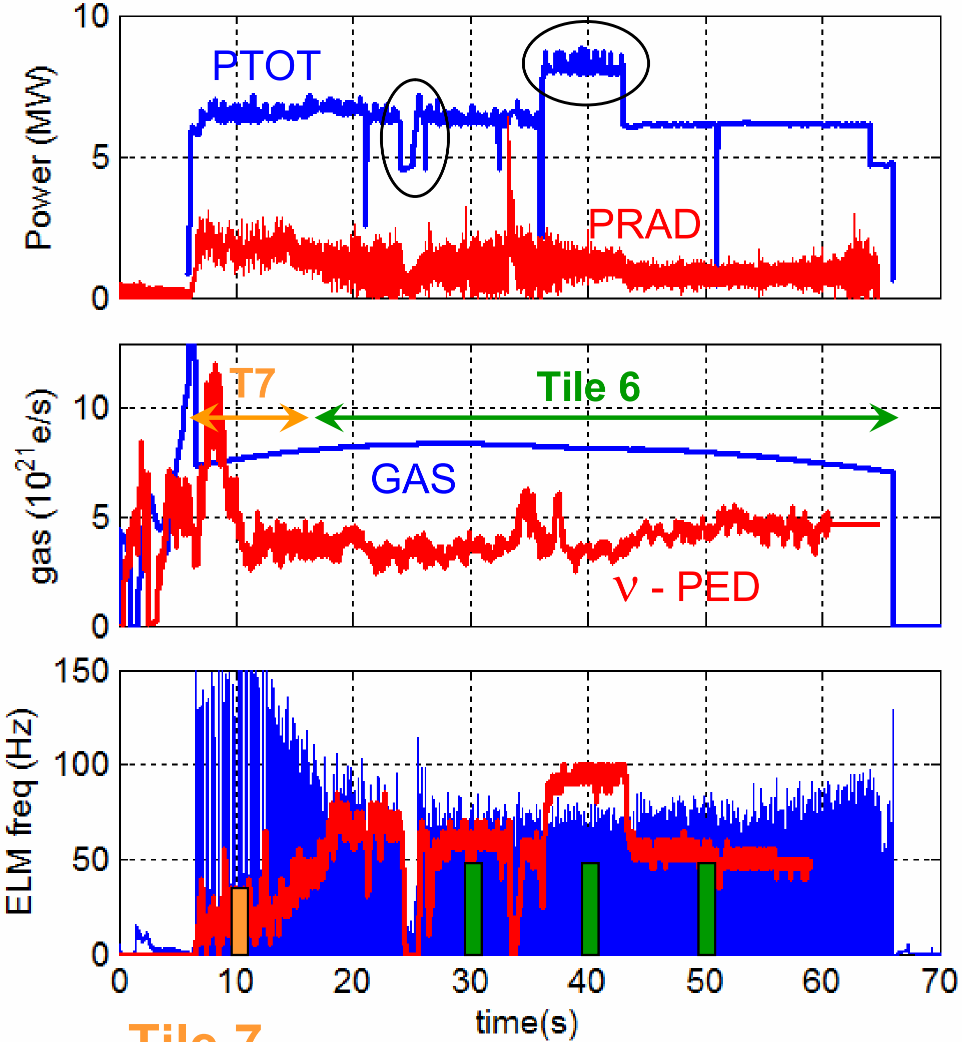
60s: Overview (Duration record)

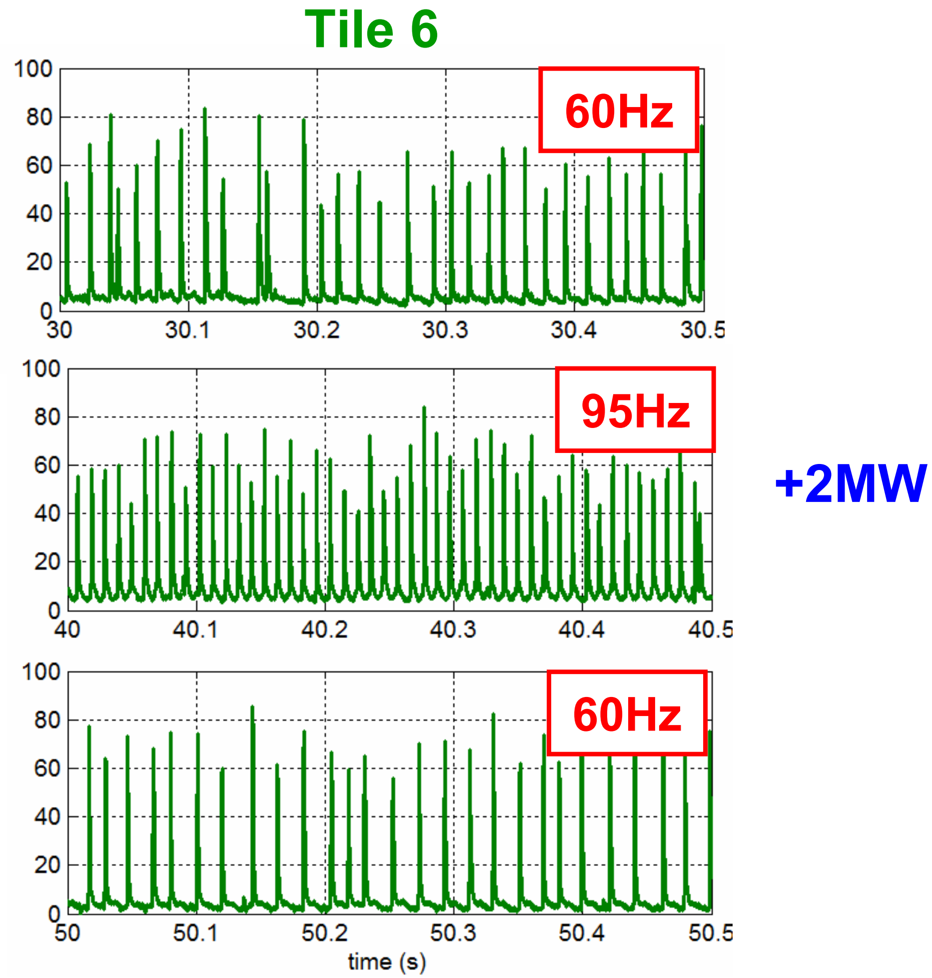
JPN 105750: Bo=1.9T, Ip=1.4MA, E_{in}=385MJ (60s)

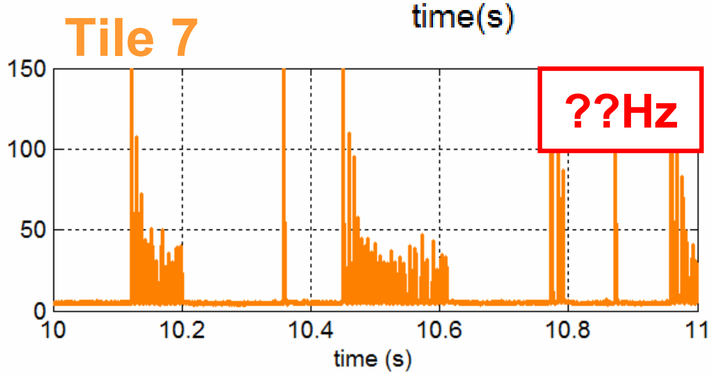


- Record plasma duration in JET-ILW (60s)
- Stationary H-mode with fair performance (Tile 6); Constant W source
- Higher P_{rad} and core SXR on Tile 7 phase (marginally stable)

60s pulses: ELM's



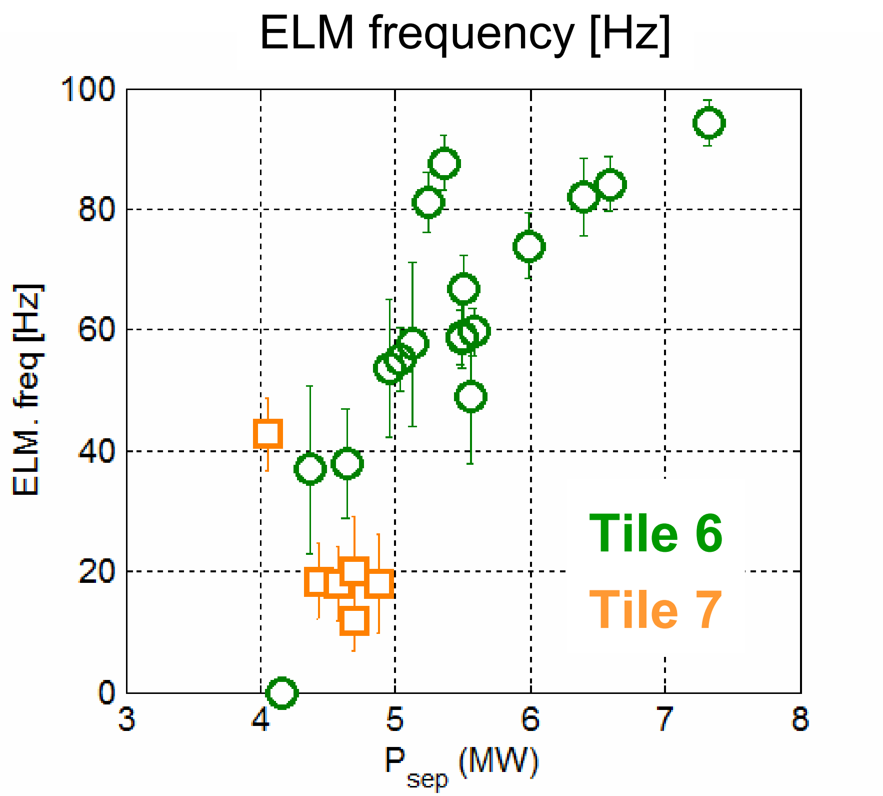


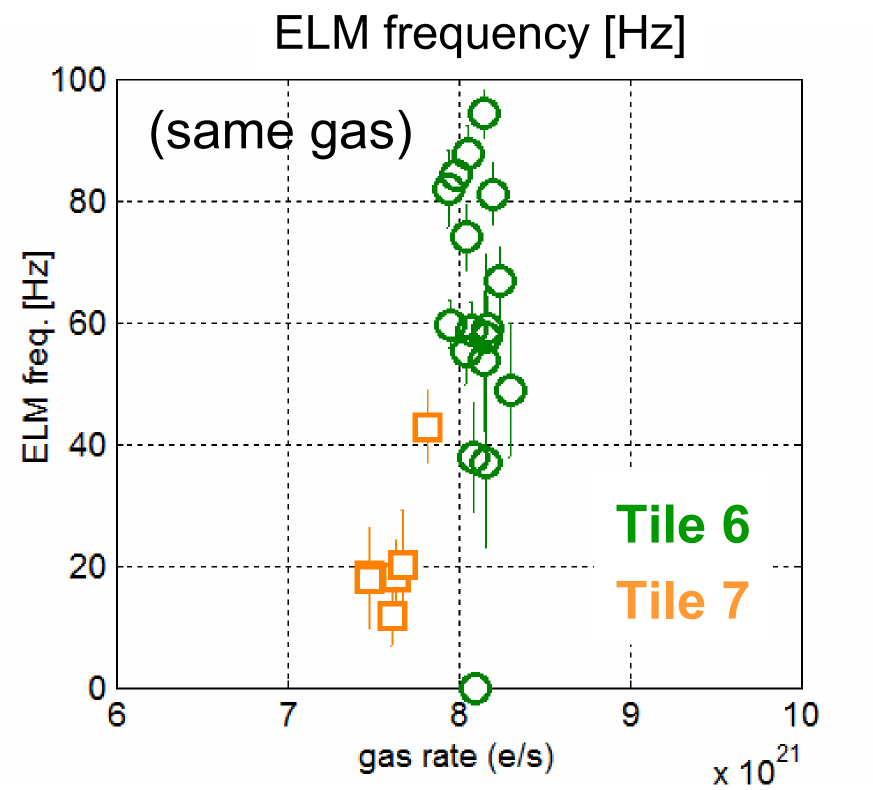


- Tile 6: Stable type-I ELMs with strong P_{sep} dependence; close to L-H threshold

- Tile 7: Marginal power for type-I ELMs (poor imp. flushing)

