WPTE Experimental program and modelling needs in view of TSVV1 deliverables

N. Vianello

On behalf of WPTE TFLs
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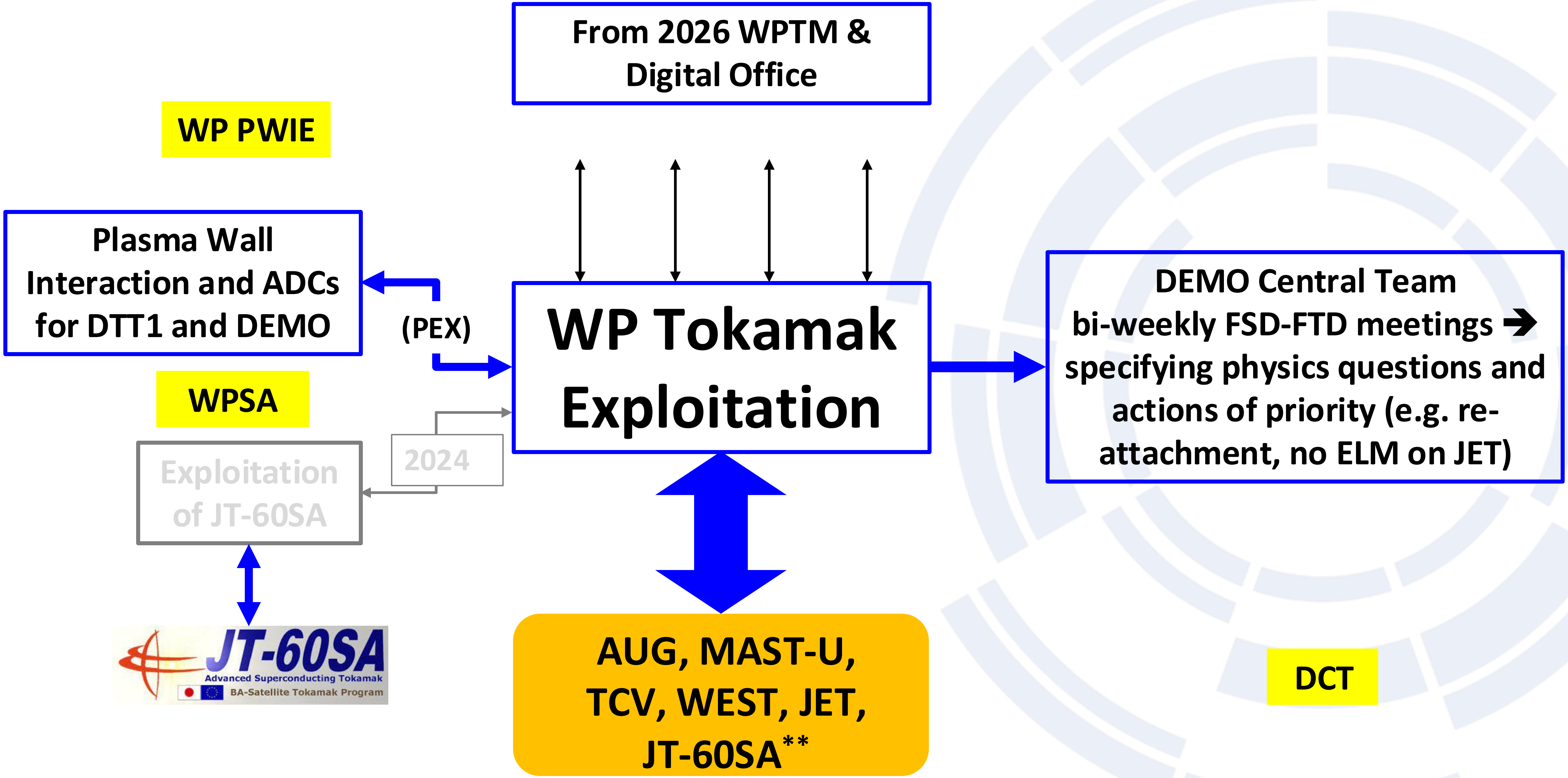
WP TE in PSD* with overarching priorities: ITER & DEMO & PEX



* Plasma Science for ITER, DEMO and stellarators Department

** From 2024 JT-60SA Scientific Exploitation included in WPTE

WPTE Programme definition

- Overarching priorities based on ITER RP, DEMO physics gaps and exploitation of PEX
- EUROfusion Grant Deliverables, GD, as defined in the Consortium Work Plan and submitted to the European Commission (EC) – need to be achieved for money to flow from EC to EUROfusion
- Milestones (as step stones to progress towards these Grant Deliverables)
- Priorities defined by the EUROfusion Roadmap towards Fusion Electricity – need to be achieved for aiding ITER to succeed and designing a power plant extending beyond GDs:
  - derived from the ITER Research Plan and discussed with IO
  - derived together with the DEMO Central Team to close DEMO physics gaps for developing viable operational scenarios for DEMO
  - For the 2026 program streamlined as result of overall budget reduction in human resources and machine time (for 2027)

WPTE Grant Deliverables for 2025 and 2026-2027 related to TSVV1 (TSVVA)

2025 Deliverables		
TE.D.09	Establishment and comparison of N and Ne-seeded partially-detached divertor in high-power operations in view of ITER radiative scenario.	Dec. 2025
TE.D.13	Recommendation on the seeding impurity mix in view of a future reactor.	Dec. 2025

2026-2027 Deliverables		
TE.D.16	Report on providing fully integrated simulation of high current partially detached plasma scenario including assessment of PFC erosion in D and DT plasma	Dec. 2026
TE.D.19	Report on qualification with experiment/modelling of the most promising no-ELM scenario in terms of confinement, exhaust capabilities and plasma wall Interaction	Dec. 2027

- Although achieved, still interpretative modelling activity on-going

WPTE Research Topic Structure kept for 2026-2027

TSVV1/A: related Research Topics

ITER

RT01: Core-Edge-SOL integrated H-mode

DEMO

RT02: Alternative to type-I ELM regimes

Physics & Control integration

RT03: Disruption & RE mitigation strategies

RT04: Machine generic integrated control

RT05: Physics of divertor detachment

RT08: Physics of high β long pulse scenario

RT09: Physics of energetic particles

RT06: preparation of efficient PFC operation

RT07: Alternative divertor configuration

PEX

Mission 1

Mission 2

Mission 1 – Plasma Regimes of Operation
Mission 2 – Heat Exhaust Systems

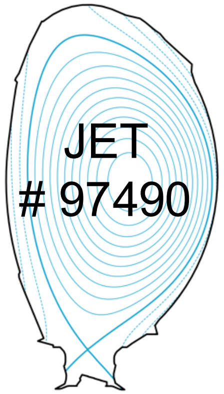
RT-01 Core-Edge-SOL integrated H-mode scenario compatible with exhaust constraints in support of ITER

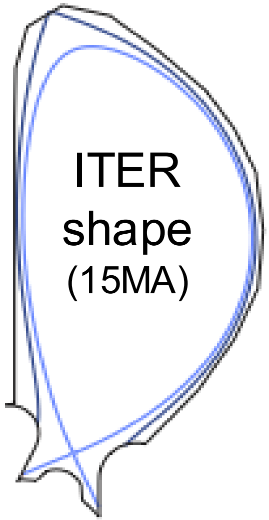
#	Scientific Objectives
D1	Develop and understand stationary H-mode scenario at low collisionality and with dominant electron heating
D2	Provide physics-based cross-field transport coefficients for heat, fuel particles and **impurities** to TSVVs for turbulence modelling
D3	Determine the impact of different impurity mixes for partially detached divertors in high power operations in view of ITER radiative scenarios
D4	Assess pedestal performances in condition closer to future devices including large SOL opacity, low pedestal collisionality, peeling limited plasma
D5	Quantify **pedestal transport** and screening of impurities in conditions relevant for next-step fusion devices

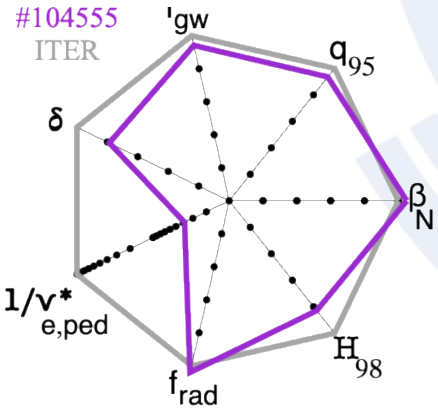
RTC: C. Giroud, L. Frassinetti, S. Wiesen, D. King (stepping down)

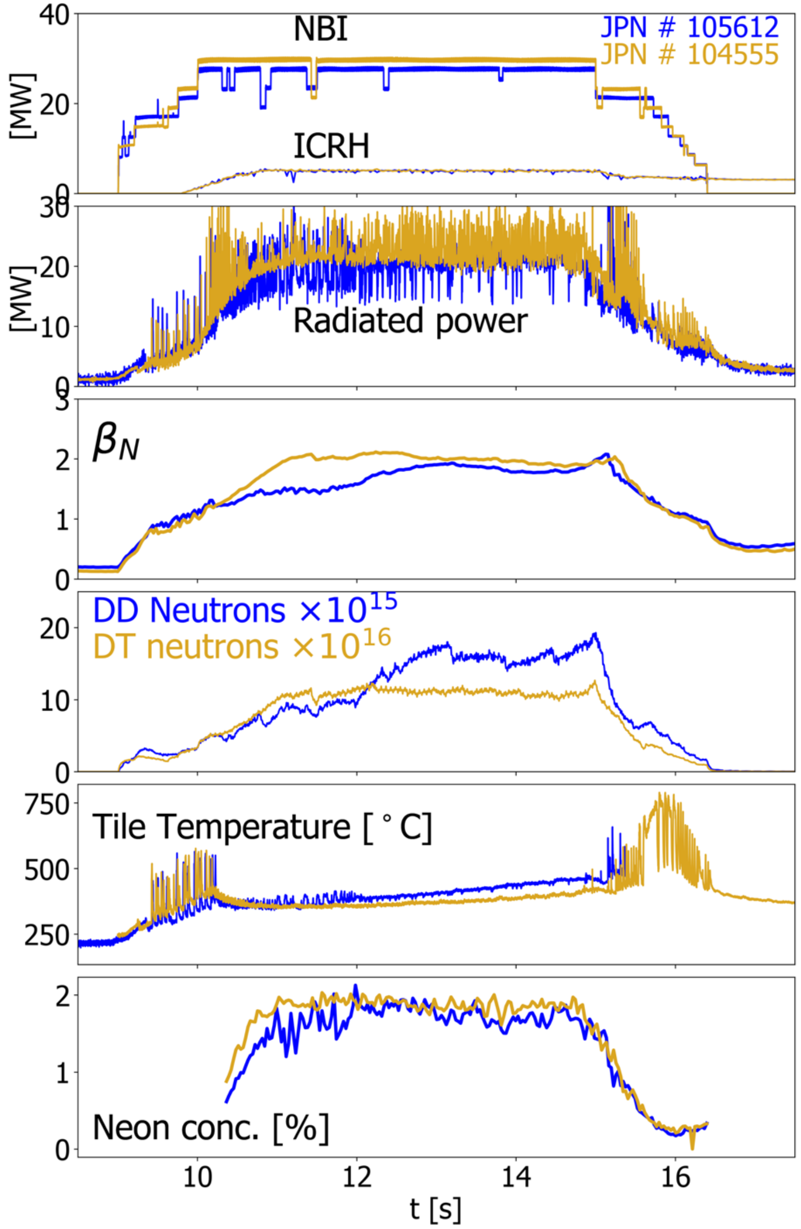
High performance Plasmas compatible with Exhaust Solution 1/

