

WPTE Experimental program and modelling needs in view of TSVV-A deliverables

N. Vianello

On behalf of WPTE TFLs

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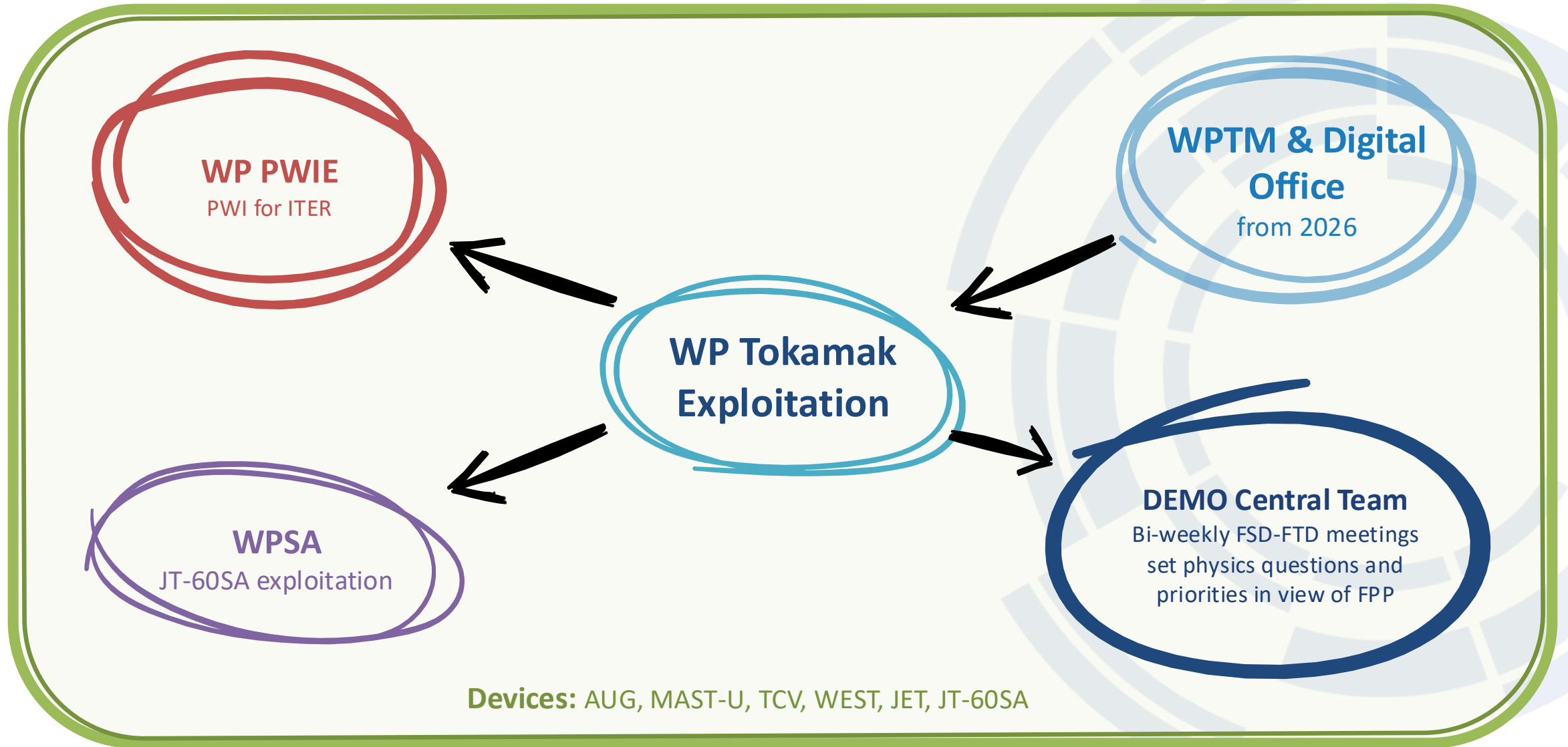


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WP TE in Fusion Science Department ecosystem





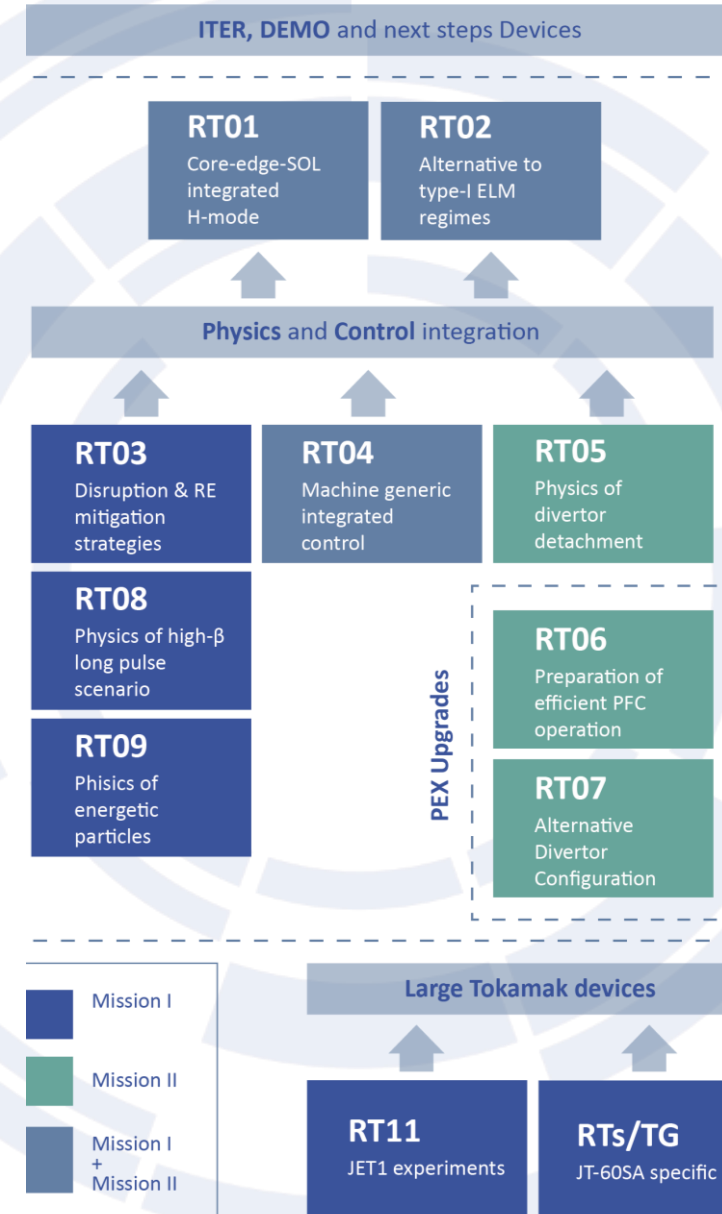
Strongly streamlined programme for WP TE in 26-27

High level objectives for 26-27

- Address urgent R&D issues related to the new ITER baseline / Research Plan (full tungsten wall) : far SOL physics and wall loads; tungsten sources, transport and screening; startup on tungsten limiters; runaways damage of tungsten first wall components and efficiency of boronisation in full tungsten devices → ITER MoU
- Provide a full qualification of the most promising no ELM scenario, focusing on X-point radiator (XPR) and quasi-continuous exhaust (QCE) now considered as a viable option for ITER / DEMO.
- Support modelling efforts for interpretation of available data from TE devices (including JET DD and DT last campaigns) --> integrated core/exhaust modelling (EFPW recommendation)
- Prepare the JT-60SA scientific exploitation in the OP2 and OP3 campaigns, pending resources becoming available.

Same structure retained for WP TE in 26-27

- 9 “programmatic” Research Topics (RT01 to RT09)
- 2 Research Topics dedicated to JET (RT10 for data validation, RT11 for analysis of JET campaigns performed before 2022 and related work)
- 8 Research Topics (RT12 to RT18) mapping the existing Topical Groups of the JT-60SA EU-JA Experimental Team.