60s pulses: ELM's

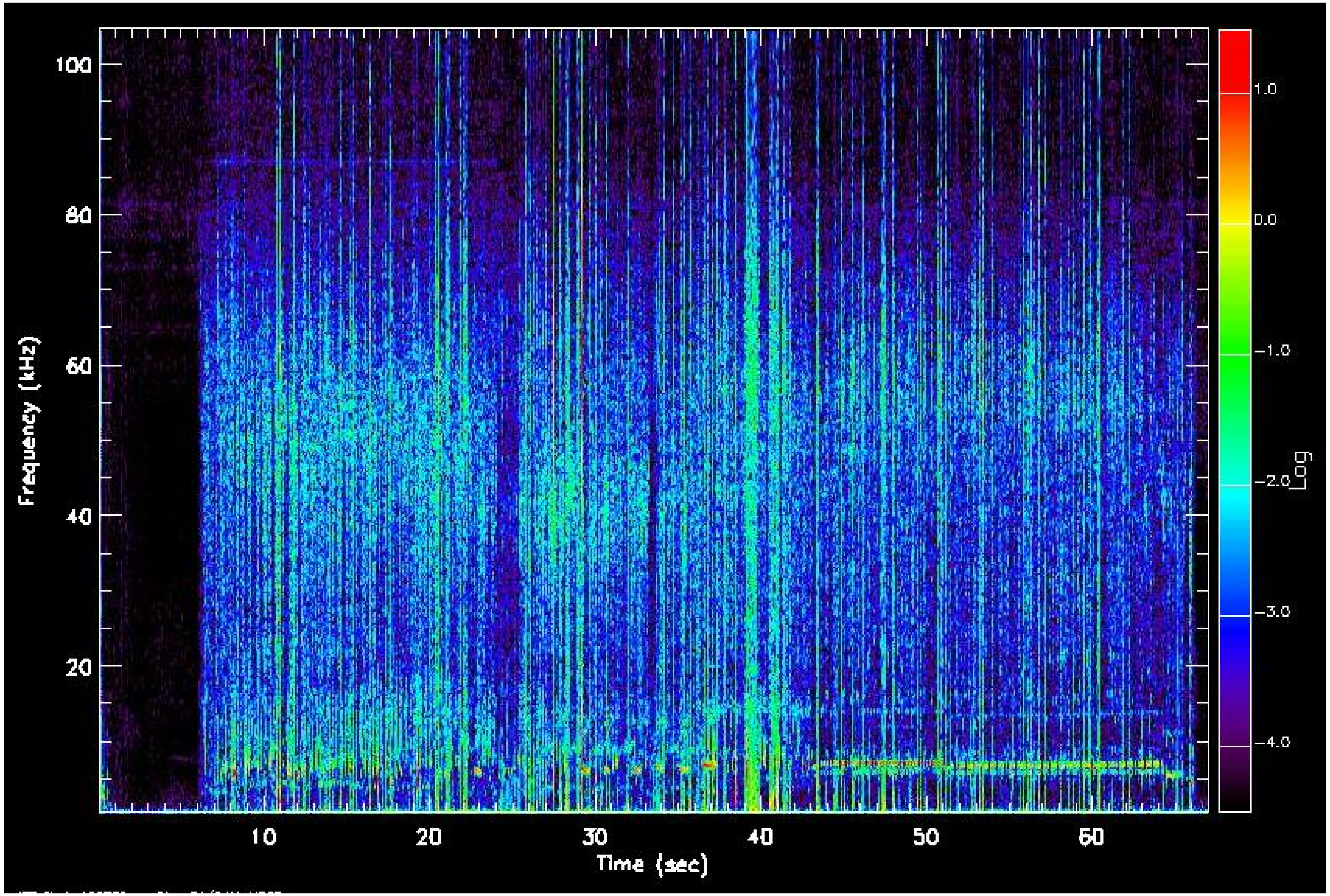




- Tile 7: Not enough P_{sep} / gas to achieve proper type-I ELMs
- Tile 6: Type-I ELMs with ~ linear P_{sep} dependence

MHD

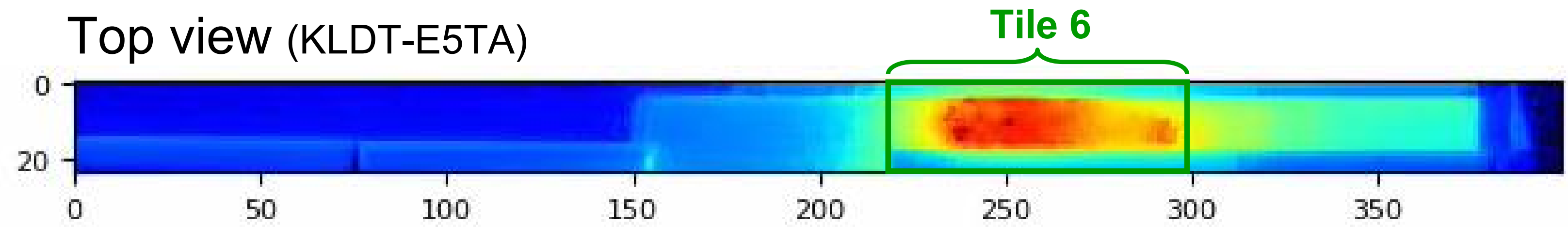
105750

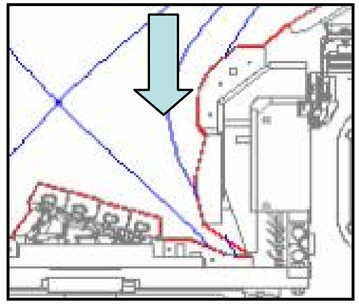


No MHD detected (exc. small sawteeth)

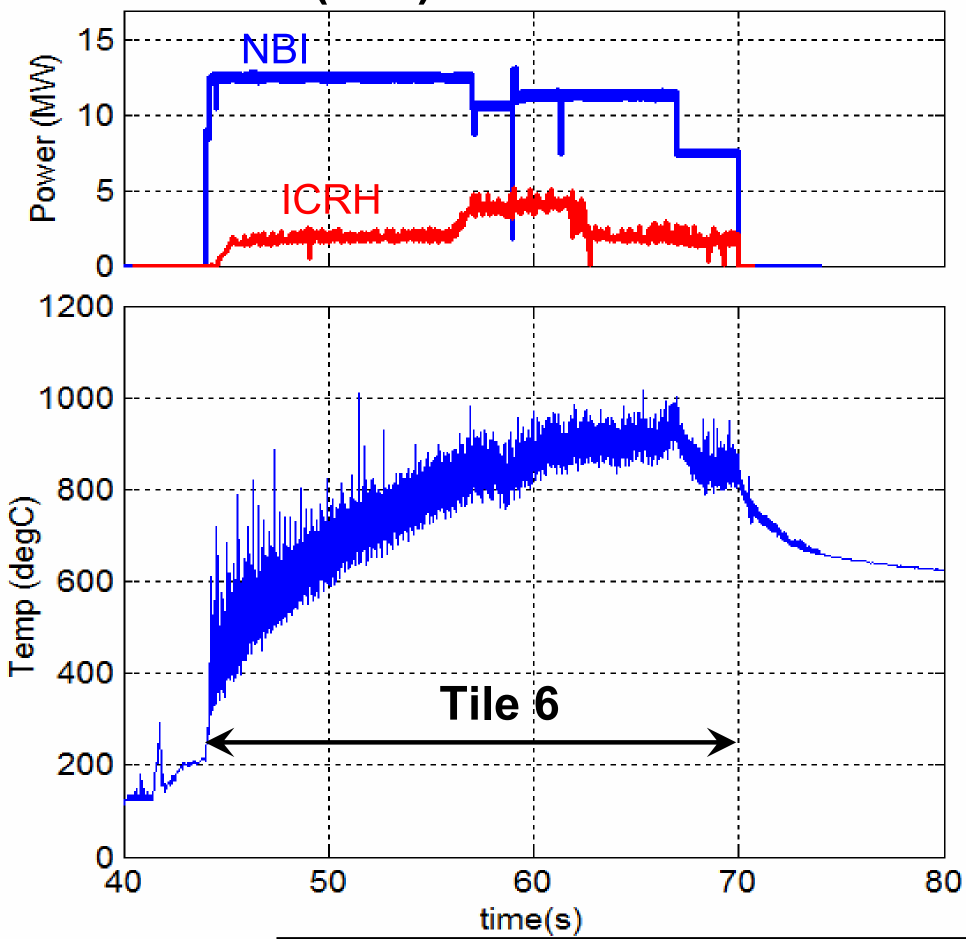
Divertor temperatures

Top view (KLDT-E5TA)

