PLASMA CONTROL EXPERIMENTS IN JET DEUTERIUM-TRITIUM PLASMAS

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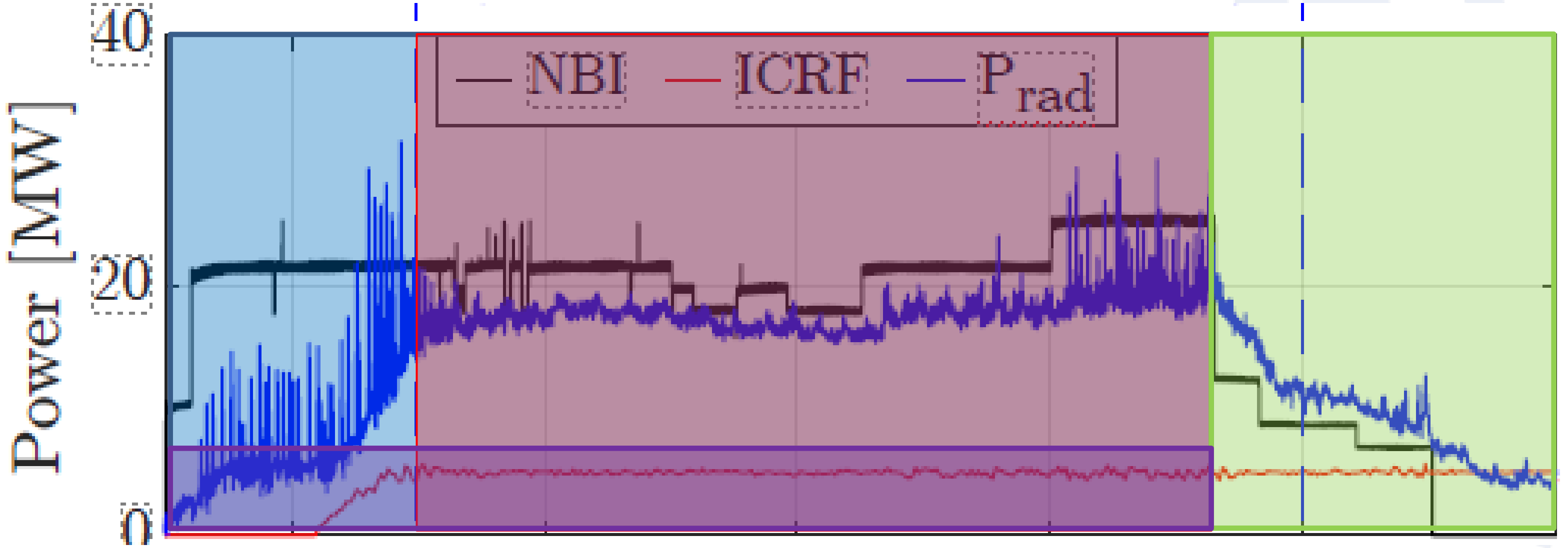
Outline

JET has carried out two Deuterium Tritium Campaigns in last 5 years, with exceptional scientific output. Several real time controllers have been developed on purpose for DT operation, or have been modified in order to cope with it

- ❑ D/T isotope concentration real time control
- ❑ XPR vertical position control
- ❑ Non Performing pulse real time detector (DUD)
- ❑ H/L power threshold control during H mode exit

- Other real time control schemes have been routinely used in D/T operation, but these did not need a specific experiment.
- The control experiments shown are the result of a long standing effort, **controllers developed on smaller tokamaks, tested in D or D/H and then ported to D/T**.



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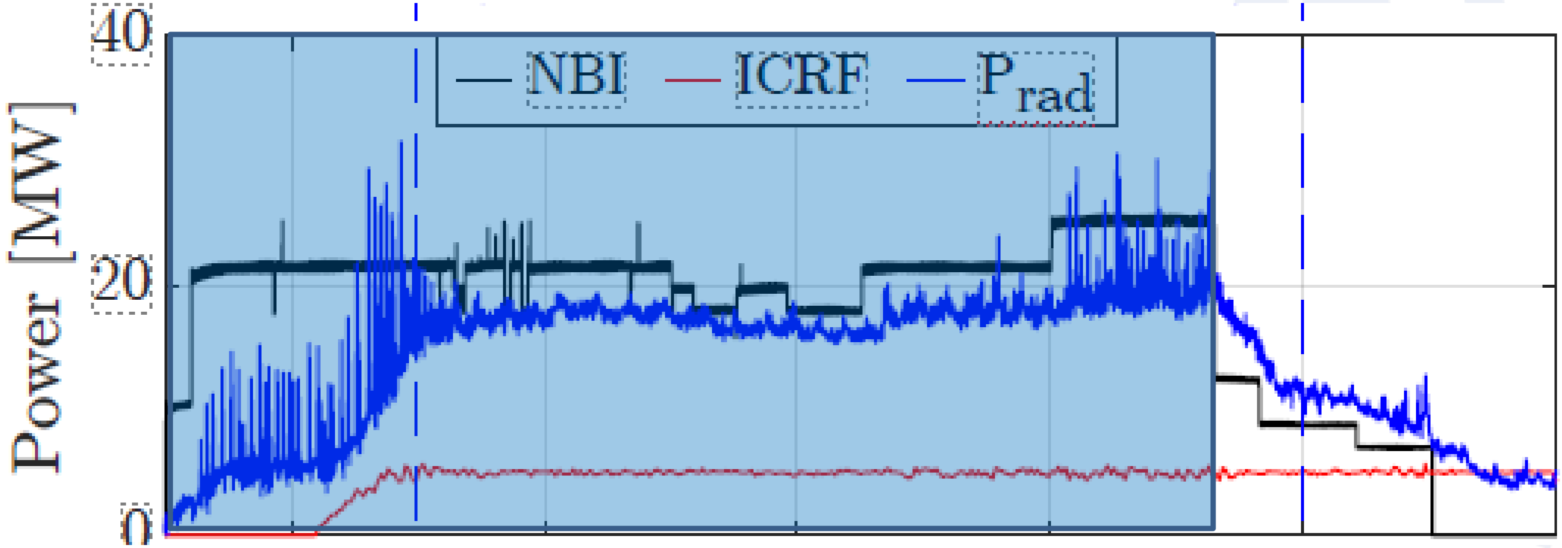


