Synergy with WPTE

N. Vianello

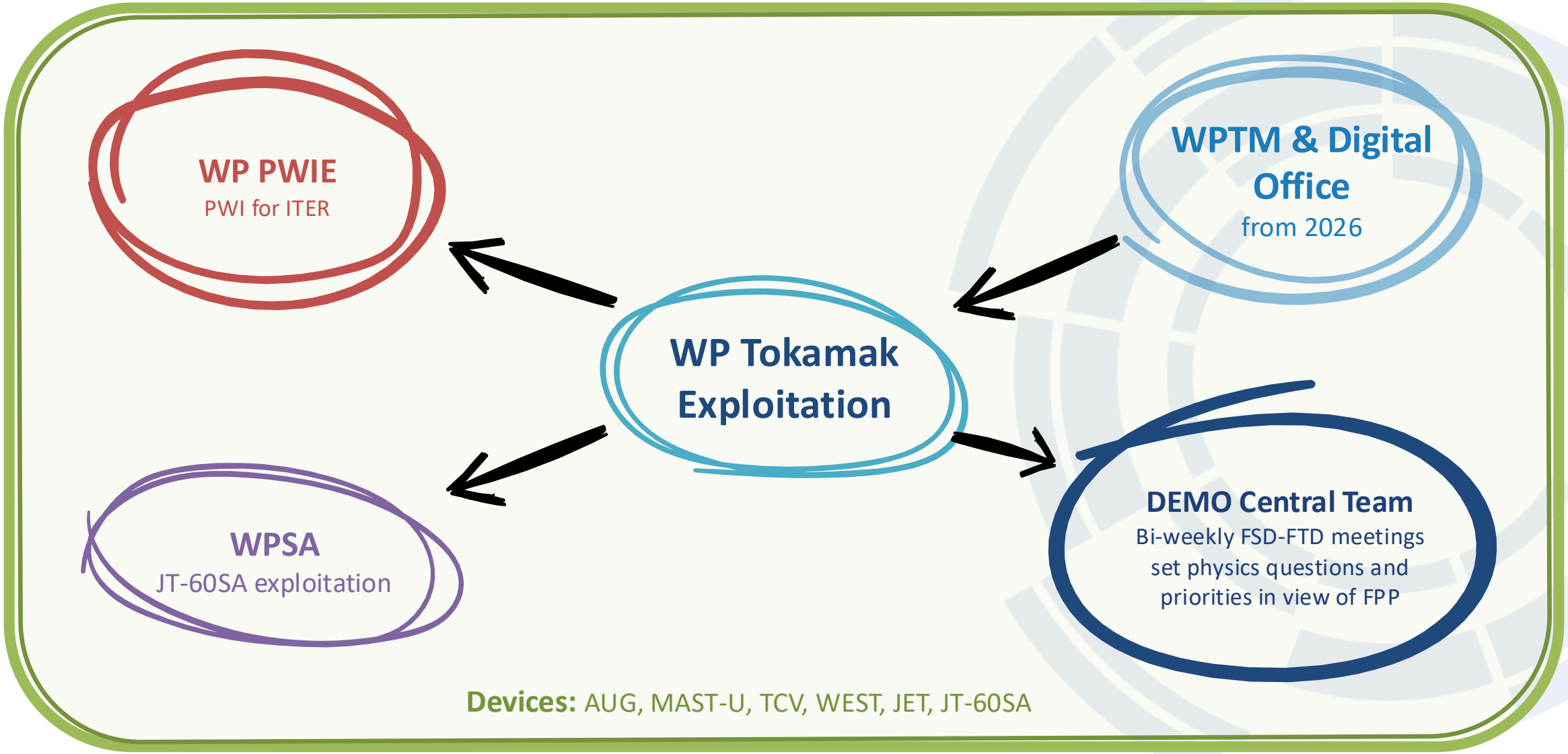
On behalf of WPTE TFLs

E. Tsitrone, N. Vianello, A. Hakola, V. Igochine, Y. Kazakov, D. Keeling, B. Labit, V.K. Zotta

Consorzio RFX and ISTP-Padova, Italy

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

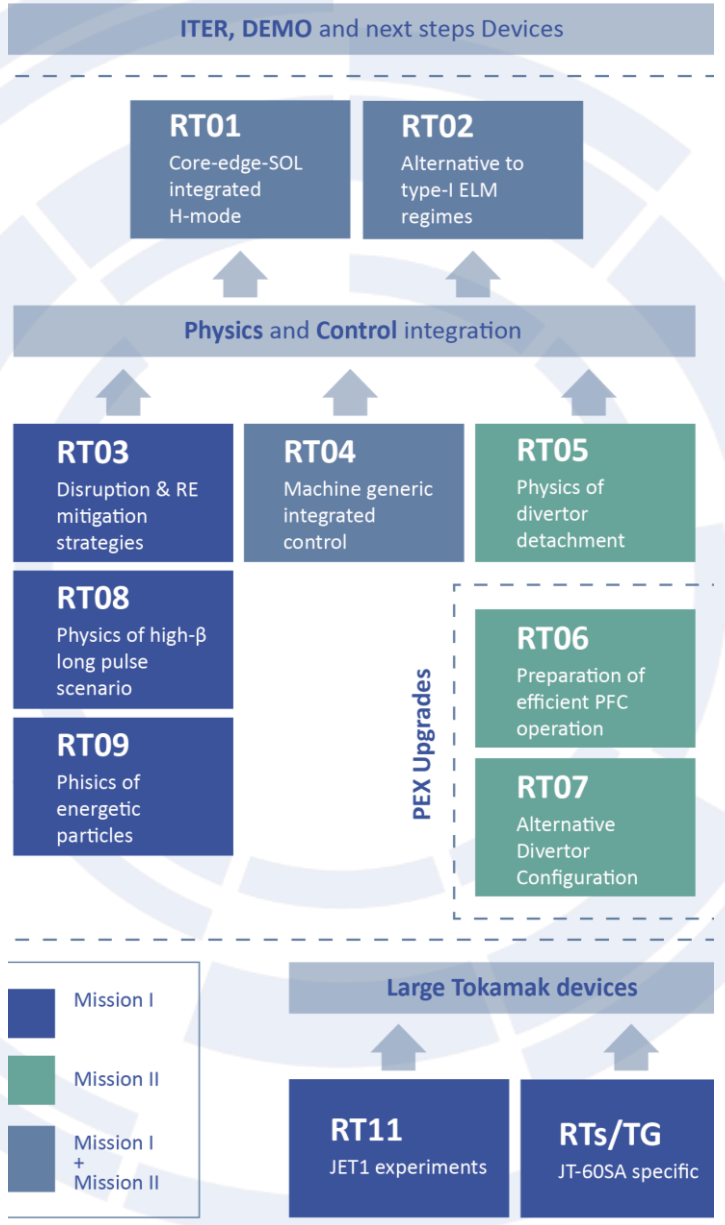
WP TE in Fusion Science Department ecosystem