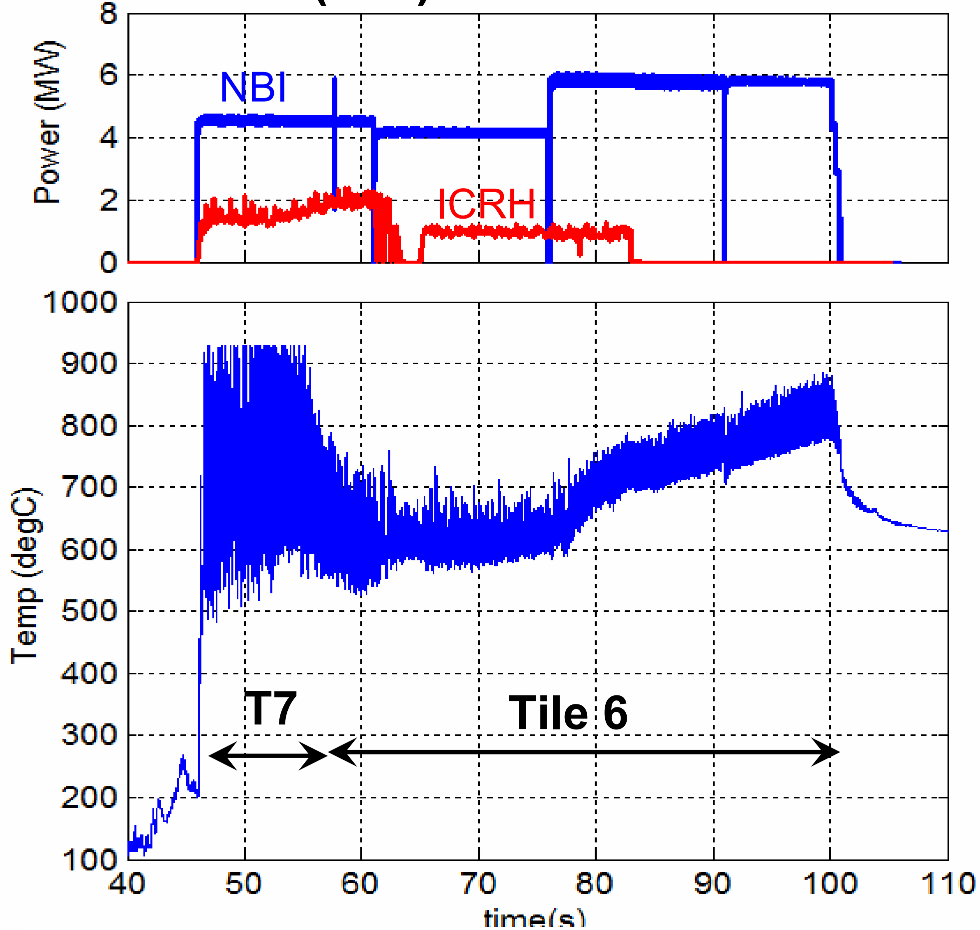




105585 **(30s)**



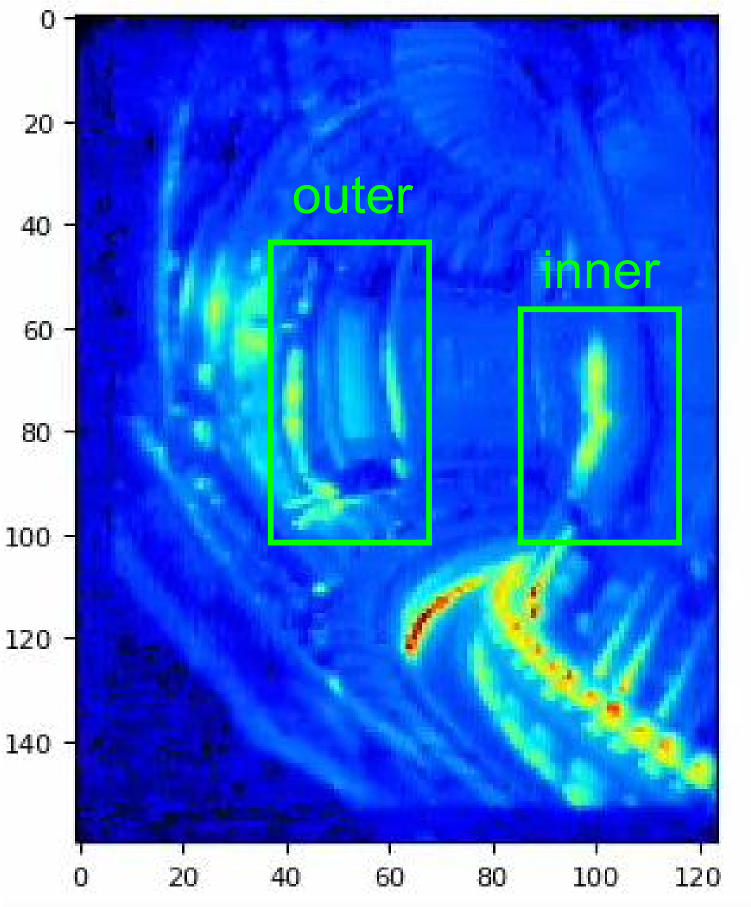
105736 **(60s)**



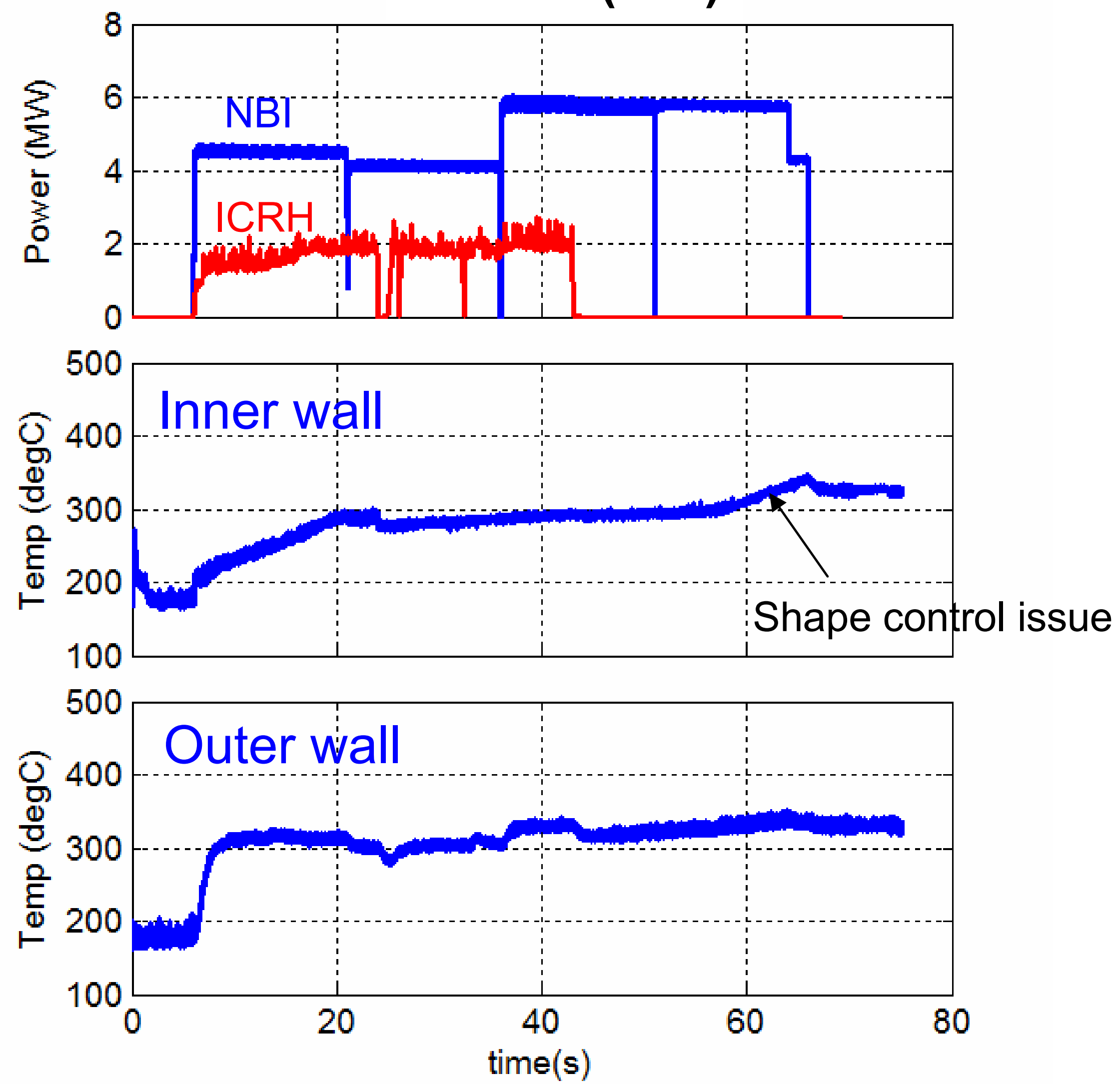
- Saturation due to heat-exchange with neighbouring structures (stronger at higher temperatures)

Main chamber temperatures

Wide angle view (KLDT-E5WC)



105750 **(60s)**



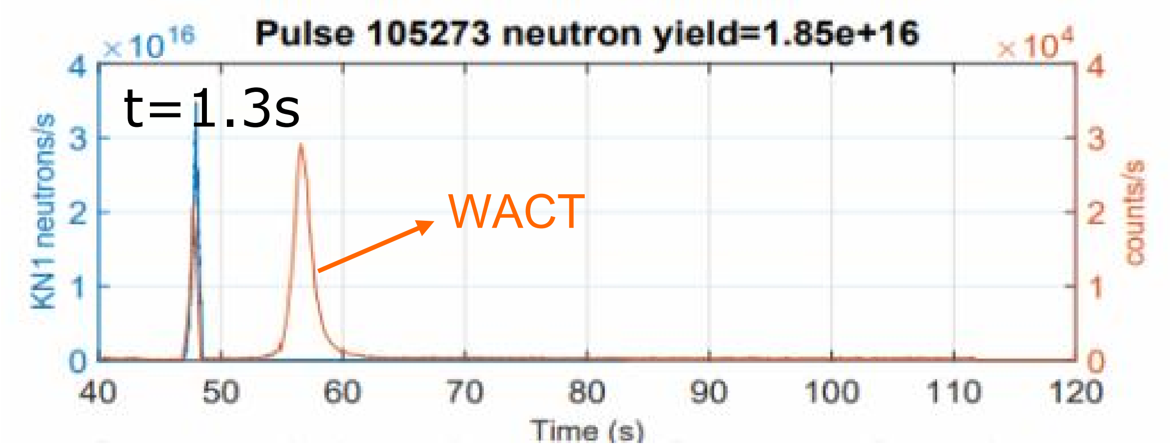
- Main chamber temperatures reach thermal equilibrium and remain well below the limit (800 degC)

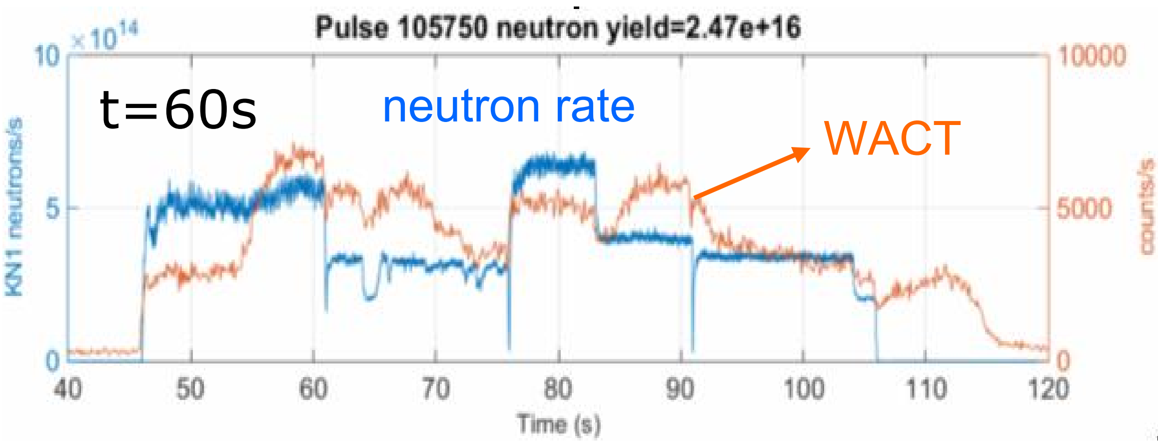
(D. Matveev)
(D. King)

Neutron activation measurements

WACT = Water activation measurements (PrIO)

Unique experiment in real tokamak water cooling loop under DT and DD

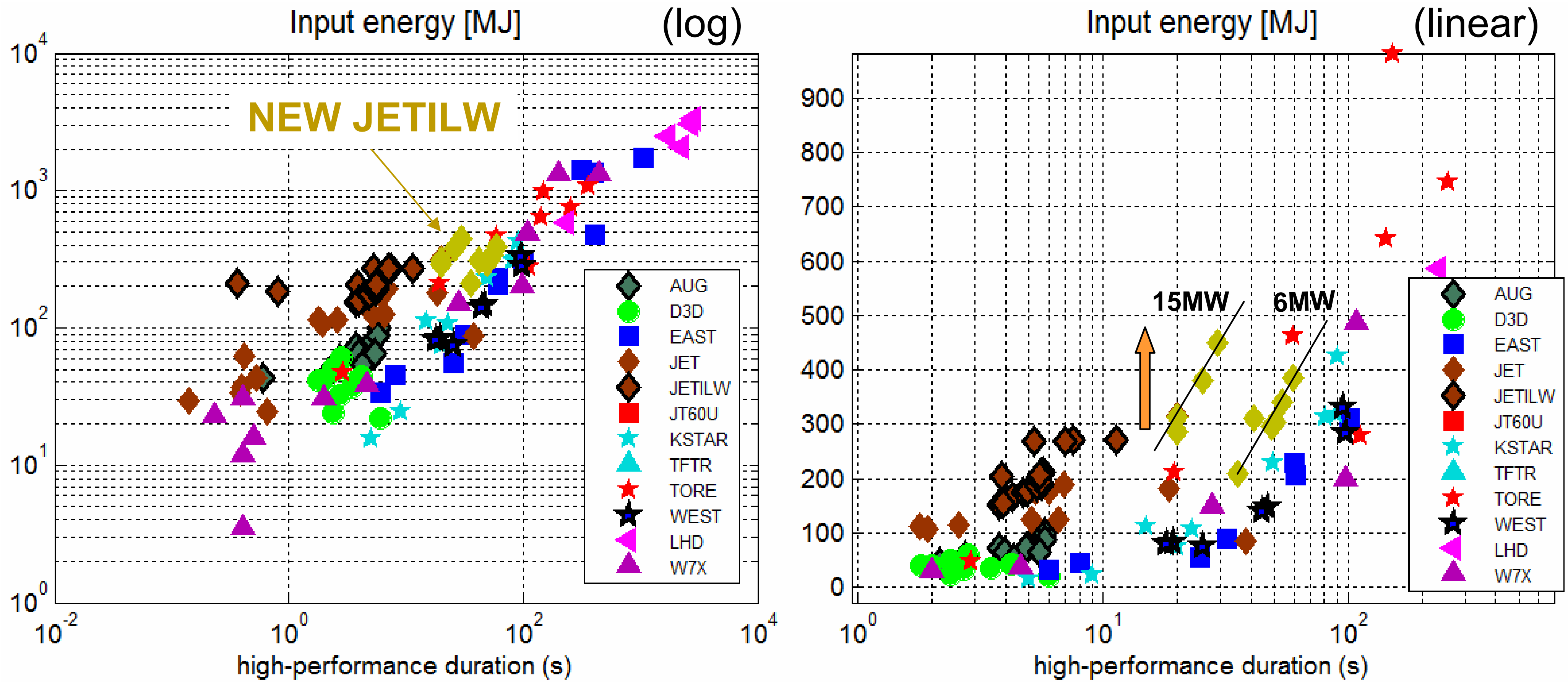




- Unique dataset for validating simulation tools for ITER and DEMO
- Short vs. Long Pulses: Clear effects of plasma operations on delayed gamma measurements and water activation peaks