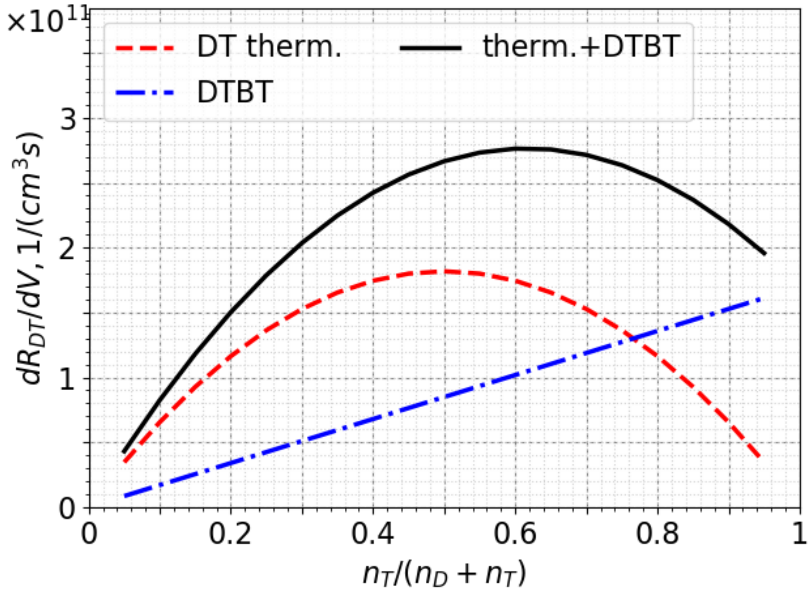
D/T ratio control experiments in JET

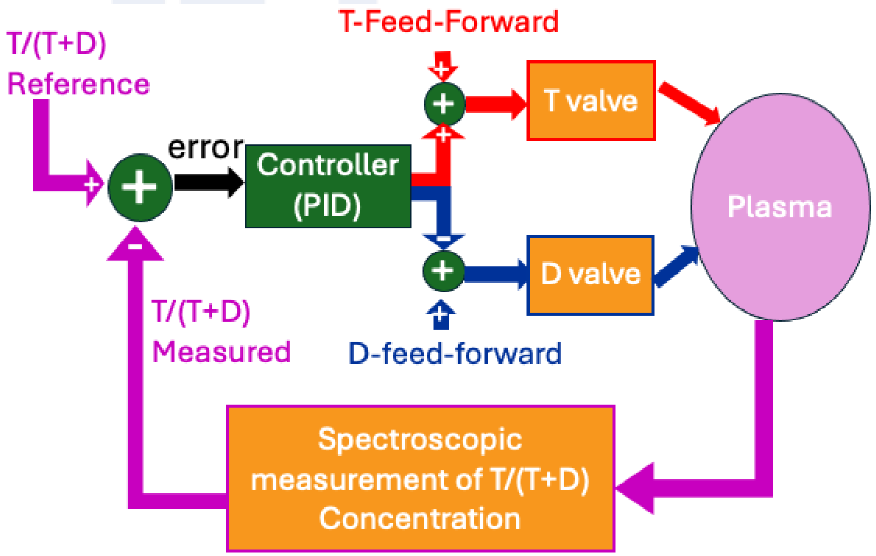
- D/T ratio needs to be controlled in future fusion devices in order to optimize performance and control burn phase

- JET DTE3 featured D/T ratio control experiments by means of RT scheme [Lennholm, M. et al, PRX Energy]

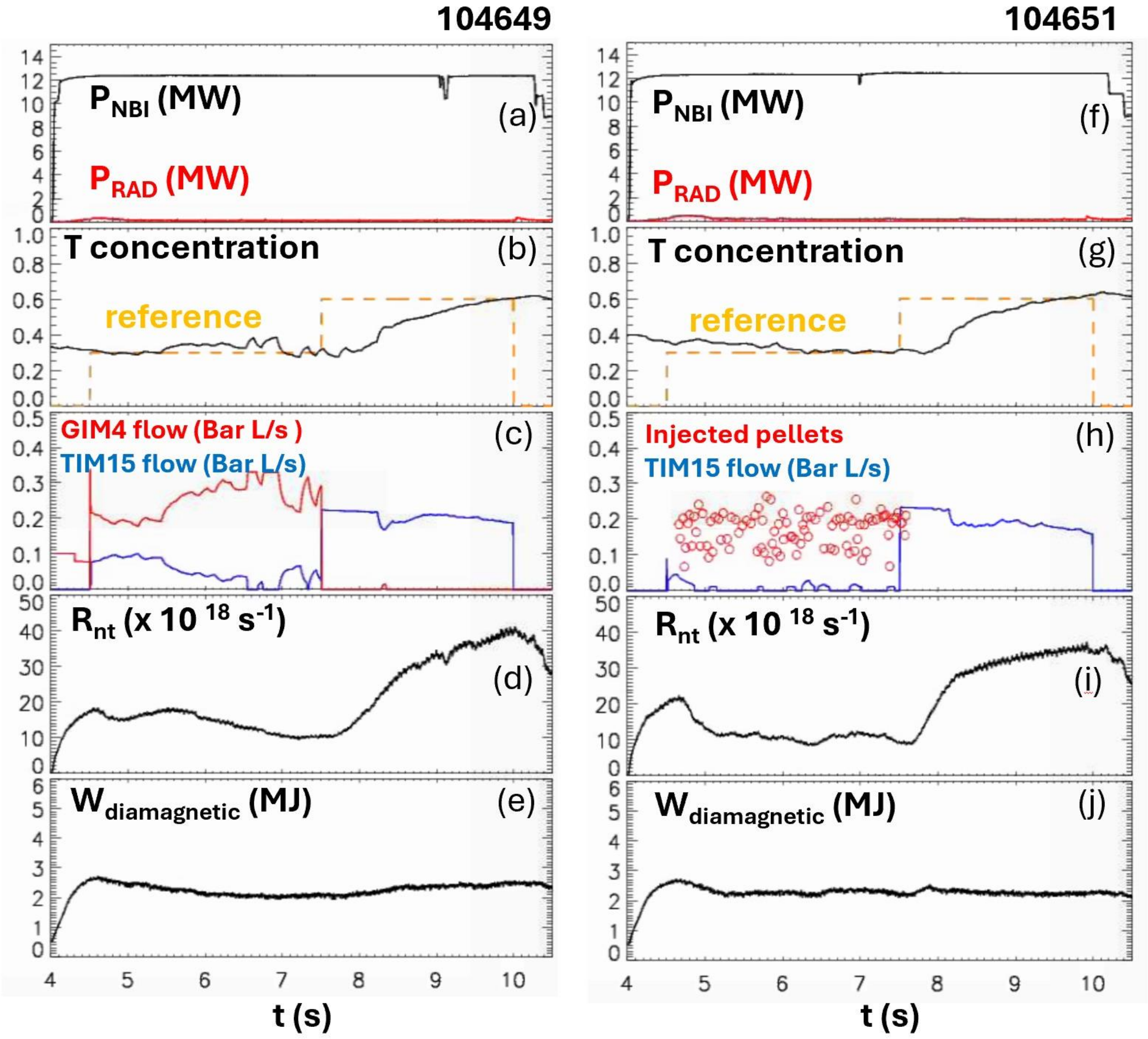
- D/T ratio measured in real time via spectroscopy in divertor and demonstrated with gas injection and pellets

- D/T ratio control coupled with ELM frequency control using gas (MIMO control)





