# WPTE Experimental program and modelling needs in view of TSVV1 deliverables

**N. Vianello**

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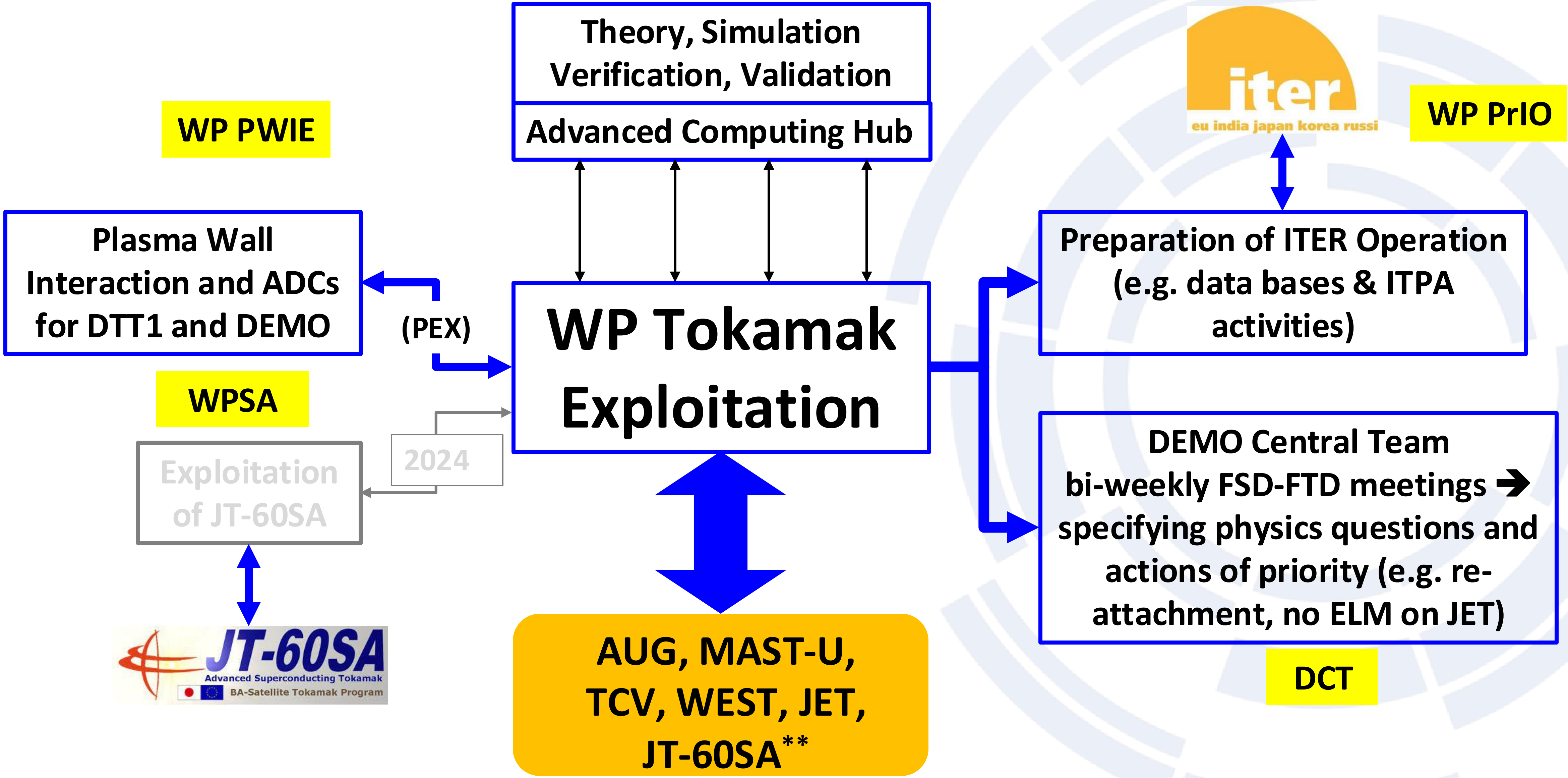
# WP TE in PSD* with overarching priorities: ITER & DEMO & PEX




* 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 2025 program focus on request for ITER – re-baseling and experiments in support of future JT-60SA scientific exploitation

# The WPTE Grant Deliverables related to TSVV1

| 2024 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. 2024 |
| TE.D.13 | Recommendation on the seeding impurity mix in view of a future reactor. | Dec. 2024 |

| Achieved deliverables | | |
|---|---|---|
| TE.D.05 | The role of turbulent and MHD driven transport in the vicinity of the separatrix for the stability of the pedestal quantified and the implications for predictions for ITER and DEMO reported. | Dec. 2023 |
| TE.D.10 | The role of electron and ion heat channels and plasma rotation on the access to H-mode for hydrogen, helium and mixed plasmas in view of the ITER non-active phase quantified. | Dec. 2023 |

- Although achieved, still interpretative modelling activity on-going

# WPTE Research Topic Structure

TSVV1: 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**

**RT06: preparation of efficient PFC operation**

**RT09: Physics of energetic particles**

**RT07: Alternative divertor configuration**

**PEX**

**Mission 1**

**Mission 2**

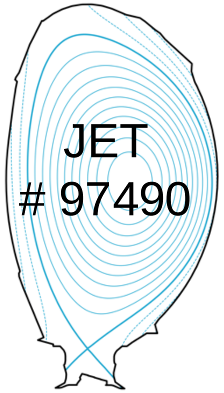
Mission 1 – Plasma Regimes of Operation
Mission 2 – Heat Exhaust Systems