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

Four Research Topics still need first-principles modelling

- Selected 2026 findings from four Research Topics, focused on where **interpretation and first-principles / reduced modelling** are still needed
- Recurring cross-cuts for ENR-05-ENEA-03:
  - separatrix / edge turbulence and core–edge–SOL coupling
  - pedestal and SOL transport closures for ITER/DEMO extrapolation
  - pedestal scaling and its relation to separatrix conditions

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

RT05
Detachment control

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

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

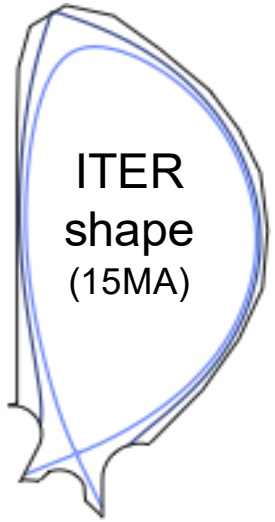
RT-01 Core-Edge-SOL integrated H-mode scenario compatible with exhaust constraints in support of ITER

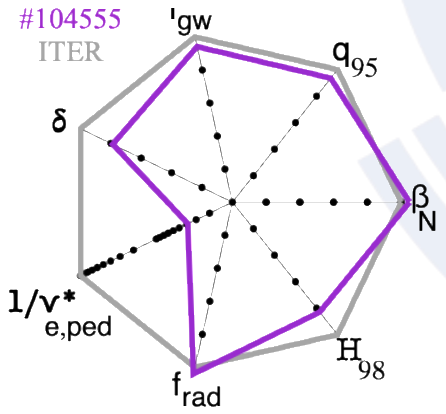
#	Scientific Objectives
D1	Develop and understand stationary H-mode scenario at low collisionality and with dominant electron heating
D2	Provide physics-based cross-field transport coefficients for heat, fuel particles and impurities to TSVVs for turbulence modelling
D3	Determine the impact of different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

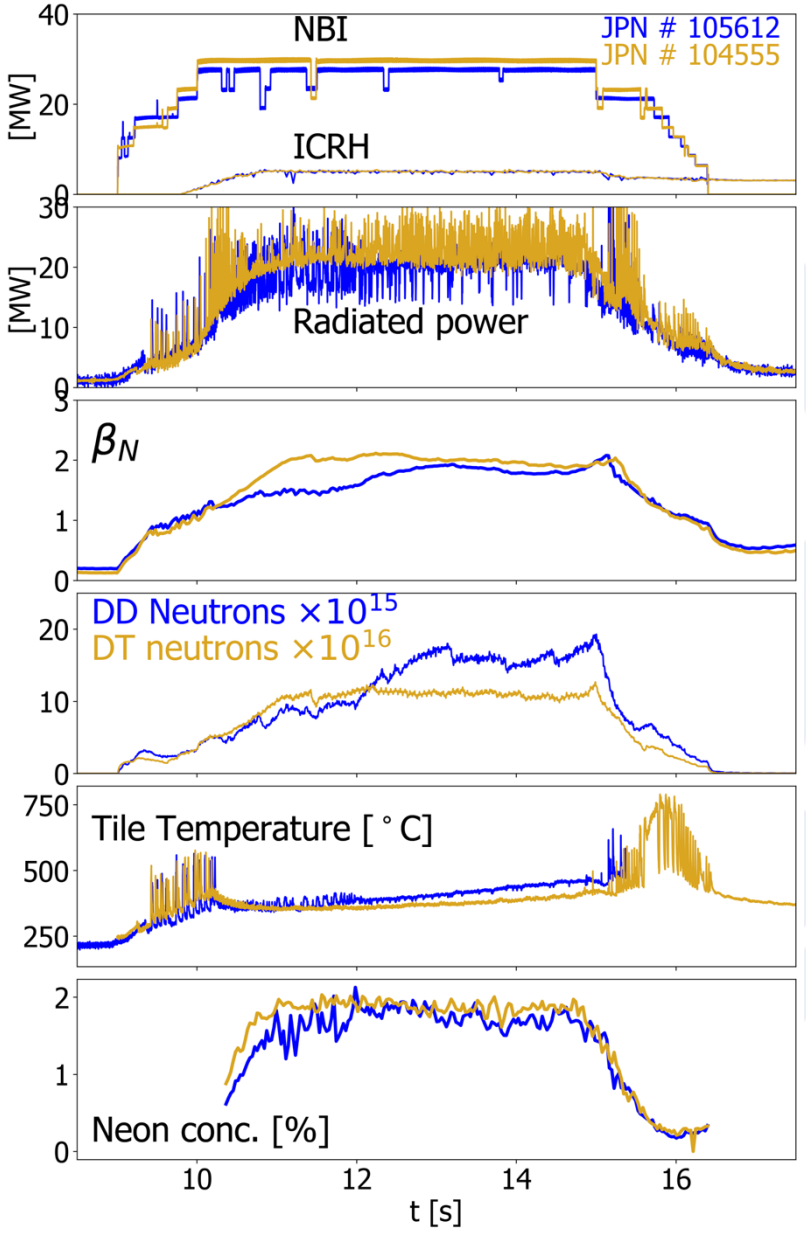
High performance plasmas compatible with exhaust solution 1/

- 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 $P/P_{L-H} < 2$, $f_{GW}=0.7, f_{GW,ped}=0.46$, $f_{rad}=0.86$, while keeping $H_{98} \sim 1$, $\beta_N \sim 2.2$, $C_{Ne} \sim 1.7\%$