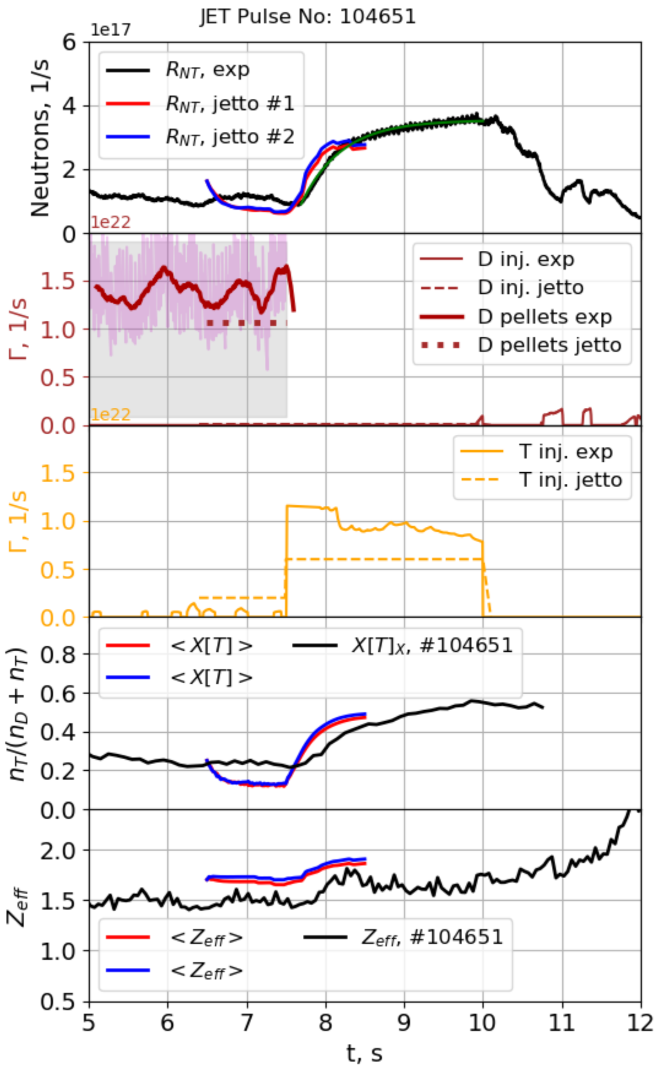
D/T ratio control experiments in JET

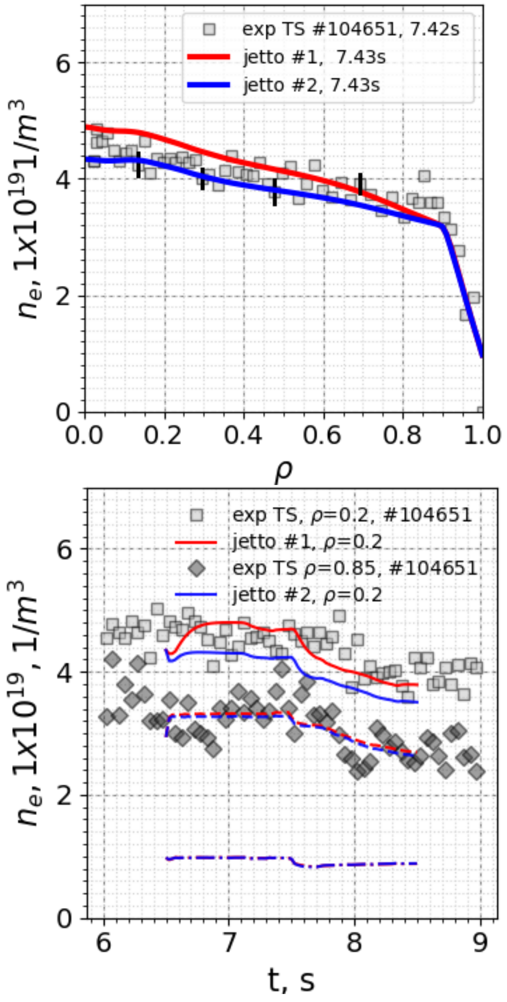


- JET DTE3 featured D/T ratio control experiments by means of gas injection (104649) and pellets (104651)
- RT control signal based on divertor spectroscopy (cyan), actuators are gas valves(blue) and pellets (black)
- T concentration reference stepped up at 7.5s
- The increase in neutron production clearly correlates with isotope concentration change
- Input power and plasma energy remains the same

Particle transport modelling for DT mixture control

Results from predictive JETTO simulations – D pellets





[K.Kirov NF 25]

- Predictive D, T densities JETTO run (Te, Ti prescribed from measurements)
- Sources modelled with FRANTIC, HPI2/continuous pellets, PENCIL
- Impurities with SANCO, Be, Ni, W. Zeff calculated
- Calculated electron density, neutrons, D/T ratio and Zeff validated versus measurements.
- BgB model used for particle transport
- This modelling approach could be used to aid design and optimization of future controllers

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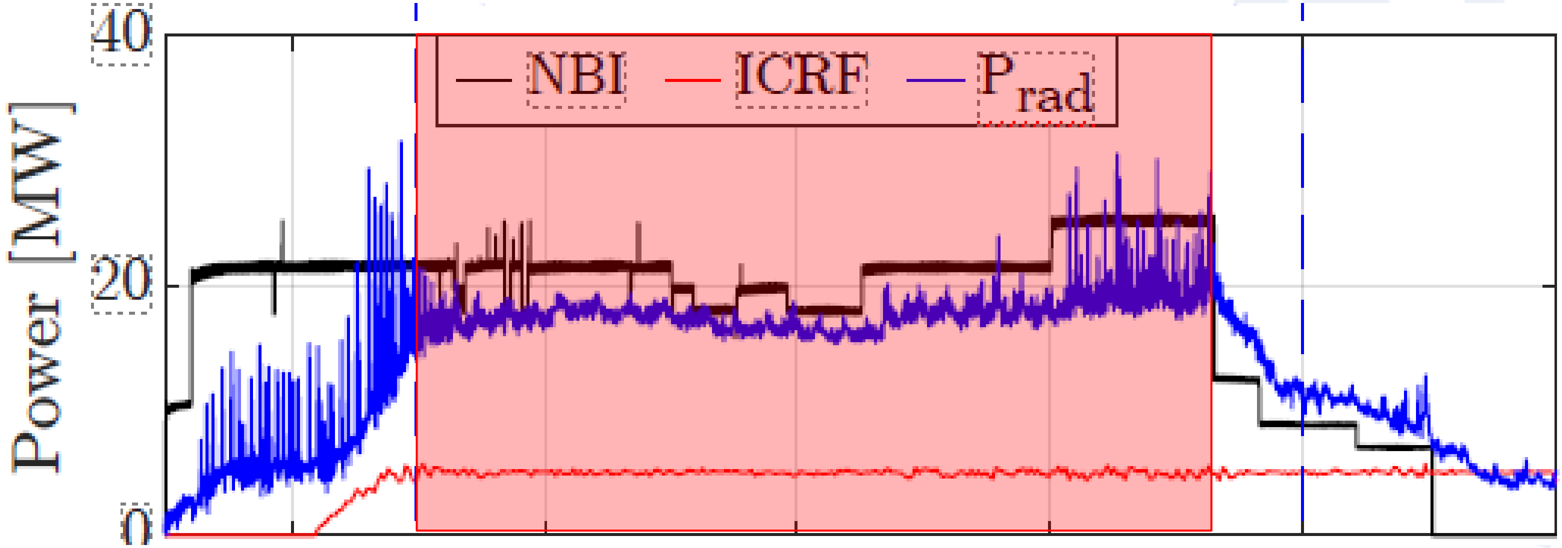


XPR control in DD and DT

- ❑ Detachment is essential for future reactor with power dissipation needed larger than 95%
- ❑ Detachment of the outer divertor is linked to an intense localized radiator in the X-point region (XPR)
- ❑ XPR has bee established in WPTE devices and at JET in deuterium
- ❑ Real-time control of XPR vertical position is needed in order to maintain a stable detachment in H mode
- ❑ XPR control scheme was adapted from AUG and optimized using System Identification pulses applying single frequency Ar modulation