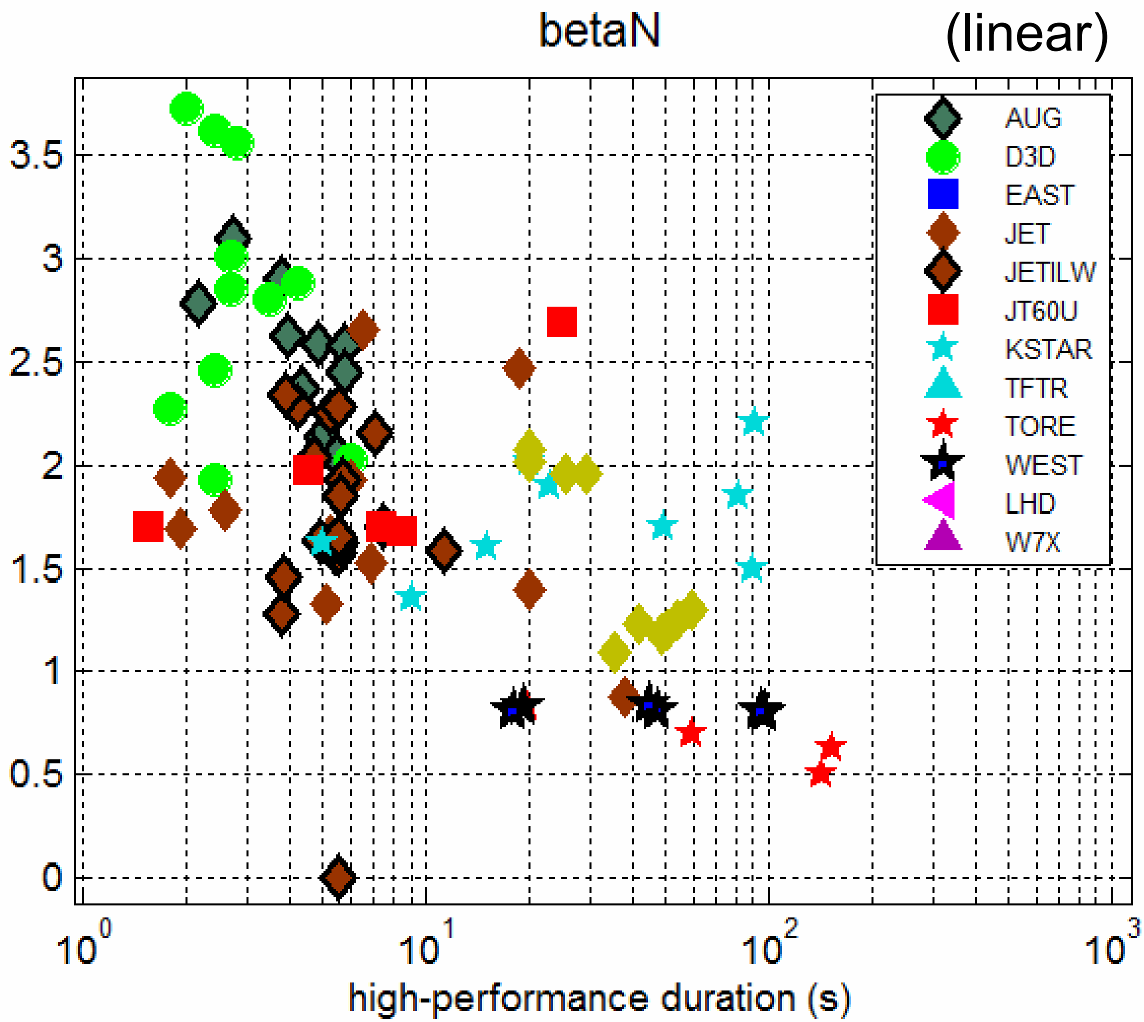
(R. Villari)

CICLOP database: Record Input energy in JET



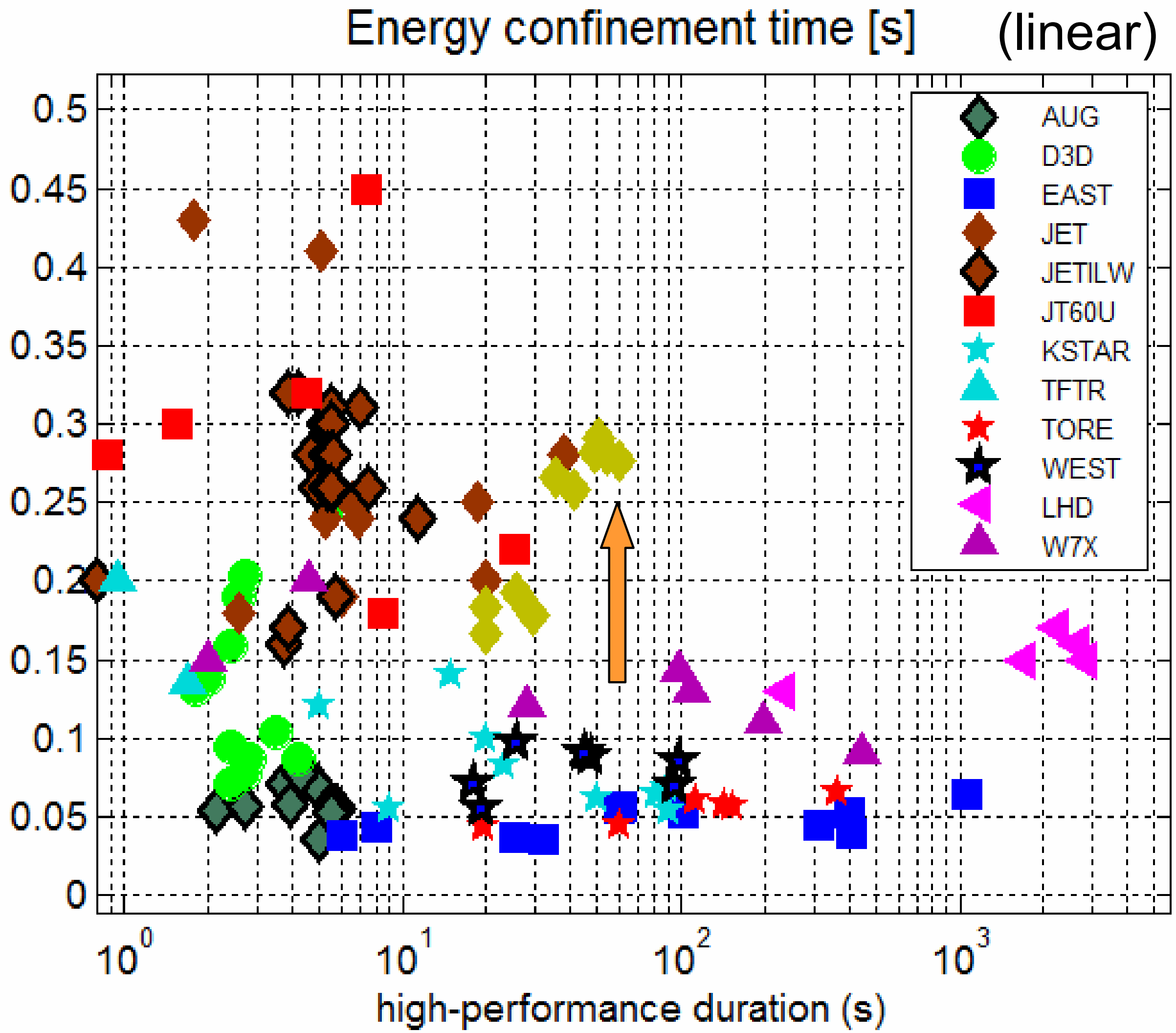
- All data in ELMy **H-mode** regime with a W divertor
- **Record** input energy in JET history: E_{IN} = 300→450MJ
- Two families: **30s** (~15MW) and **60s** (~6MW)

CICLOP database: Good performance



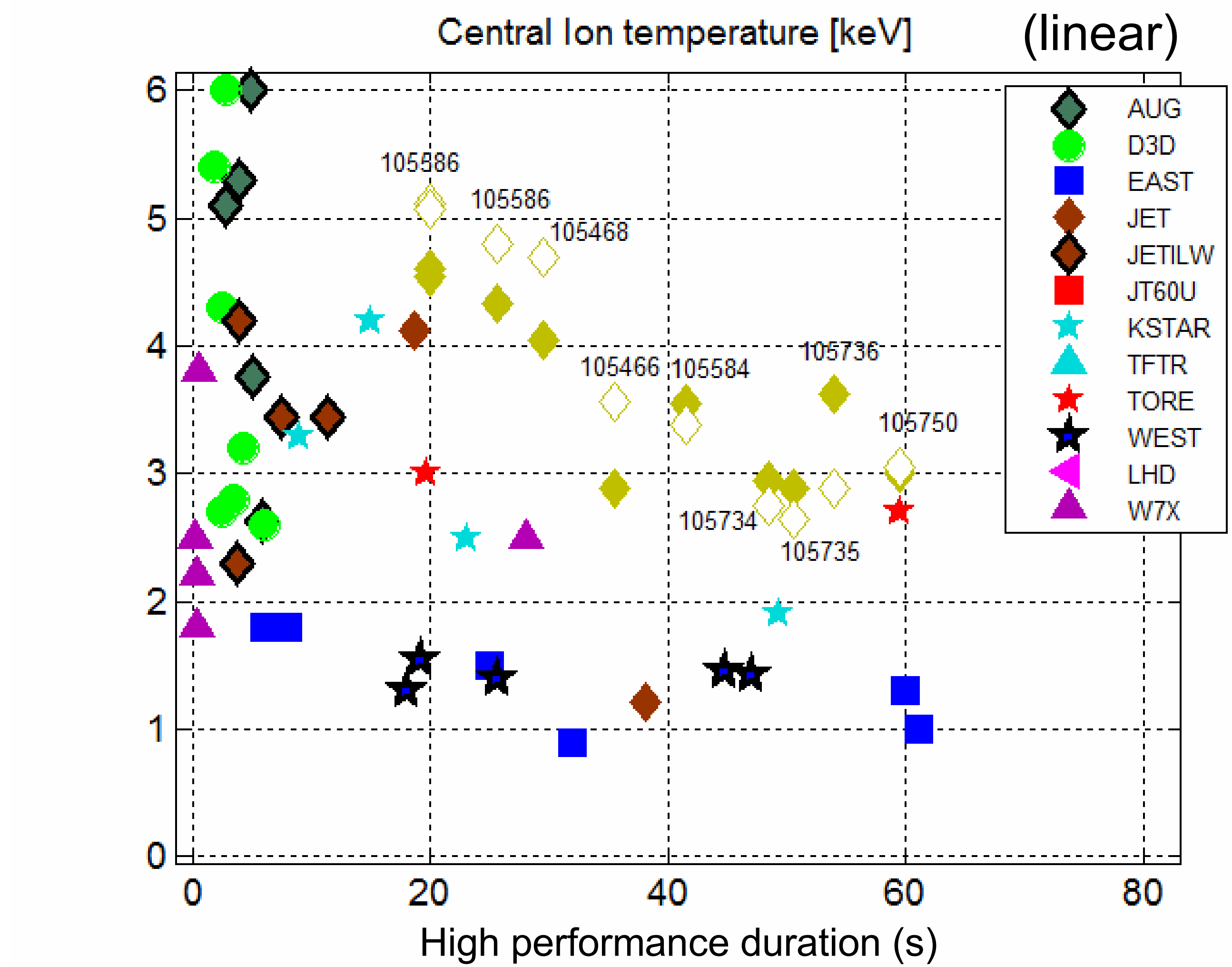
- Good performance for 30s, somewhat less for 60s pulses (still higher than other data exc. KSTAR)
- Stored energy comparison would be more evident (ongoing)

CICLOP database: Good confinement for long pulses



- Good confinement achieved in long pulses (w.r.t. database)
- Better confinement at moderate power (τ_E = 0.2s → 0.3s)
  - power degradation?
  - partly compensates for lower T_i in n.τ.T

CICLOP database: Elec vs. Ion temperature



◊ Te (HRTS)

♦ Ti (CXRS or XCS)