List of Grant Deliverables 2026-2027

ID	Deliverables Table	Date
TE.D.16	Report on fully integrated simulation of high current partially detached plasma scenario including assessment of PFC erosion in D and DT plasma	Dec 2026
TE.D.17	Report on reduced model validation for plasma reattachment on multiple devices and wide operational space	Dec 2026
TE.D.18	Report on providing input on design and operation of conditioning systems for next step full W devices and focus on standard boronization systems	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
TE.D.20	Report on optimized scheme for “benign termination” of runaway beams documented in view of possible applicability for ITER	Dec 2027

List of Milestones 2026-2027

ID	Milestones Table	Date
TE.M.09	Proper figure of merit for cross-scenario comparison among no-ELM / ADC defined	Dec 2026
TE.M.10	First wall particle and heat fluxes quantified in XPR in metallic devices	Dec 2026
TE.M.11	ADCs characterized in H-mode conditions in all relevant TE devices	Dec 2026
TE.M.12	Modelling of SPI experiment on JET and ASDEX-Upgrade completed	Dec 2027
TE.M.13	Impact of N-NBI on plasma behaviour documented in JT-60SA and extrapolation to ITER investigated*	Dec 2027

* Pending resources are made available for JT-60SA related work



Experimental highlights and open modelling questions for TSVV-A

- Selected 2026 findings from four Research Topics, focused on where **interpretation and first-principles / reduced modelling** are still needed
- Recurring cross-cuts for TSVV-A:**
 - separatrix / edge turbulence and core–edge–SOL coupling
 - edge E_r , $E \times B$ shear and L–H access (drift-configuration asymmetry)
 - impurity (Ne/Ar/N/W) effects on transport
 - pedestal & SOL transport closures for ITER/DEMO extrapolation

RT01 Core–edge–SOL

Integrated H-mode for ITER
JET · AUG · TCV · MAST-U · WEST

RTC: C. Giroud, L. Frassinetti, S. Wiesen, M. Cavedon

RT02 ELM-free regimes

QCE · EDA · NT · QH · RMPs
AUG · TCV · MAST-U · JET

RTC: M. Faitsch, E. Viezzer, tbn, tbn

RT05 Detachment control

X-point radiator, reduced models
AUG · TCV · MAST-U · WEST · JET

RTC: P. David, N. Rivals, H. Reimerdes and S. Henderson

RT11 JET L–H transition

Thresholds · isotope · edge turbulence
JET-ILW (D, DT, T)

SC: E. Solano and P. Vincenzi

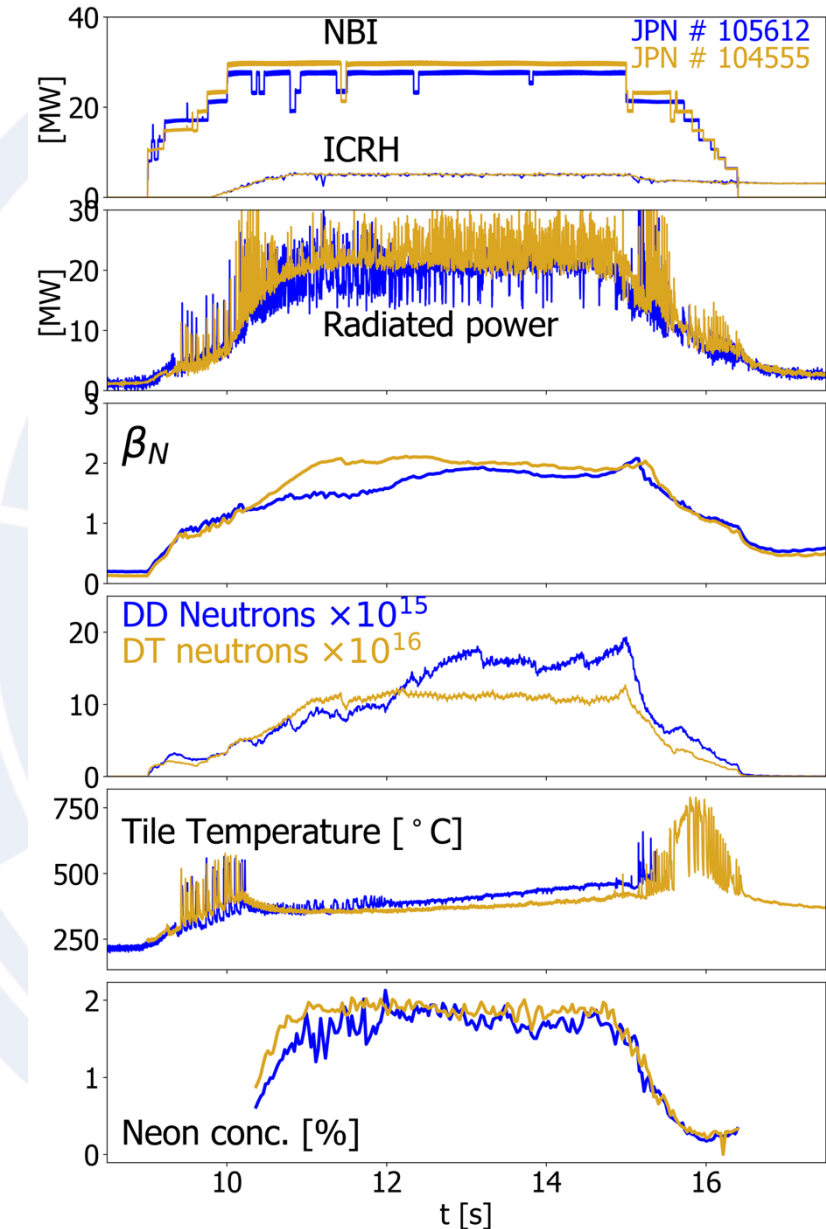
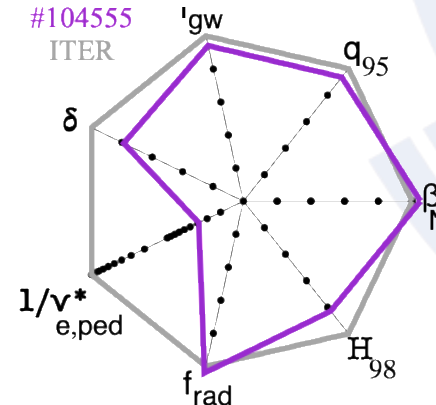
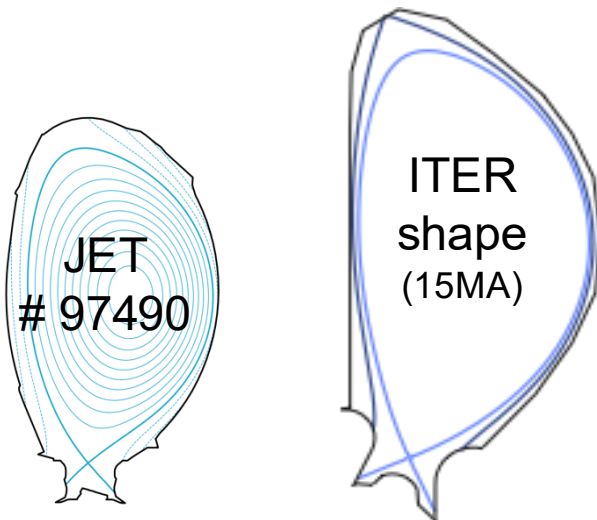


#	Scientific Objectives
D1	Develop and understand stationary H-mode scenario at low collisionality and with dominant electron heating
D2	Provide physics-based cross-field transport coefficients for heat, fuel particles and impurities to TSVVs for turbulence modelling
D3	Determine the impact of different 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



High performance Plasmas compatible with Exhaust Solution 1/

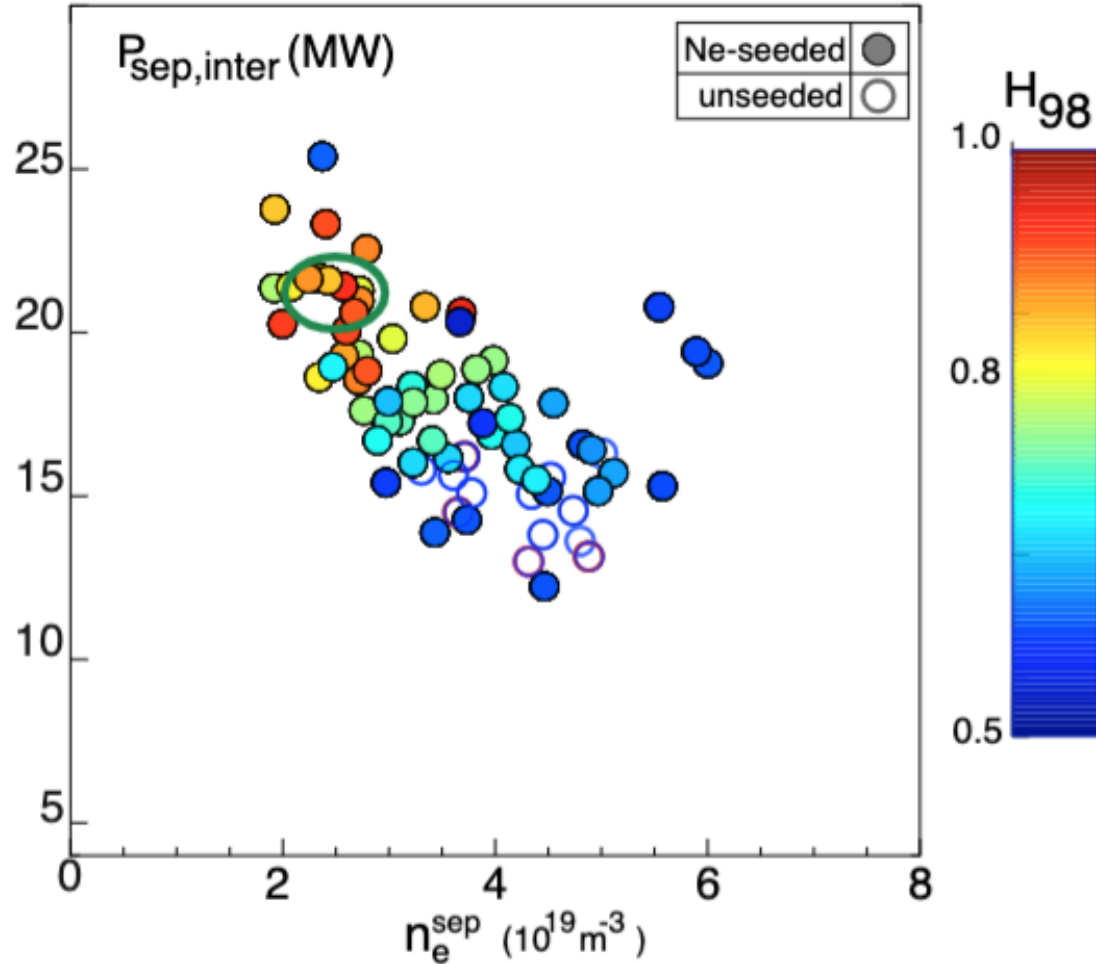
- At full performances ITER operation requires high confinement scenarios with heat load withstanding capabilities to avoid W re-crystallization
- The chosen strategy achieved via a combination of high gas throughput (high divertor neutral pressure) and extrinsic impurity seeding
- A core-edge integrated 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 $P/P_{L-H} < 2$, $f_{GW}=0.7, f_{GW,ped}=0.46, f_{rad}=0.86$, while keeping $H_{98} \sim 1, \beta_N \sim 2.2, C_{Ne} \sim 1.7\%$