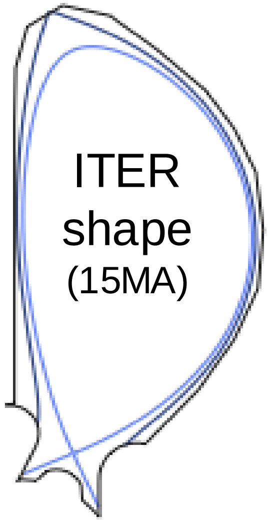
# RT-01 Core-Edge-SOL integrated H-mode scenario compatible with exhaust constraints in support of ITER

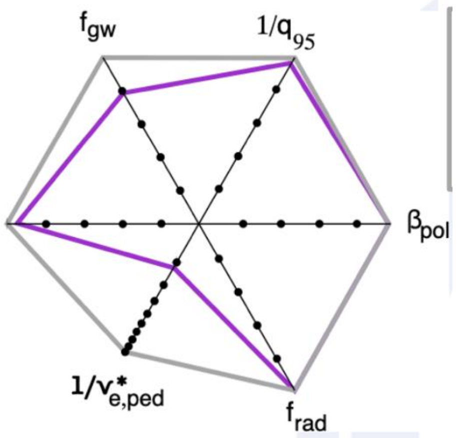
| # | Scientific Objectives |
|---|---|
| D1 | Develop and understand stationary H-mode scenario at low collisionality and with dominant electron heating |
| D2 | Provide physics-based cross-field transport coefficients to TSVVs (1, 3, 4 and 11) for turbulence modelling |
| D3 | Determine the impact 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 impurity screening for high temperature pedestals |

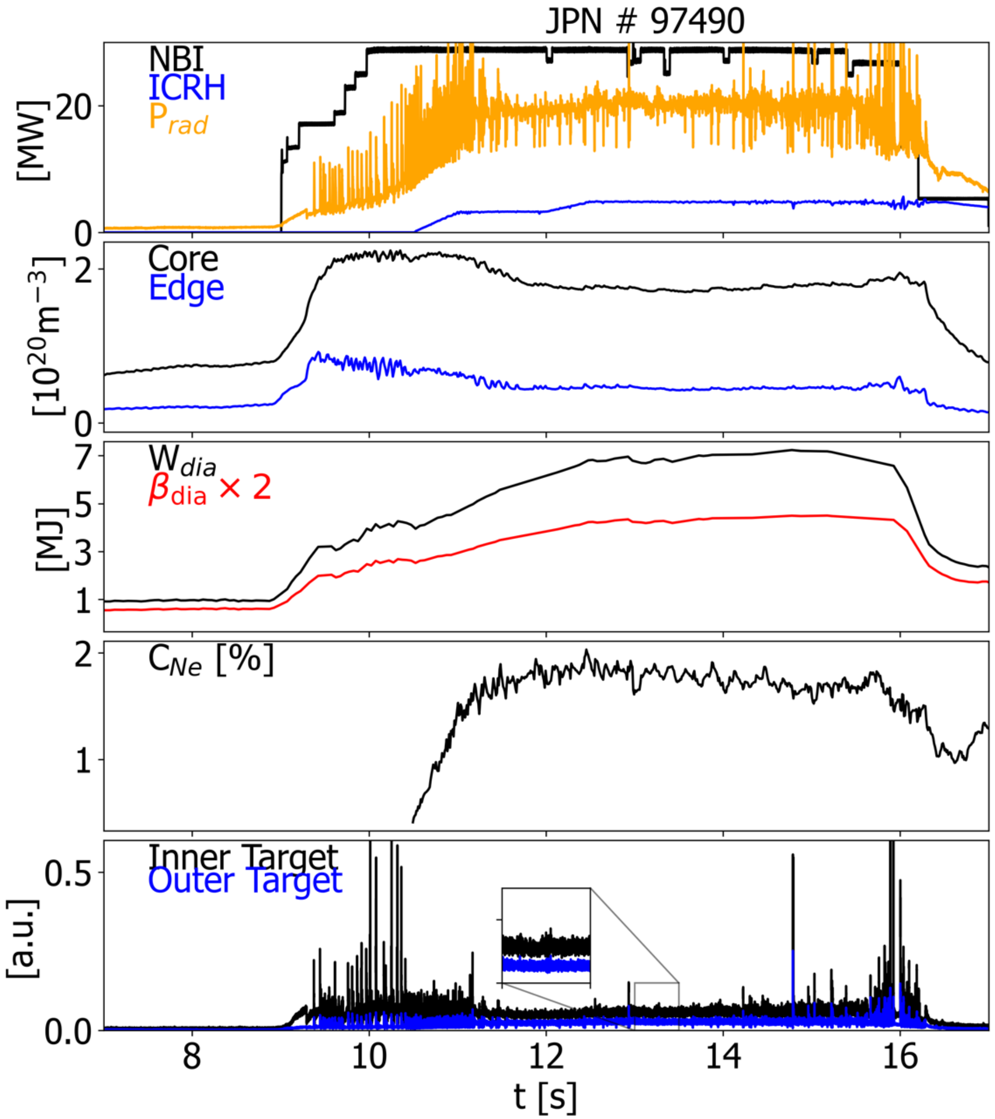
# High performance Plasmas compatible with Exhaust Solution 1/

- 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 $H_{98} \sim 1$, $\beta_N \sim 2.2$, $C_{Ne} \sim 1.7\%$