- At full performances ITER operation requires high confinement scenarios with heat load withstanding capabilities to avoid W re-cristalization
- The chosen strategy achieved via a combination of high gas throughput (high divertor neutral pressure) and extrinsic impurity seeding
- A core-edge integrated scenario with ITER like shape sustained for 4s without W accumulation and no ELM at 2.5MA/2.7T in D
- It already approaches ITER relevant parameter with $P/P_{L\text{-}H} < 2$, f_{GW}=0.7,$f_{GW,ped}$=0.46, f_{rad}=0.86, while keeping $H_{98} \sim 1$, $\beta_N \sim 2.2$, $C_{Ne} \sim 1.7\%$



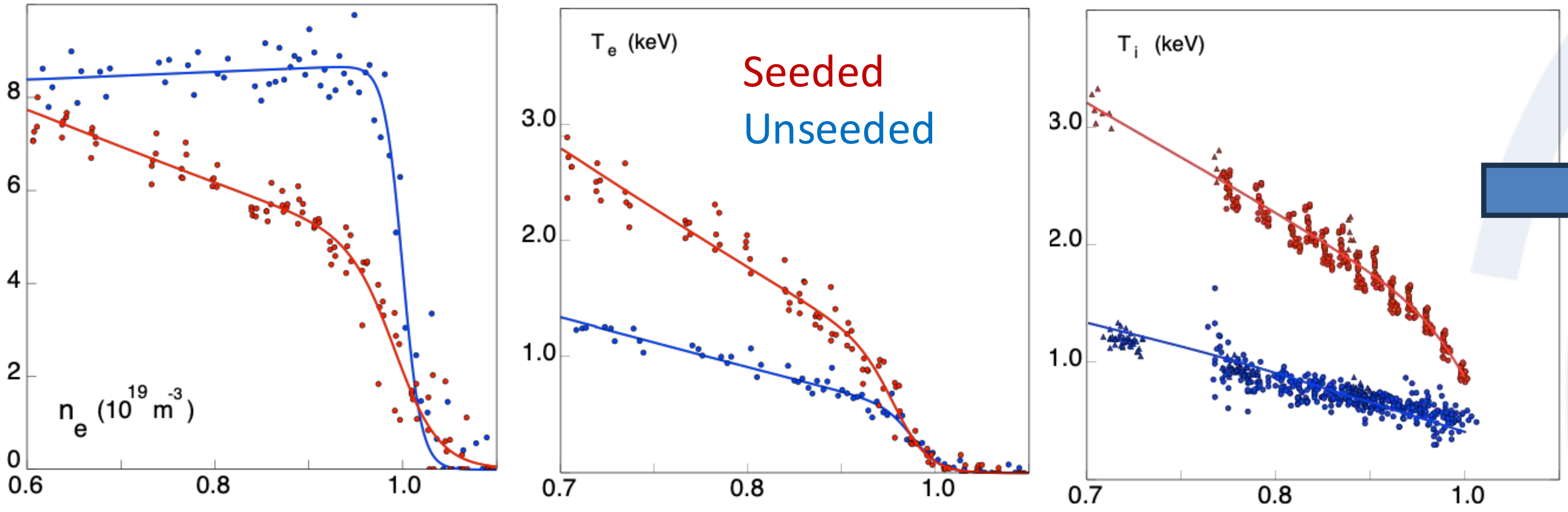


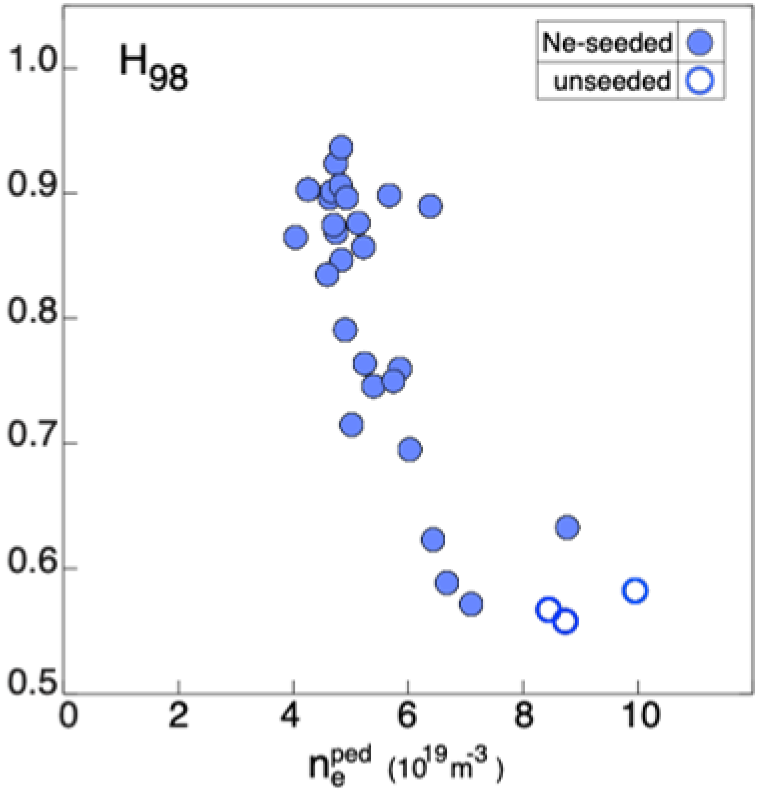




High performance scenario compatible with exhaust solution 2/

Operational space at 2.5MA/2.7T increased, with wide range of gas/seeded levels achieving good performances with clear increase of pedestal pressure and increase rotation





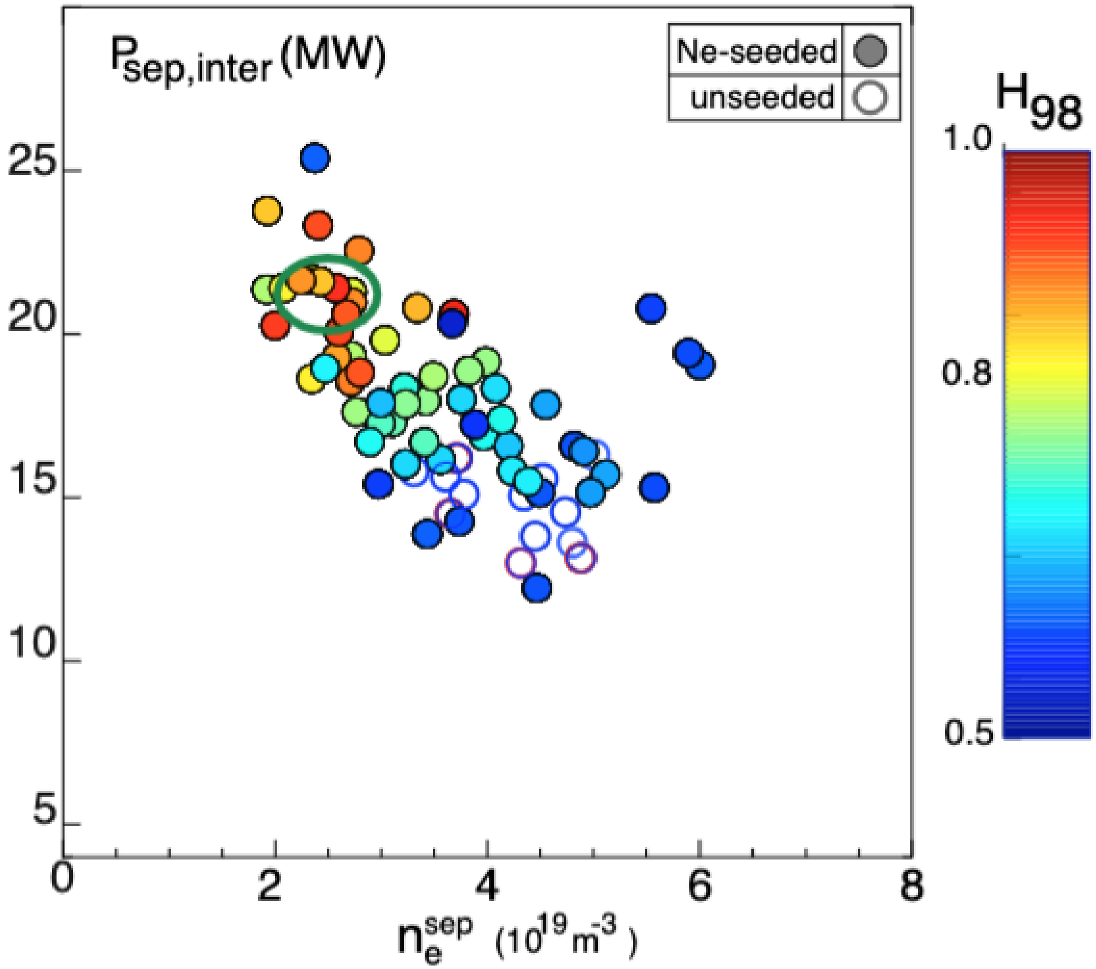
- Ne seeding beneficial for confinement at high Ne concentration (C_{Ne}> 1.3%) → primarily (but not only) because of improve pedestal performances
- Te/Ti decoupling

High plasma current (3.0MA & 3.2MA) type I ELMy H-mode challenging even at max P_{IN}=37MW

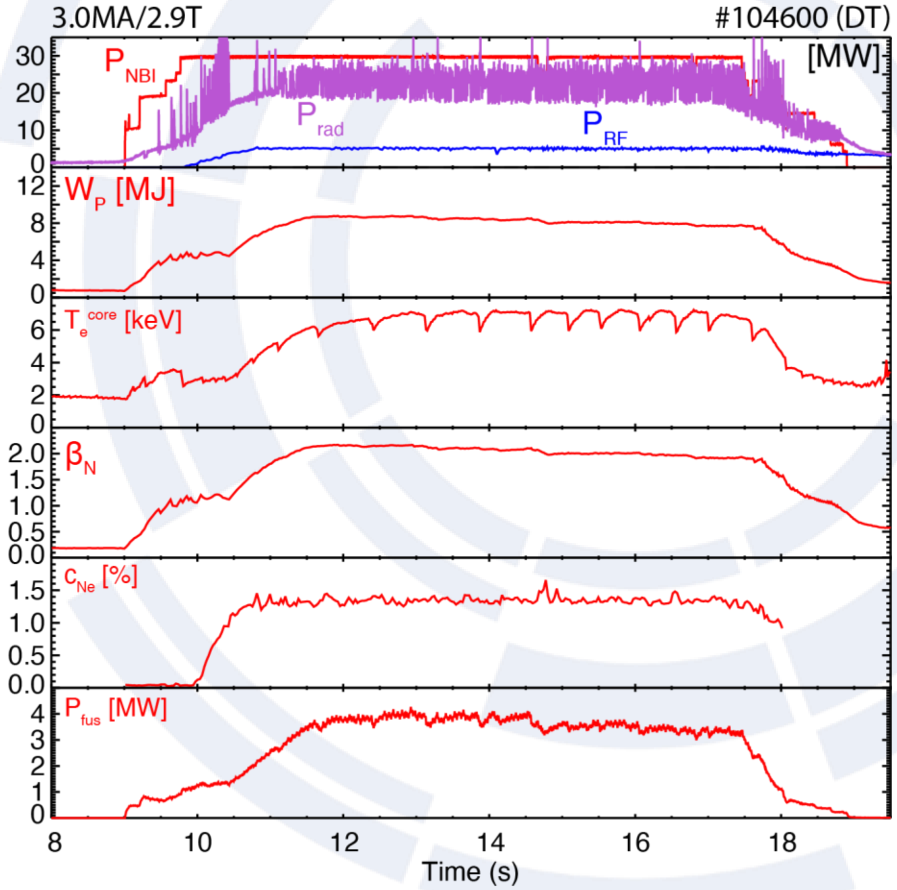
See C. Giroud, IAEA FEC 2025 regular oral Wednesday 15/10 @ 16.10