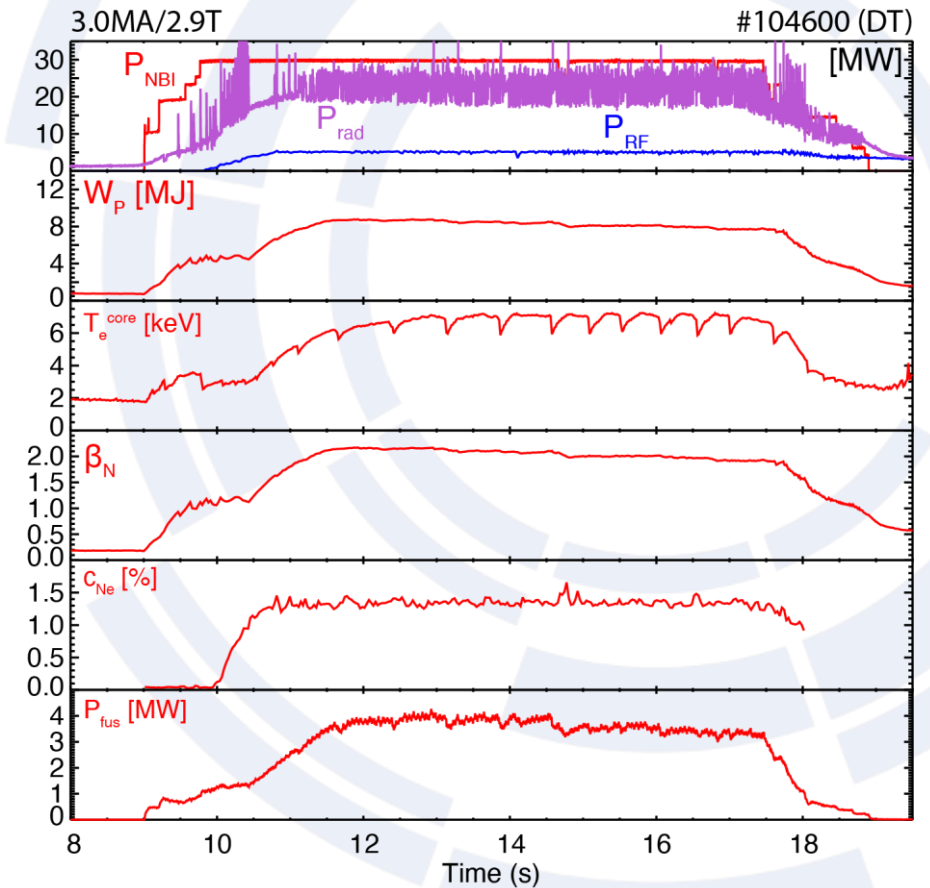


High performance scenario compatible with exhaust solution 2/

2.5MA all gas-rate ($\Gamma_D = 1.5\text{--}6.0 \times 10^{22} \text{ el.s}^{-1}$)



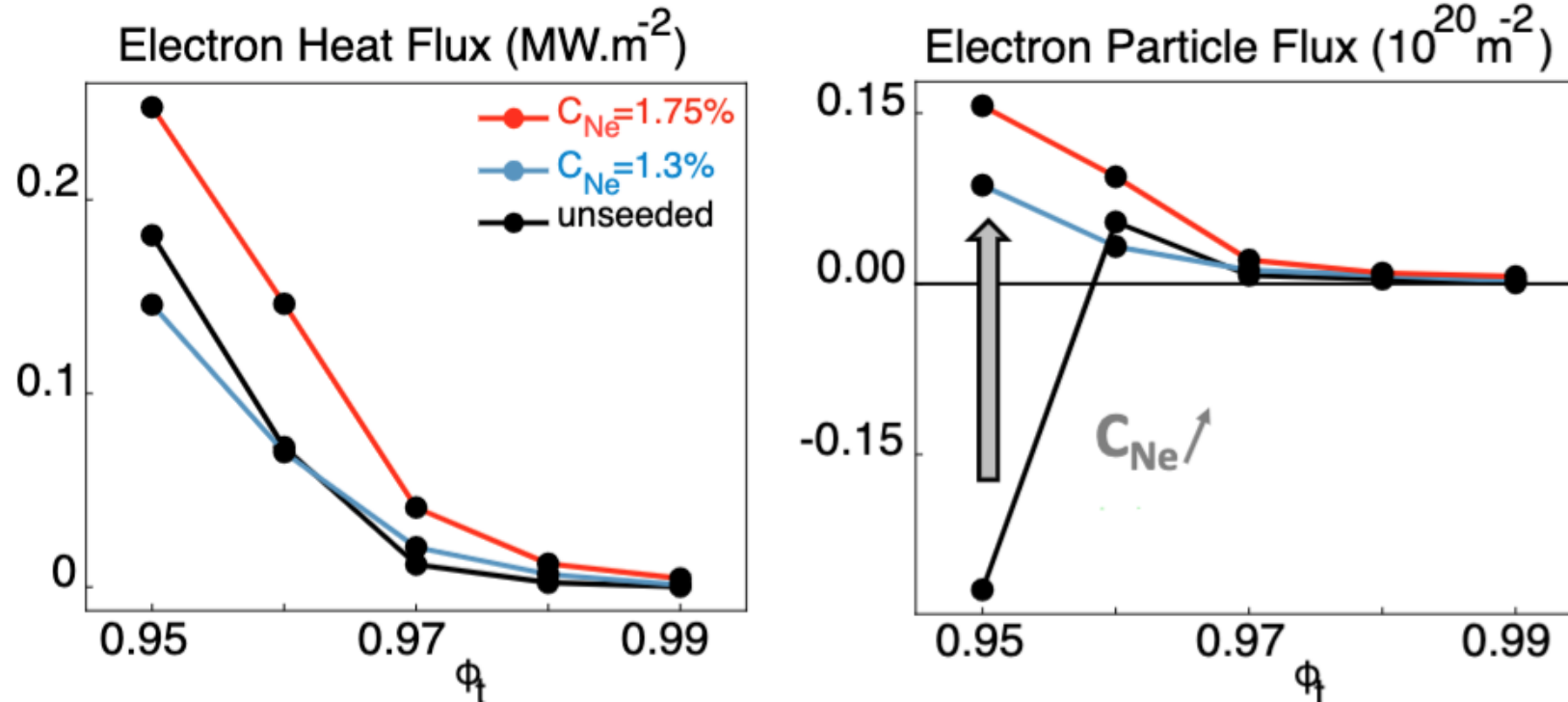
- No-ELM plasma domain exists at low $n_{e,\text{sep}} = 2\text{--}3 \times 10^{19} \text{ m}^{-3}$ & $P_{\text{sep}}/\text{PLH} \gtrsim 1.25$ (high C_{Ne} and enough power)
- 20% reduction in PLH threshold in D-T opens access to high-performance 3MA plasmas