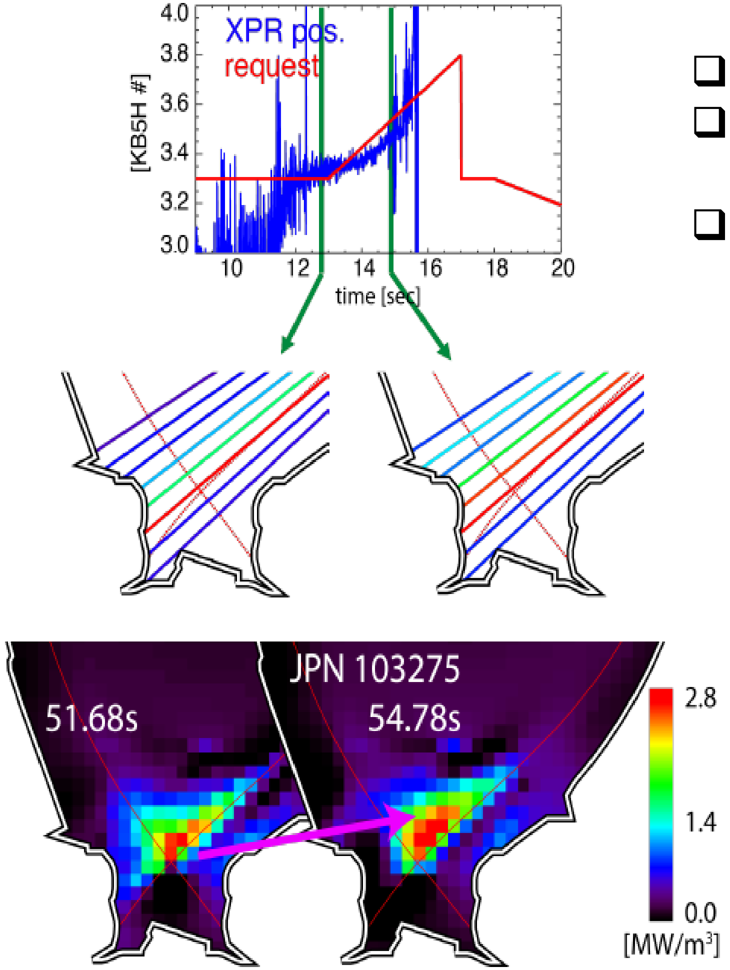
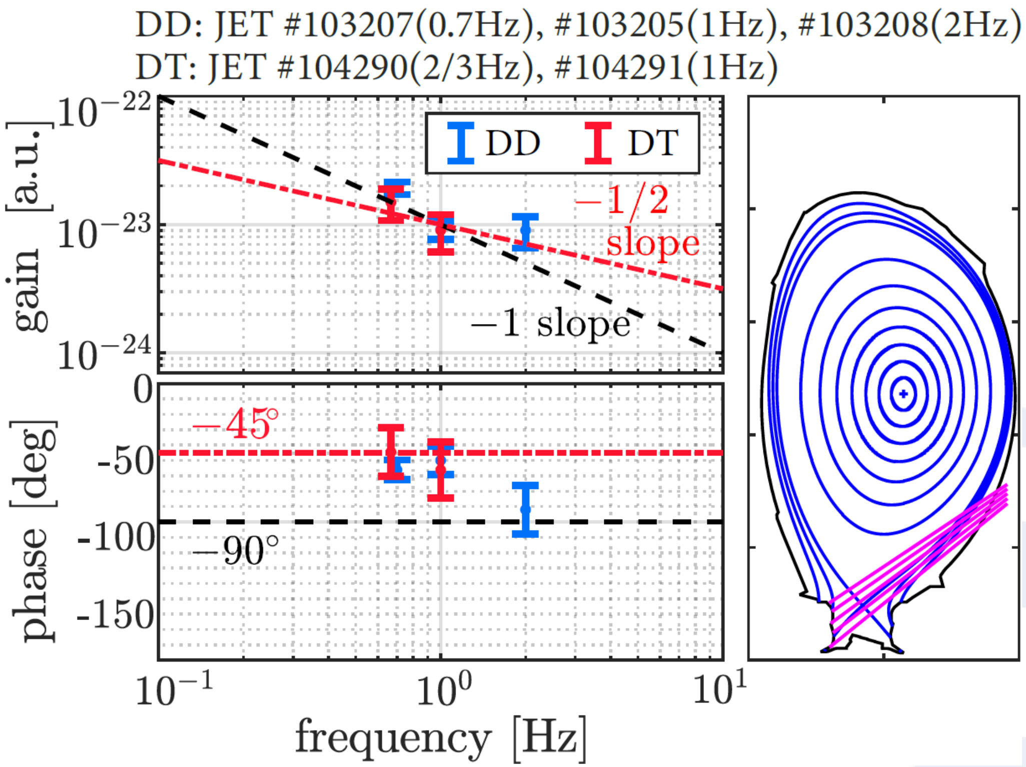
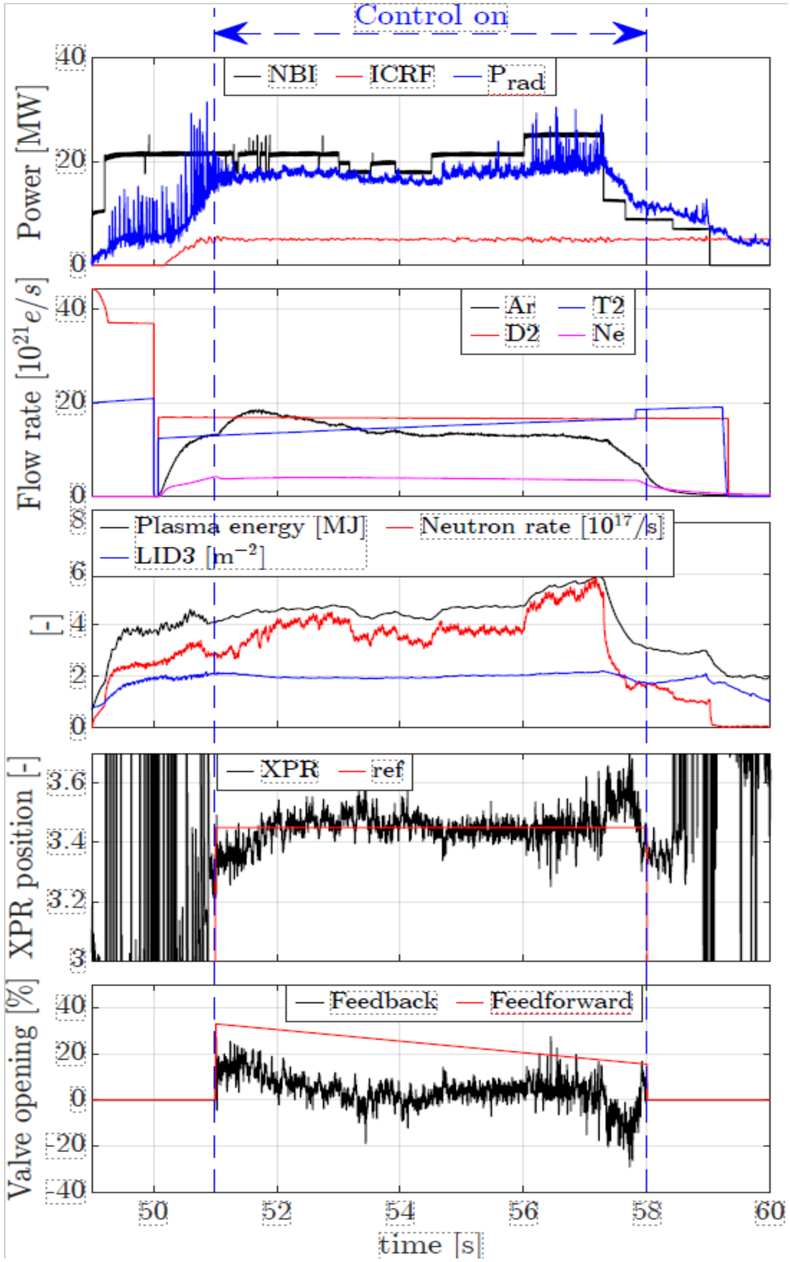


Fig. M. Bernert et al, PSI 2024



BERNERT M. et al Nucl. Mater. Energy 43 (2025) 101916

XPR control in DT



- Real-time control of XPR was also applied in DT, showing similar behavior as in D
- The controller successfully maintains a stable XPR position and fairly constant neutron rate and plasma internal energy along the discharge, withstanding strong power modulations and pellets
- Despite constant requested XPR position, the Ar injection is ramping down, in order to counteract impurity accumulation in the plasma