High performance scenario compatible with exhaust solution 3/

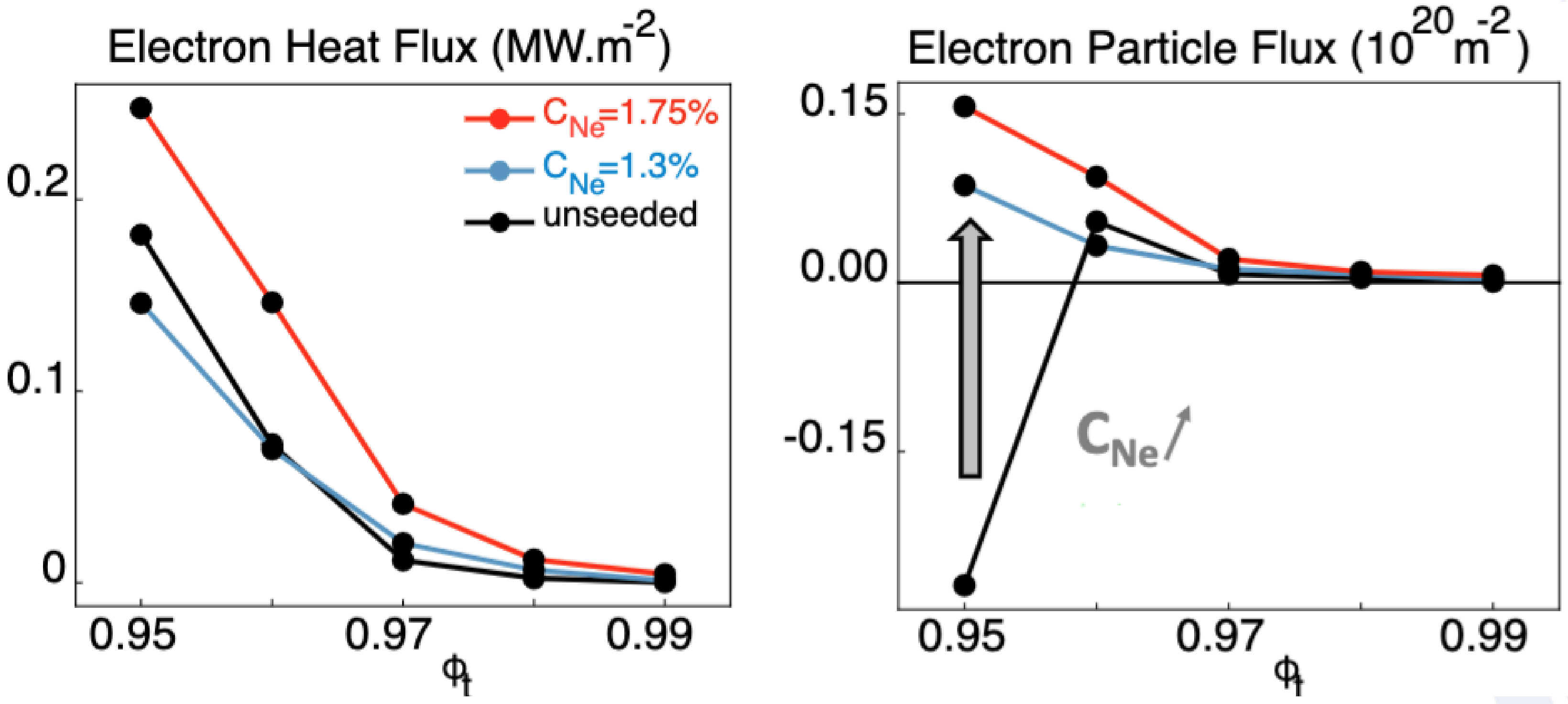
2.5MA all gas-rate (Γ_D=1.5-6.0 x10^{22} el.s^{-1})



- No-ELM plasma domain exists at low $n_{e,sep}$= 2-3 x 10^{19} m^{-3} & Psep/PLH ≳1.25 (high C_{Ne} and enough power)
- 20% reduction in PLH threshold in D-T opens access to high-performance 3MA plasmas



High performance scenario compatible with exhaust solution 4/



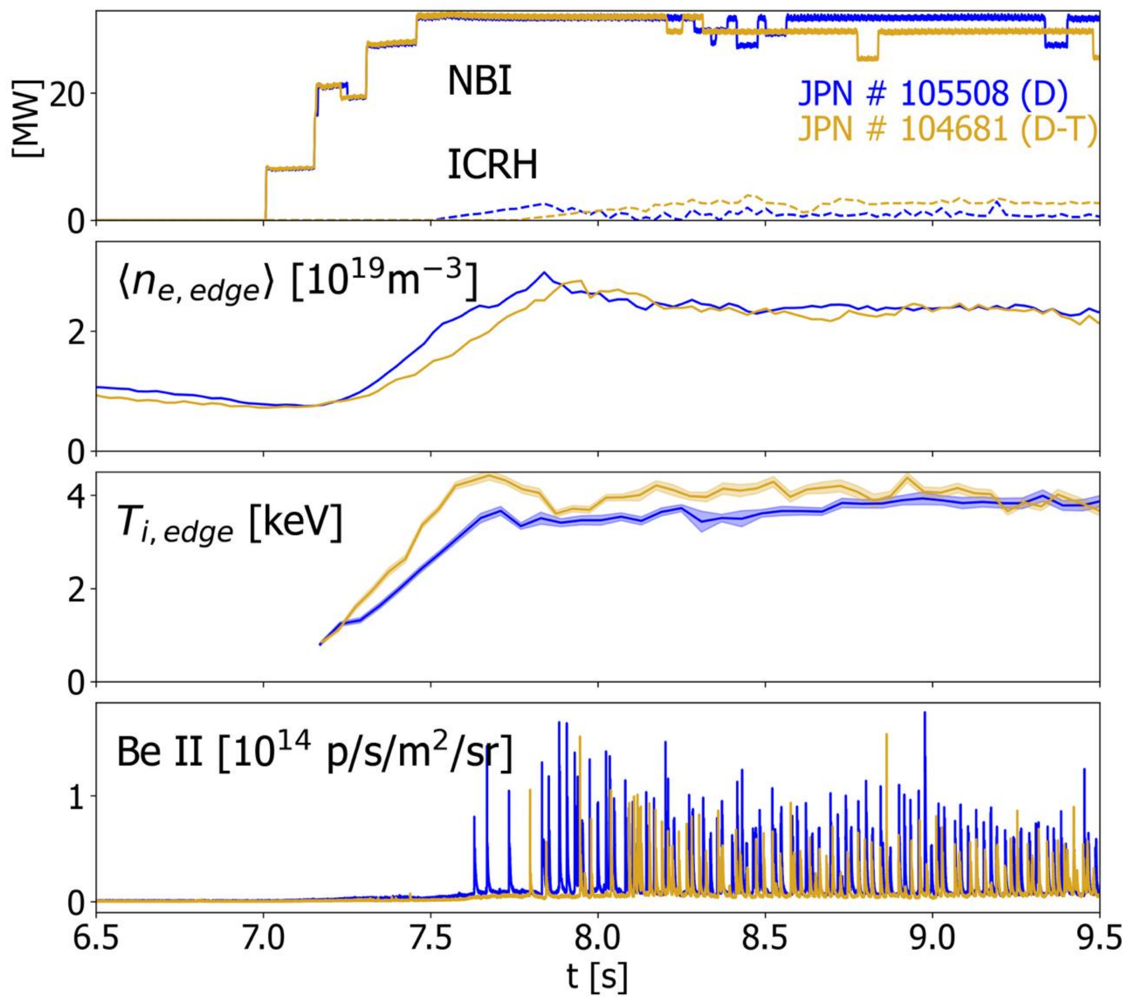
- **Total heat transport increases at high C_{Ne}** : increased Ti/Te destabilises ETG modes and stabilises ITG modes
- **Possible particle flux reversal from unseeded to seeded** : low Ti/Te at low seeding
  - inward particle flux at the pedestal top due to low wavenumber turbulence
  - compatible with higher pedestal densityLocal and global simulations in process to quantify the latter point

I. Predebon, A. Mariani, M. Marin, M. Dicorato

High performance Plasmas compatible with Exhaust Solution 3/

- Available database:
  - Current scan 2.5-3.2MA
  - Gas scan
  - Impurity scan and multiple impurities (N, Ne, Ar)
  - Isotope scan (D and D-T)
- On-going modelling effort
  - Impurity effect on the pedestal from GK perspective in D (I. Predebon/A. Mariani)
  - 2D Edge transport modelling SOLPS-ITER (O. Pan)
  - Integrated modelling JINTRAC (V. K. Zotta,S. Gabriellini, M. Marin, V. Parail)
  - Interest from US colleagues (BOUT ++/XGC) for targeting the effect of impurities up to the no-ELM regimes

Operation with low W concentration and W screening

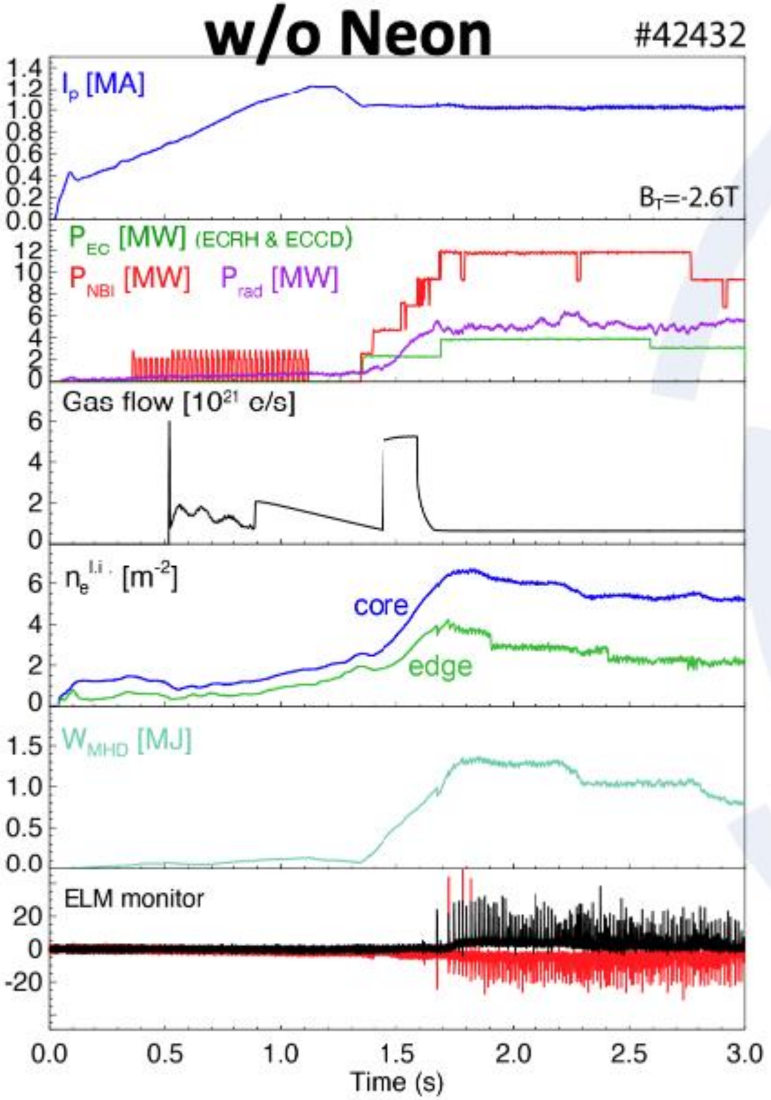


- **Scenario further optimized to improve screening condition :**
  - ✓ Lowering plasma current for further reduction of n_e
  - ✓ Tailoring of gas injection for diagnostic coverage optimization and time occurrence and size of first ELM
  - ✓ Increase of B_t in DT to account for lower L-H power threshold in ELM timing

- **Stronger W screening experimentally observed** from bolometry measurements in optimized scenario (D. King, this conference)
- NC computation via FACIT Code (D. Fajardo PPCF 2023) **unable to reproduce** the observed experimental screening (A. R. Field, submitted to NF): collisions with mid-Z impurities not accounted for? non-local effects? increased SOL screening?