High performance scenario compatible with exhaust solution 3/

More on next presentation by I. Predebon, A. Mariani, and M. Dicorato

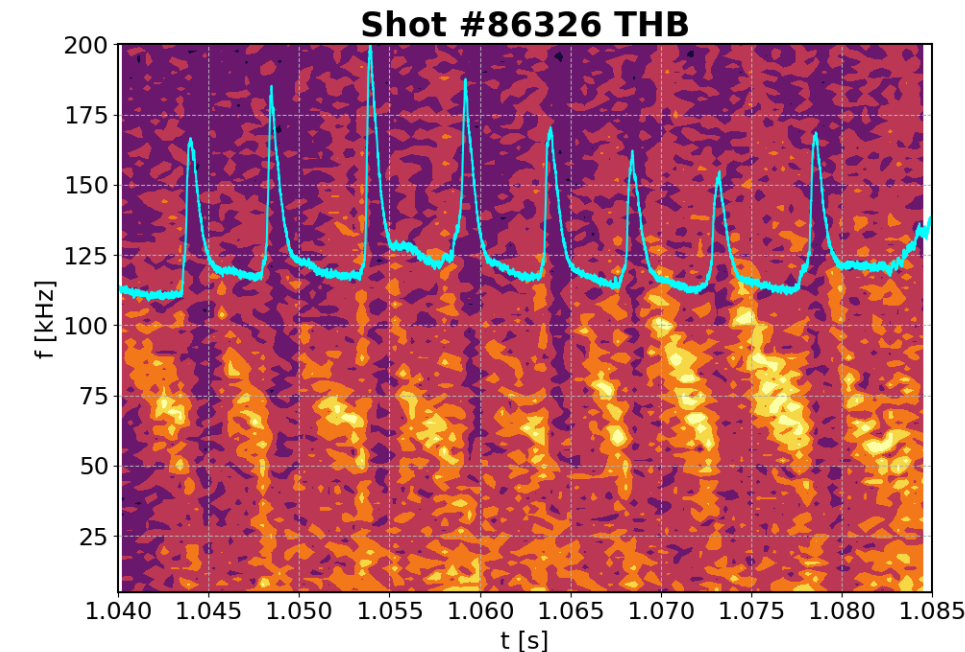
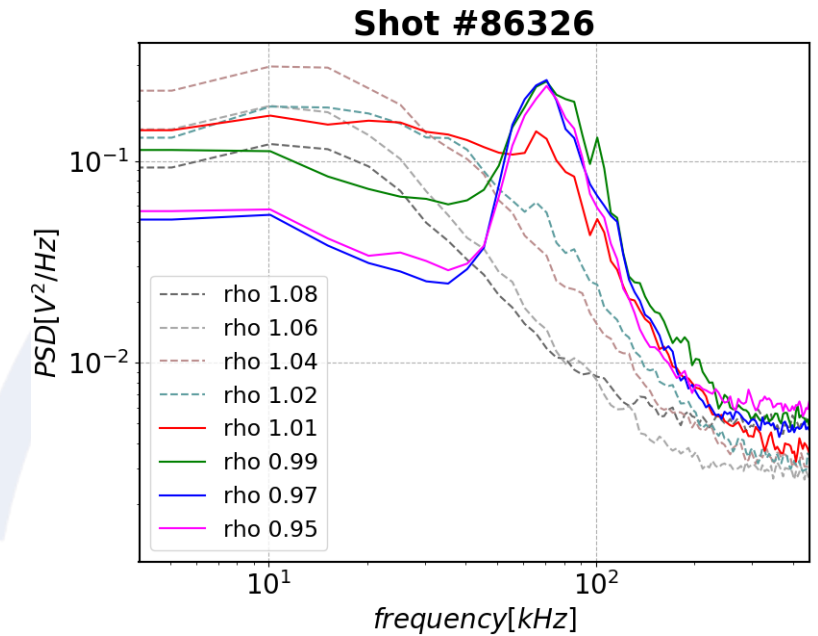


- **Total heat transport increases at high C_{Ne}** : increased Ti/Te destabilises ETG modes and stabilises ITG modes
- **Possible particle flux reversal from unseeded to seeded** : low Ti/Te at low seeding
- **Role of pedestal foot/separatrix Ti/Te (and corresponding gradient length) to be further understood**



Low ν^* / peeling limited pedestal

- Inter-ELM modes are observed only inside the separatrix.
- The mode frequency is observed chirping from a higher frequency value to a lower one during the ELM cycle
- Observed a correlation with MHD activity at low and high ν^*
- Propagating (in the laboratory frame) in the e-diamagnetic direction with velocity $\sim 5\text{km/s}$ and $\lambda_z \sim 80\text{mm}$

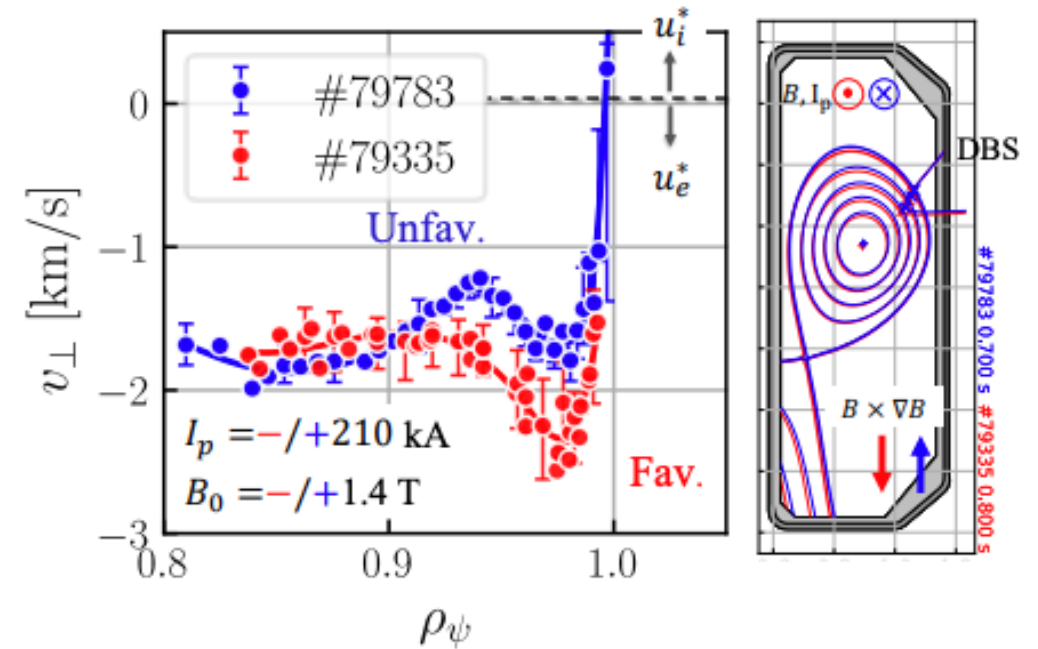
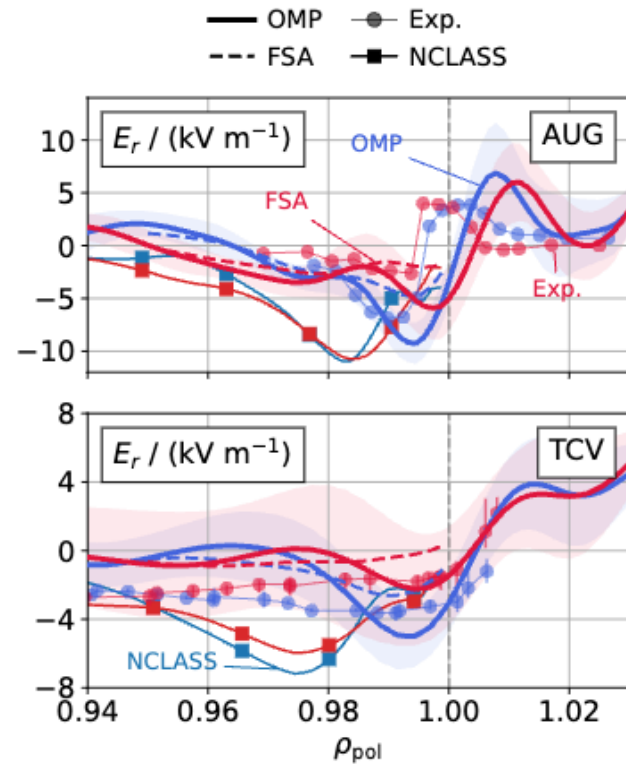




RT01- Linking Edge Flows to the Magnetic Geometry Asymmetry in Tokamaks

RT01

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



- Now modelled via GENE-X trying to disentangle the role of turbulence in setting the difference between favorable and unfavorable configuration (B. Frei Submitted to PPCF and [arXiv:2610.06144](https://arxiv.org/abs/2610.06144))