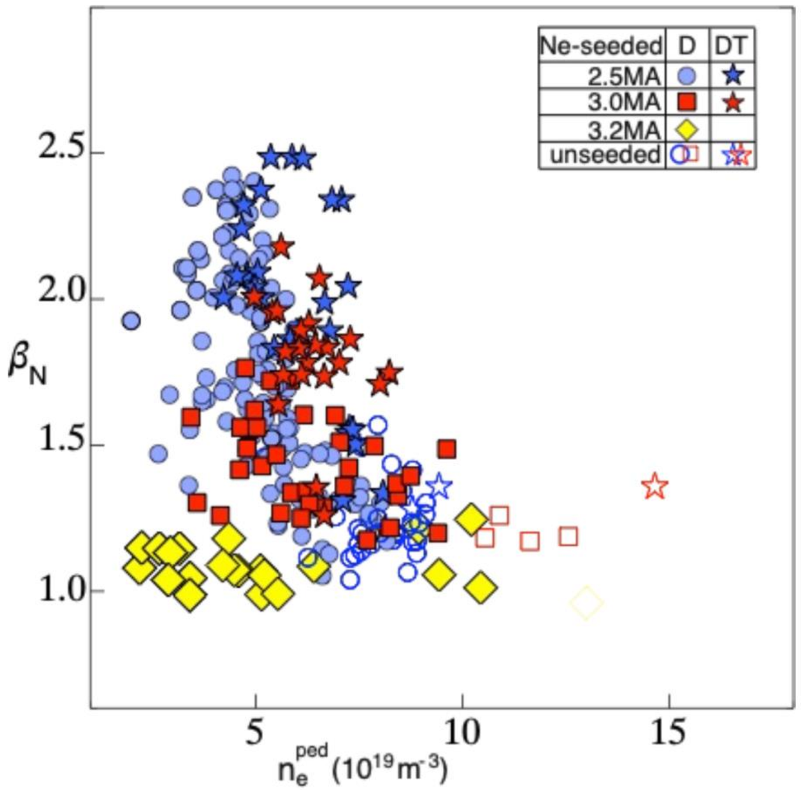


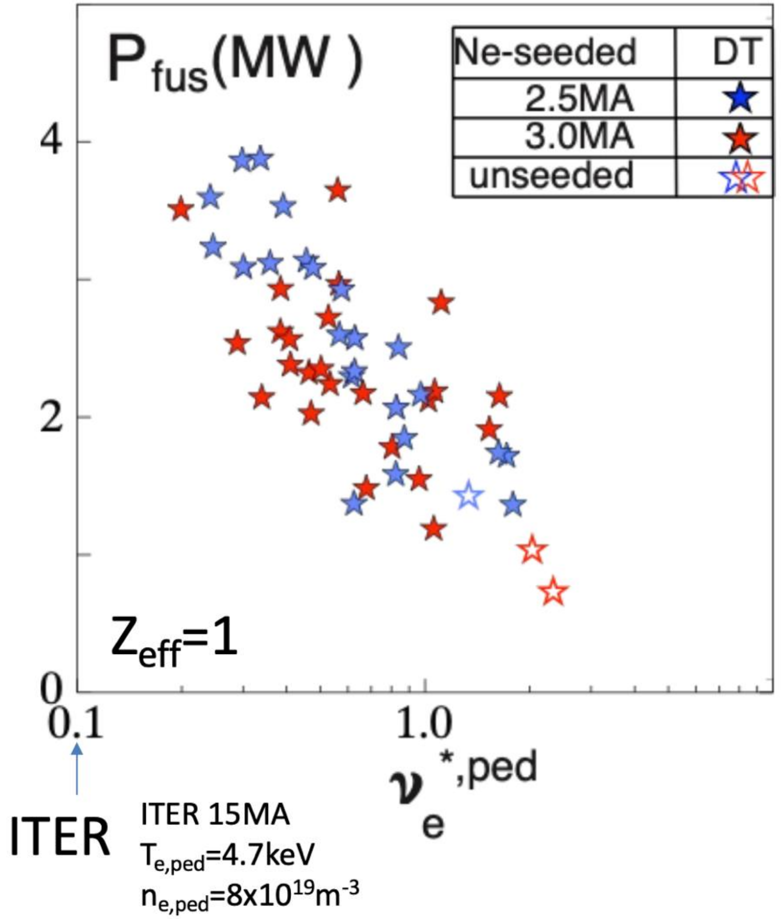



# High performance Plasmas compatible with Exhaust Solution 2/




- Scenario extended to higher plasma current and power and explored in DT
  - To achieve lower pedestal $\nu^*$
  - To explore more opaque SOL
  - To explore detachment operational at narrower $\lambda_q$
  - To further extend and test the differences among radiating species