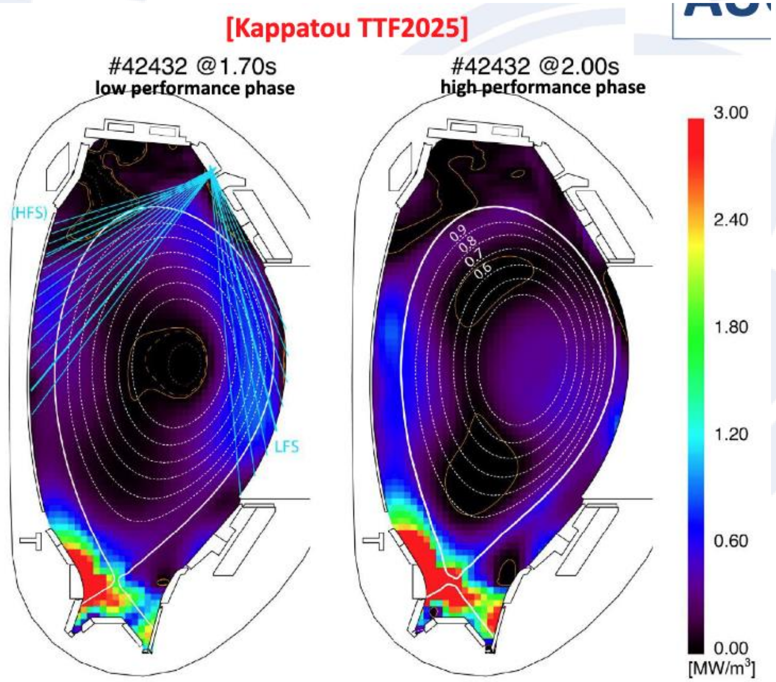
See D. King, regular poster Wednesday 15/10 AM

W screening experiment on AUG



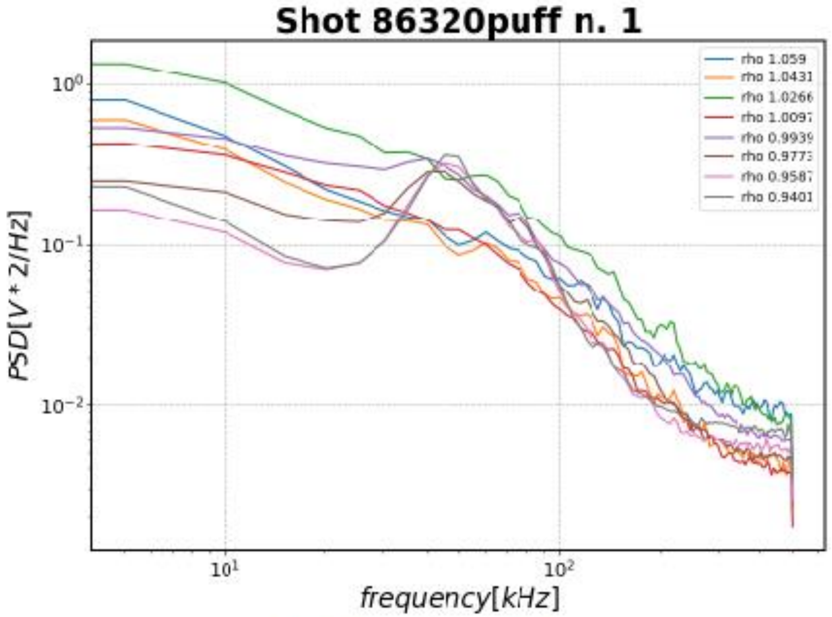
T_i^{ped} ~$2keV$
T_i^{core}~$9keV$
n_e^{ped}~$4e19m^{-3}$
n_e^{core}~$9e19m^{-3}$

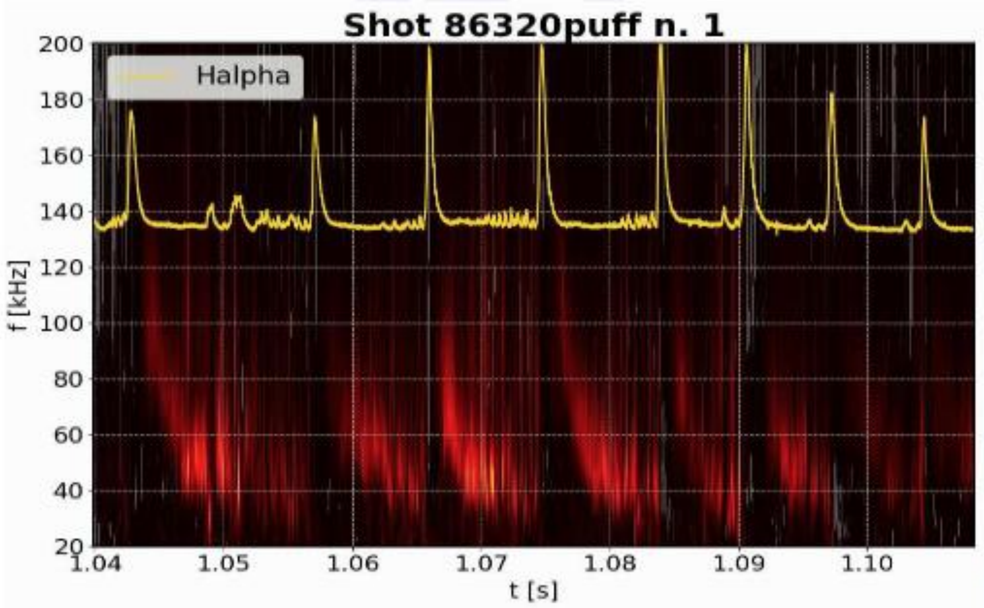
- Scenario with high performance and high Ti achieved
- Radiation at the impurity mantle is reduced in the high performance phase
- Transport analysis (FACIT)temperature screening(outward convection) of tungsten inside the pedestal top



Low ν^* / peeling limited pedestal

- Inter-ELM modes are observedonly inside the separatrix.
- The mode frequency is observed chirping from a higher frequency value to a lower one during the ELM cycle

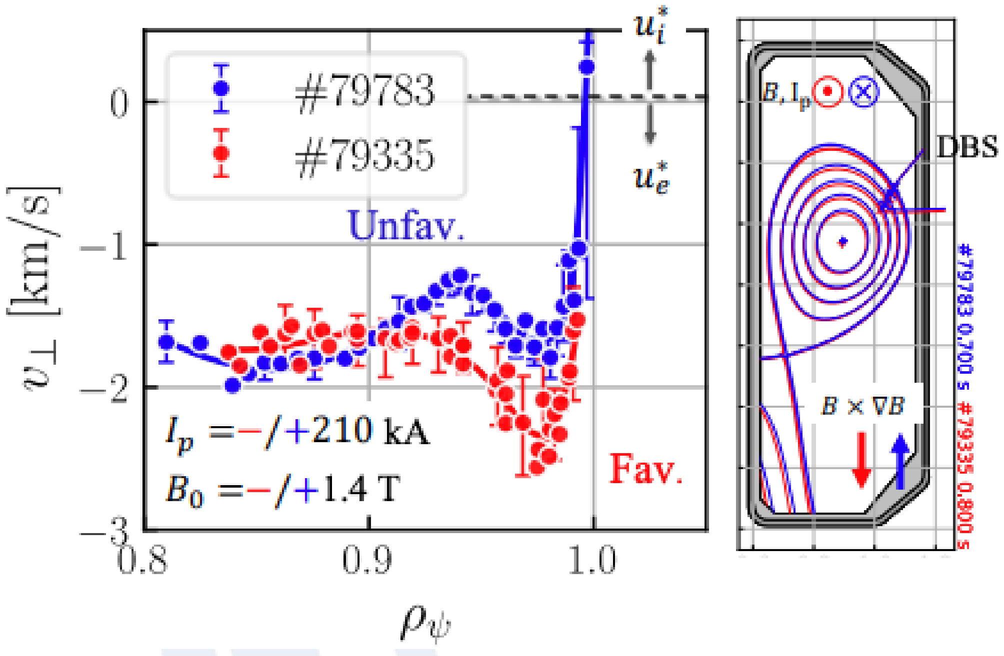


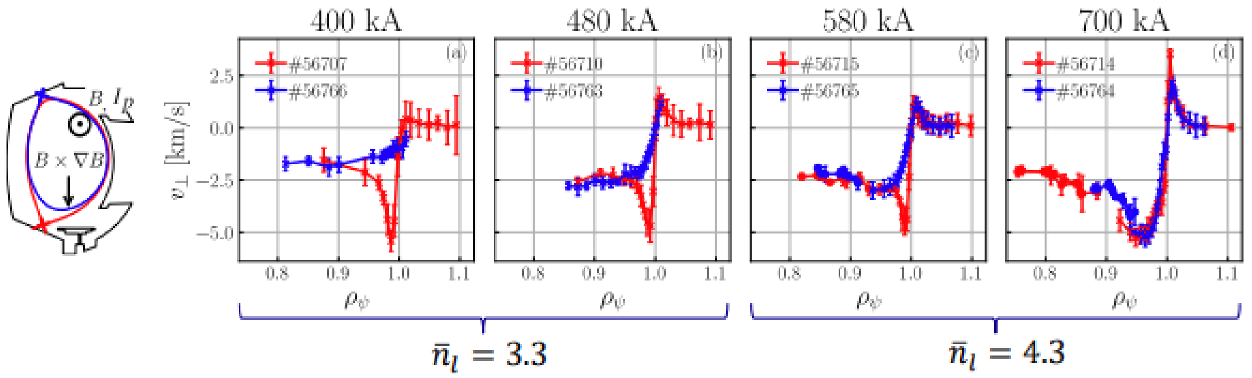


La Matina EPS2025

RT01- Linking Edge Flows to the Magnetic Geometry Asymmetry in Tokamaks

- Multi-machine (WEST/TCV) investigation of edge flows in favorable/unfavorable ion $B \times \nabla B$ drift direction
- Deeper Er observed in favorable configuration in both devices
- On WEST Clear deepening of Er with Ip in Unfav. (not only Ohmic) discharges