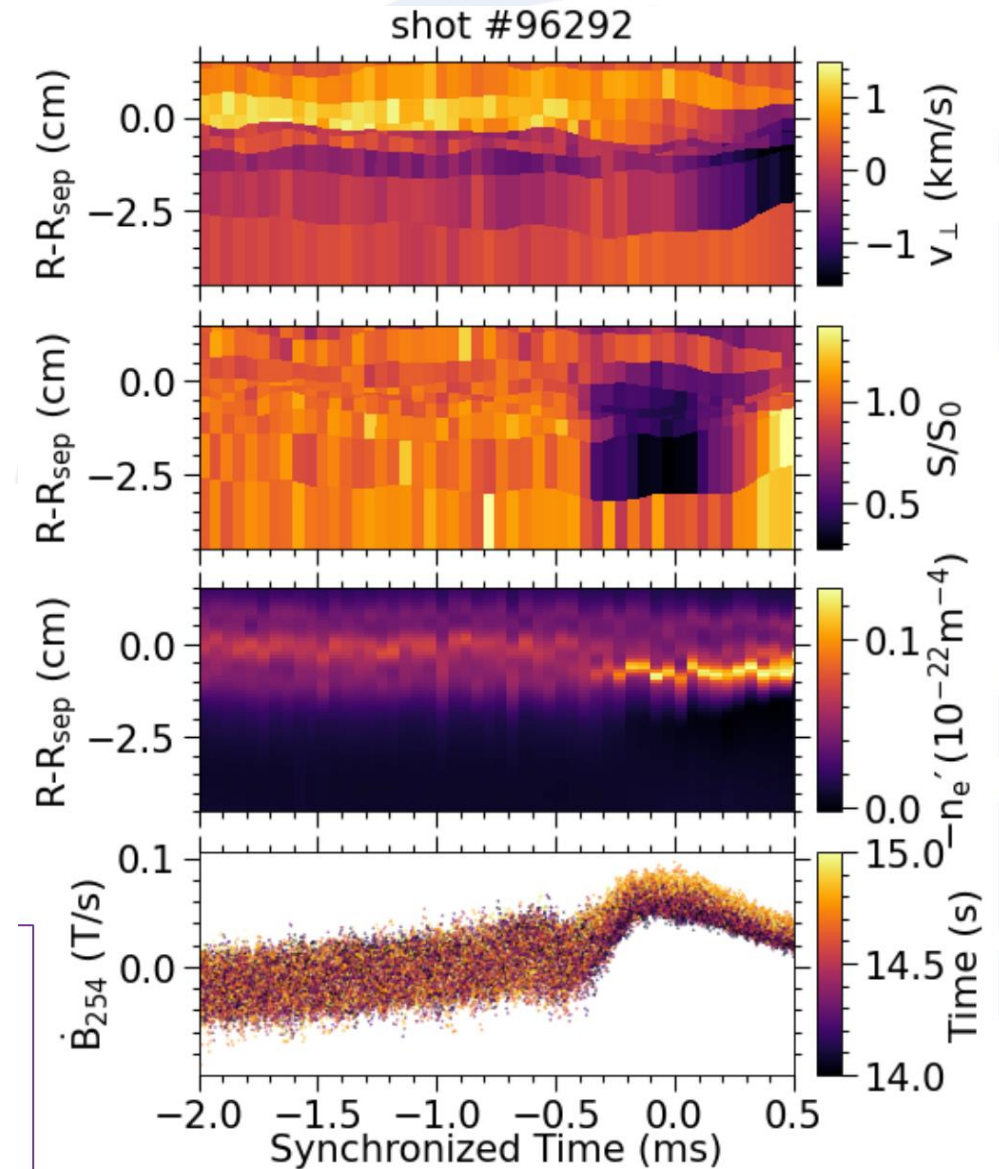


Spatio temporal evolution of edge flows and turbulence across the L-H transition

RT11

- Synchronized data shows evolution from dithering transitions
- No clear trend in $v_{\perp}$ or turbulence levels as transition is approached
- Transition begins with localized (2–3 cm) reduction in turbulence, from just inside the pedestal top to the separatrix, spanning both the inner and outer shear layers.
- Largest reduction in turbulence observed near inner shear layer, ~pedestal top. Smaller reduction in turbulence at separatrix.
- The transition is approximately simultaneous across the steep gradient region (within 50 μ s resolution).
- The density gradients steepen on a similar timescale but within a more restricted radial region.
- The L–H transition is not initiated by an increase in flow shear.

C. Silva et al, invited talk at EPS 2026





Isotope Studies on H-mode edge Confinement using full-f GJ

Turbulence simulations in JET

RT11

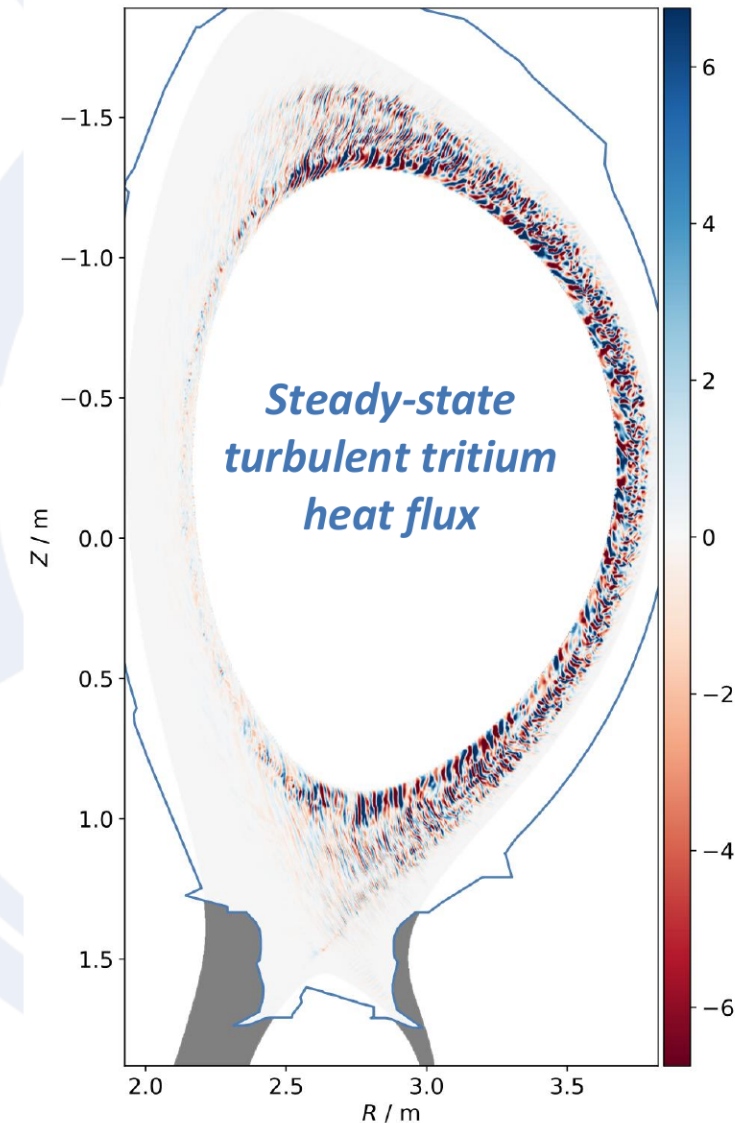
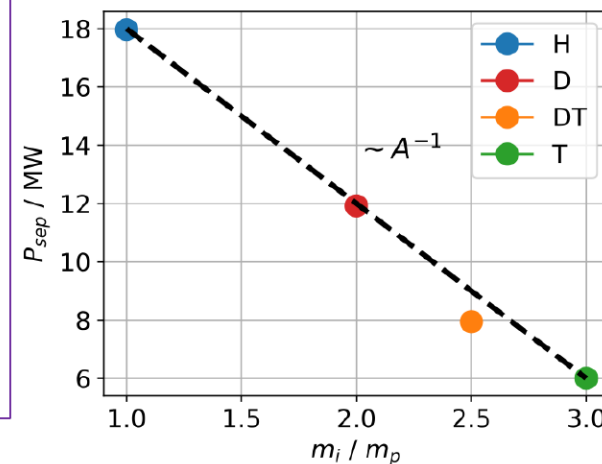
B. J. Frei and P. Ulbl

2026:

- First-ever GK turbulence simulations at JET (JPN97094(H)) with different isotopes *H*, *D*, *T* including *D-T* with the full-f GK code **GENE-X** [B. J. Frei et al, CPC 2025] in **JET diverted Corner geometry in H-mode**
- **Only** n and $T_{e/i}$ at core boundary (from exp.) **as inputs** $\Rightarrow$ **self-consistent evolution of profiles and fluctuations.**
- **Preliminary results:**
 - ▶ $1/A_{eff}$ effective mass scaling of P_{sep} to achieve experimental profiles
 - ▶ Similar profiles, but larger fluctuations with small A_{eff} .
 - ▶ Particle transport overestimated

Plans for 2027:

- ☐ Density source scan to assess particle confinement
- ☐ Role of global effects (e.g. ExB shearing) vs. local GK
- ☐ Publication on isotope effects in H-mode
- ☐ Extend to L-H transition physics: dependence of P_{LH} on χ_{eff} and A_{eff}



P. Vincenzi WPTE Review Meeting 2026



Does the underlying equilibrium impact plasma properties? Fluctuations & transport

Equilibrium criticality change in number of solutions of Grad-Shafranov (mostly mathematics)

- Importance of boundary between para vs diamagnetic regions [E.R. Solano EPS 1999](#), [PPCF 46 L7 2004](#)

Connecting diamagnetism and transport barriers (mostly physics)

- Critical Behavior of Magnetically Confined Plasma Regimes, J. Garcia and G. Giruzzi [PRL 104, 205003 2010](#)
- Magnetic phase transitions in plasmas and transport barriers, ER Solano & R.D. Hazeltine, [NF 52 114017 2012](#)

Being discovered again in 2025-2026?