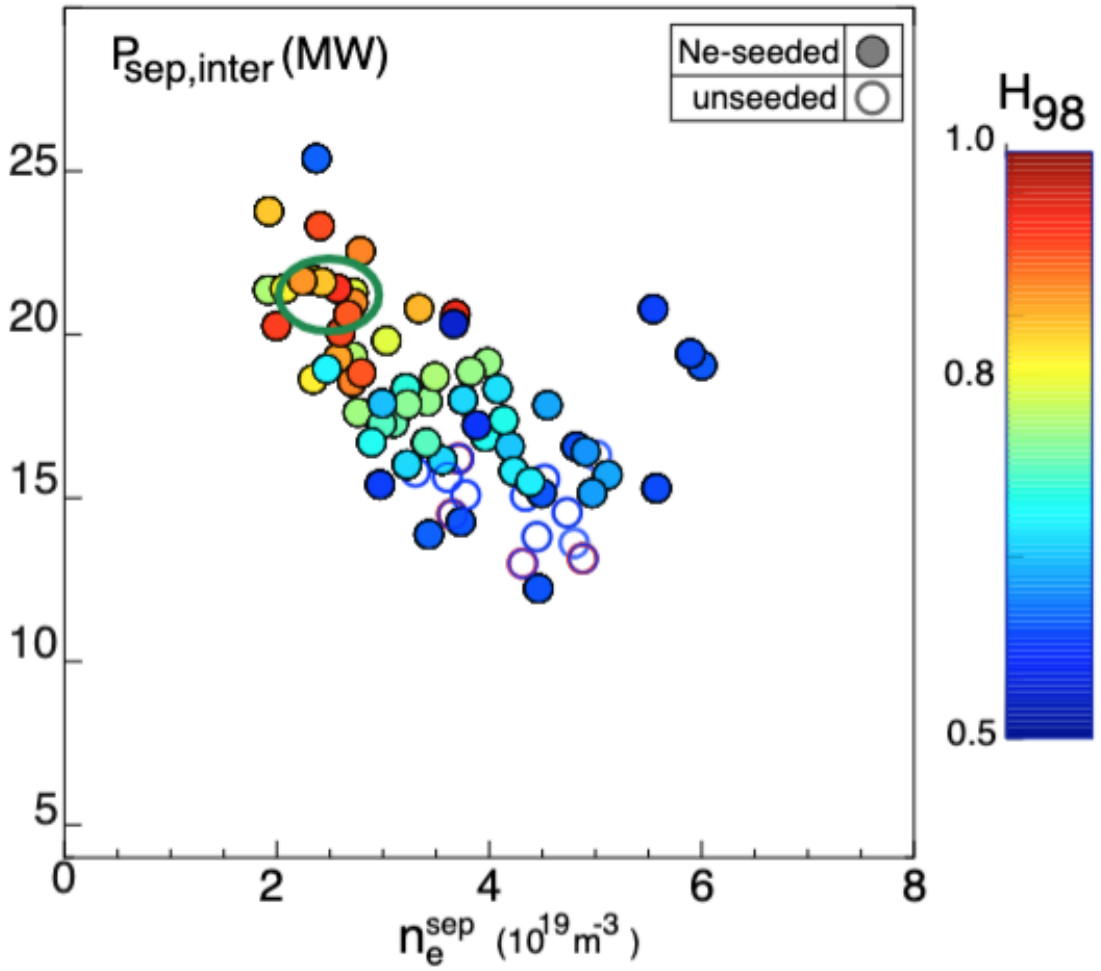




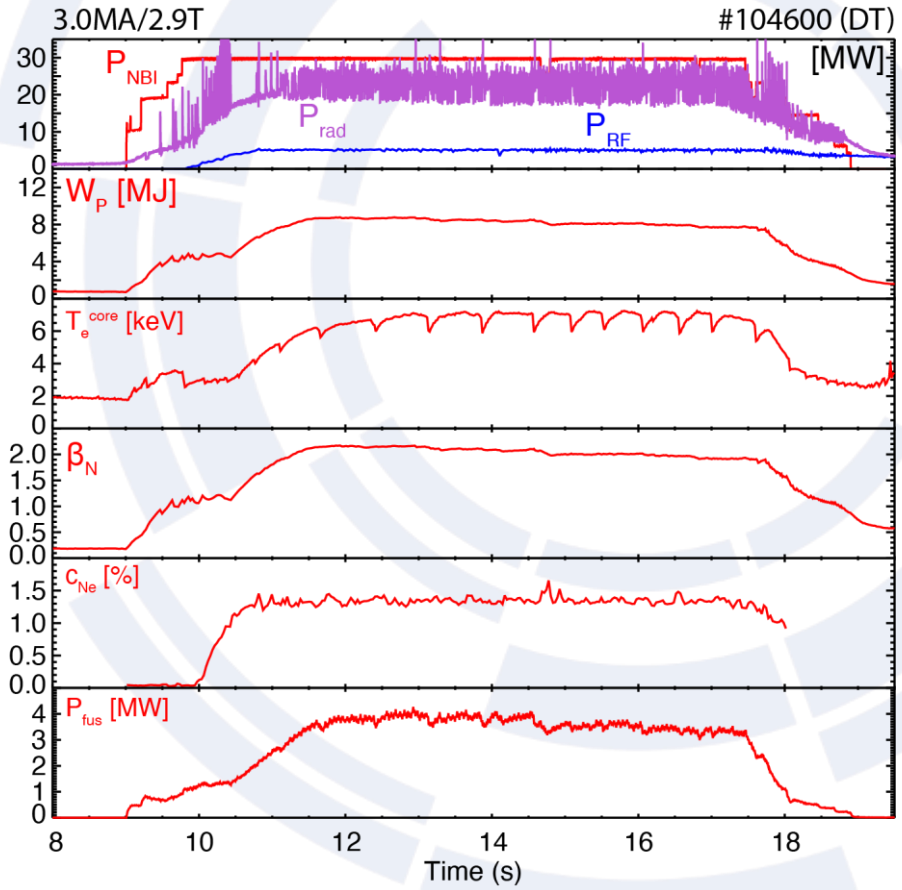


High performance scenario compatible with exhaust solution 2/

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

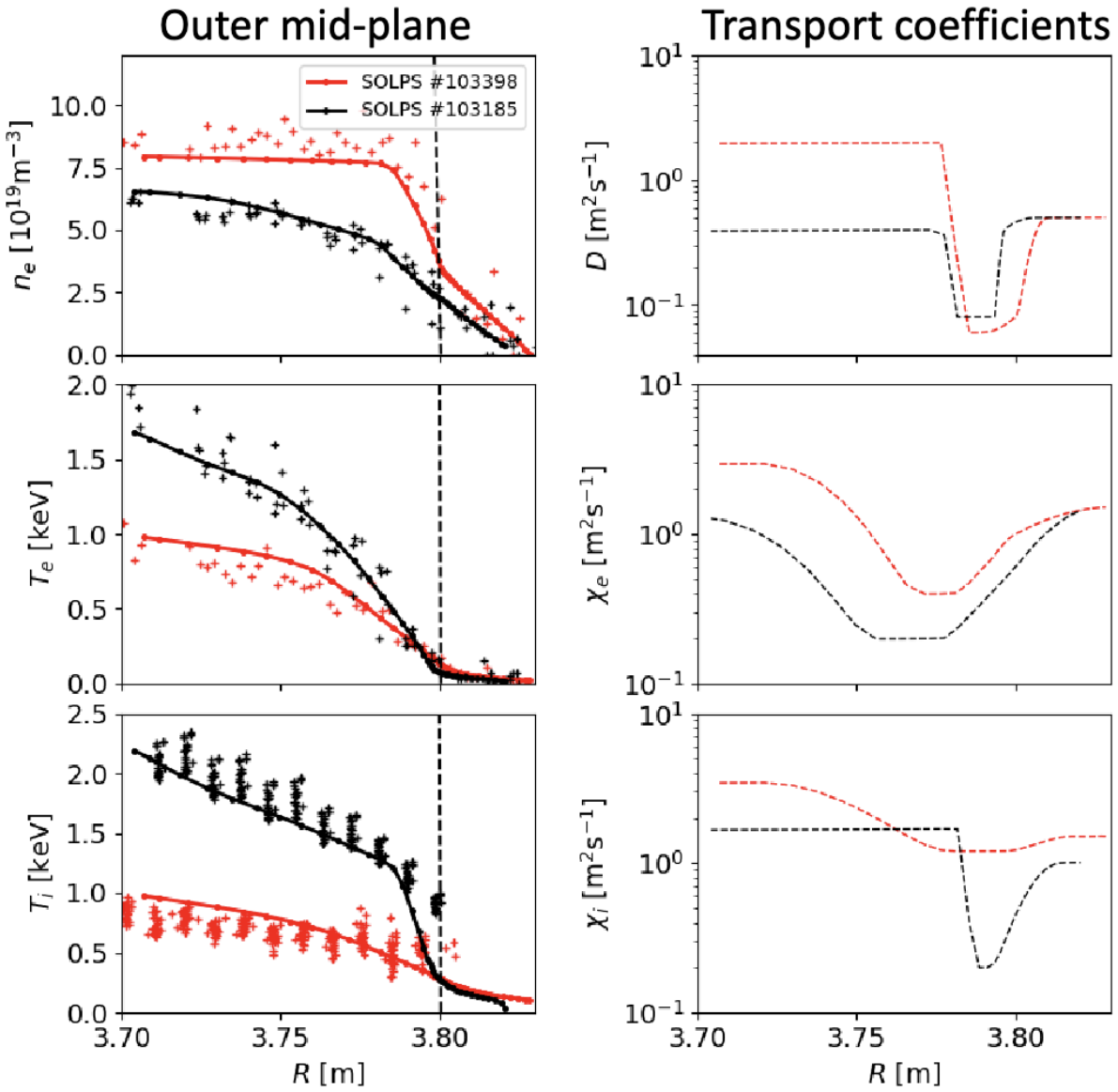


- No-ELM plasma domain exists at low $n_{e,sep}$= 2-3 x 10^{19} m^{-3} & Psep/PLH ≳1.25 (high C_{Ne} and enough power)
- 20% reduction in PLH threshold in D-T opens access to high-performance 3MA plasmas

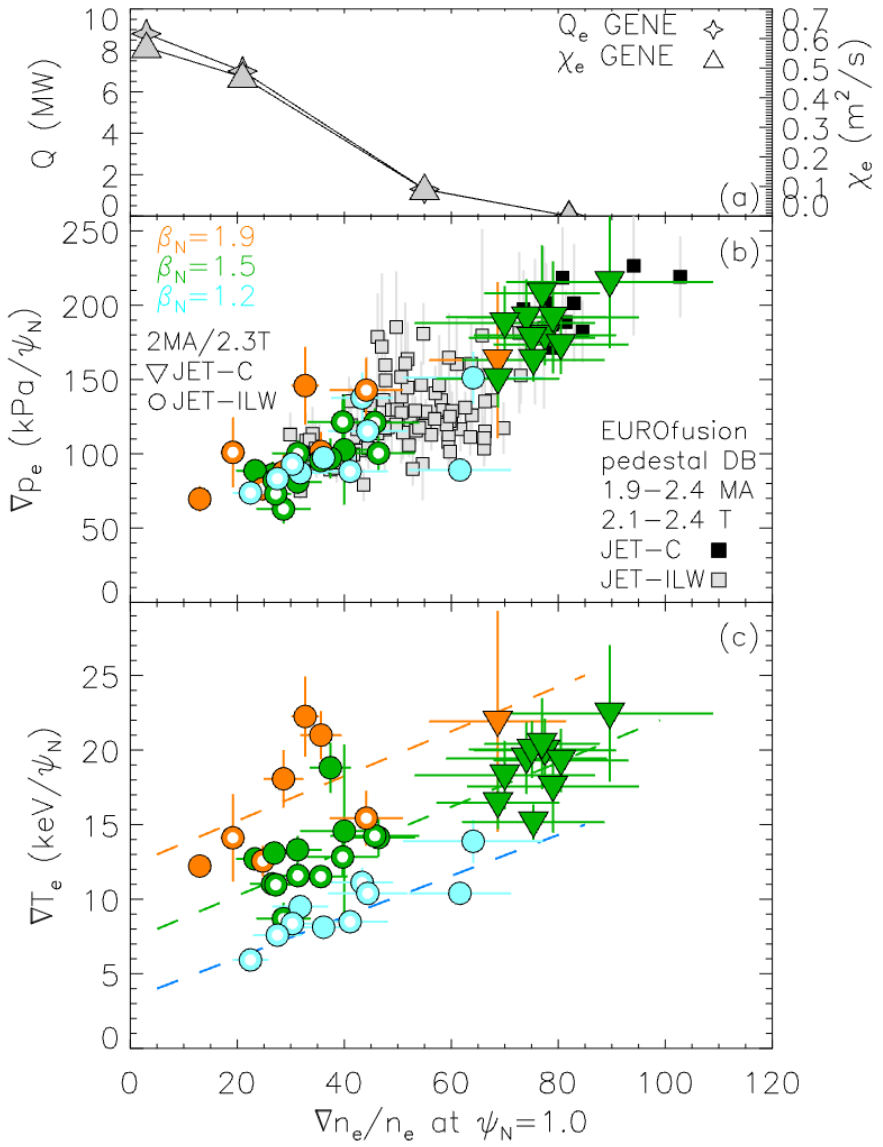


SOLPS matches JET Ne-seeded ITER-baseline profiles