# High performance Plasmas compatible with Exhaust Solution 5/

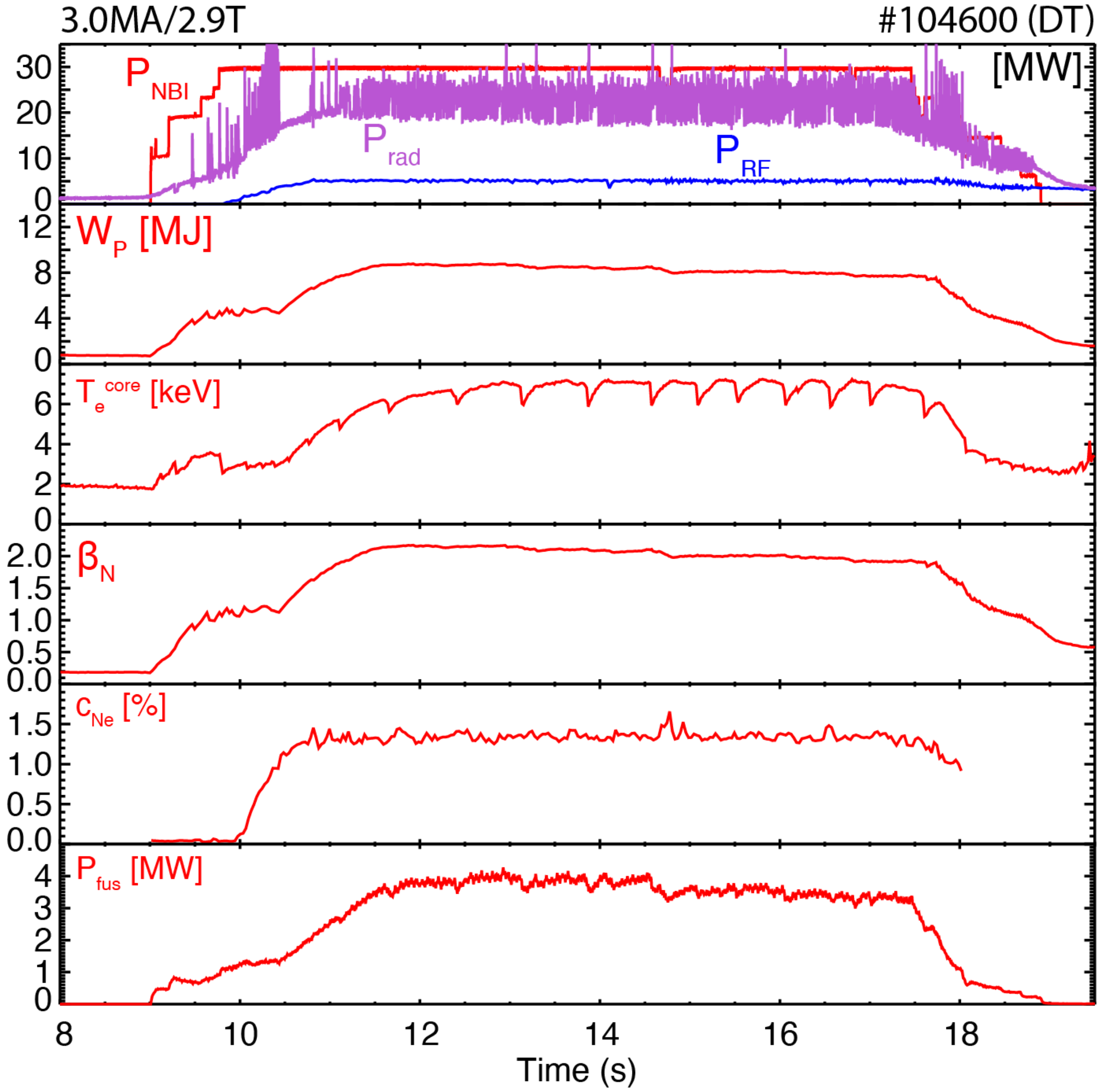



Fig. courtesy C. Giroud

- Achieved very long pulse at high confinement and high recycling divertor conditions (7.4s NBI at 30MW), stationary ($H_{98}$ ~ 0.9 (fast particle corrected))
- Best performance DT-seeded plasmas with high-recycling divertor
- Extensive set of:
  - D and DT plasmas
  - seeded and unseeded

  for comparison and for code validation

C. Giroud, D. King, L. Frassinetti, S. Wiesen

➢ C. Giroud et al, PSI 2024

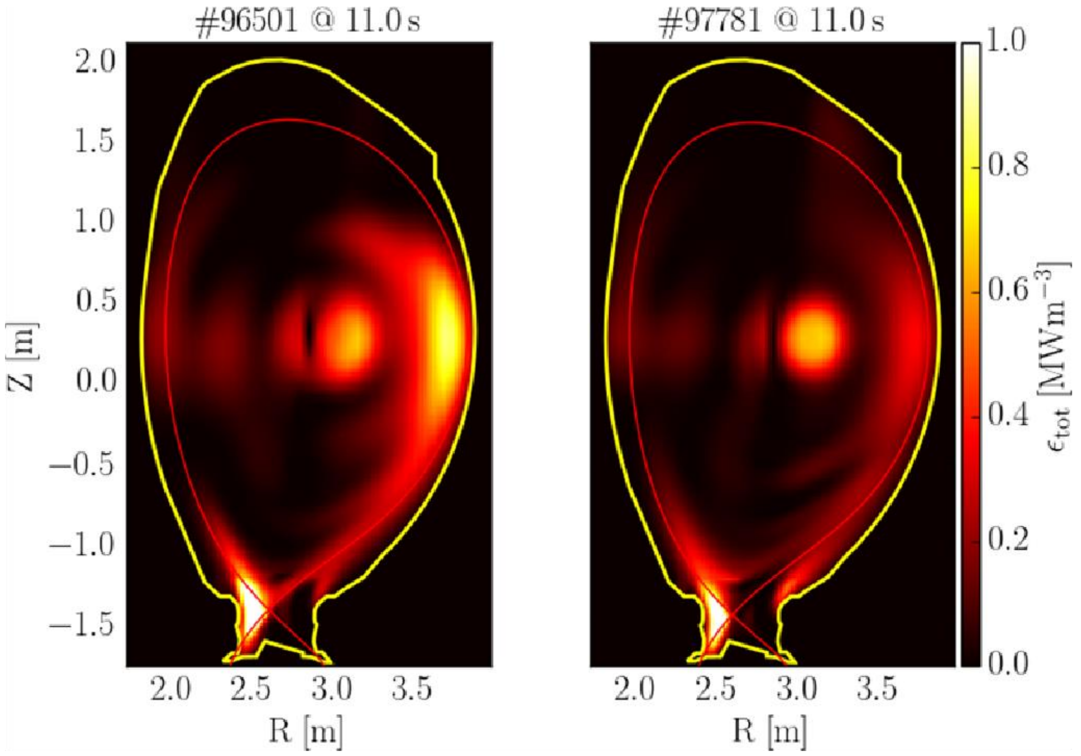
# High performance Plasmas compatible with Exhaust Solution 3/