- W Zholobenko et al, [Phys. Rev. Lett. 136, 075101 2026](#)
assumed H-mode equilibrium during L-phase, then obtained transition
- R.J.J. Mackenbach et al, [arxiv 2026](#)
observes “turbulence second stability” as ratio of L-mode and H-mode equilibrium goes towards H
- Y. Narbutt et al, [arxiv 2026](#)
effect of Shafranov shift stabilization on turbulence, evolving profiles

It would be very valuable to explicitly study if para vs diamagnetic plasma edges lead to different transport

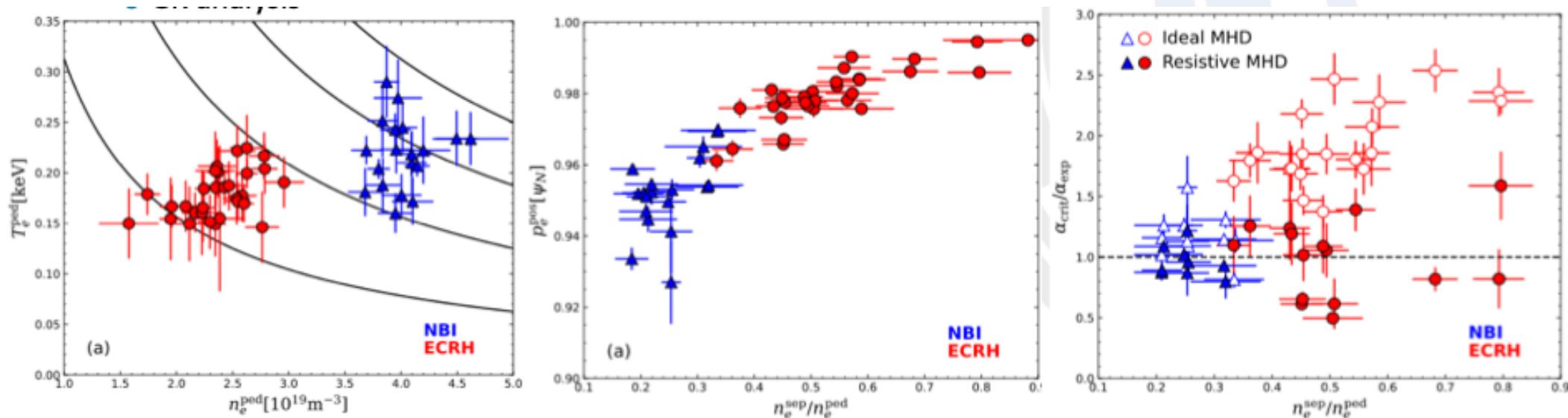
E. Solano



ECRH heated vs NBI heated pedestal

- ECRH heated dataset has lower n_e^{ped} and lower p_{ped}
- The lower n_e^{ped} in ECRH heated plasmas is likely due to the lack of NBI fuelling
- ECRH heated plasmas have the pedestal shifted outwards $\rightarrow$ this degrades the pedestal stability due to resistive MHD effects and can explain the lower p_{ped}
- Work in progress:
- Pedestal predictions
- Quantify pedestal heat diffusivity with ASTRA
- GK analysis (on top of peeling limited pedestal investigation by O. Krutkin see later talk)

A. Lafay EPS 2026





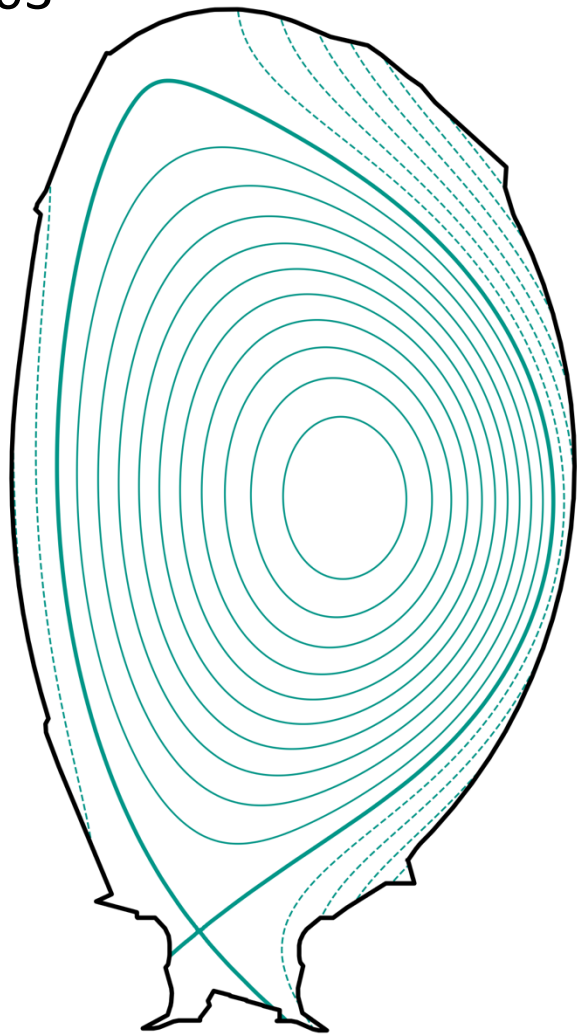
RT02 - Physics understanding of alternatives to Type-I ELM regime

#	
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 P_{sep}/R and/or pedestal top collisionalities 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 FOAK

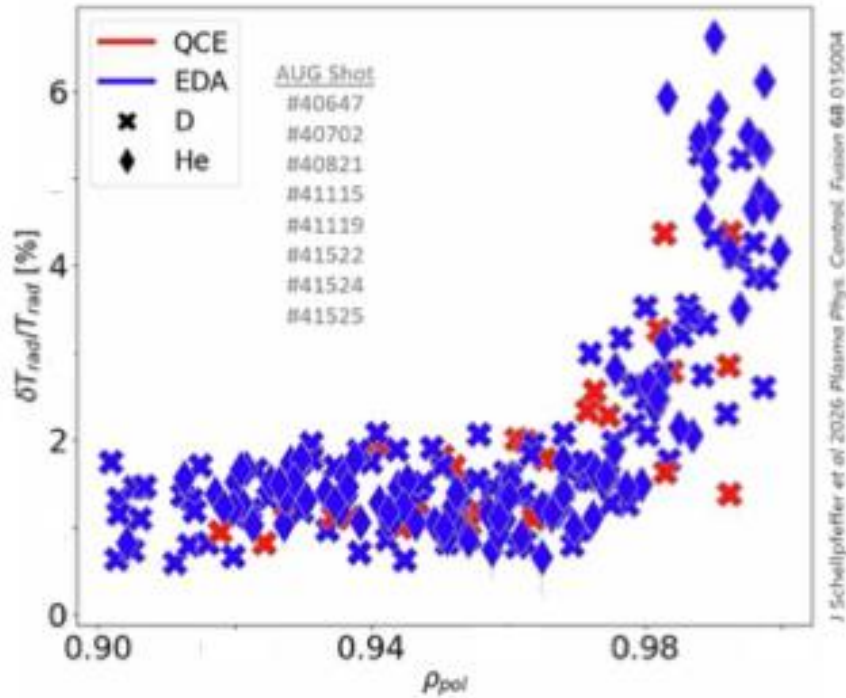
JPN # 102103



- 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
 - Need work to distinguish between ideal and resistive effect



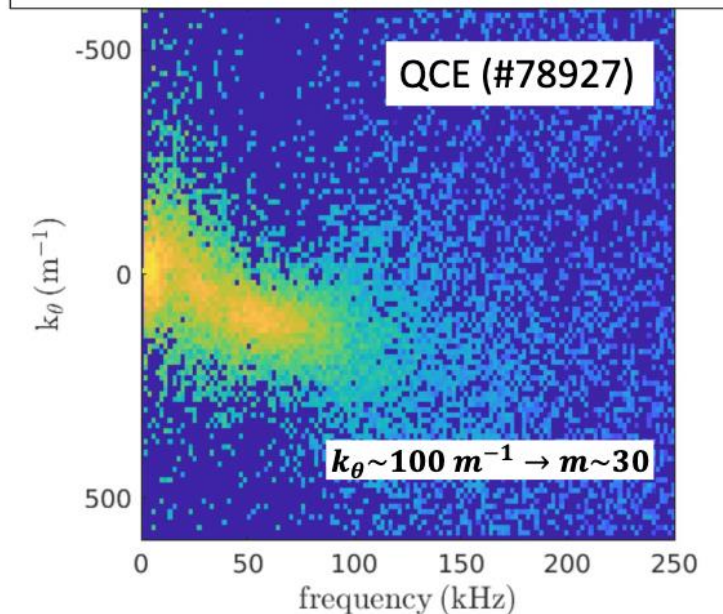
Increased characterization of QCE turbulence properties



- Studies to disentangle triangularity, elongation and closeness to double null (A. Miller AUG/TCV) or higher order effect as squareness (K. Imada and S. Saarelma MAST-U)
- Turbulence characterization with DBS (X. Liu) and CECE (J. Schellpfeffer) the latter showing similarities on Temperature fluctuations between QCE/EDA