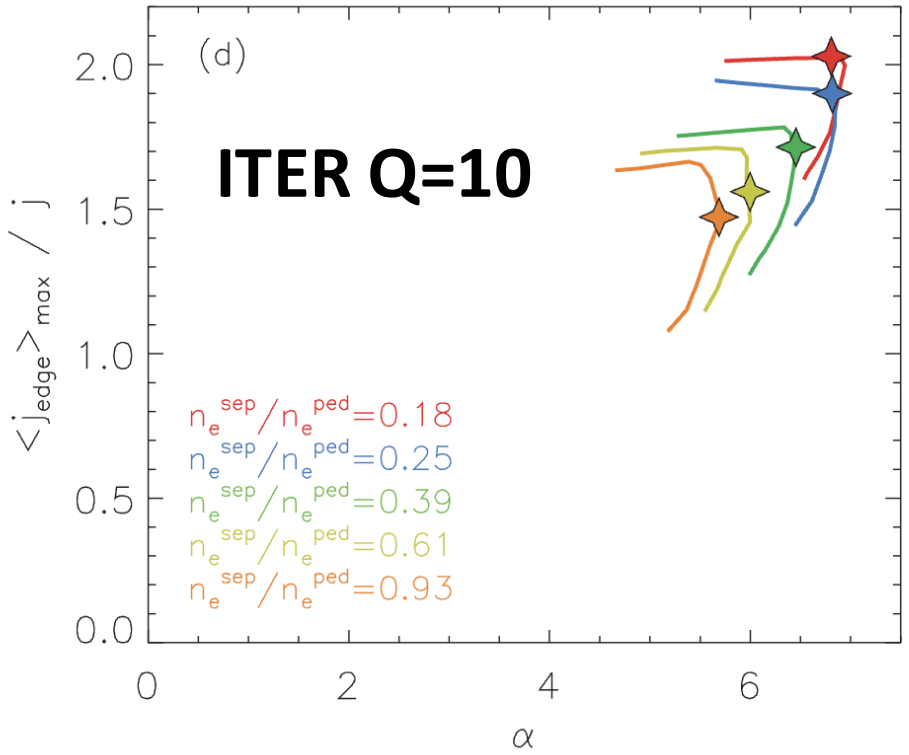
- **Same JET ITER-baseline scenario with Ne seeding:** #103398 (red, higher density, lower temperature) vs #103185 (black, lower density, higher temperature)
- **SOLPS reproduces** the measured n_e, T_e and T_i outer mid-plane profiles across pedestal and SOL
- **D, χ_e and χ_i drop at R ≈ 3.78–3.80 m:** both pulses need an edge transport barrier just inside the separatrix
- **Open question:** Understand the reason for observed decoupling of Te/Ti across separatrix which propagates into the pedestal