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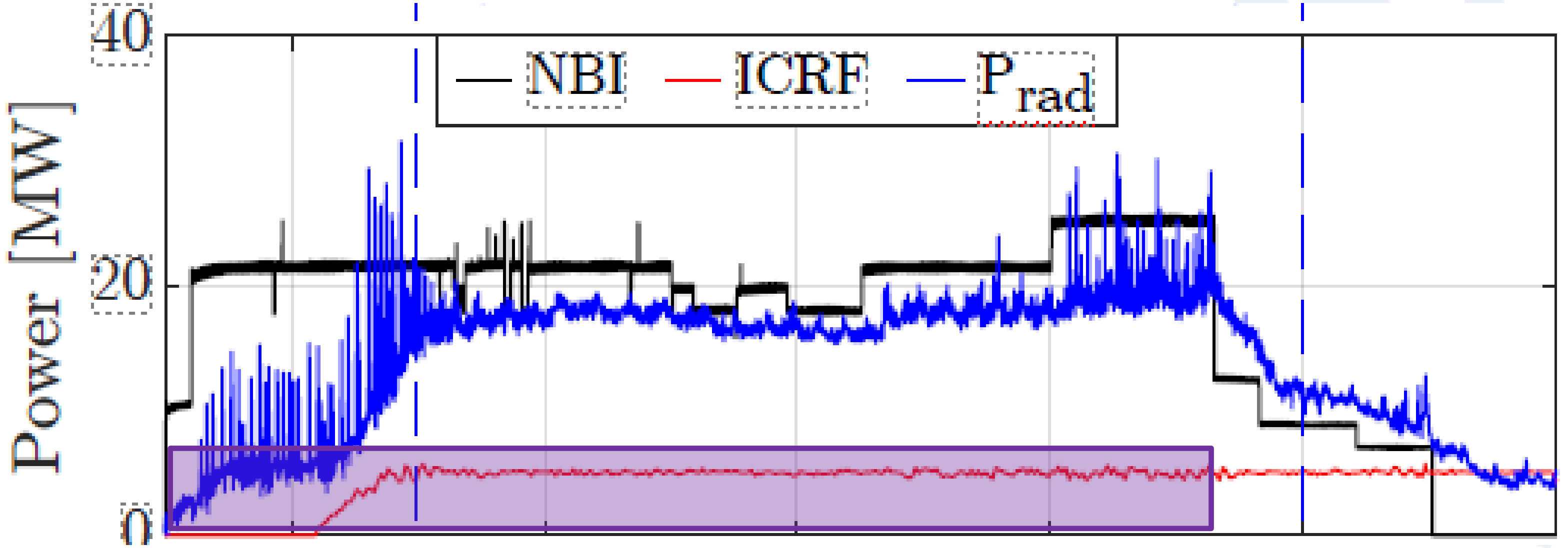
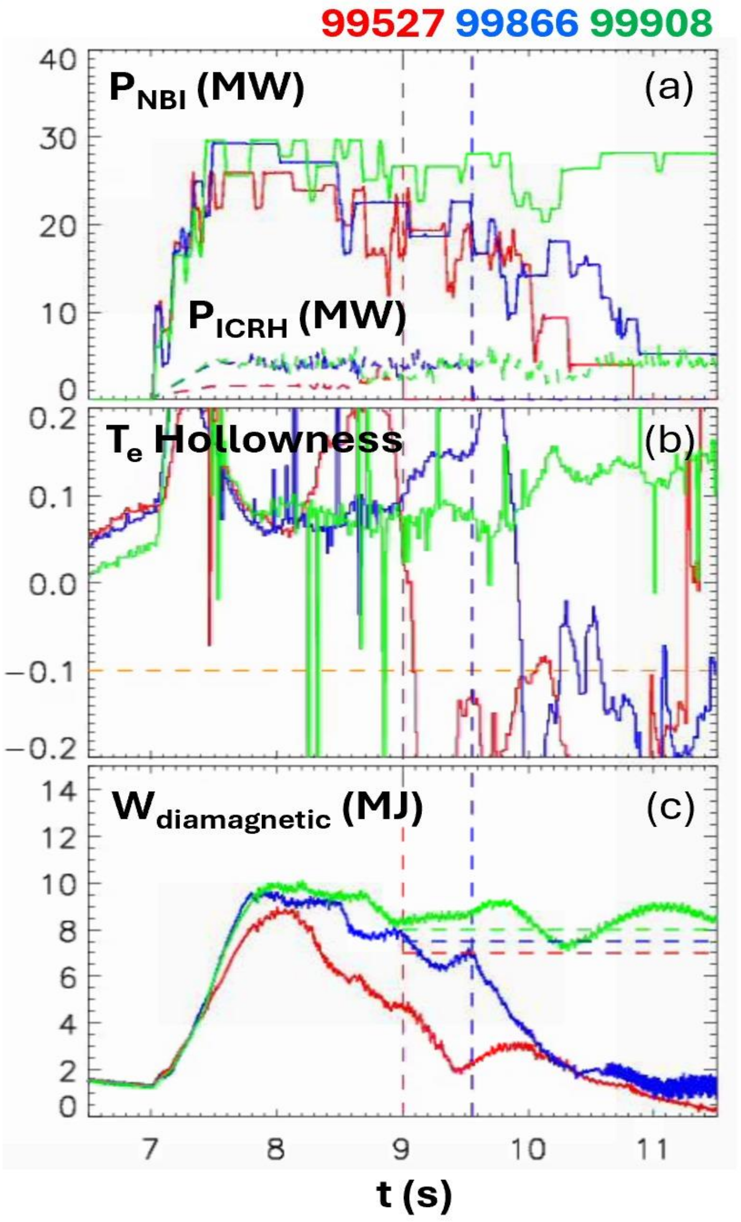


Non performing pulse detection in JET DT plasmas



- In JET D/T pulses, dud detector has been used to terminate pulses that were not reaching the expected plasma performance.

- For hybrid D/T scenarios, the dud detection was based on the following metrics:
  - the electron temperature hollowness indicator
  - the evolution of the diamagnetic energy
  - If their values were below empirically identified thresholds, the plasma was terminated safely.

- Non performing pulse detection based on surrogate neutron rate signals for JET DTE1,2,3 and TFTR have been investigated

L. Piron, poster 3035, B65, 16/10

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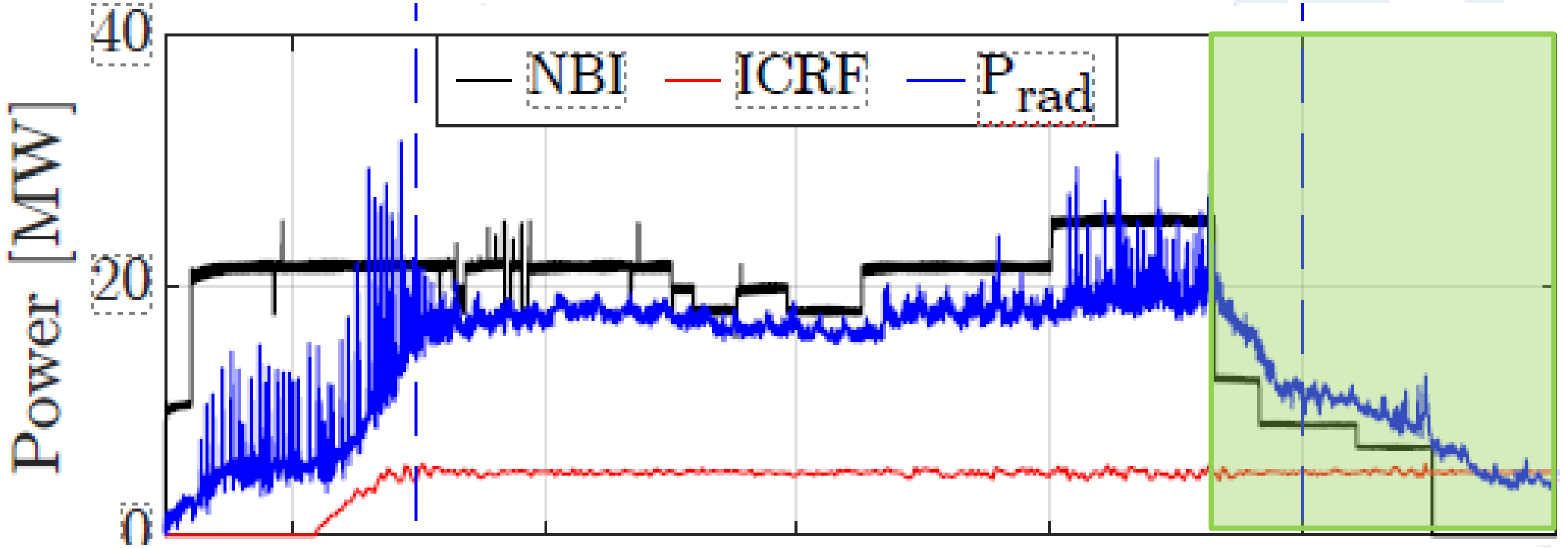