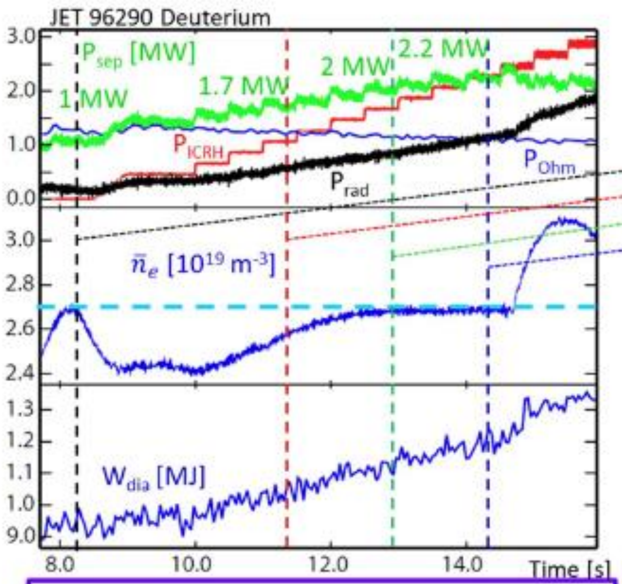
- Nevertheless opposite trend observed for unfavorable Er profile modification with Ip
- Work in progress for addressing the modification with linear/non-linear GK modelling

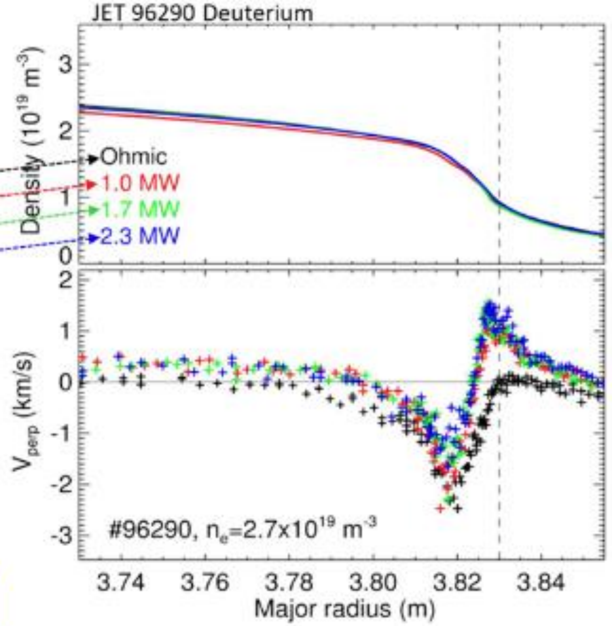
Courtesy from S. Rienäcker, L. Vermare, P. Hennequin

L-H transition studies in JET

From E. Solano WPTE Review meeting talk 29/09

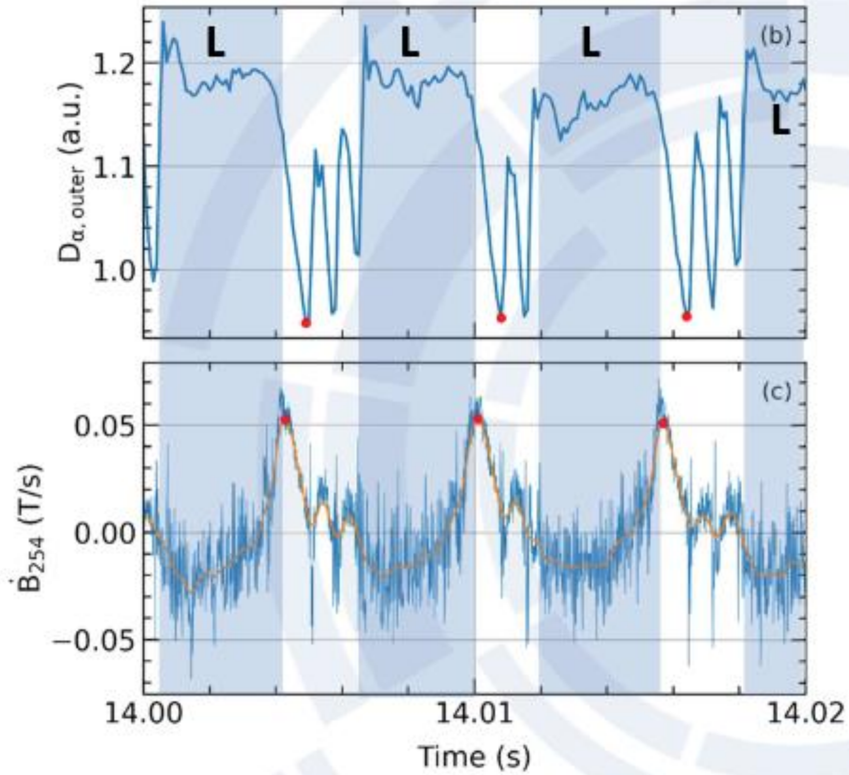
Previously established:
No evolution of the $v_\perp$ profile in L-mode along heating ramp up to the L-H transition (~300 ms).





C. Silva, Nucl. Fus. 61 126006 (2021)

Dithering L-H (L-M-mode) transitions

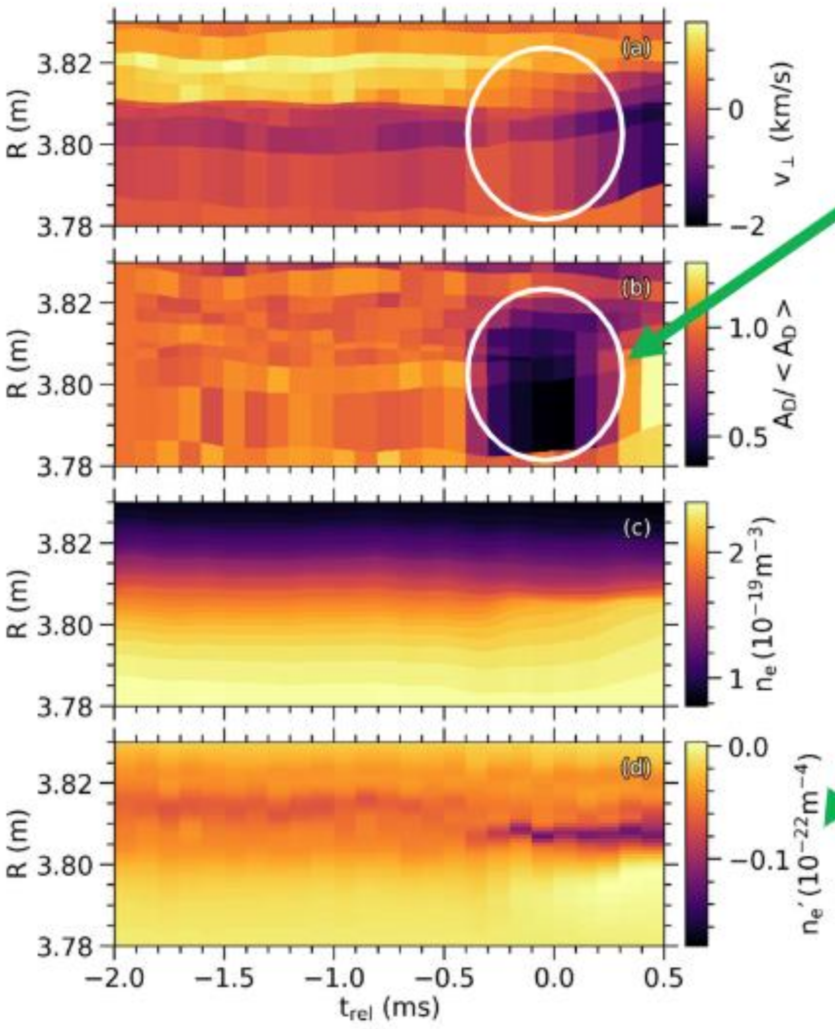


- *2026: Do density fluctuation level, auto-correlation time, radial correlation length evolve along the heating ramp?*
- *Save PPFs?*

✓ Synchronizing reflectometry signals with divertor magnetics enables reconstruction of evolution from L to H in fast time-scale

C Silva, Mário Vaz (student), …

Fast spatio-temporal evolution of Er & turbulence across L-H transition



- ✓ Synchronizing reflectometry signals with divertor magnetics reconstruct profile evolution from L to H in sub-ms time-scale
- ✓ When fluctuations low, $v_\perp$ unreliable. Reliable in L-mode.
- ✓ No clear trend seen in $v_\perp$ nor A_n approaching L2H
- ✓ Clear reduction in fluctuation level, localized from the separatrix to pedestal top (2-3 cm)
- ✓ Density gradients steepen within a similar time scale
- ✓ Density gradients steepen within a similar time scale but appears to be restricted to a narrower radial region

C. Silva JET L2H Meeting 23/09/2025

2025-2026:

- *finalize this analysis, publish, conference?*

From E. Solano WPTE Review meeting talk 29/09

Isotope mix Gyrokinetic Study with GENE

IPP MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK JET

✓ **Experimental observations: Horizontal Target, 1.8 T 1.7 MA**

- Pure **D** : $P_{L\text{-}H}$ = 1.81 MW
- 50% **H** + 50% **T** : $P_{L\text{-}H}$ = 2.97 MW

same critical n_e, T_e profiles

Although it is the same effective mass: **isotope mixture effect !**

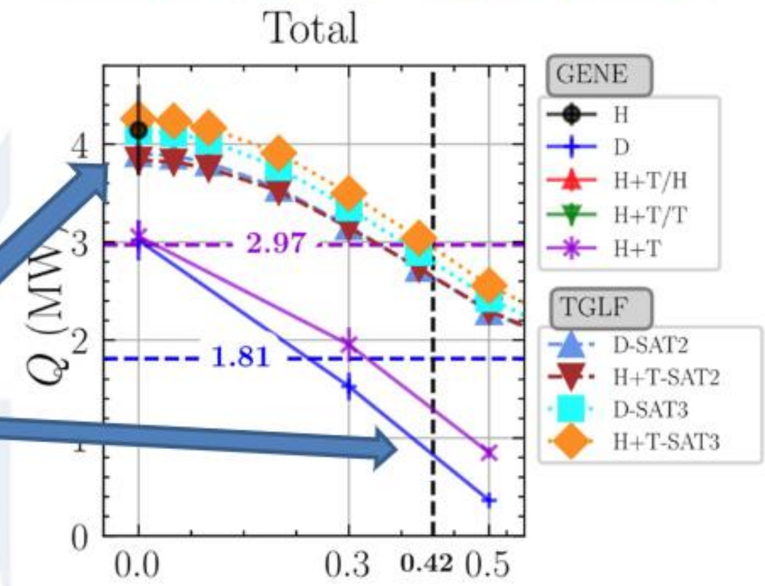
✓ **GENE & TGLF simulations**

w/o ExB shear: no difference between pure **D** and 50% **H** + 50% **T**

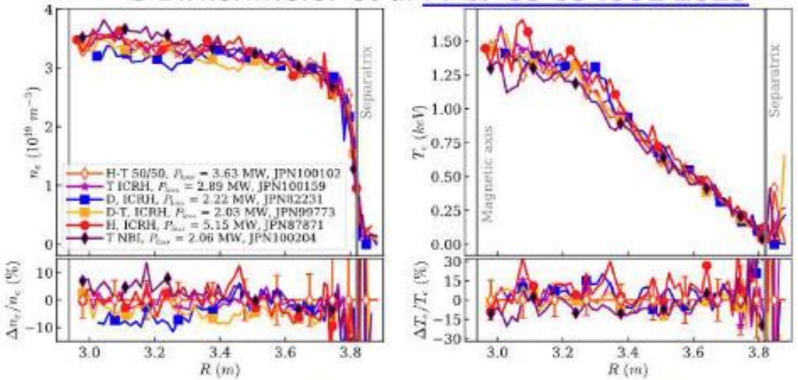
With imposed ExB shear: experimental behaviour retrieved:

- pure **D** shows lower heat flux than the **H+T** mixture
- effect increases with imposed ExB shear amplitude
- TGLF SAT-2 and 3 do not reproduce the GENE behaviour