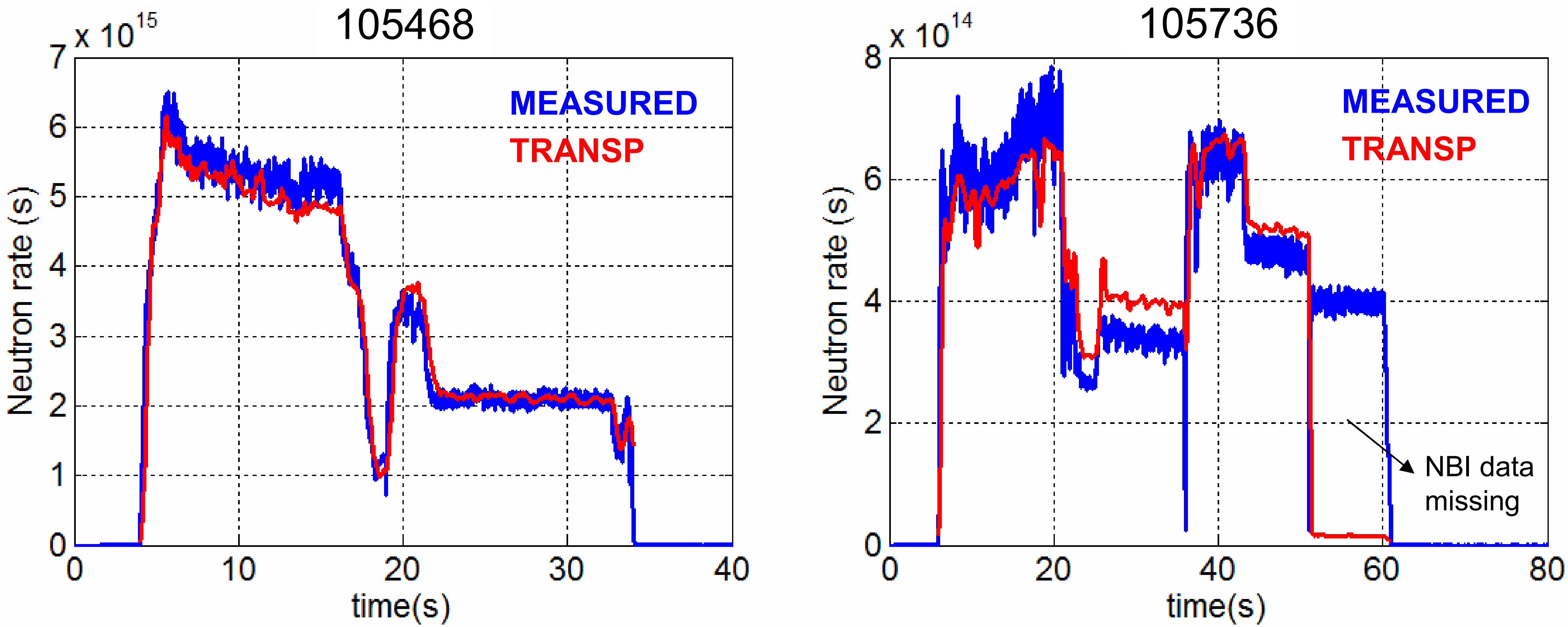
Needs final validation!

- Larger T_i than other machines (dominant ion heating)
- Some T_i data is missing or not yet validated (T_e is OK)
- TRANSP runs with T_i=T_e match well the total neutron yield

TRANSP simulations with Ti=Te

TRANSP: - Pressure constrained equilibrium (Be, Ni, Ne to match Z_{eff})

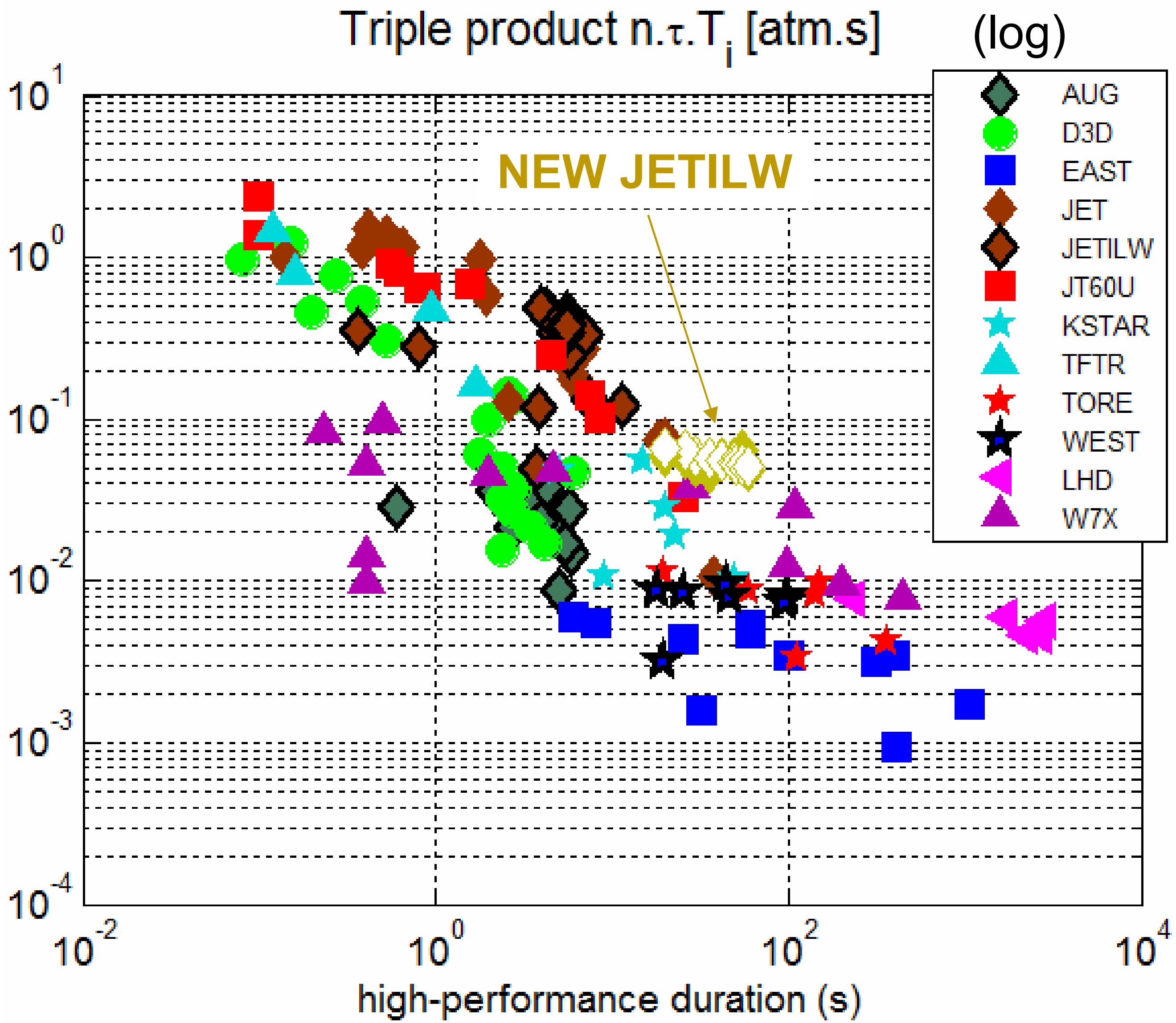
- All simulations with T_i=T_e

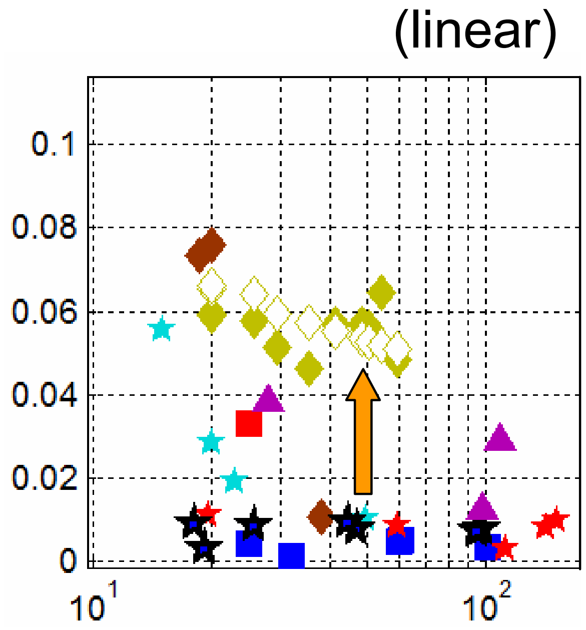


• Interpretative TRANSP simulations with T_i=T_e show good agreement with measured neutron rate

(M. Poradzinski)

CICLOP database: triple product





- Important contribution to the n.τ.T database
- Only comparable data are recent W7X results

Summary

• High power **30sec** pulses and medium power **60sec** pulses were successfully achieved in JET-ILW

- Record input energy = 450MJ
- Record H-mode pulse duration = 60s

• All plasmas were stationary with type-I ELMs, no MHD and no radiation increase (no impurity accumulation, constant W source)

• Combined NBI+ICRF heating leads to T_i~T_e (waiting final validation)

• Many engineering / operational limits were reached (D. King)

• Wall saturation (const. recycling) was reached in all pulses (D. Matveev)

• Divertor / main chamber thermal equilibrium reached in some cases

• Good data for novel neutron activation measurements (WACT) (R. Villary)

• Excellent dataset for different physics studies

• **Valuable contribution for the CICLOP LP database (t>30s, T_i~T_e)**

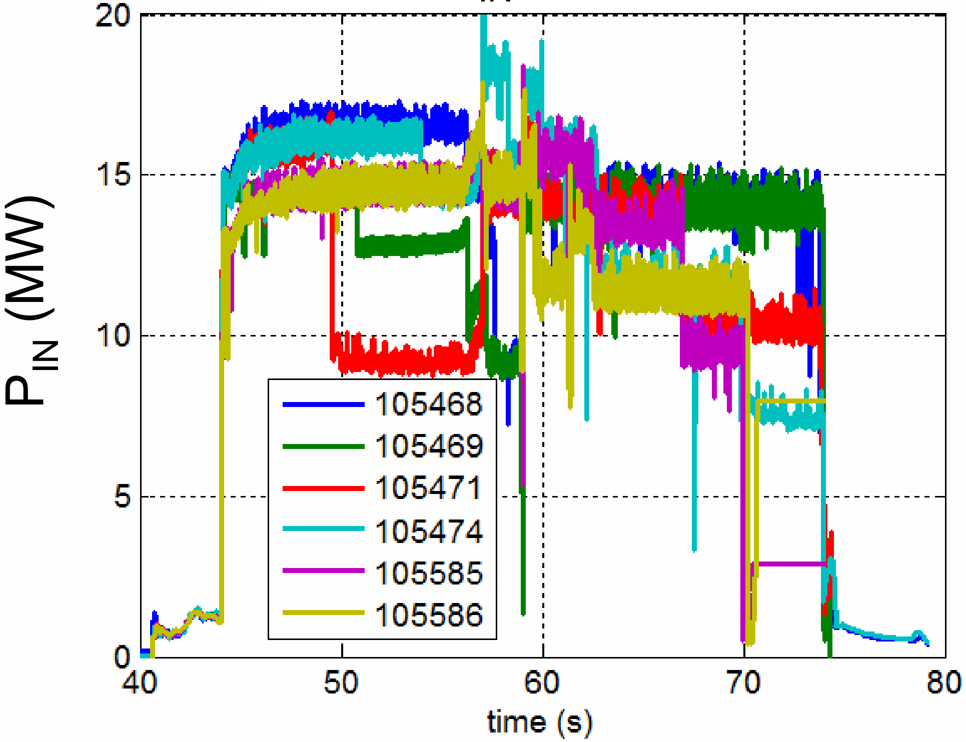
(X. Litaudon, dedicated meeting on Friday 18/10/2024 AM)