- 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 in the plasma core 1/

low ∇Ti → ELM flushing

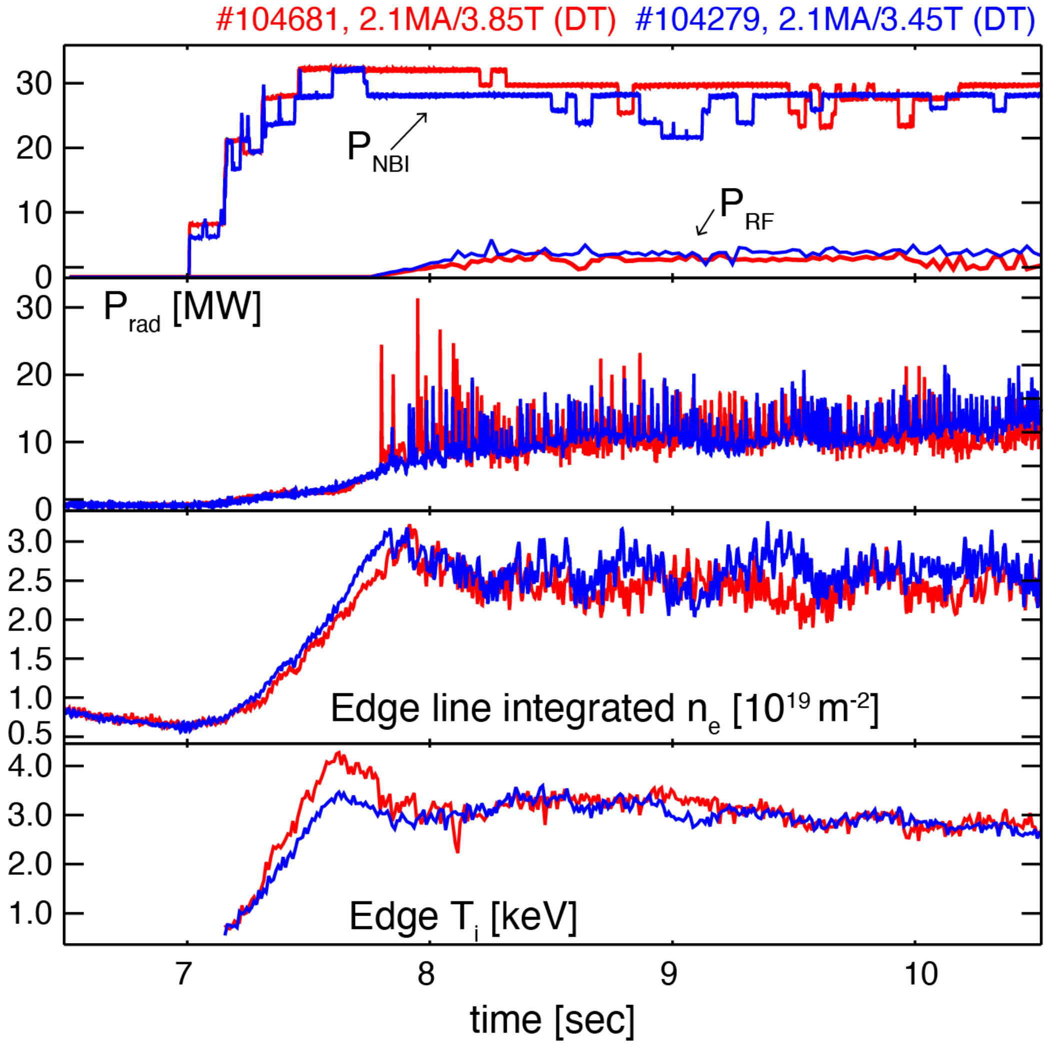
high ∇Ti → peripheral screening




*A. Field et al, Nucl. Fusion* **63** *016028 (2023)*

- W screening with high ion temperature gradient confirmed in hybrid scenarios in DD operation (A. Field, NF 2023)
- DTE2 results  confirmed deuterium observation, although data quality hampered by non-optimal diagnostic compatiblity with hybrid scenarios (J. Hobirk NF 2023)

# Operation with low W concentration in the plasma core 1/



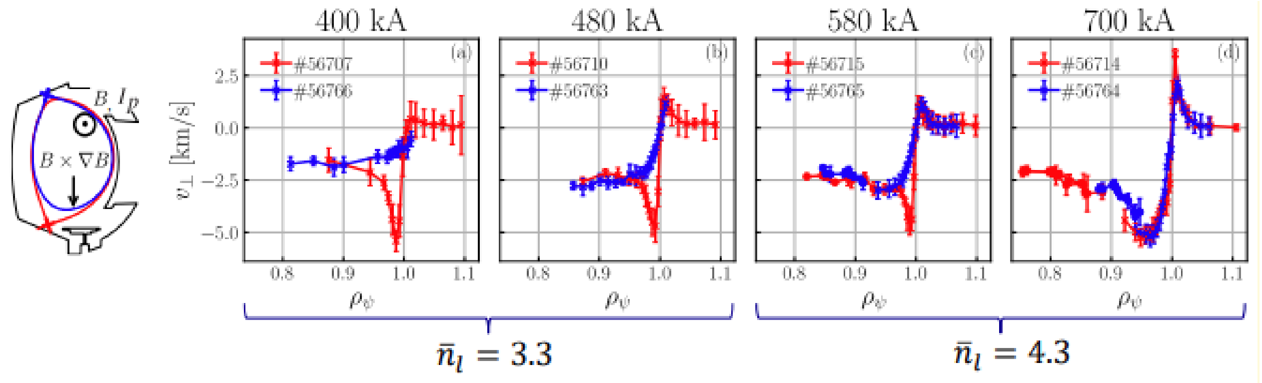

- W screening with high ion temperature gradient confirmed in hybrid scenarios in DD operation (A. Field, NF 2023)
- DTE2 results confirmed deuterium observation, although data quality hampered by non-optimal diagnostic compatiblity with hybrid scenarios (J. Hobirk NF 2023)
- DTE3 improved diagnostic coverage and quality and enlarged the parameter space to investigate W screening