Separatrix density sets pedestal transport and the MHD limit



Frassinetti NF 2021

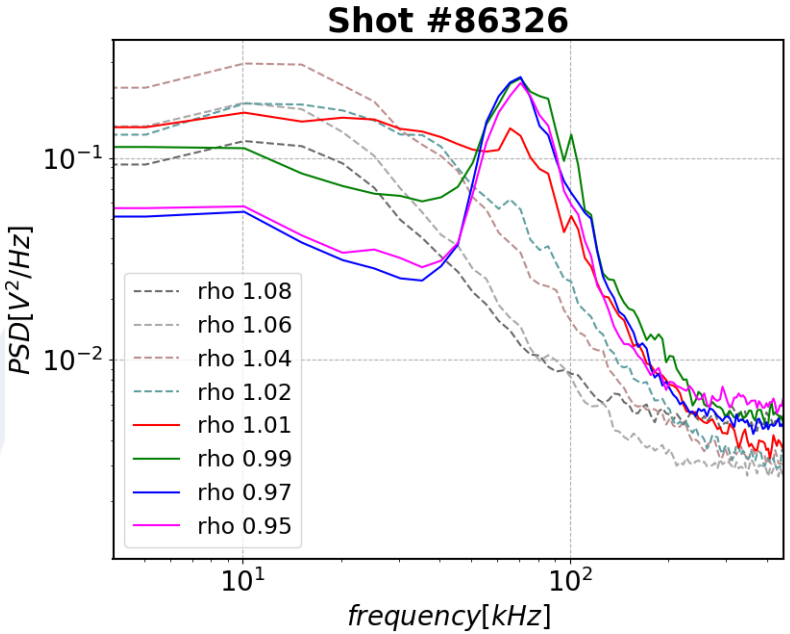


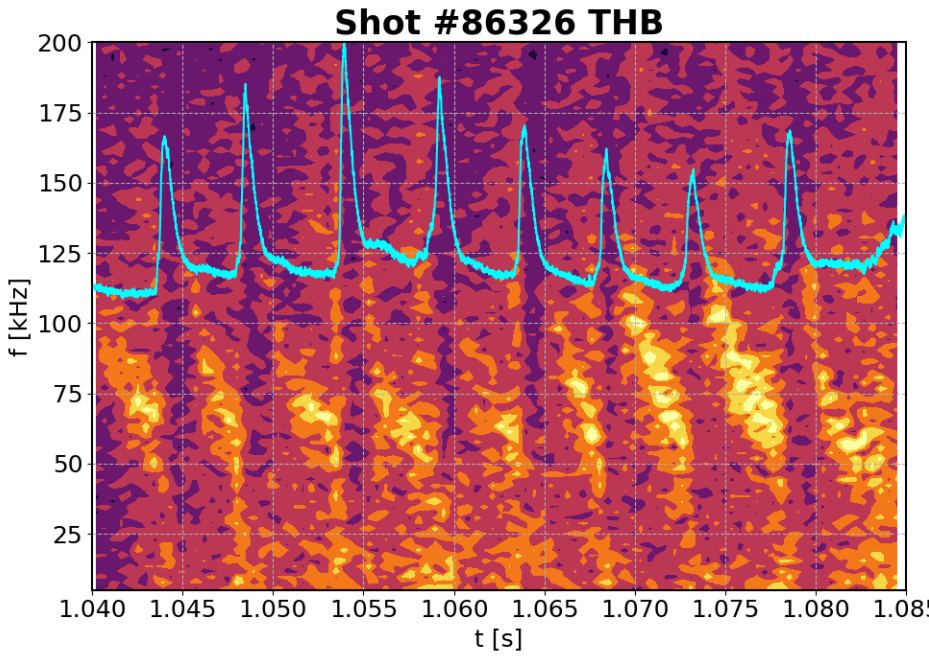
Frassinetti NF 2026

- **Local separatrix density gradient sets pedestal transport:** GENE fluxes and JET pedestal data scale with $\nabla n_e/n_e$ at the separatrix
- **n_e^{sep}/n_e^{ped} changes the limiting MHD mode:** from 0.18 to 0.93 the ITER Q=10 stability boundary moves to lower α and edge current

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 nu*
- Propagating (in the laboratory frame) in the e-diamagnetic direction with velocity ~ 5km/s and λ_z~ 80mm





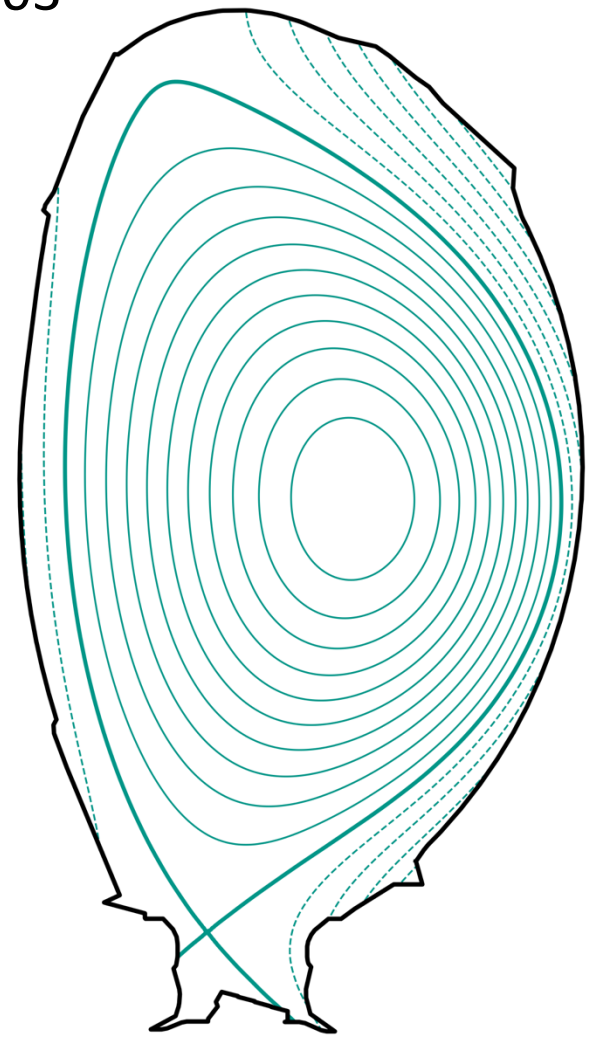
La Matina PPCF 2025 and ITPEA Sept 2026

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

#	Scientific Objectives
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 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