Published G. Lo-Cascio *et al* 2025 *Nucl. Fusion* **65** 106034



G Birkenmeier et al PPCF 65 054001 2023



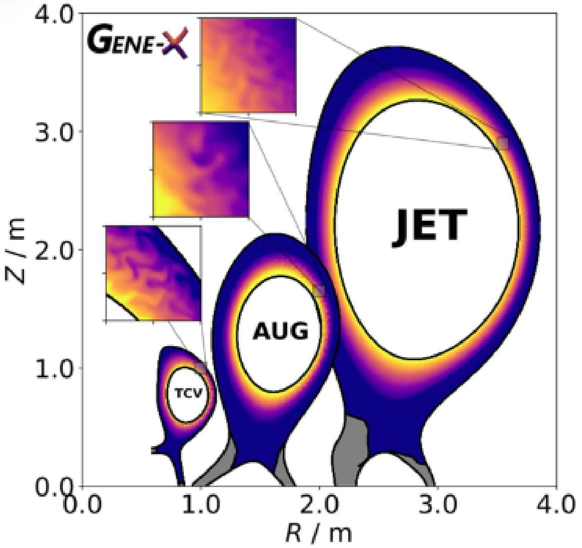
➢ ***Future work – started on Pitagora HPC since August:***

- *Check other mixtures like 50% D – 50% T vs 25% H – 75% T*
- *Compare with a single ion of mass 2.5 →*
  relevant to other simpler approaches
- *Expect new analysis done 2025, publication 2026*

G. Lo-Cascio, C. Angioni et al.

First code validation of global gyrokinetic edge and SOL turbulence in JET has been performed with GENE-X

IPP MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK JET GENE-X



***Top:** Snapshot of global JET turbulence compared to previously simulated medium-sized tokamaks at scale.*

[1] D. Michels et. al, CPC264 (2021)
[2] P. Ulbl et. al, PoP30 (2023)
[3] B. Frei et. al, CPC316 (2025)
[4] N. Bonanomi et. al, NF59 (2019)
[5] G. Lo-Cascio et. al, NF65 (2025)

✓GENE-X [1-3] uses a **global, full-f, electromagnetic, collisional gyrokinetic** model. Kinetic electrons, real mass ratio

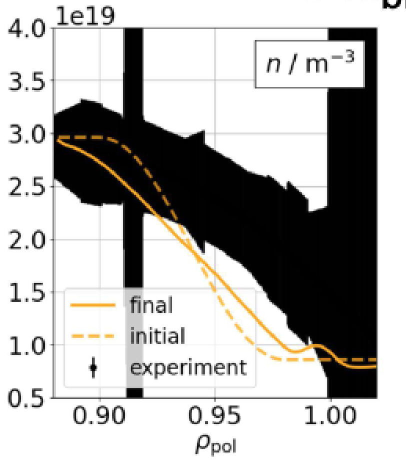
JET Deuterium **L-mode** chosen for **code validation**. #82231, t=57.13 s B_0~-1.816 T, P_{heat}~2.33 MW, P_{sep}~1.81 MW

Same profiles as GENE **D** and **H**+**T**

✓ **Turbulence has key features of drift modes**

- Similar particle and heat fluxes for ions and e's
- Turbulent **cross phases are drift-wave like** $\alpha(T_{||e},\Phi)$ is significant (in contrast to pure TEM)
- Propagation in **electron direction** with $\sim\omega_e^*$
- Most likely **drift modes + ITG & TEM**
- Linear GENE analysis confirms these features
- In agreement with previous GENE studies [4,5]
- P Ulbl JET L2H team talk 02/09/2025

P Ulbl



2025-2026

to be continued by P. Ulbl (2025) and B. Frei (2026)

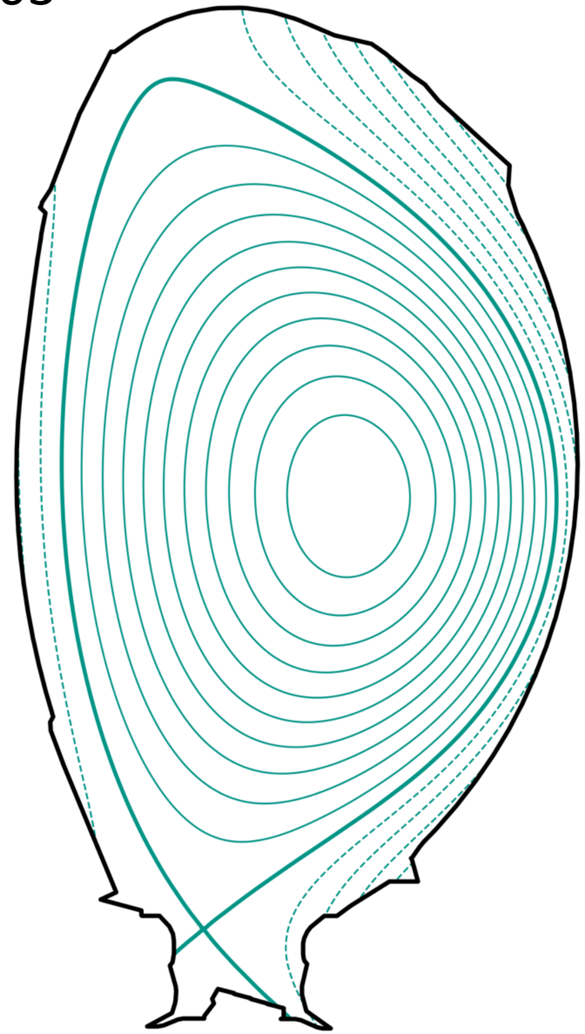
- ➢ Compare output with data, refine profiles?
- ➢ Publish **D** results so far
- ➢ Study **H**+**T** mixture: does turbulence change?
- ➢ Add neutral source to match density profiles
- ➢ Try flux-driven set-up?

RT02 - Physics understanding of alternatives to Type-I ELM regime

#	
D1	Quantify turbulent and MHD driven transport in the vicinity of the separatrix and implications for predictions for ITER and DEMO
D2	Quantify first wall load in no-ELM scenarios and provide model for SOL transport extrapolation
D3	Extend the parameters space of no-ELM scenarios to large Psep/R and/or pedestal top collisionallities relevant for ITER and DEMO
D4	Determine the key physics mechanisms regulating edge transport in order to access no-ELM regimes
D5	Quantify the level of ELM mitigation with 3D fields in low torque plasmas and its impact on W transport
D6	Quantify the overall performance, primarily improved confinement, of negative triangularity plasmas in view of next-step devices

Small ELM scenario for DEMO

JPN # 102103



- One of the most promising small ELM regimes: Quasi-Continuous Exhaust (QCE) *[G. Harrer et al, PRL 2022; M. Faitsch et al, NF 2023]*
  a. formerly known as type-II ELM or small-ELM
  b. a natural type-I ELM-free H-mode.
  c. enhanced filamentary transport at plasma edge
- Key ingredients are
  - **Strong shaping** $S_d = \kappa^{2.2}(1+\delta)^{0.9}$ to stabilize global peeling-ballooning modes
  - **High separatrix density →** to drive separatrix ballooning modes preventing too steep gradient

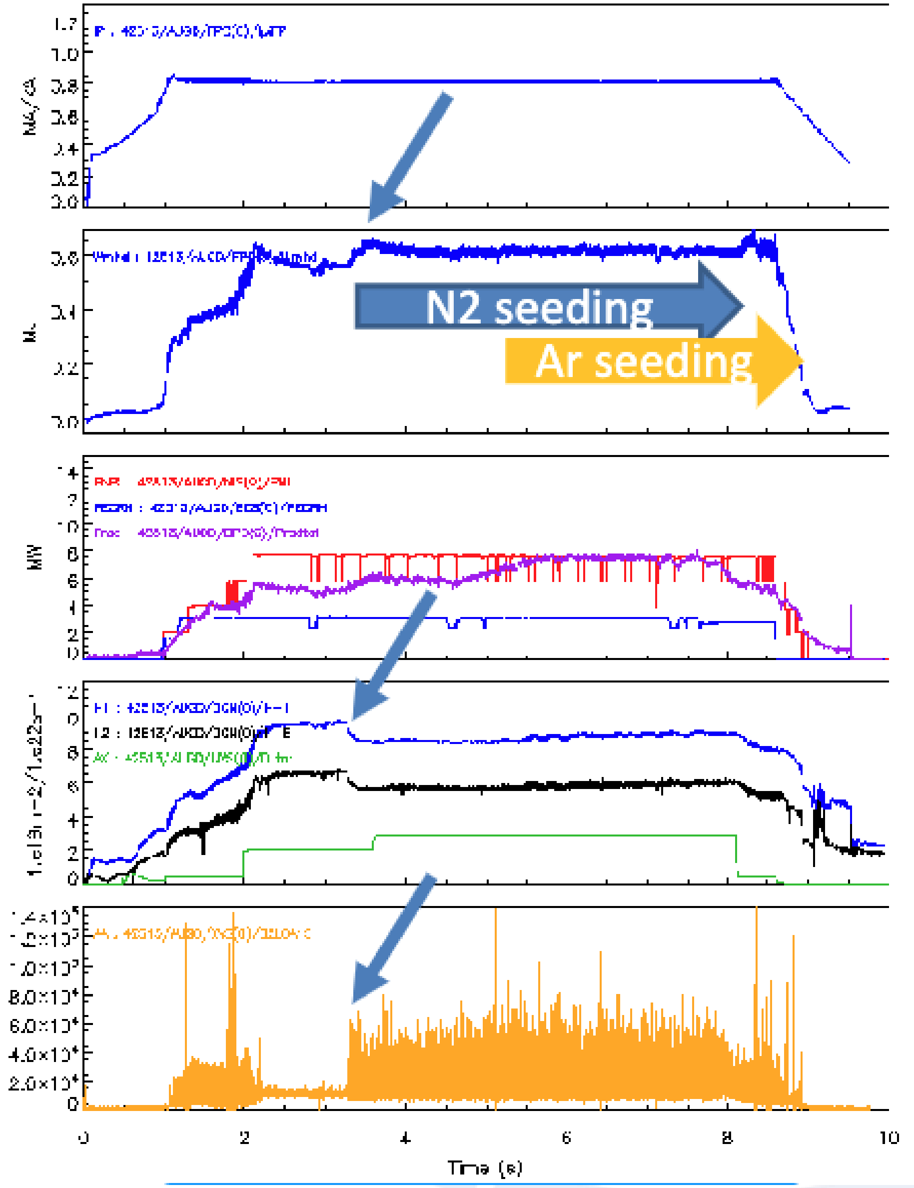
M. Faitsch, M. Dunne, O. Sauter, E.Viezzer