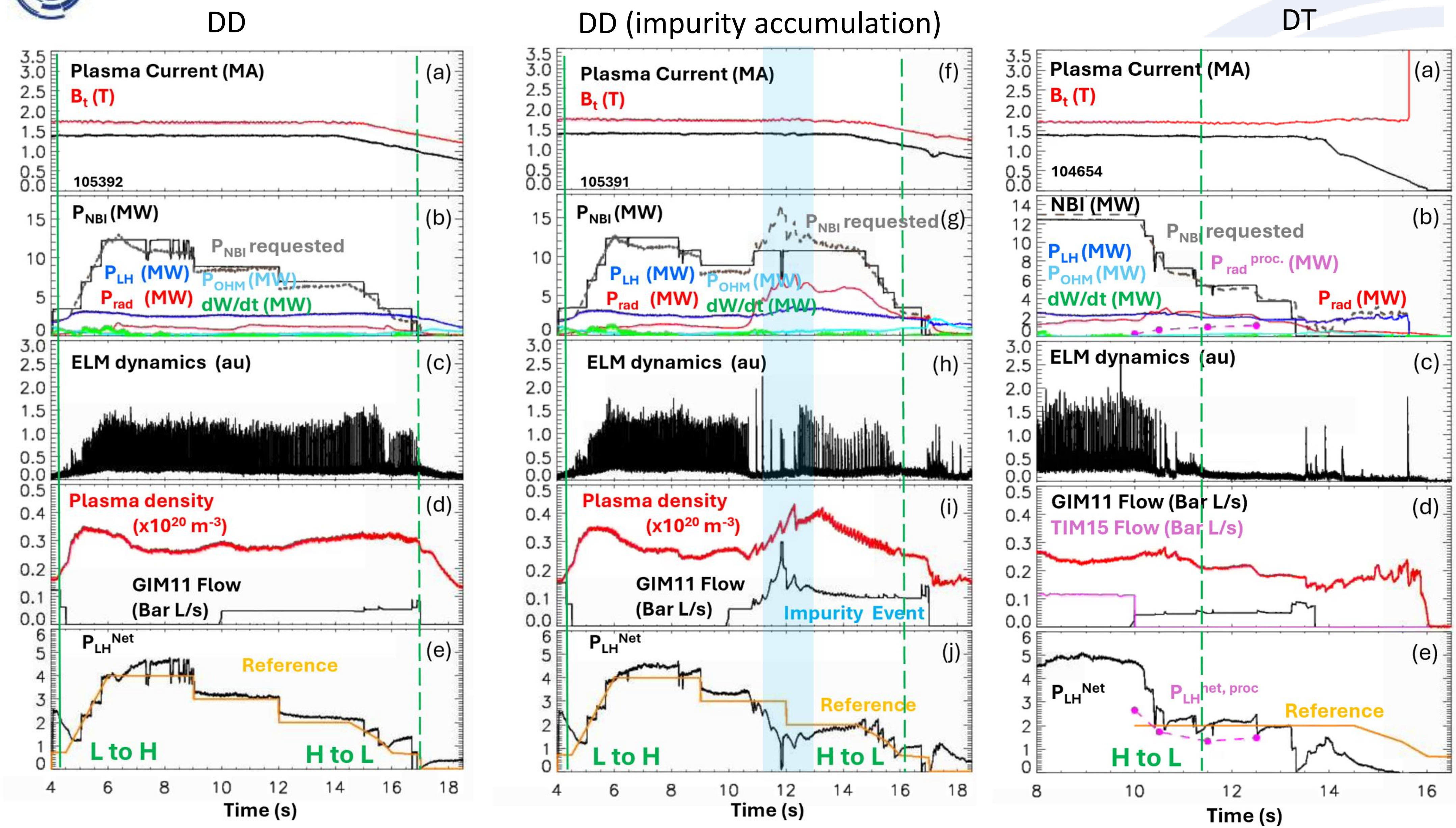
The P_{LH} controller

- It is important to maintain large enough power over P_{LH} during plasma termination in order to avoid disappearance of ELMs and W accumulation.
- The P_{LH} controller calculates the excess of power across the separatrix with respect to the P_{LH} scaling law using some approximations:
  - Martin's scaling law used for both L-H and H-L transitions, assuming no hysteresis. This is due to the absence of an analytical scaling law for the reverse H to L transition.
  - Martin's scaling law has been deliberately adjusted by a factor of 0.7 to accommodate prediction uncertainty.
  - Regarding the calculation of P_{sep} the Ohmic power and the time variation of the stored energy have been neglected.

- Two actuators have been exploited to tailor the P_{LH}^{Net} dynamics during the controller tests: the divertor gas injection module (GIM11) and the NBI power. Gas used to regularize ELMs (impurity flushing)

L. Piron et al Plasma Phys. Control. Fusion 67 (2025) 055006

The P_{LH} controller (DD an DT)



P_{LH}^{Net} has shown some issues due to interference of T injection modules on bolometry (overestimation of P_{LH}^{Net}). Post processing was needed in order to cope with this effect (purple).

Take home message

In the run up to DT operation several real-time controllers have been developed on purpose for D/T operation, or have been modified in order to cope with it

- Development of these controllers is a long-standing effort carried out in multiple experimental campaigns, based on the testing and concept development in Deuterium operation or in D/H at JET

- Some controllers have been tested in smaller WPTE tokamaks, and then ported to JET

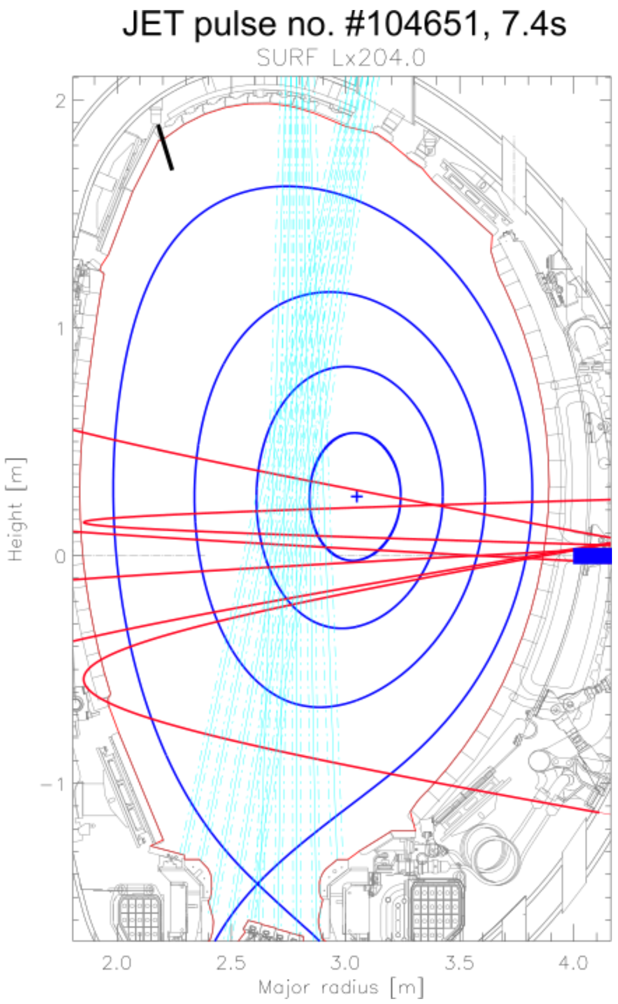
- Simple models have proven to be effective as a starting point for tuning of D/T controllers starting partially from Deuterium data (Sys Identification, Integrated transport modelling)