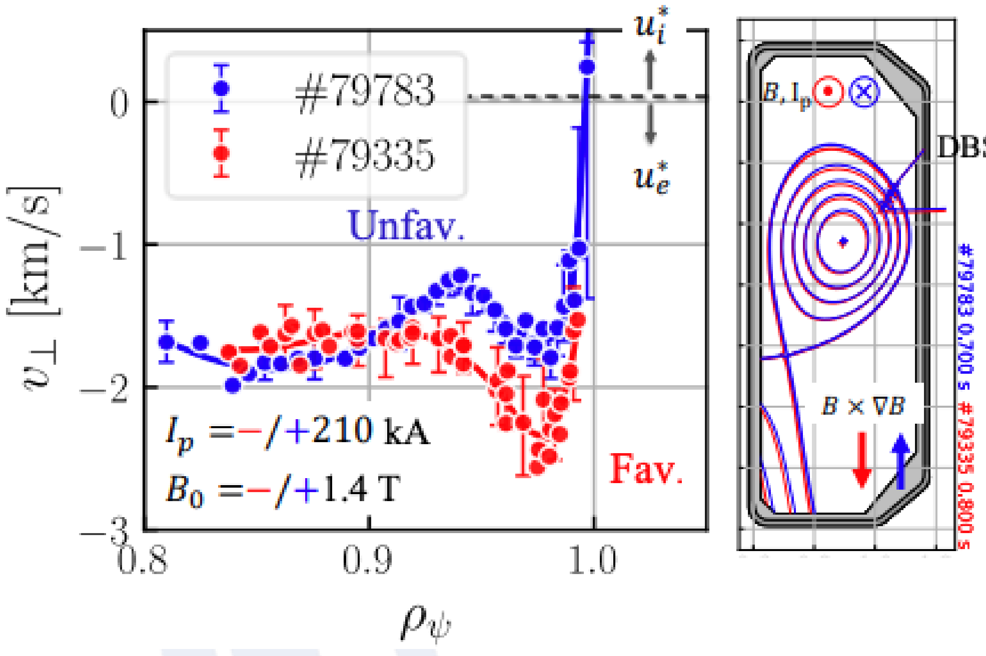
# Operation with low W concentration in the plasma core 2/

- NEO calculations show that there is certainly N-C $T_i$ gradient impurity screening across the mantle region just inside the pedestal top, enhanced by higher edge $T_i$ and rotation $\Omega_{\phi}$ in such pulses
- However, calculations using FACIT suggests that NC transport alone cannot account for the observed impurity screening across the pedestal gradient region
- Open question – Does turbulent particle transport play a significant role in screening out the W across the pedestal? GK modelling of turbulent impurity transport. Strong interest from XGC community (J. Dominiski)

# 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

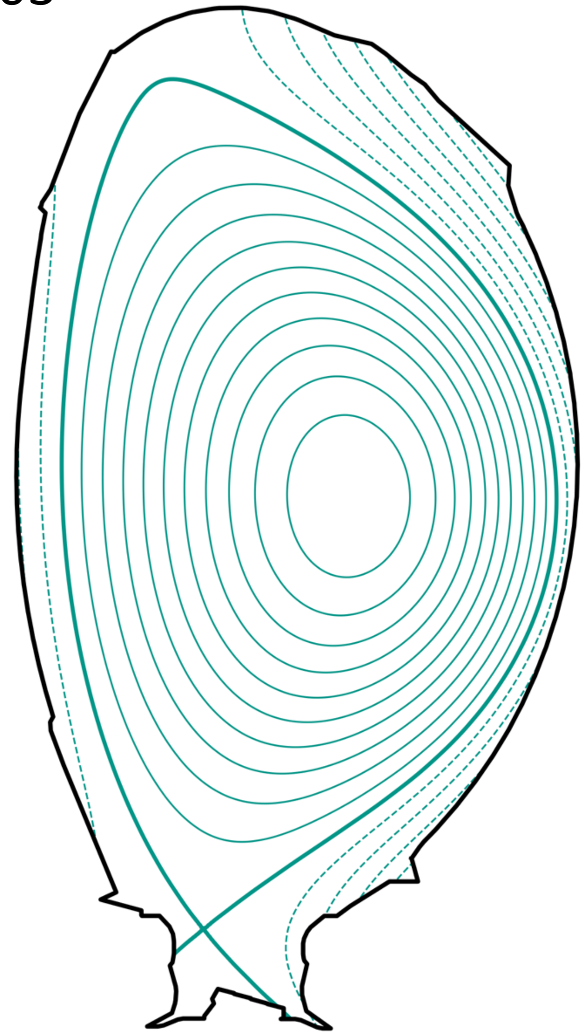
Courtesy from S. Rienäcker, L. Vermare, P. Hennequin

# 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 | Determine access window and physics understanding for RMP ELM suppression and its compatibility with ITER FPO scenarios |
| D6 | Quantify the overall performance of negative triangularity plasmas in view of DEMO |