RESERVE

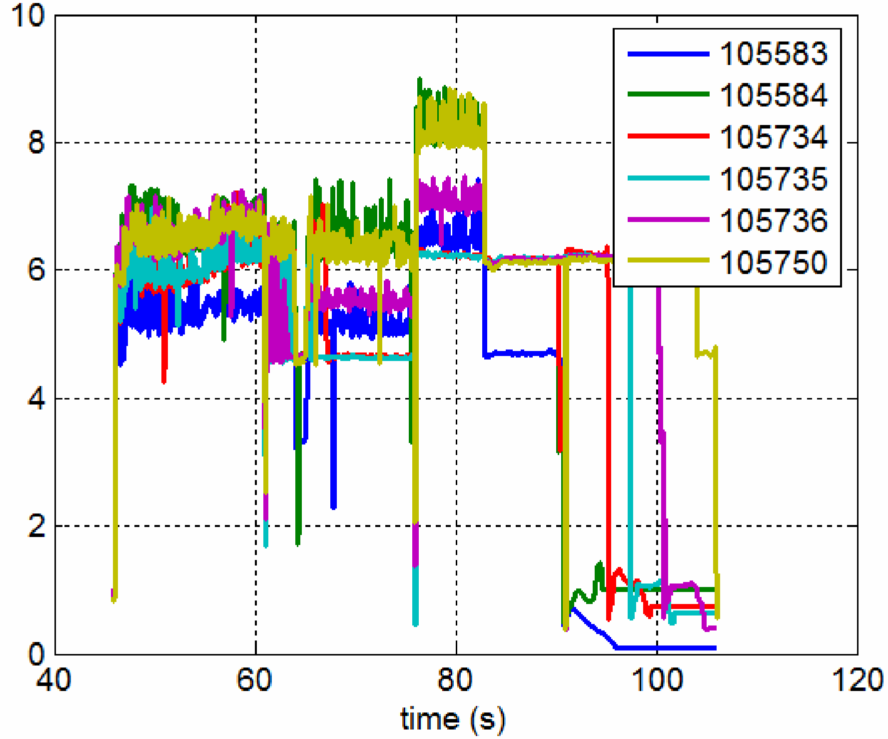
Input power

• Overview of **30s** and **60s** pulses **(1.9T, 1.4MA)**

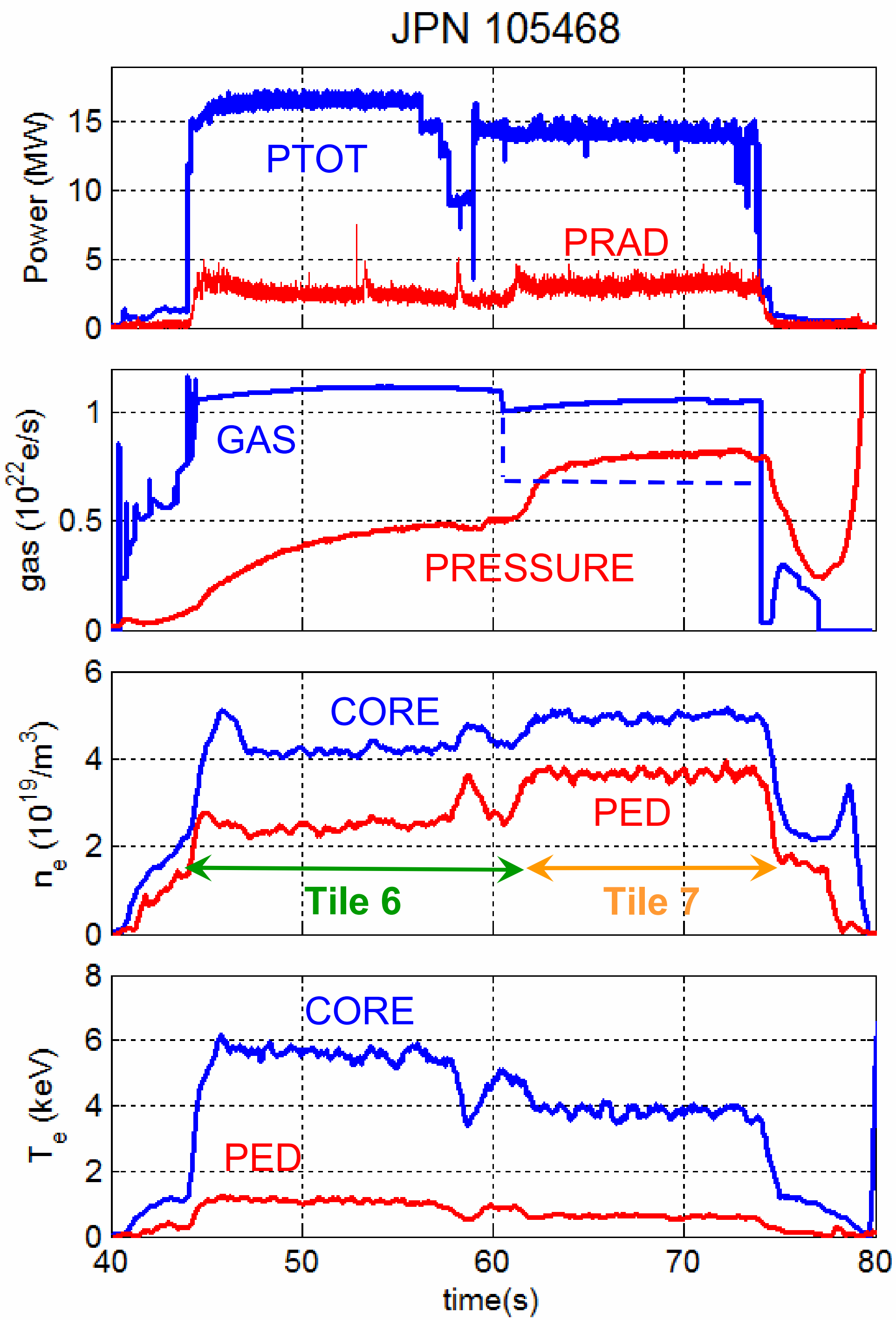
30s (<P_{IN}>=14-16MW)

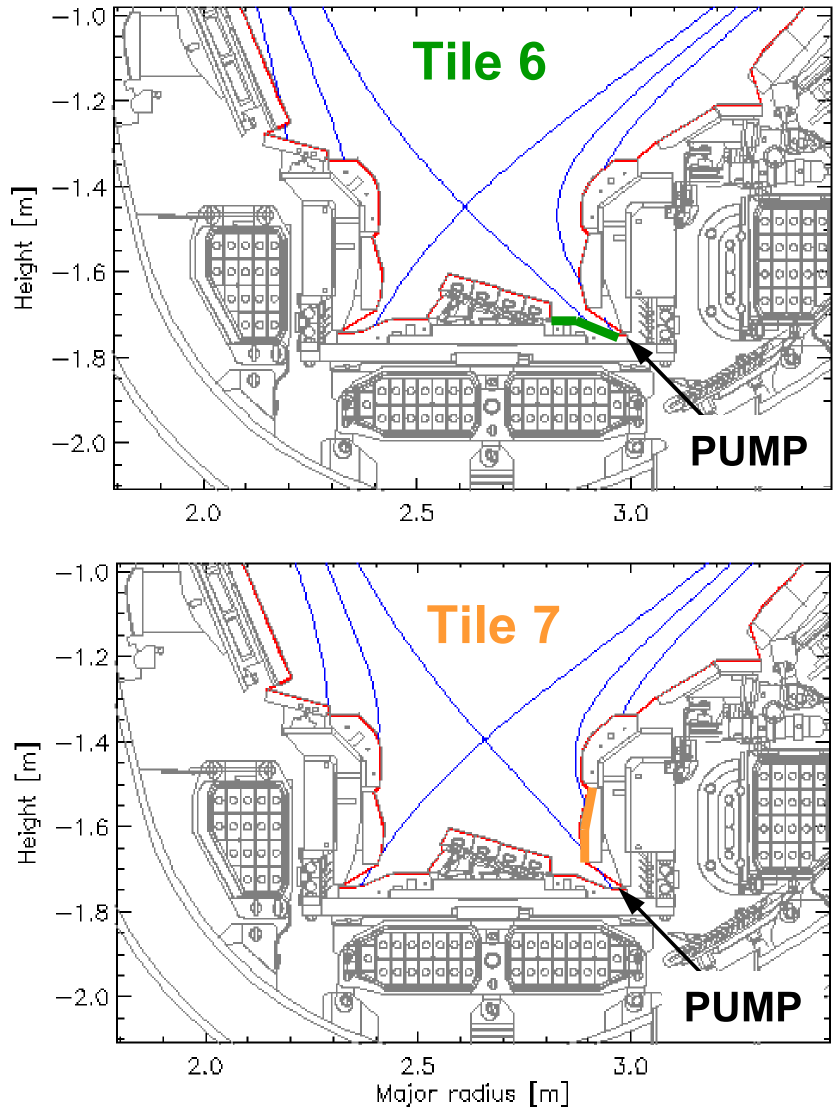


60s (<P_{IN}>=6-7MW)



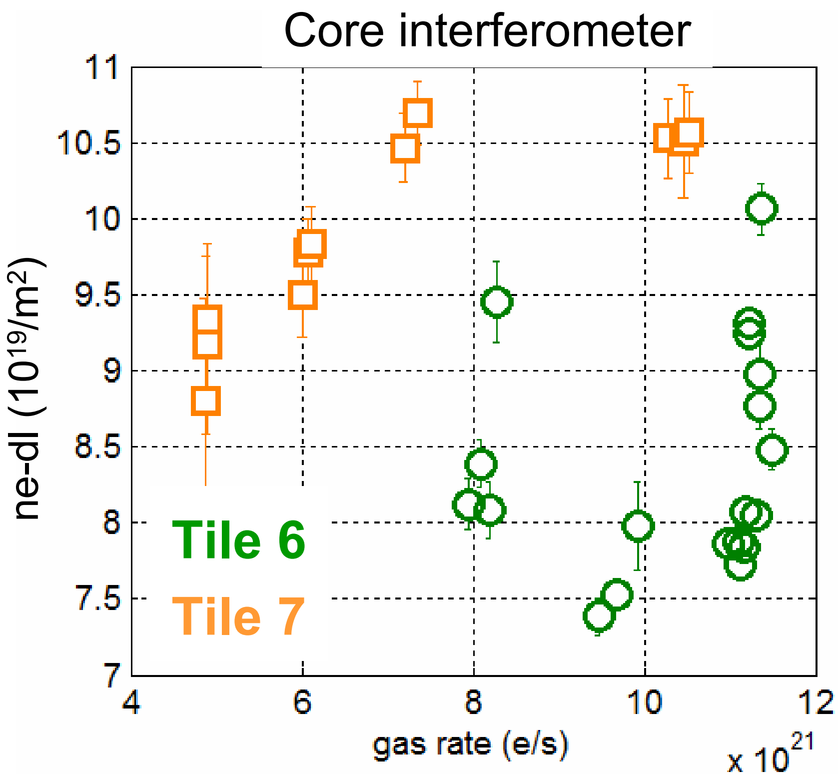
30s pulses: Tile 6 vs. Tile 7 performance

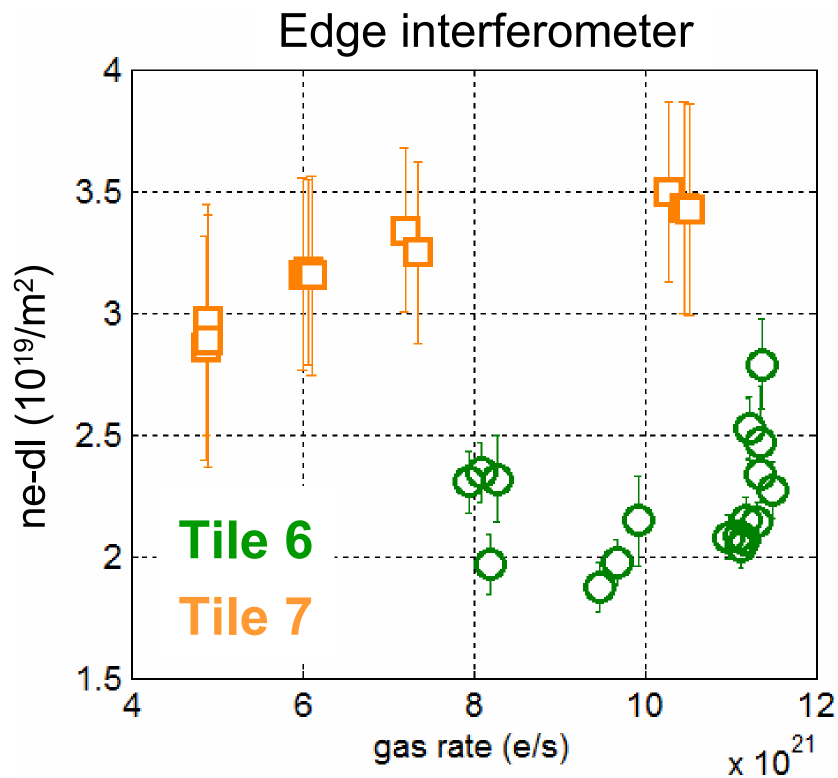


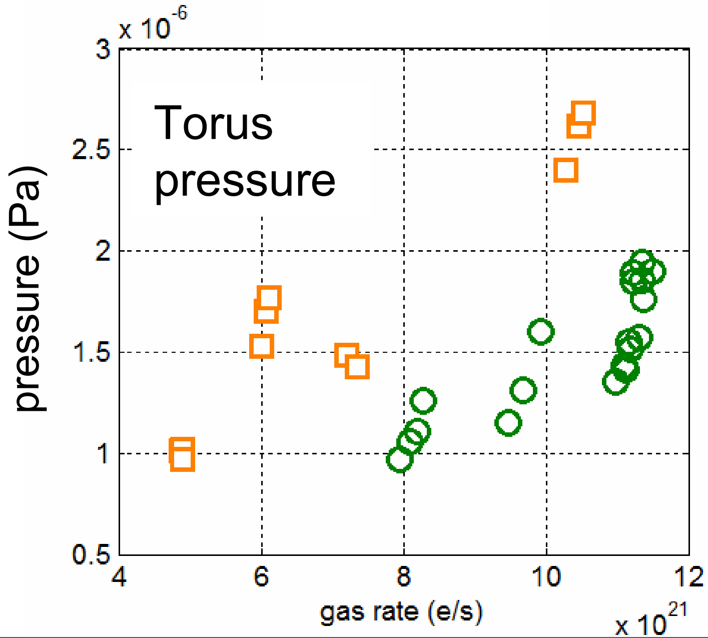


- Larger density / lower temp. on Tile 7
- Tile 7 = lower pumping (less gas?)