M. Faitsch, M. Dunne, O. Sauter, E.Viezzer M. Faitsch et al, NME 2025; M. Dunne et al , FEC 2025

ASDEX Upgrade: QCE and EDA

QCE accessible across all tested shapes; the QCM sits in the E_r well

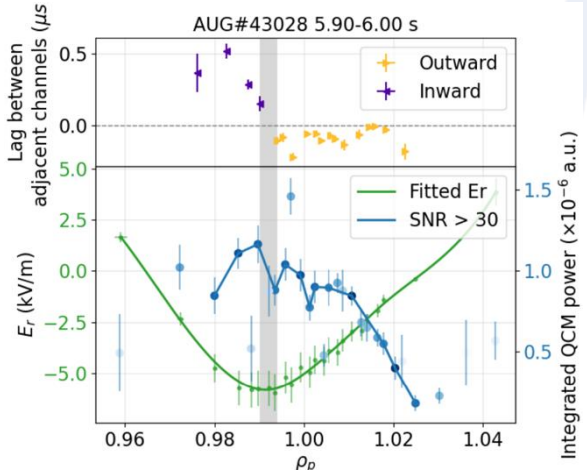
Shape scan

Triangularity, elongation and distance to double null varied separately

QCE reached in every combination (dR_XP 1 to 13 cm)

A second X-point changes the S_d prefactor

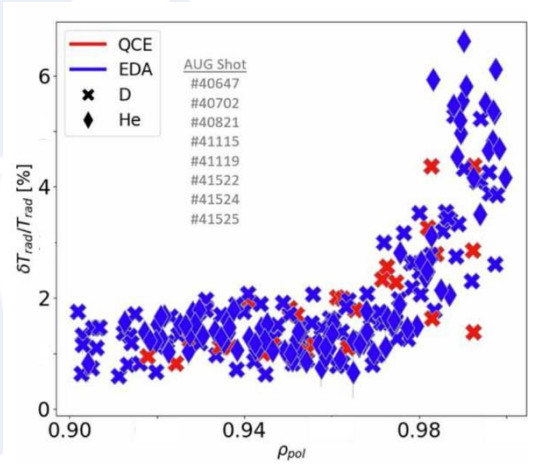
QCM seen by DBS



QCM sits in the E_r well (grey band)

Inward and outward peaks cross where filaments are likely born

QCM seen by CECE



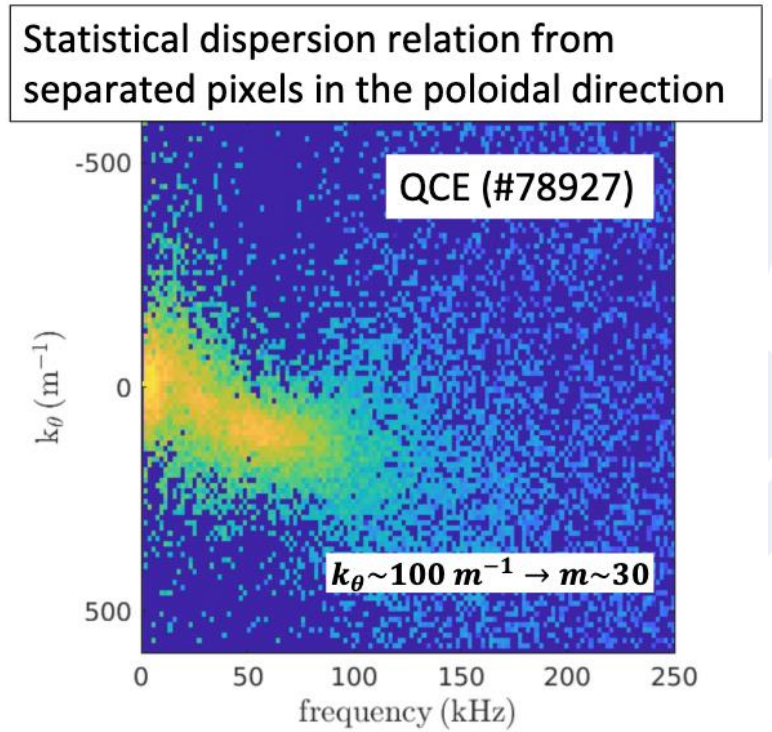
Edge δT/T of 4–6 %, L_c ≈ 1–2 cm

QCE and EDA nearly identical

A. Miller; X. Liu; J. Schellpfeffer et al 2026 PPCF 68 015004 · RT02 WPTE Review Meeting, 25 Sep 2026

QCE beyond AUG: shaping on MAST-U and the QCM on TCV

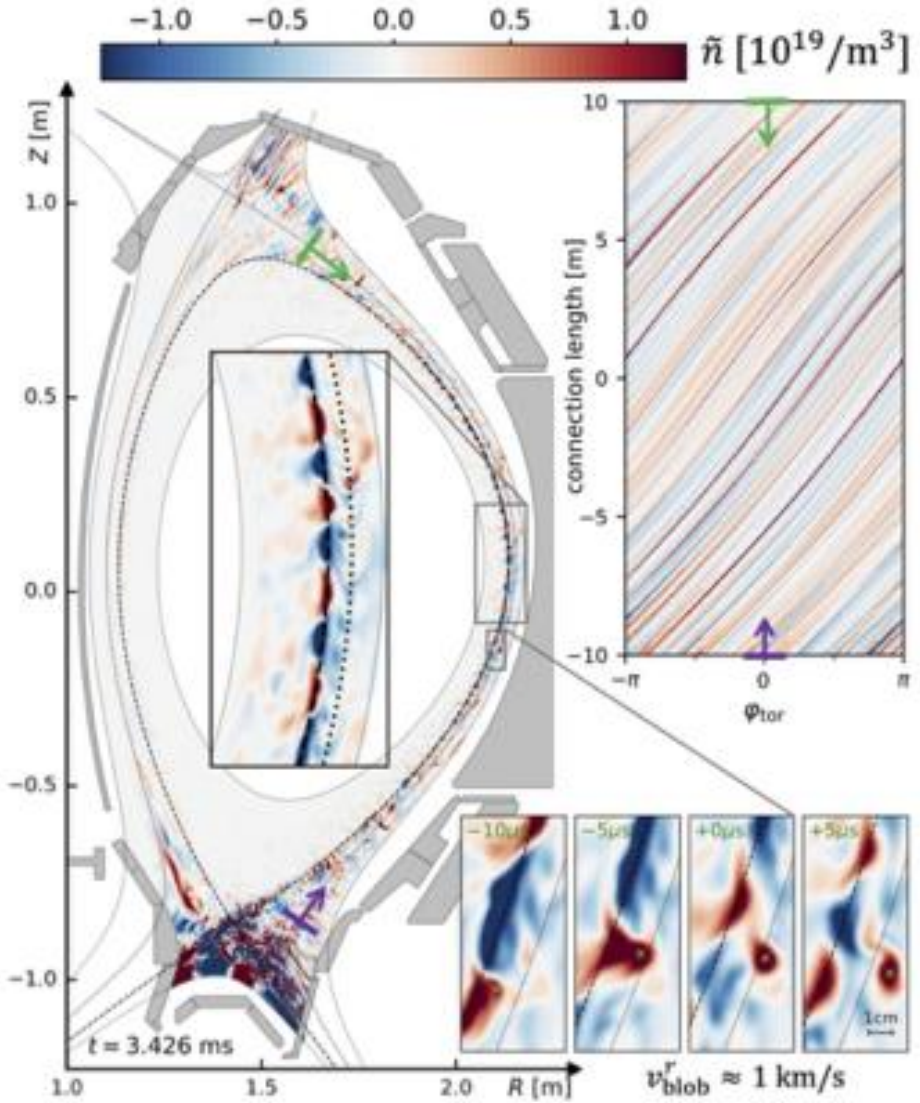
- Higher-order shaping: **squareness** effect on QCE under study (K. Imada and S. Saarelma, MAST-U)
- **Quasi-coherent mode (~50 kHz)** detected just inside the separatrix with several diagnostics (here GPI-mid, TCV)
- $k_\theta \approx 100\ m^{-1}$ ($m \approx 30$): **consistent with the AUG QCM**