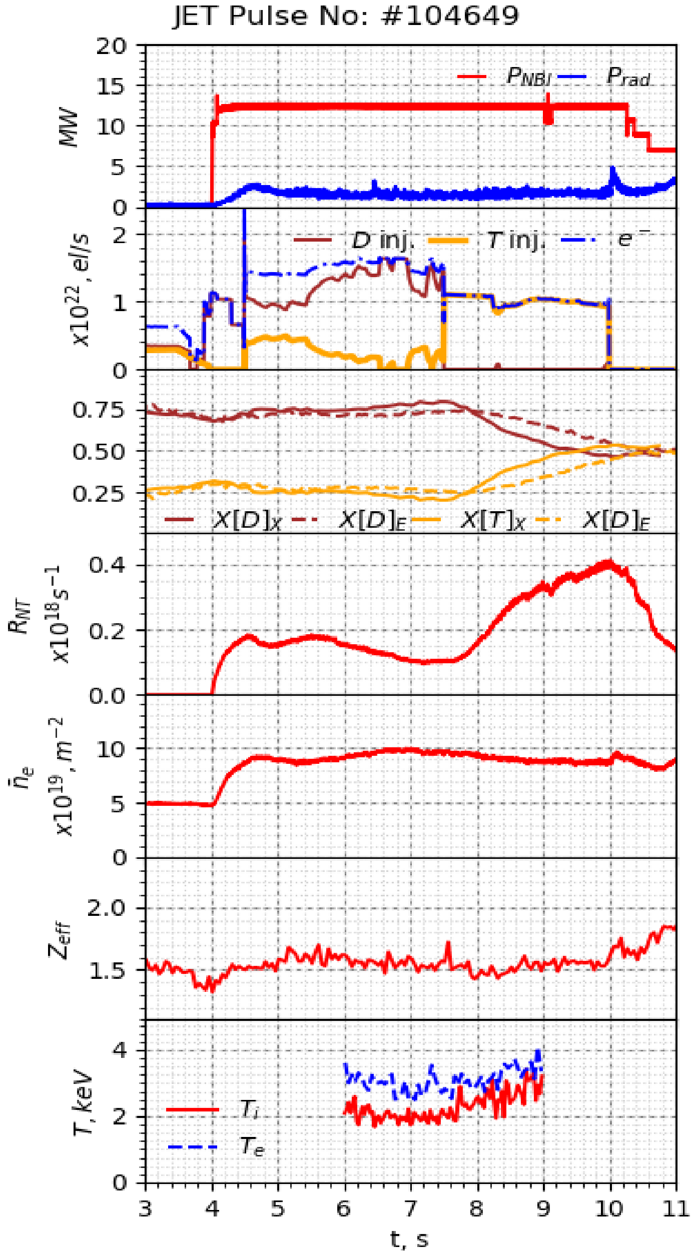
- Developed controllers are specific to D/T operation, while maintaining enough machine agnosticism to be ported to future tokamak devices

- The methodology shown of developing controllers in D or D/H and then porting them to D/T can serve as a template for the development of controllers for future D/T operating devices

Backup Slides

DT mixture control experiments at JET DTE3, 1.4MA/1.7T

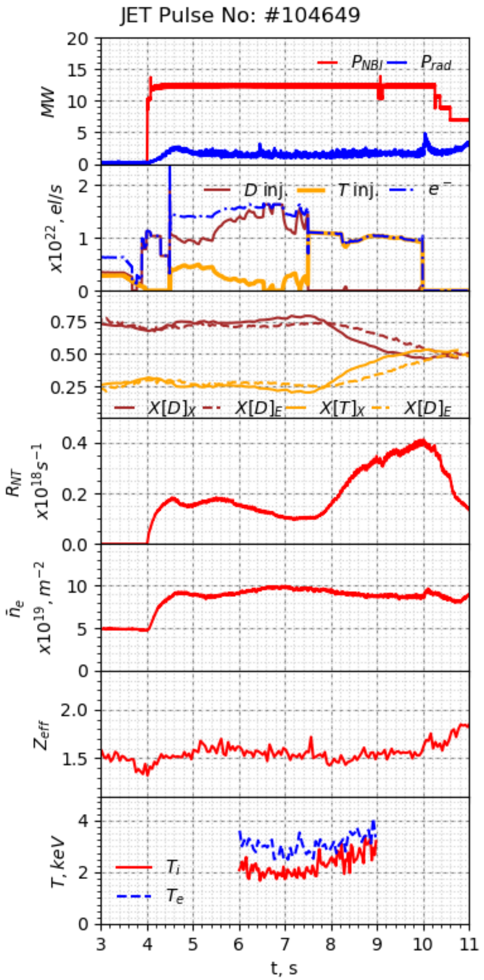


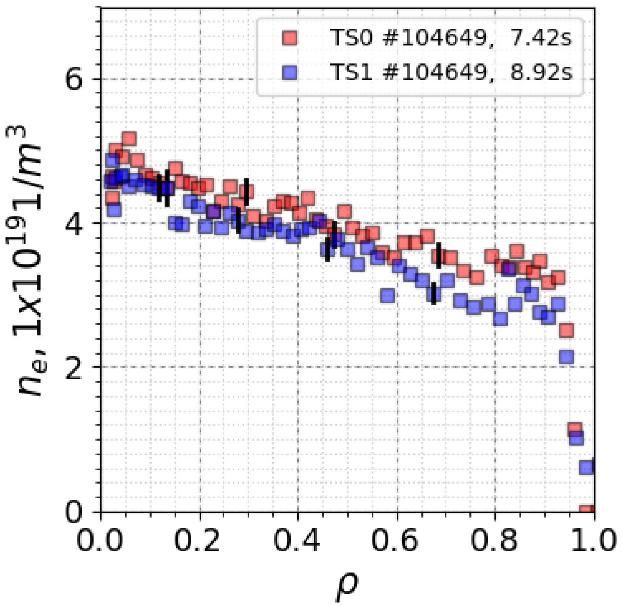


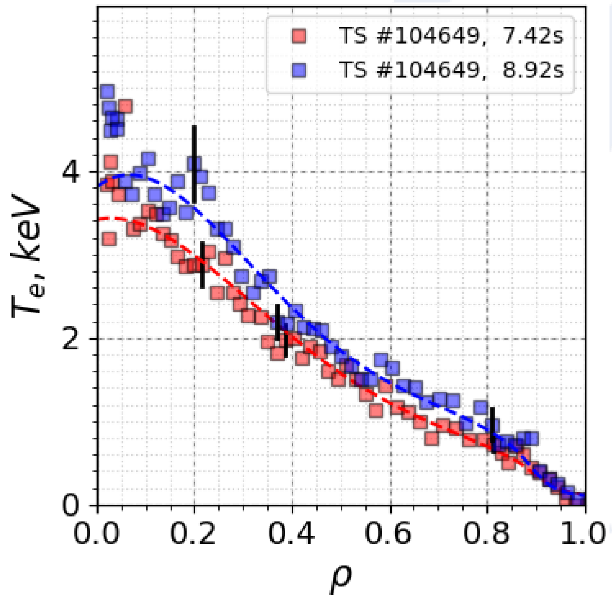
pulse	phase	D/T target and achieved ratio as measured by HRS at time t[s]	D/T RT control sources
#104648	#1, 4.5-7.5s	D/T~0.7/0.3 D/T~0.75/0.25, at 7.45s	D by gas injection; T by gas injection
	#2, 7.5-10s	D/T~0.4/0.6 D/T~0.5/0.5, at 10s	D by gas injection; T by gas injection
#104649	#1, 4.5-7.5s	D/T~0.7/0.3 D/T~0.8/0.2, at 7.45s	D by gas injection; T by gas injection
	#2, 7.5-10s	D/T~0.4/0.6 D/T~0.47/0.53, at 10s	
#104650	#1, 4.5-7.5s	D/T~0.7/0.3 D/T~0.75/0.25, at 7.45s	D by pellets;
	#2, 7.5-10s	D/T~0.4/0.6 D/T~0.44/0.56, at 10s	T by gas injection
#104651	#1, 4.5-7.5s	D/T~0.7/0.3 D/T~0.77/0.23, at 7.45s	D by pellets;
	#2, 7.5-10s	D/T~0.4/0.6 D/T~0.44/0.56, at 10s	T by gas injection