➢ M. Faitsch et al, NME 2025; M. Dunne et al , FEC 2025

QCE: detachment studies

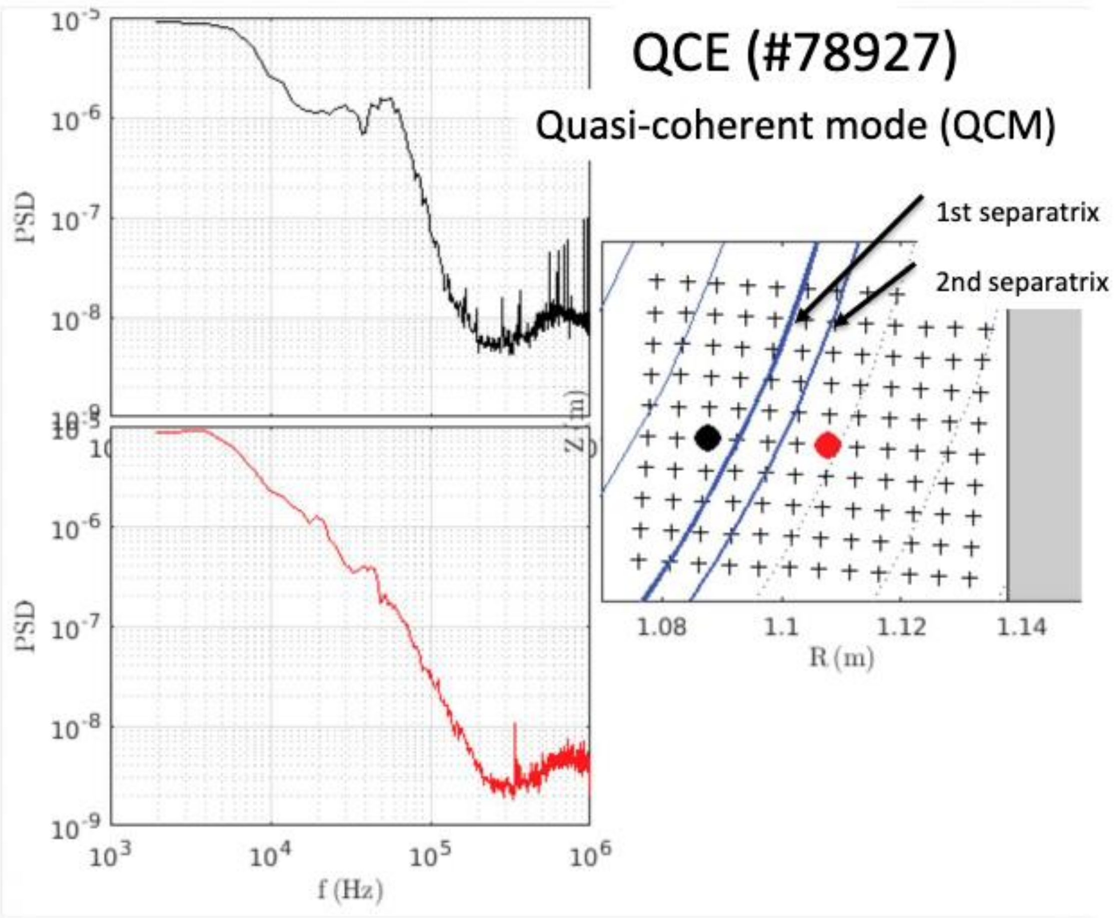
Contact: M. Faitsch

- Adding N2 leads to density drop and re-appearance of ELMs
- Adding more D2 and Ar did not change the behavior
- Using Ne as in JET also brings back small ELMs →needs more comparison to the ELMs of the JET QCE scenario

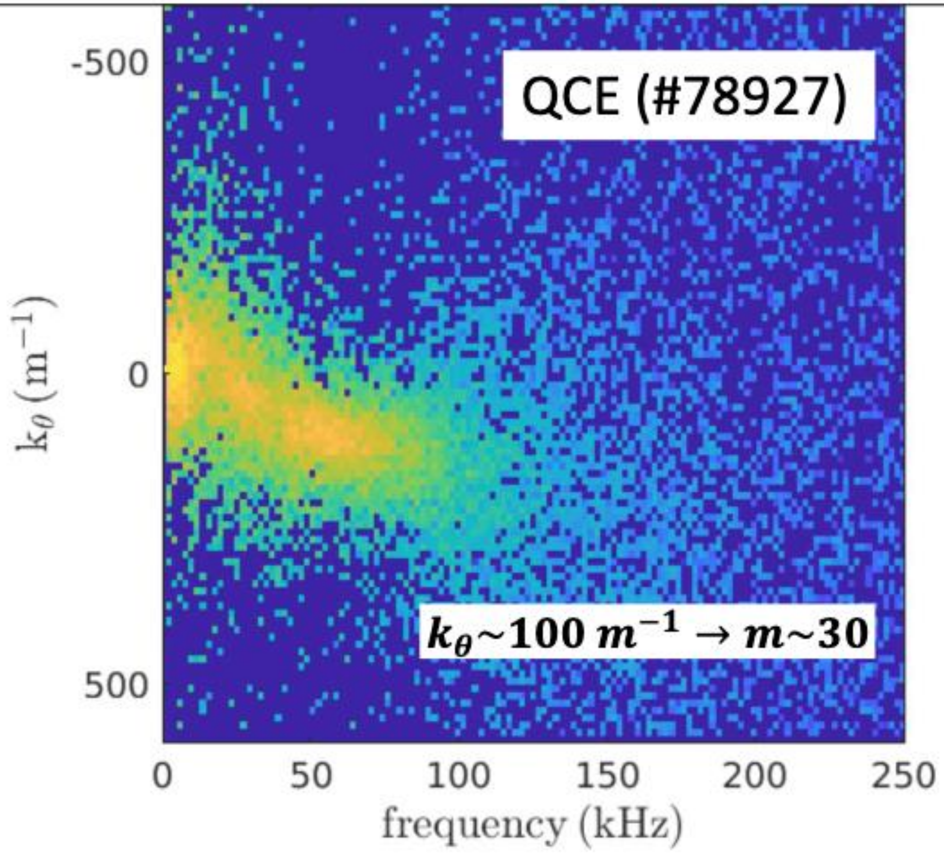


QCE and QCM

Quasi-coherent mode (~50 kHz) detected just inside the separatrix with several diagnostics (here GPI-mid) -> Consistent with AUG observations



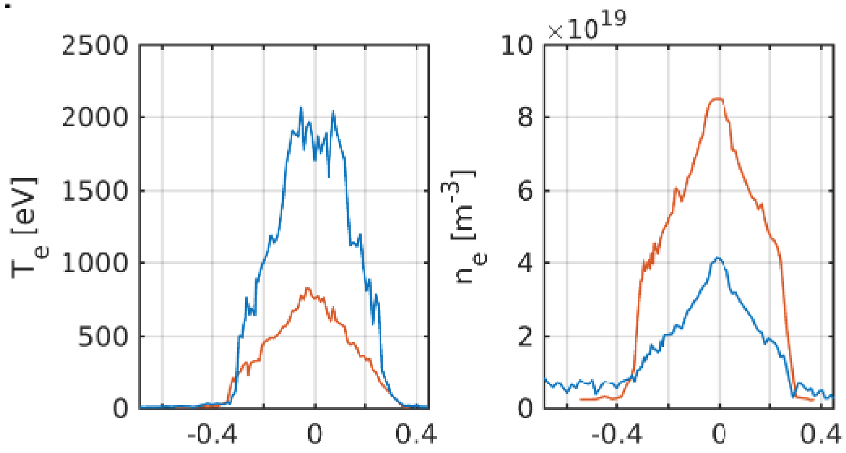
Statistical dispersion relation from separated pixels in the poloidal direction



New no-ELM regime identified at TCV

Contact: A. Merle

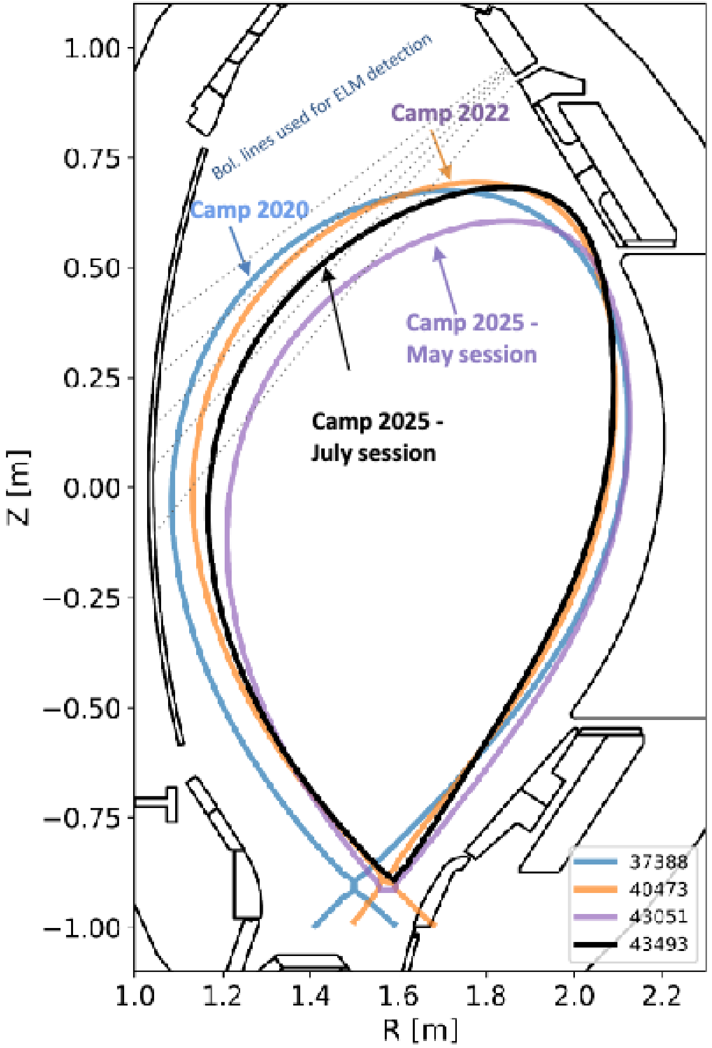
- QH candidate scenario carried out with both beams (NB1 co, NB2 ctr), performed I_p and gap scans
- Achieved ELMy H-mode (86243, blue case) at low density and high power (1.5MW NBI, 1.6MW X2 ECRH). without strong MHD activity
- Without EC, ELMs disappear/are strongly reduced (red)
- Preliminary edge profile analysis suggest presence of pedestal in this new regime
- Removing NB2, ELMy H-mode is recovered
- Regime achieved robustly: performed NBI power scan, I_p scan 130-175 kA, increased top triangularity (0.3→0.4).
- QH-mode unlikely, collisionality higher compared to ELMy H-mode