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

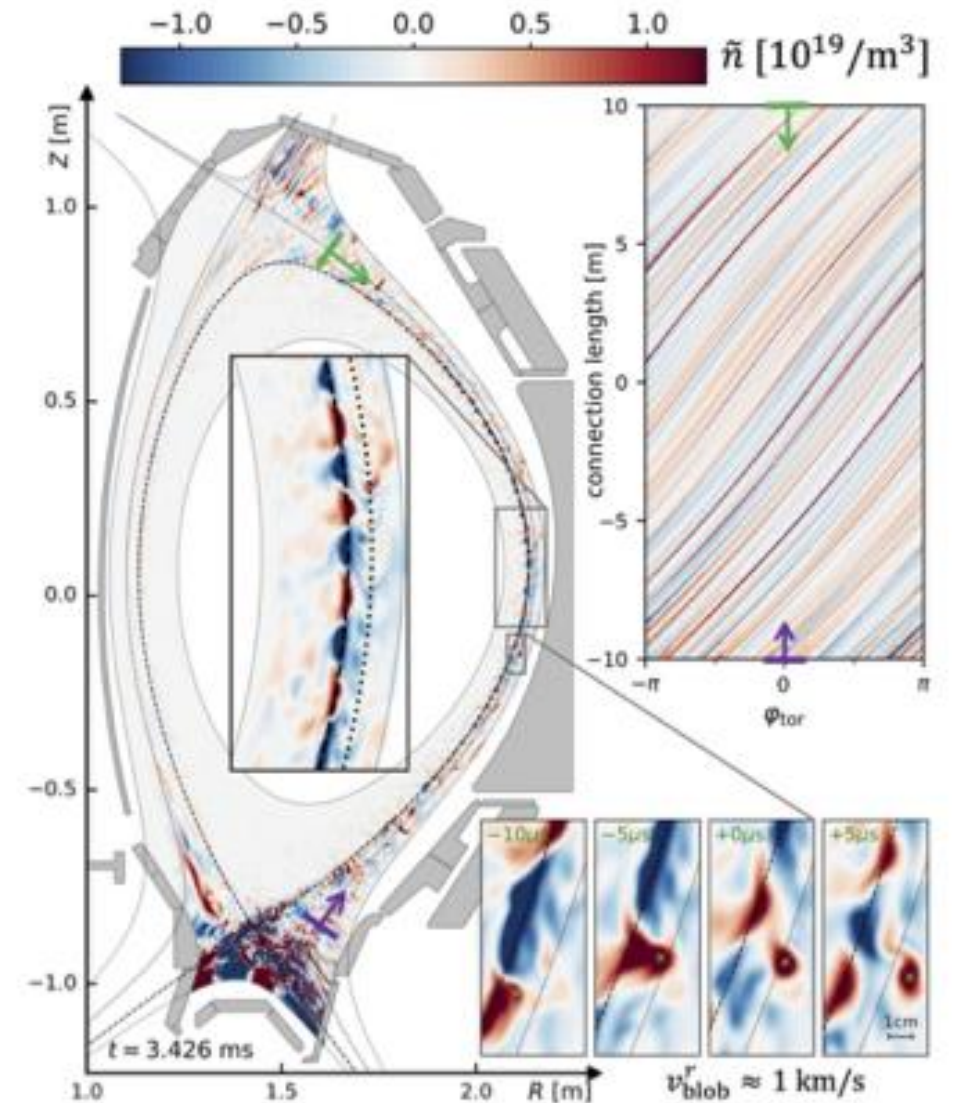
Statistical dispersion relation from separated pixels in the poloidal direction





GRILLIX used to simulate AUG QCE discharges (*Zhang PRL 2026*):

- QCM identified as kinetic ballooning mode confirming Experiment observation (*Kalis PPCF 2026*)
- SOL filaments as results of QCM and RXM coupling (needs high X-point collisionality)
- Extending the work to other devices (see H. Zhang talk). Is there a test to work the strength of the coupling in view of extrapolation to less collisional SOL? What about impurities?



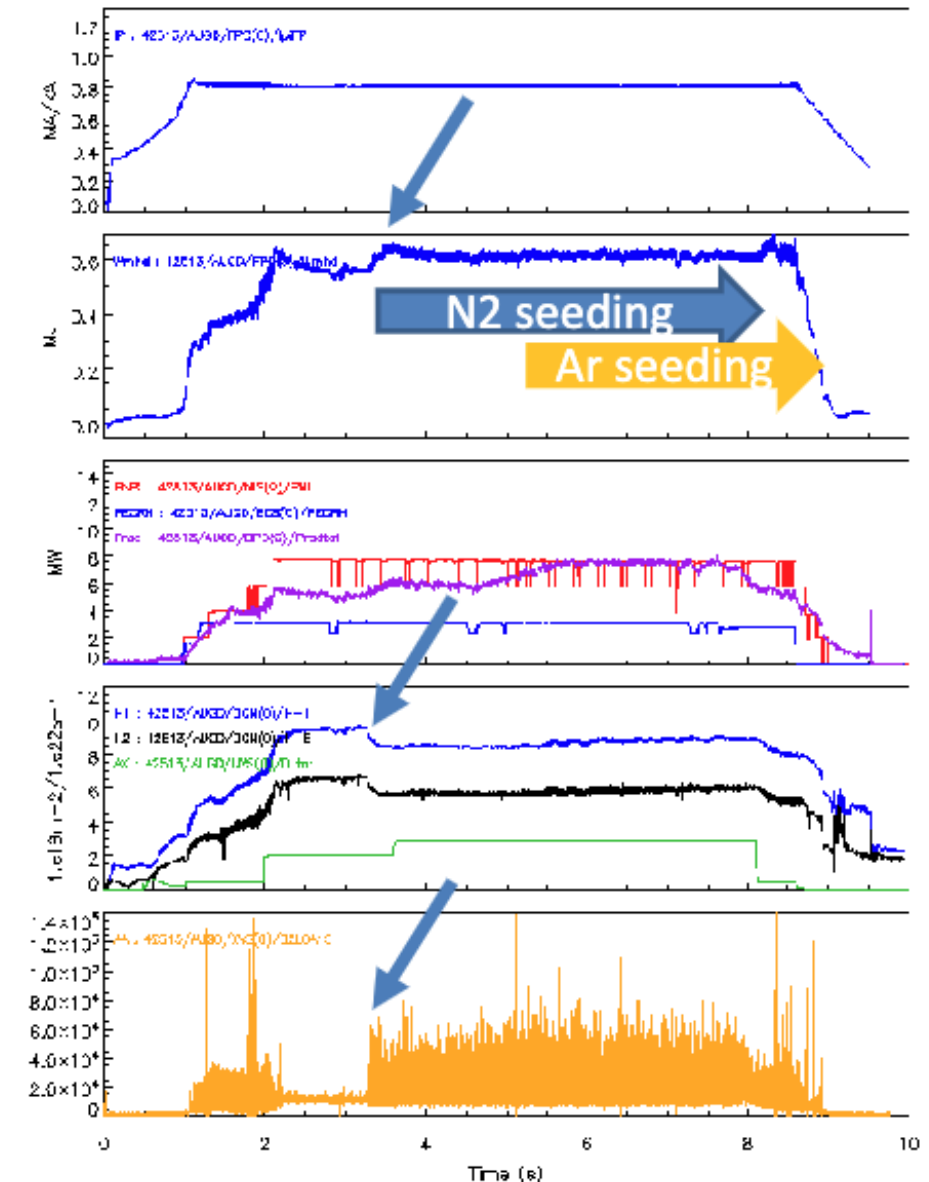


QCE: detachment studies

RT02

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





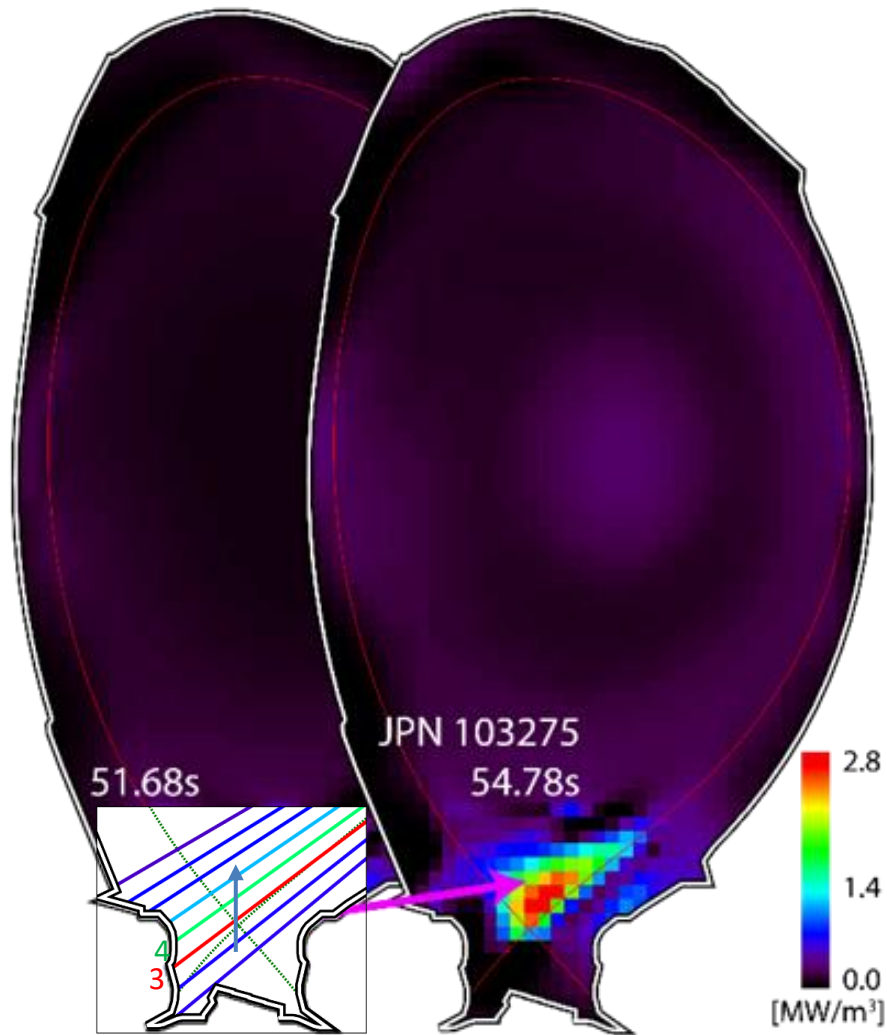
RT05 Physics of divertor detachment and its control for ITER, DEMO and HELIAS operation