# 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

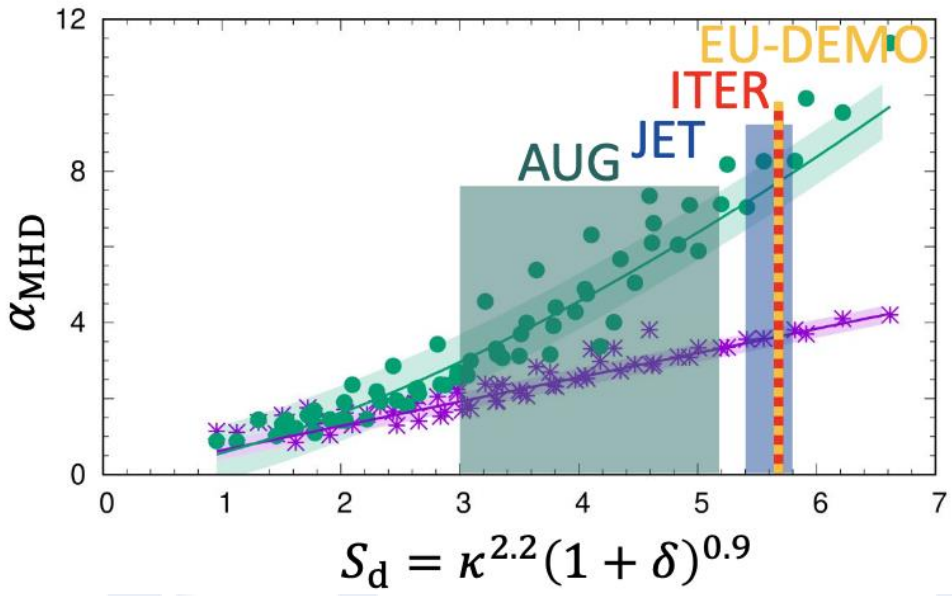
M. Faitsch, M. Dunne, O. Sauter, E.Viezzer

➢ M. Faitsch et al, PSI 2024; M. Dunne et al , EPS 2024

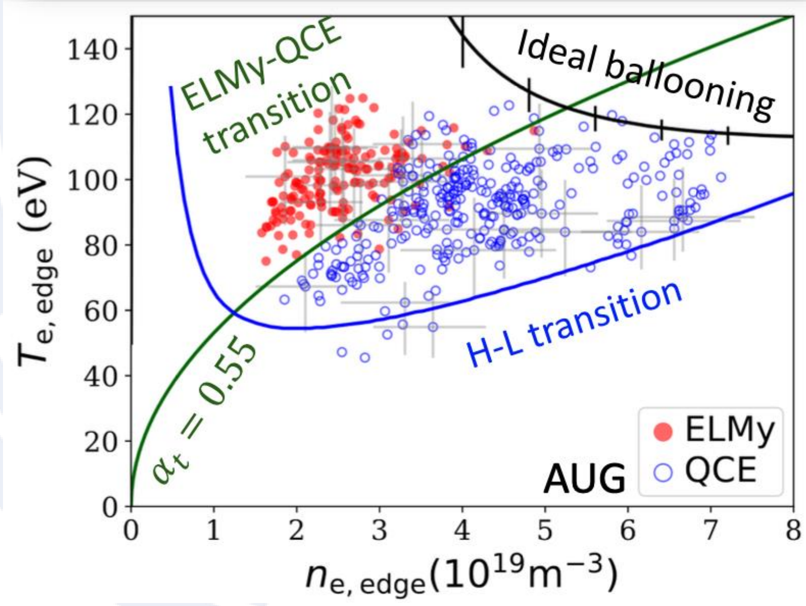
# RT02-Small ELM scenario for DEMO

The quasi-continuous exhaust (QCE) regime ingredients:

- ✓ at high plasma shaping
  - Elongation, triangularity and closeness to double null
- ✓ with high density




- ✓ According to shaping a stability region exhists within global peeling mode (located at region of maximum gradient) and infinite local balloning (close to the separatrix) → QCE operational space opens with $S_d > 3$
- ✓ Fueling dependence might have different explanation
  - Ideal MHD (local pressure gradient needs to be above a critical value) (*Harrer, Radovanovic*)
  - Resistive MHD Turbulence. SepOS theory (*Eich & Manz*)