GRILLIX simulation on QCE

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

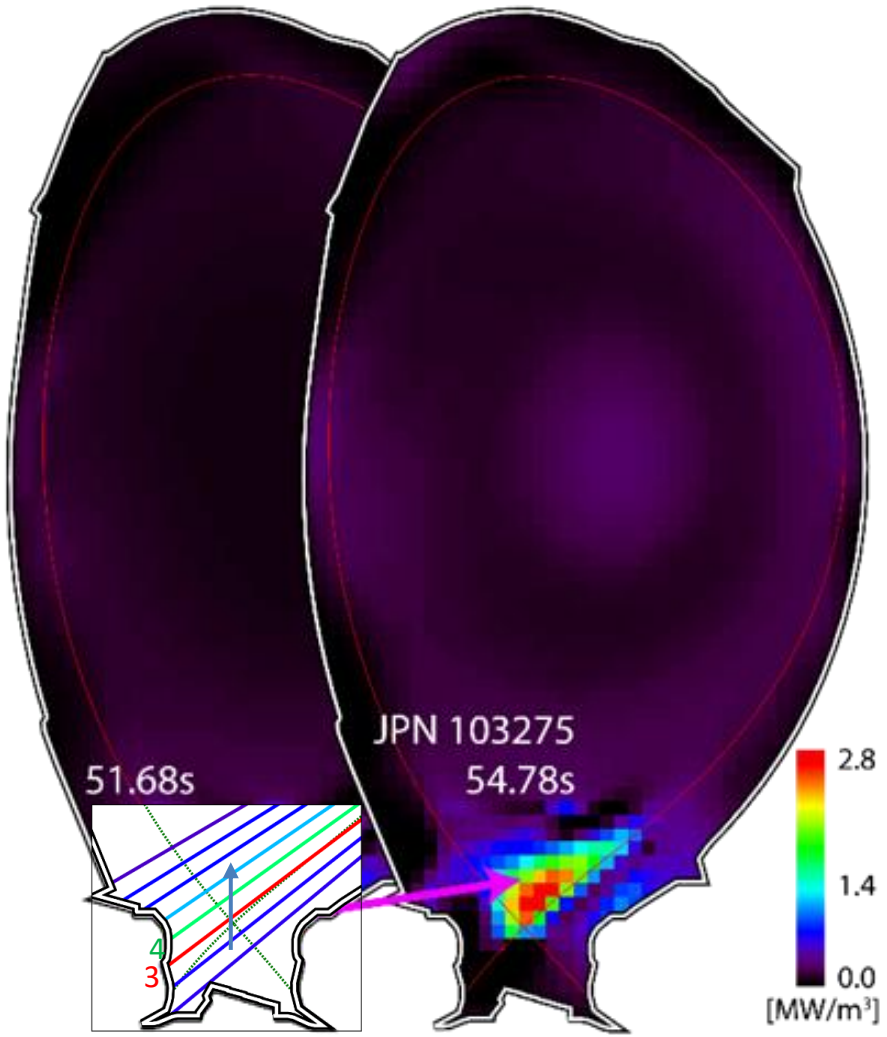
- QCM identified as kinetic ballooning mode confirming Experiment observation *(Kalis PPCF 2026)*
- SOL filaments as results of QCM and RXM coupling (needs high X-point collisionality)
- Extending the work to other devices (see H. Zhang talk). Is there a test to work the strength of the coupling in view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



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

#	Scientific Objectives
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)

X-Point Radiator (XPR): a power exhaust solution for DEMO 1/



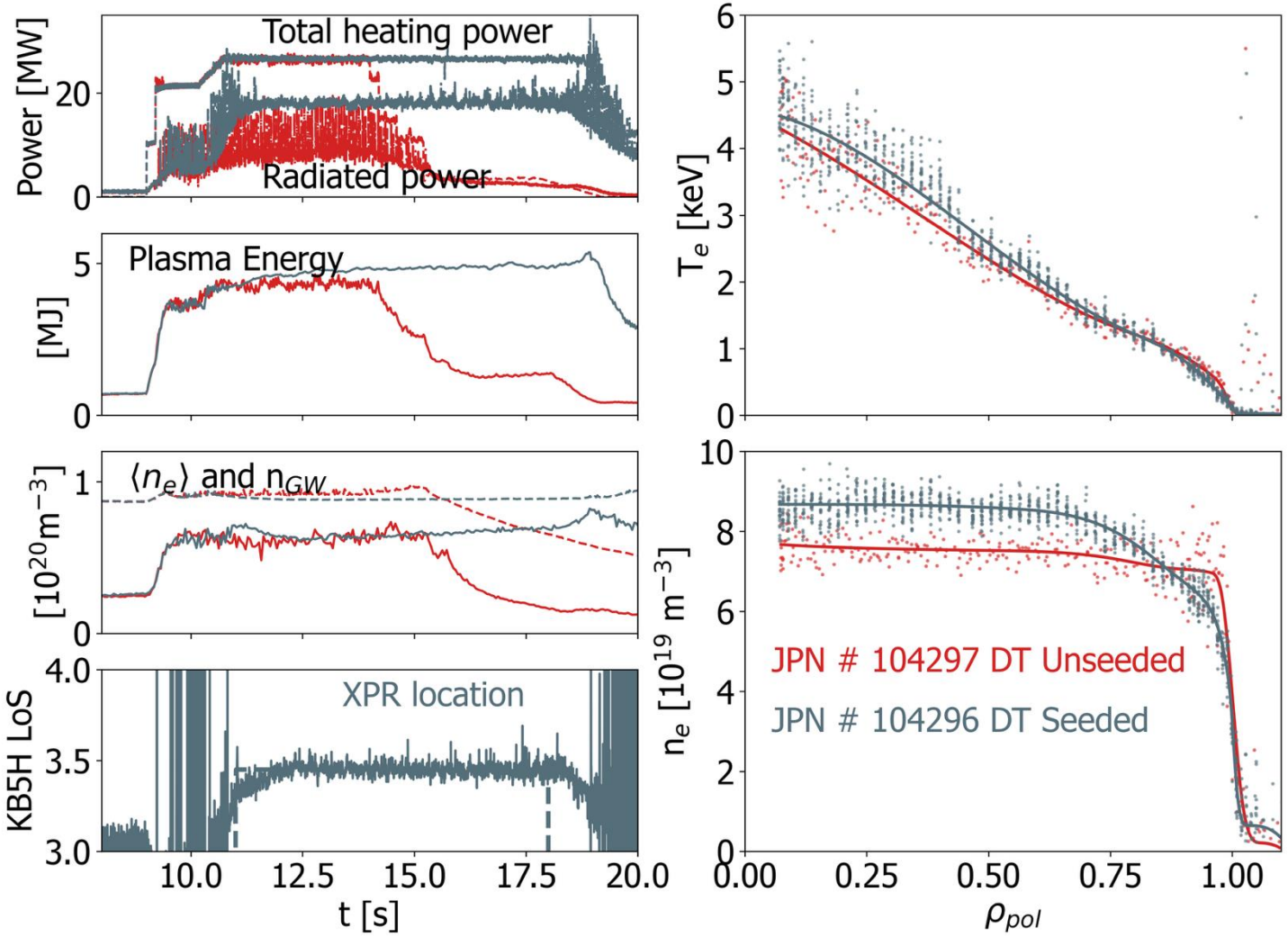
- **The X-Point Radiator Regime (XPR): viable stable solution for high radiation fraction (>90%), fully detached plasma with H-mode grade confinement***
- Solutions is robust, resilient to transients, controllable and can provide ELM suppression
- Characterized by a small region of high radiation, low 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