30s pulses: Tile 6 vs. Tile 7 density control





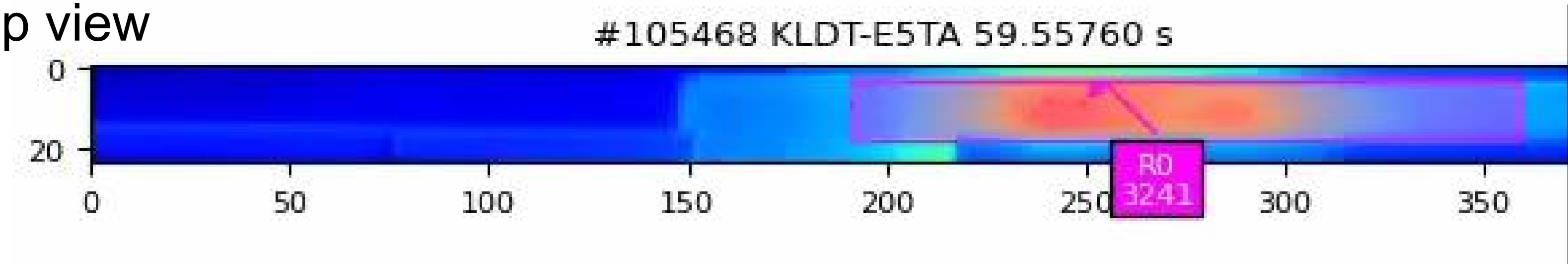


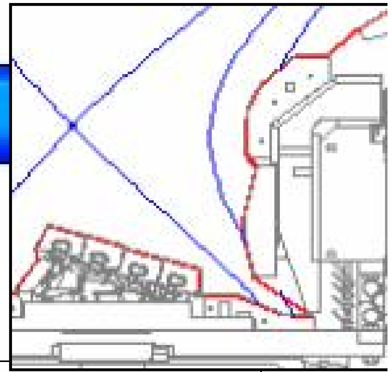
- Core density approx. matched with lower gas but edge density always higher on Tile 7
- Partly pumping, partly recycling & shaping
- Tile 6 performance could never be recovered on Tile 7

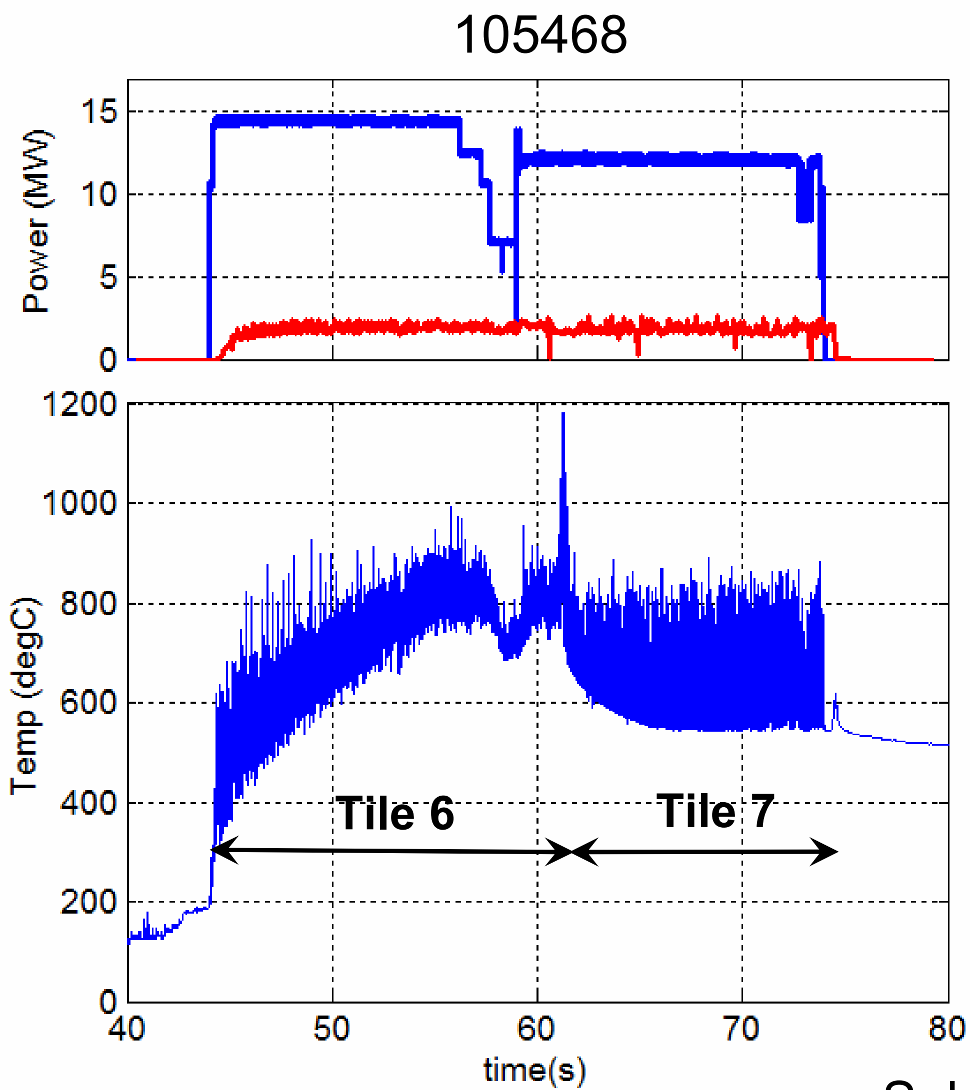
(Damian?)

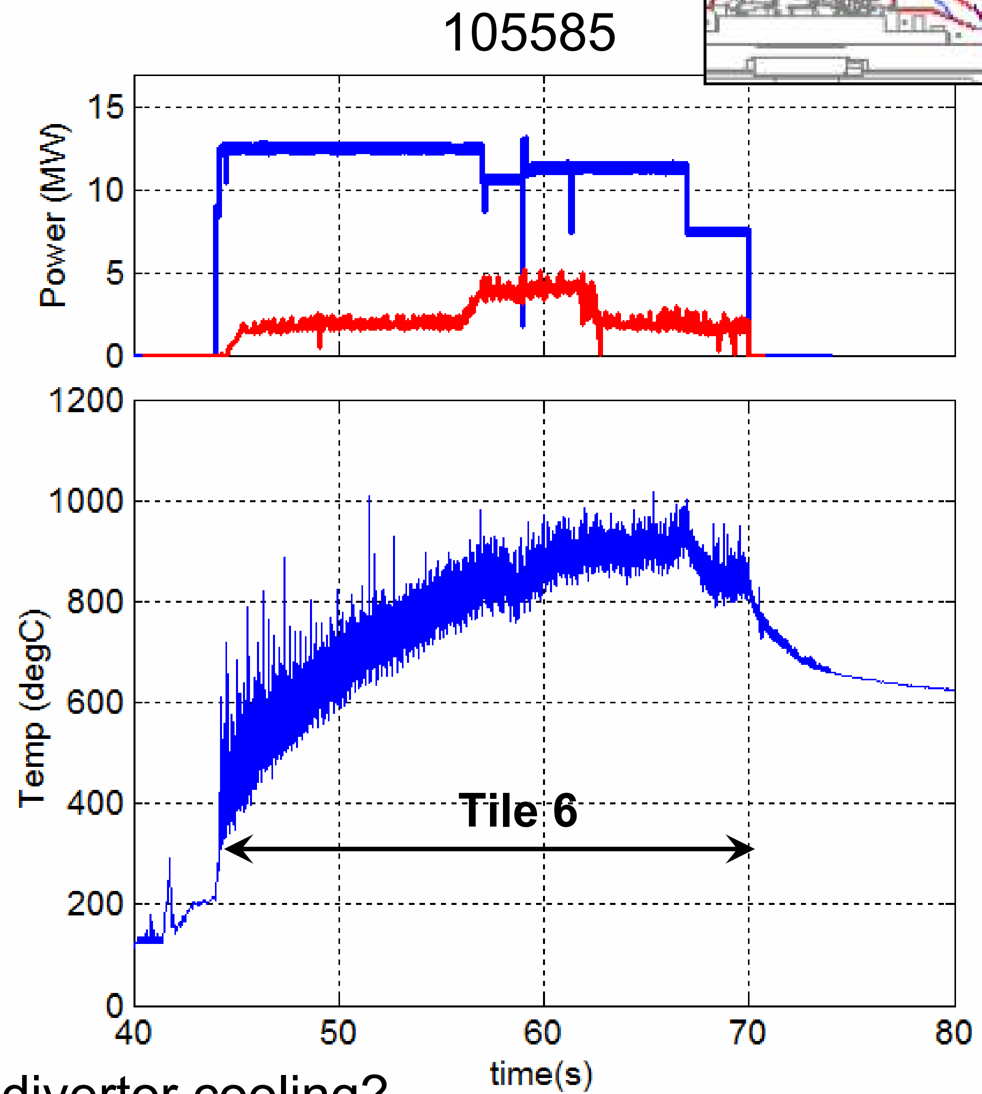
Divertor temperatures (30s)