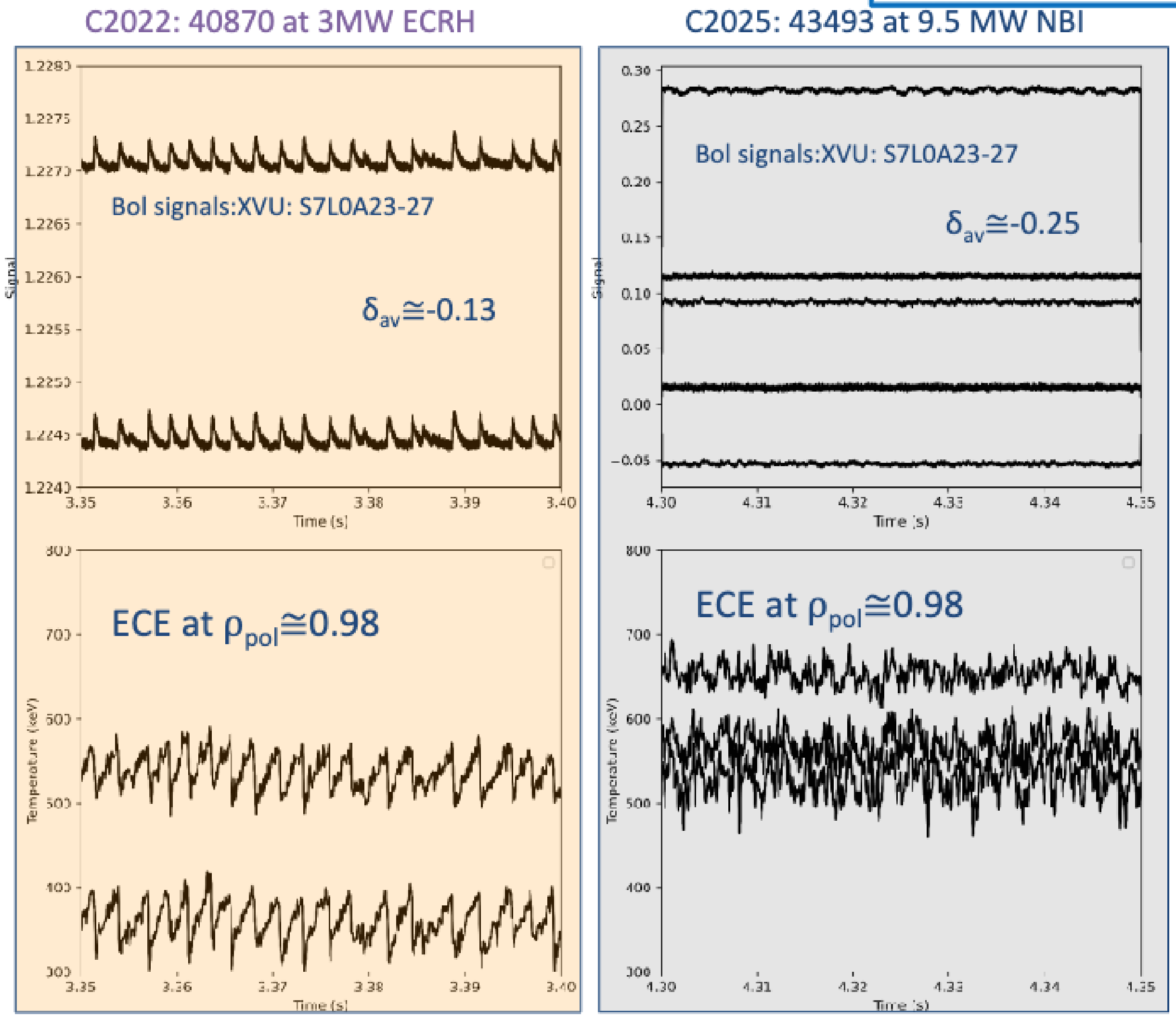


RT02 RTCs I WPTE review meeting I 15 September 2025 I Page 12

NT studies: Dithering behavior of NT edge in stronger shaping

Contact: B. Vanovac



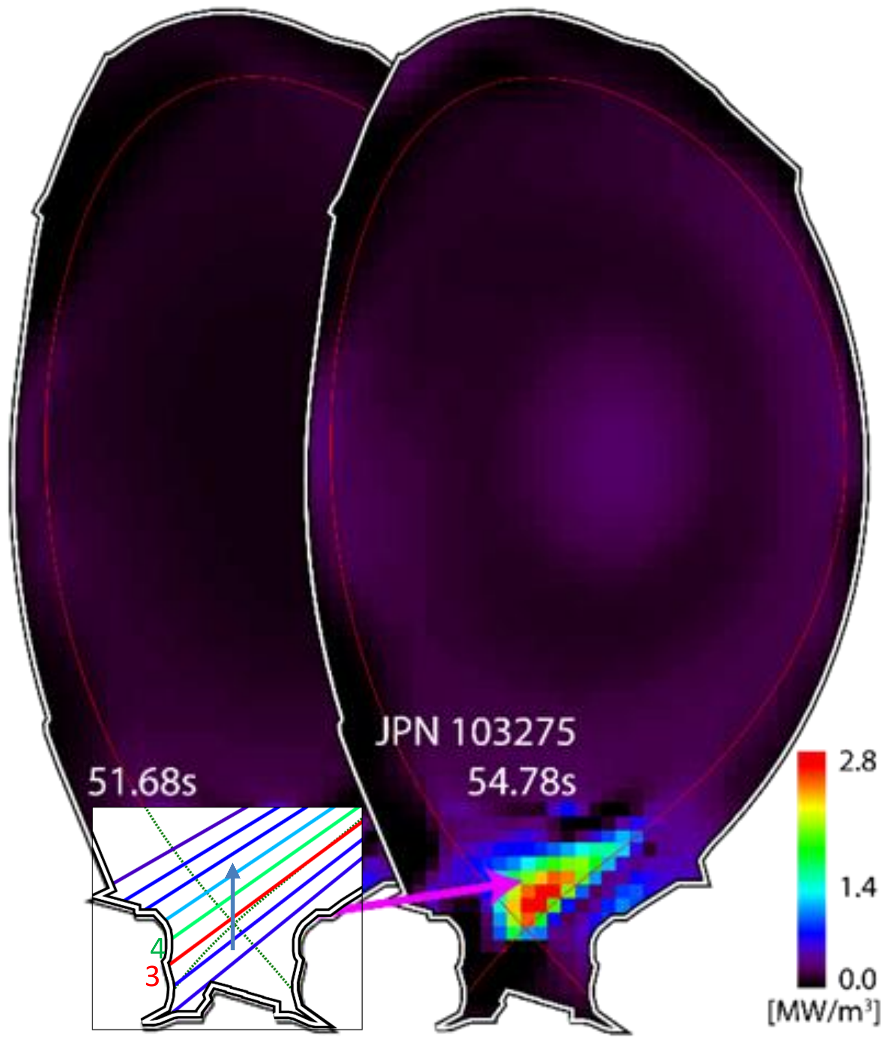


RT02 RTCs I WPTE review meeting I 15 September 2025 I Page 16

RT05 Physics of divertor detachment and its control for ITER, DEMO and HELIAS operation

#	
D1	Characterize detachment access and core plasma performance in scenarios using different fuelling schemes, different impurity mixtures
D2	Develop reduced physics model which can be included in radiative detachment control schemes or extrapolations to DEMO/ITER
D3	Quantify edge-SOL particle, impurity, and heat transport, above and below the X-point under detached conditions
D4	Assess the compatibility and stability in terms of overall confinement of X-point radiator regimes
D5	Quantify the degree of ELM heat load mitigation achievable by impurity seeding, investigating the dependences on relevant machine parameters
D6	Assess the evolution of detachment under slow transients (L-H transitions, sawtooth, loss of impurity seeding)

The X-Point Radiator XPR: a power exhaust solution in view of DEMO



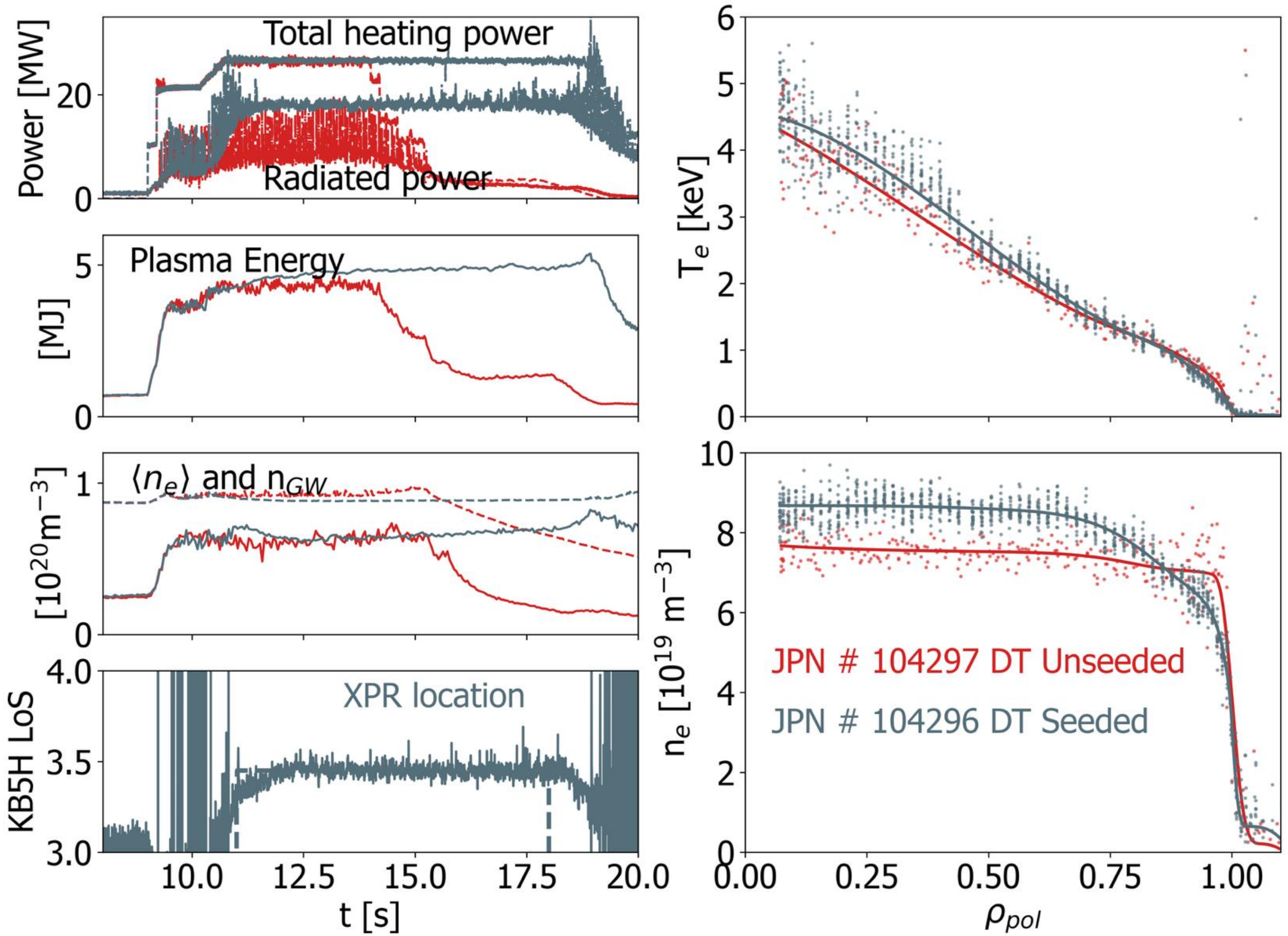
- **The X-Point Radiator Regime (XPR): viable stable solution for high radiation fraction (>90%), fully detached plasma with H-mode grade confinement***
- Solutions is robust, resilient to transients, controllable and can provide ELM suppression
- Characterized by a small region of high radiation, low temperature and high density inside the confined region at/above the X-point
- Operation extended from medium-size tokamaks to JET with implementation of Real-Time control compliant with ITER constraints**

*M. Bernert et al, NME 2025

**T. Bosman et al, NF 2025

The X-Point Radiator XPR: a power exhaust solution in view of DEMO

- Operation at 2.5MA/2.T at medium power (25 MW). **Combined seeding of Ar (feedback controlled) + Ne (feed forward) provided the more stable solution compatible and successfully exported to DT operation**



Scenario achieved:

- RT control implemented both in DD and DT
- full detachment
- small to no ELM
- smooth L-H and H-L transition
- Beneficial effect of seeding on confinement w/o edge deterioration

Call cycle

Call for Proposal 2026-2027

- September 2025 (included call for RTC) 08/09-10/10

Review meeting

- Mid September 2025 15-16 & 29/09 (See talks on WPTE Wiki-page)

Call for participation 2026

- November 2025 31/10-05/12

GPM

- **4-6/11/2025 in Lausanne hybrid meeting**

Proposal assessment in IMS

- Resources loaded by December 2025

Conclusions

- WPTE continues its ambitious program with strong emphasis on the cross-device approach
- A similar Research Topic structures will be likely maintained in 2026-20275 where we are keen to focus on topics relevant to recent ITER re-baselining (e.g. pedestal impurity transport) and to support experiment in preparation to future JT-60SA exploitation
- We look forward in strentghening the collaboration with TSVV in this last period of FP9 to progress in global understanding as well as in validating our extrapolation capabilitiees