RT05

#	
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**

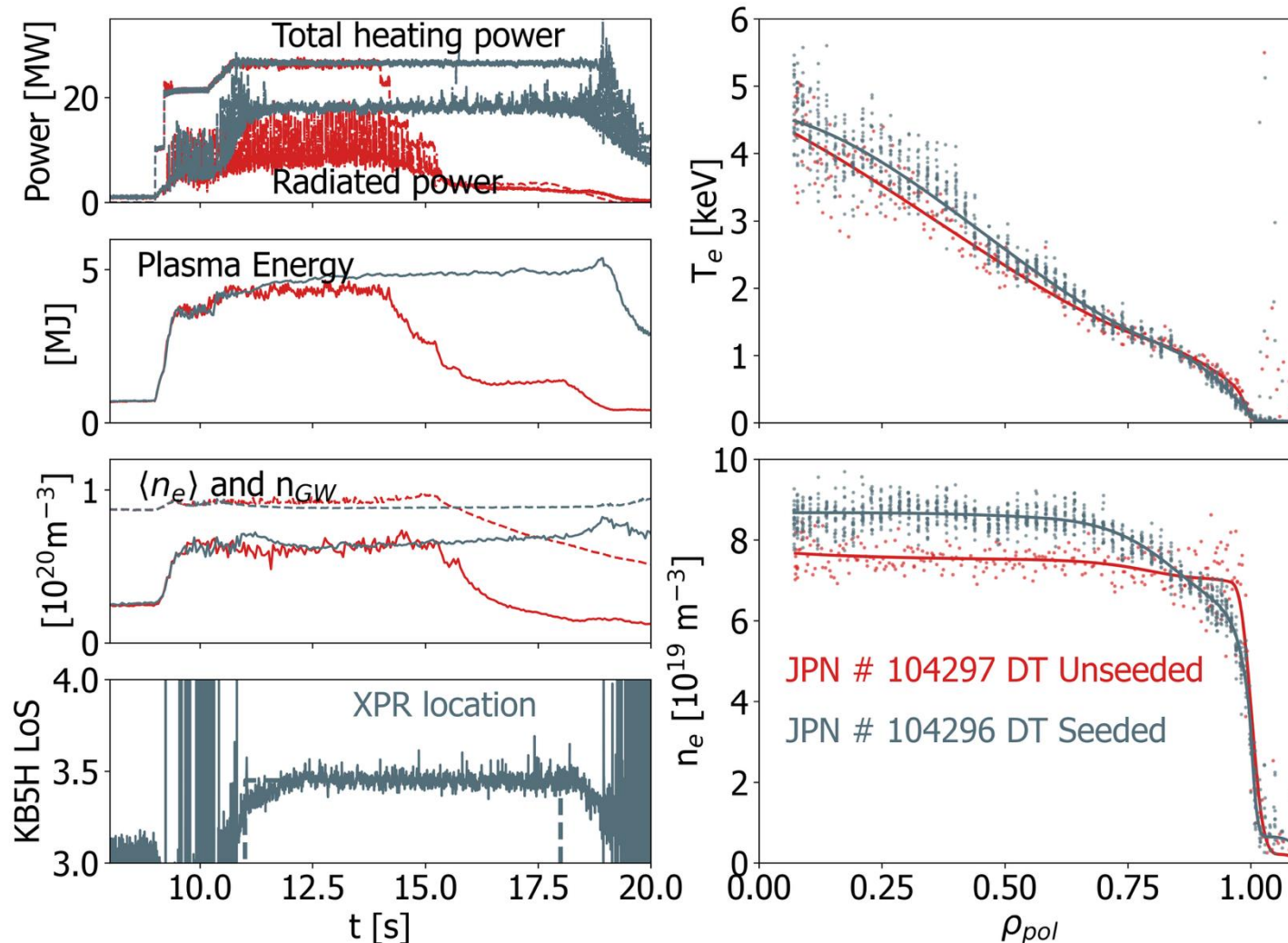
*M. Bernert et al, NME 2025

**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:

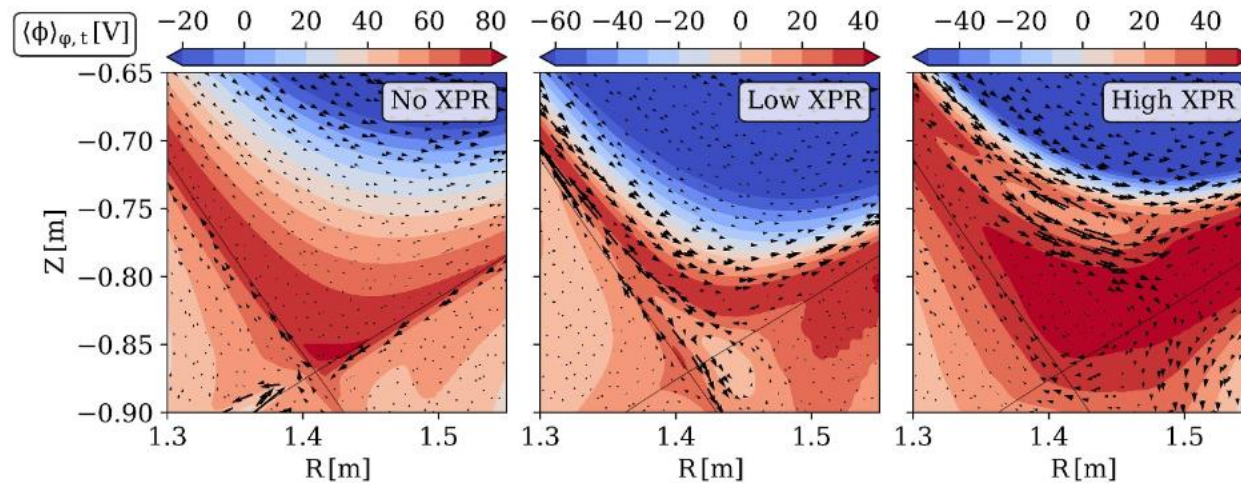
- RT control implemented both in DD and DT
- full detachment
- small to no ELM
- smooth L-H and H-L transition
- Beneficial effect of seeding on confinement w/o edge deterioration



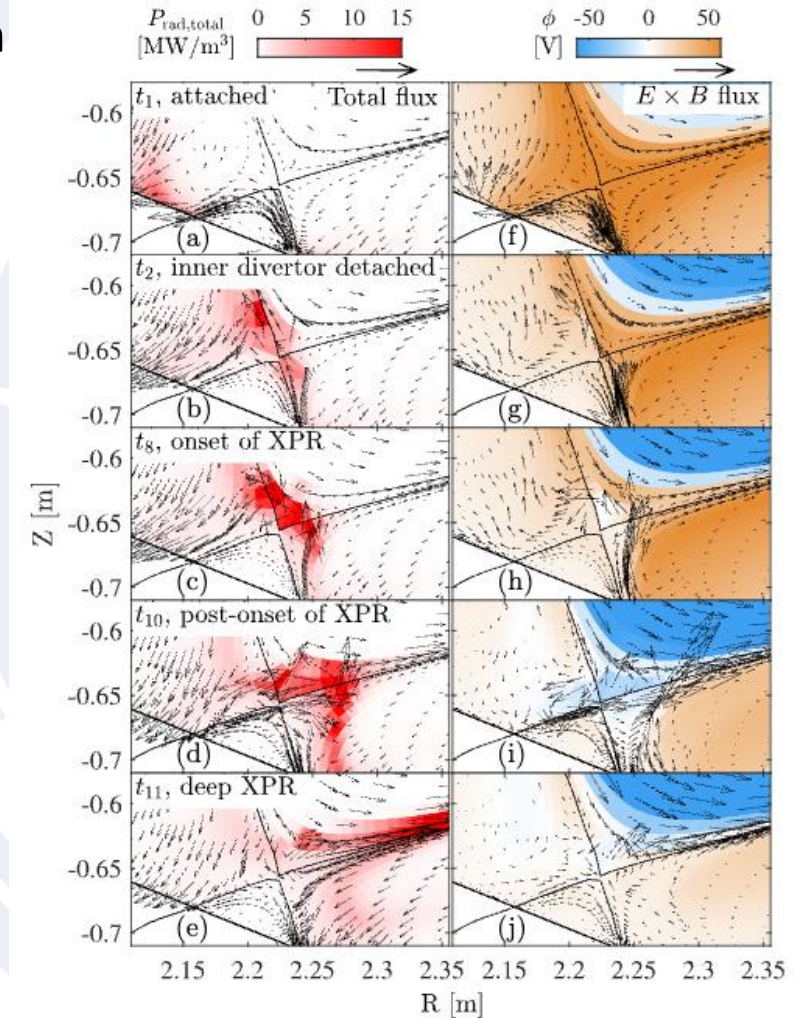
XPR modelling

RT05

- XPR simulation tackled by turbulence self-consistent codes (although with not fully consistent impurity treatment) only in the L-mode phases
- Clear appearance of an asymmetric vortex like structure contributing to local density accumulation
- Lacking H-mode edge simulations accounting for observed pedestal modification



Eder, K. et al. NF 2025



Yang, H. et al. PRL 2026



Call cycle for 2027





Conclusions

- WPTE continues its ambitious program with strong emphasis on the cross-device approach
- A similar Research Topic structures in place till end of FP9 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
- Collaboration and mutual fertilization grown during the last year: looking forward to continue this combined effort