Top view



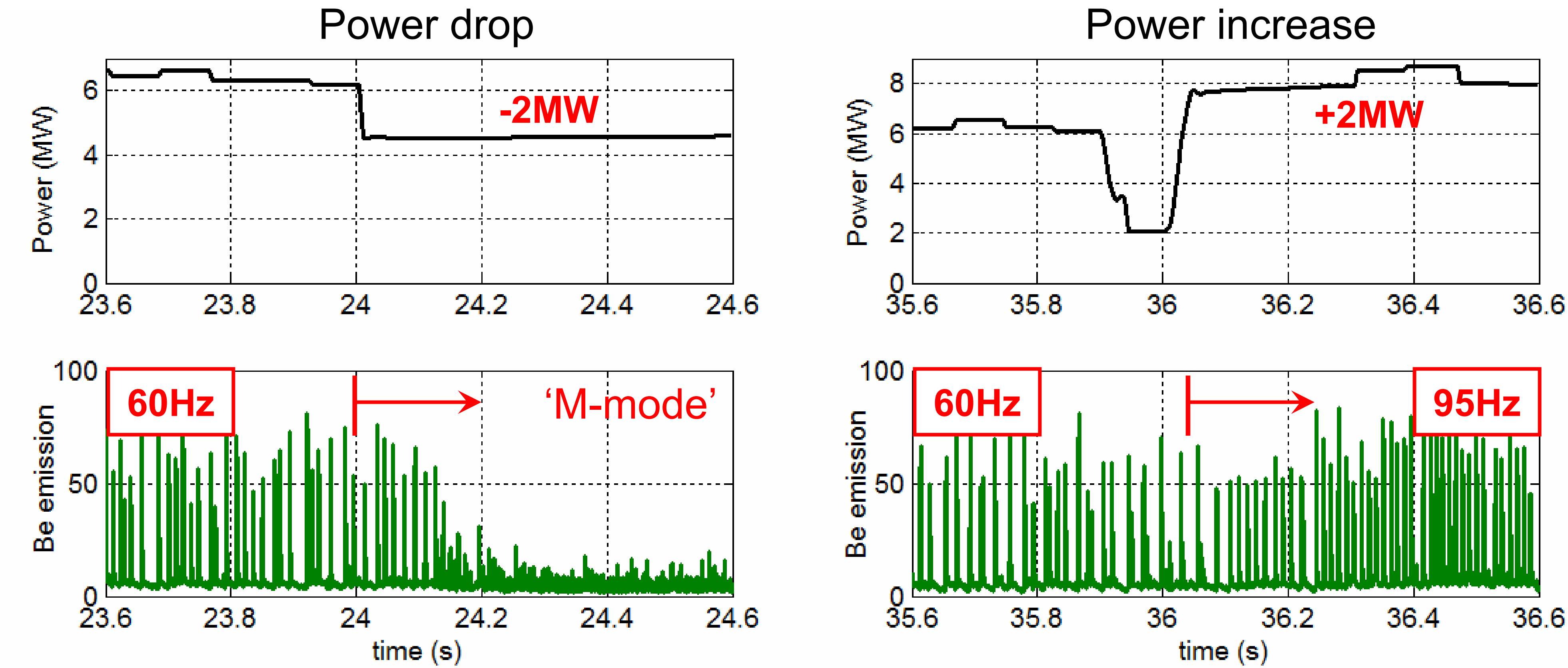






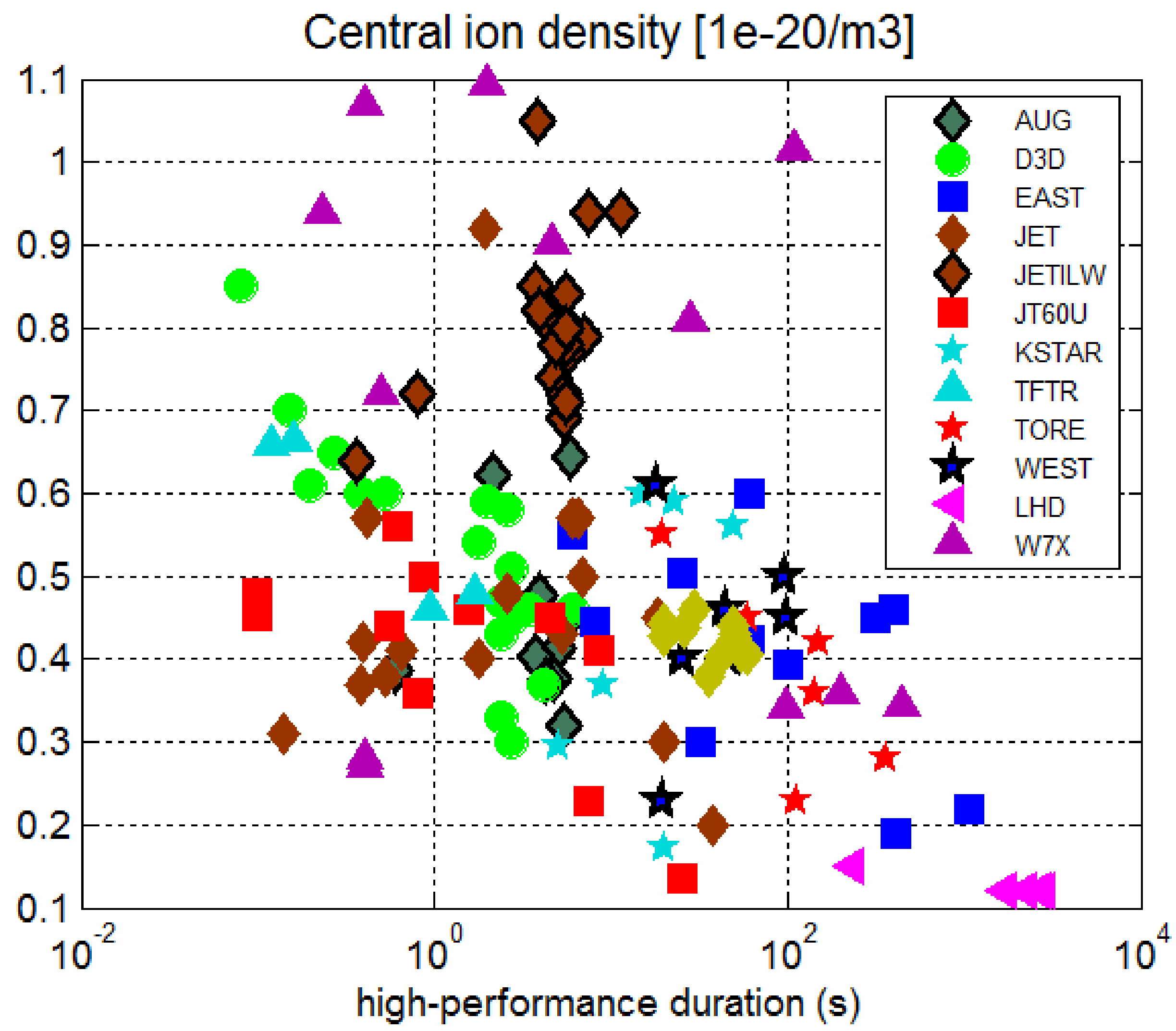
Sub-divertor cooling?

60s pulses: ELM behaviour vs. power



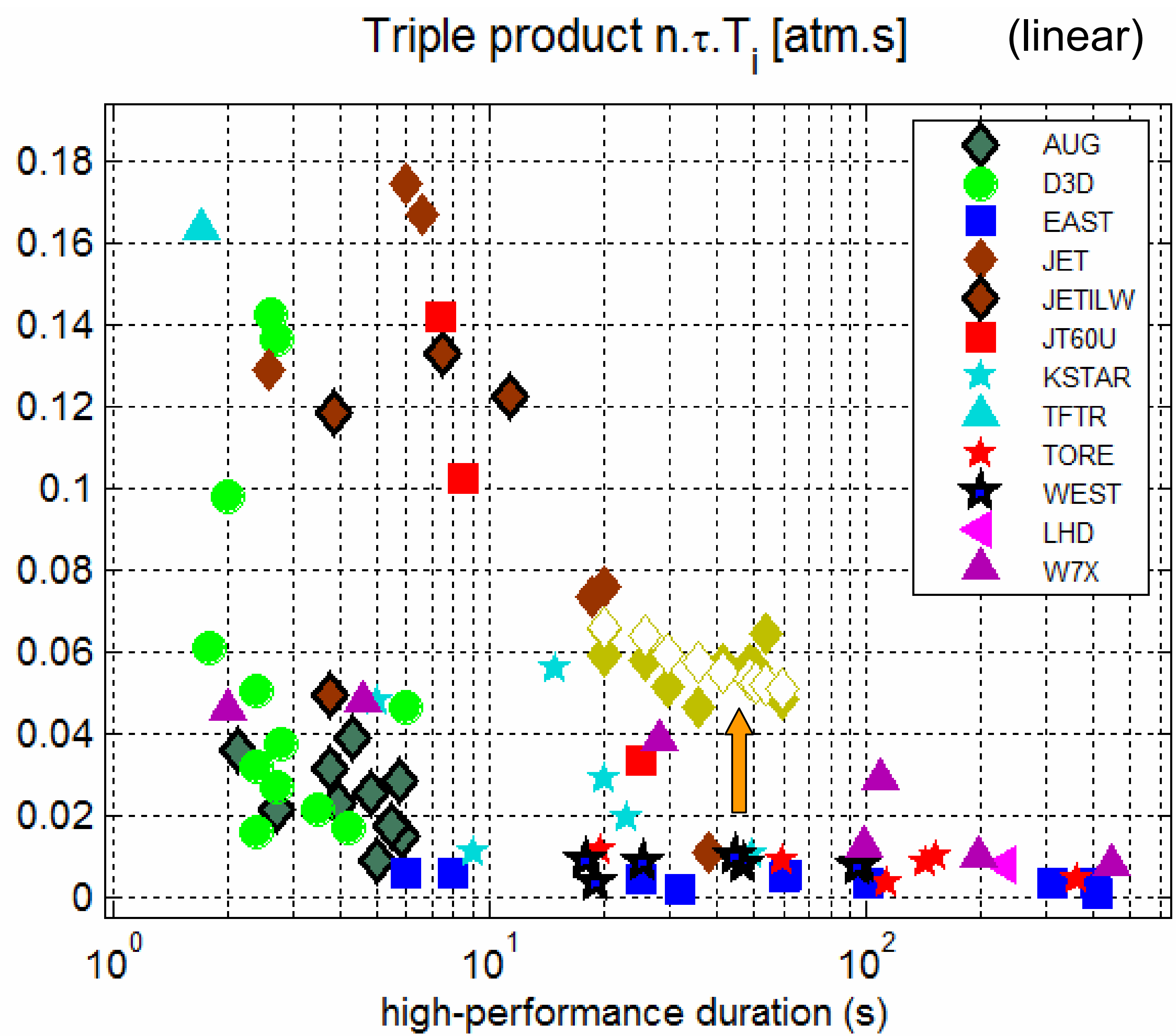
- Input power (6MW) is close to L-H threshold
- ELM frequency very sensitive to input power
- ELMs take about 0.2s (~τ_E) to respond to power change

CICLOP database: density



Similar densities as other machines (n_0=4e19/m^3)

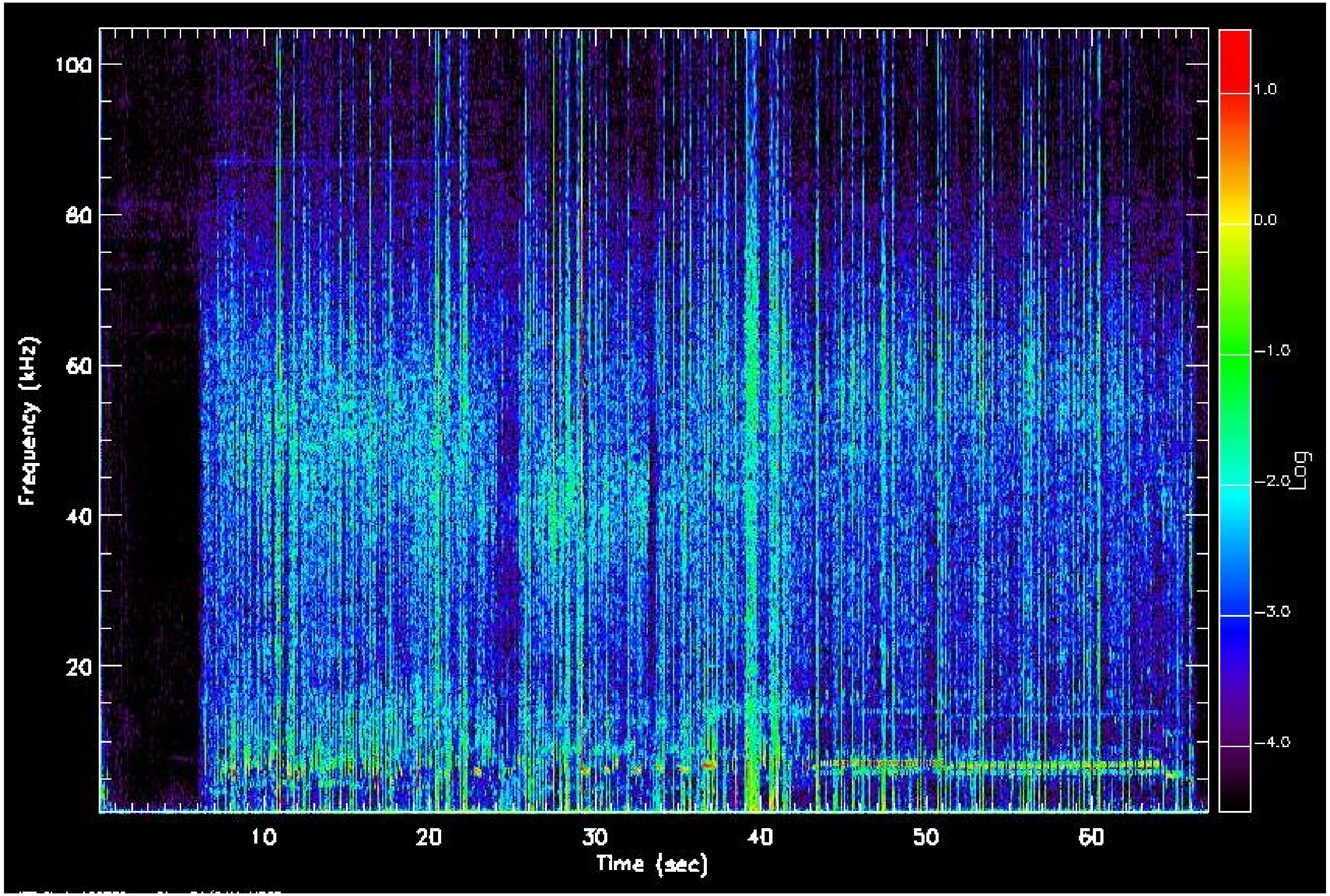
CICLOP database: triple product



(reserve)

MHD

105750



No MHD detected (exc. small sawteeth)