X-Point Radiator (XPR): a power exhaust solution for DEMO 2/

- 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

What sets the H-mode separatrix density?

Motivation

n_e,sep controls pedestal stability, detachment and ELM suppression

Next-step devices need it predicted from engineering parameters alone

Observation

171 H-modes from C-Mod, AUG and JET, analysed with one common method

Key results

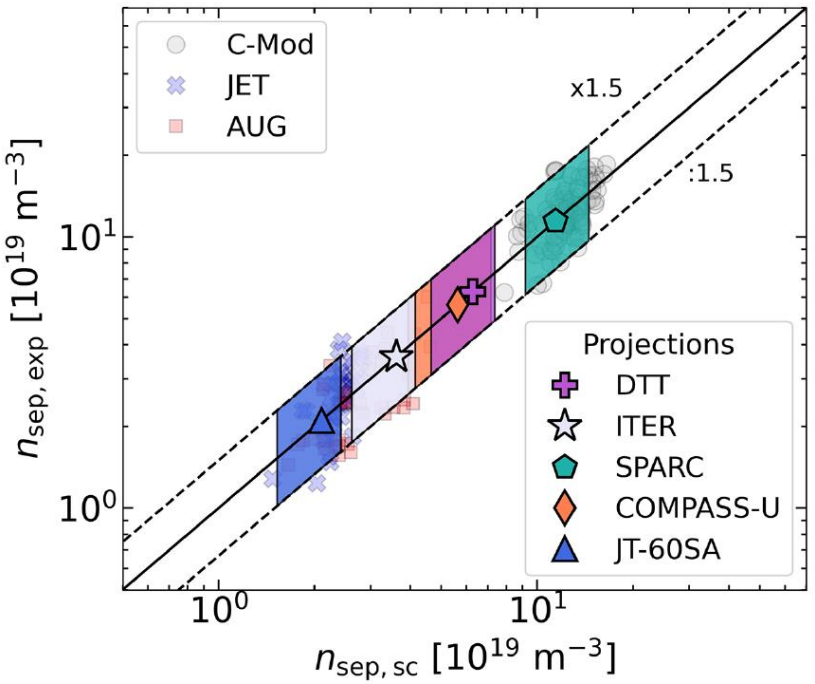
$$n_{e,\mathrm{sep}} = C_{2\mathrm{pt}} \cdot 0.93\, p_{0,\mathrm{div}}^{0.20} \left(\frac{P_{\mathrm{SOL}}}{R_{\mathrm{geo}}}\right)^{0.17} a_{\mathrm{geo}}^{-0.39} B_t^{-0.15} I_p^{-0.01}$$

Up with p0,div and P_SOL/R, down with B_t and size, flat in I_p

Regression and two-point model both predict n_e,sep within $\times$**1.5**

Projections for ITER, SPARC, DTT and JT-60SA agree with SOLPS

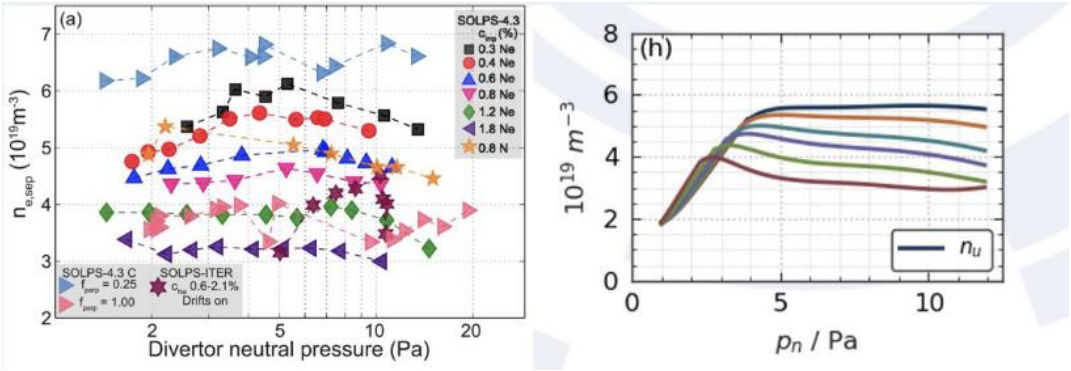
D. Silvagni et al 2026 Nucl. Fusion 66 126040



Measured vs scaled n_e,sep; bands show next-step projections (Fig. 6)

Separatrix density: new reduced model and AUG scan

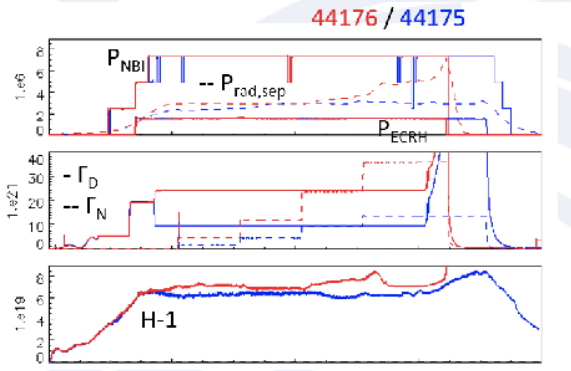
Separatrix density reduced model



- New model finds a **mechanism** for why ITER SOLPS simulations show **no pressure dependence** of separatrix density
- Contrary to **current machine observations**

S. Henderson, NF paper in draft

Experimental dependences of $n_{e,sep}$



- **Well-diagnosed AUG H-mode** scan of Γ_D and Γ_N/Γ_D
- Results will **develop and challenge reduced models** and feed SOLPS runs
- Complementary results also obtained on **MAST-U**

D. Silvagni, A. Stagni

Conclusions

- Extrapolation capabilities to next step devices strongly rely on appropriate Core-Edge-SOL integrated modelling to guide definition of operational points
- SOL conditions observed to guide and determine transport in the confined region. WPTE has several scenario waiting for inputs for extending interpretative and extrapolating modelling on main scenarios

Call cycle for 2027