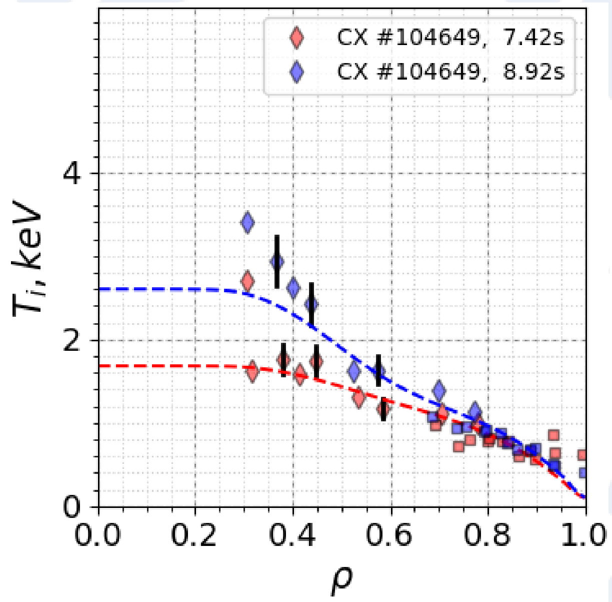
- RT control signal based on divertor spectroscopy (cyan), actuators are gas valves(blue) and pellets (black)
- Profiles show the change in isotope concentration and neutron rates after 7.5s

DT mixture control experiments at JET DTE3, 1.4MA/1.7T profiles



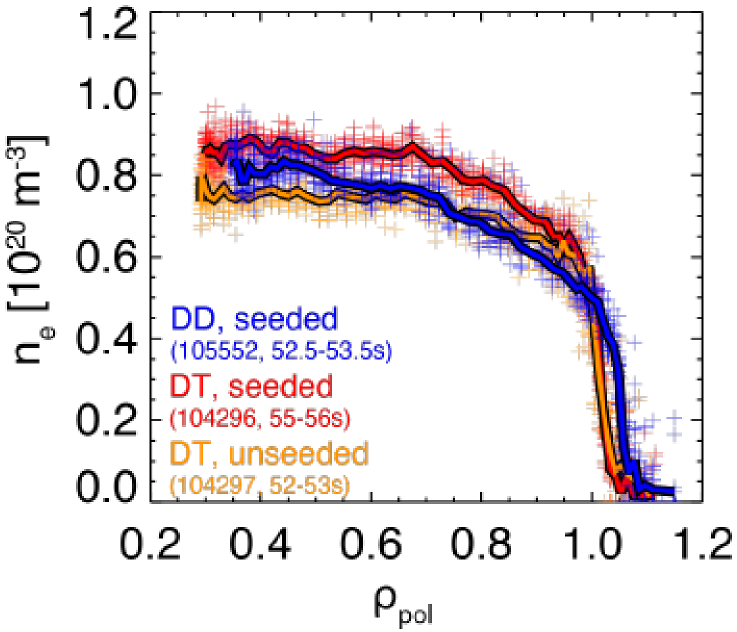


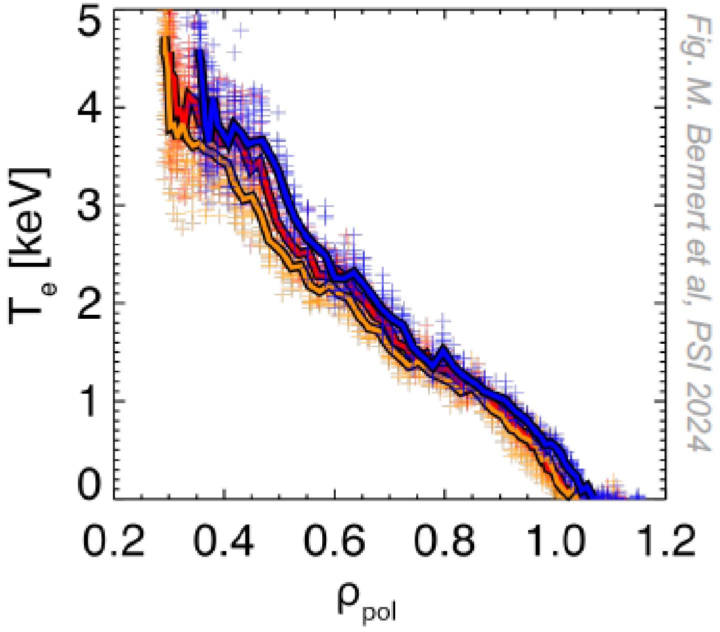




XPR control in DD and DT

2.5MA/2.65T, low-δ, P_{in}~26-27MW





Higher n_e in D-T

Similar T_e in D-T

In D: Unseeded $H_{98(y,2)}$~0.65
Seeded $H_{98(y,2)}$~0.7-0.8

- The XPR exists also in DT plasmas and can be successfully controlled, helping to establish similar conditions
- As in D, in these conditions (high power, Ar/Ne seeding), the XPR has no detrimental impact on confinement in D-T
- Higher stored energy in D-T

M. Bernert et al, PSI 2024

Particle transport modelling for DT mixture control

- This study demonstrates that simple models and assumptions for D/T transport can be successfully used to predictively model the behaviour of RT controllers for D/T ratio control. This approach was able to reproduce the experimental data for the density, DT ratio and neutrons and therefore can be used to simulate the behaviour of future RT controllers in conditions at different scenario, particle sources and plasma parameters.
- For future D/T ratio RT controller development, the models presented here would serve as a foundation for further improvements.
- TRANSP modelling shows: RT scheme based on simple quasi-neutrality and Z_{eff} calculations could be implemented successfully.
- Modelling the response of D/T ratio control across various scenarios, as demonstrated through JETTO predictive particle modelling, would be a valuable outcome from this study. For adjusting and optimizing RT controllers, this workflow could save experimental time and reduce the need for expensive computations.

Machine learning aided neutron yield for dud detection based on JET DT plasmas

- A surrogate machine-learning (ML) model for Neutron yield has been built based on Deuterium-Tritium discharges performed during DTE2-DTE3.
- The Input signals are NBI, ICRH power, Wp, Te, Ne, Isotopic ratio.
  - The input database includes
    - M21-03 baseline,
    - M21-02 beam-target,
    - M21-01 hybrid,
    - M21-09 AT plasmas.

- Once included in the real-control system, the Neutron yield model can generate synthetic data in case of hardware/diagnostic failure and can be used for non performing pulse (dud) detection

- The JET-derived surrogate ML model for Neutron yield is under validation against:
  - DTE1 data
  - DT TFTR data

L. Piron, this conference