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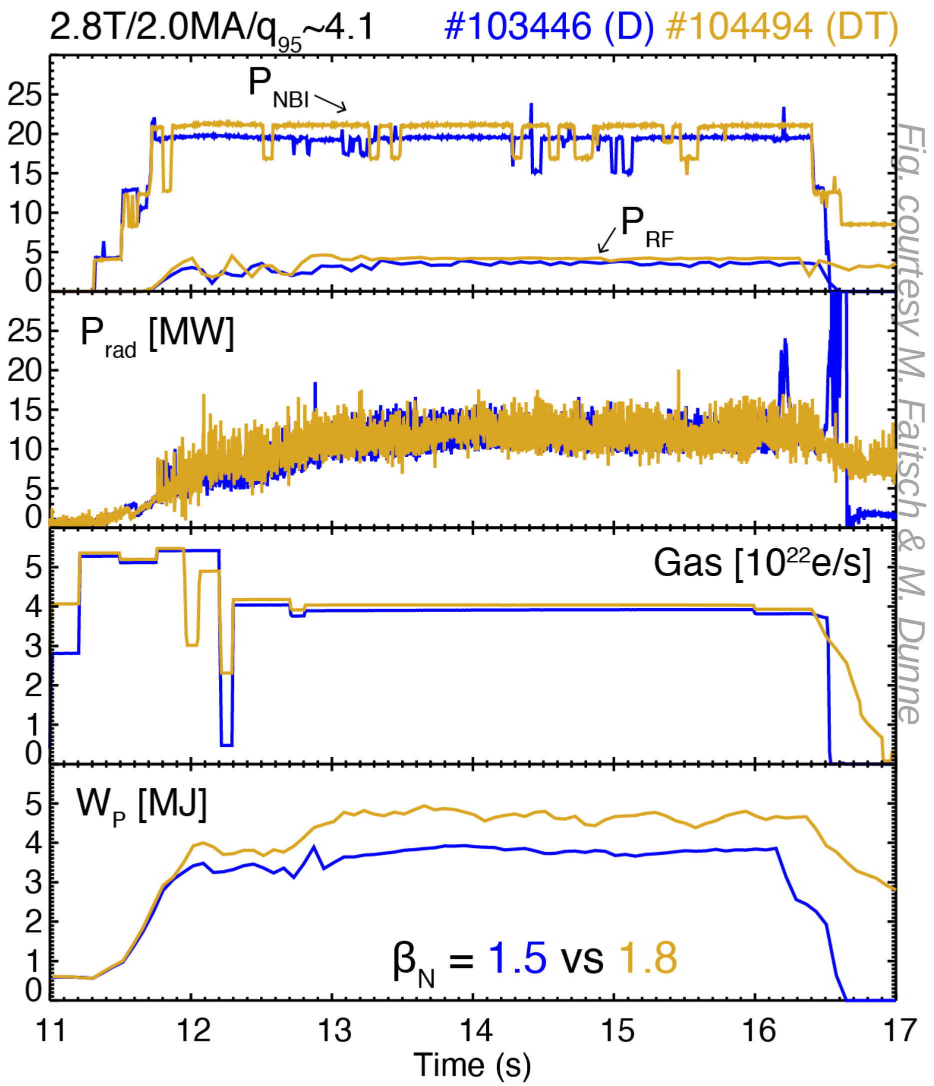
# RT02-Small ELM scenario for DEMO




a. Succesfully demonstrated on JET up to 2.25 MA in D

b. Succesfully ported in D-T featuring an higher confinement due to know isotope effects

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

➢ M. Faitsch et al, PSI 2024; M. Dunne et al , EPS 2024

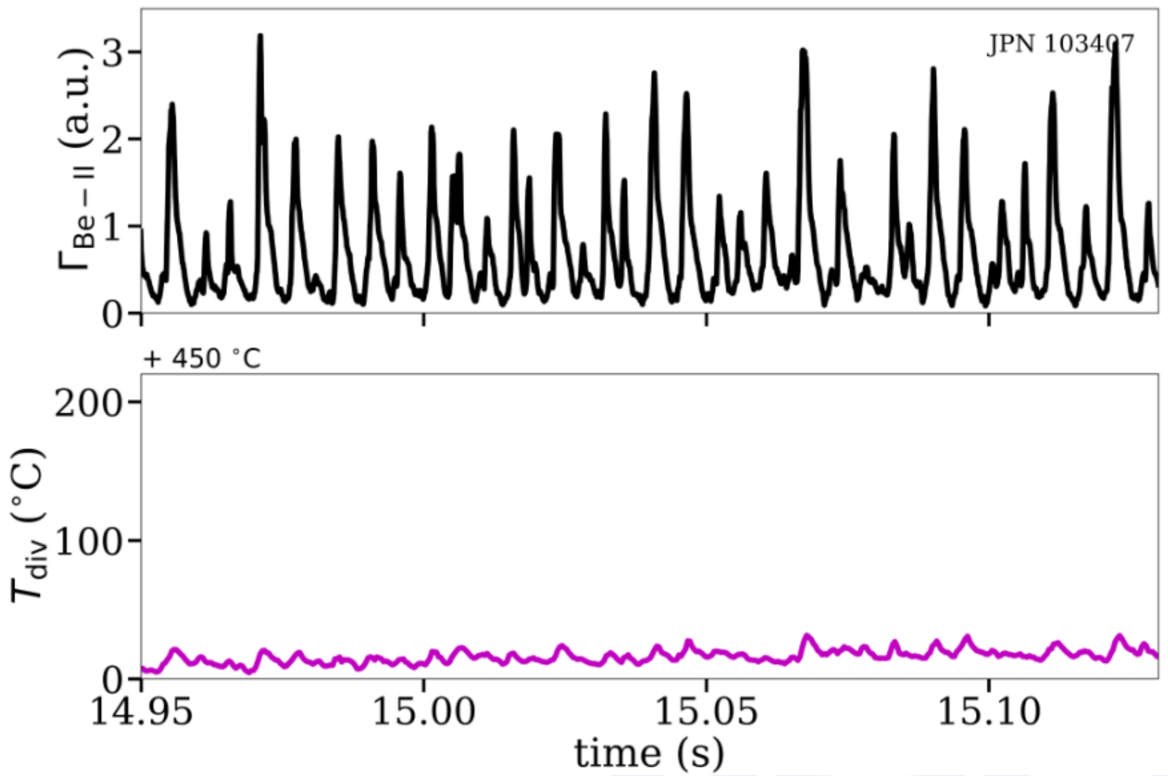
# RT02-The influence of neon seeding

- ELMs are suppressed by enough fuelling or Ne seeding

Small amount of seeding

- $\Gamma_D \approx 3.6\ 10^{22}$ e/s
- $\Gamma_{Ne} \approx 0.1\ 10^{22}$ e/s

- No primary mechanism identified so far!
- Ne seeding has multiple effects:
  - Increased $P$rad: 6 MW → 11 MW [$P$heat ≈ 21MW]
  - Decreased $\Delta T$ div: 130 T $°C/s$ → 40 T $°C/s$
  - Increased $Z$eff,edge, recycling, … ?




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

➢ M. Faitsch et al, PSI 2024; M. Dunne et al , EPS 2024

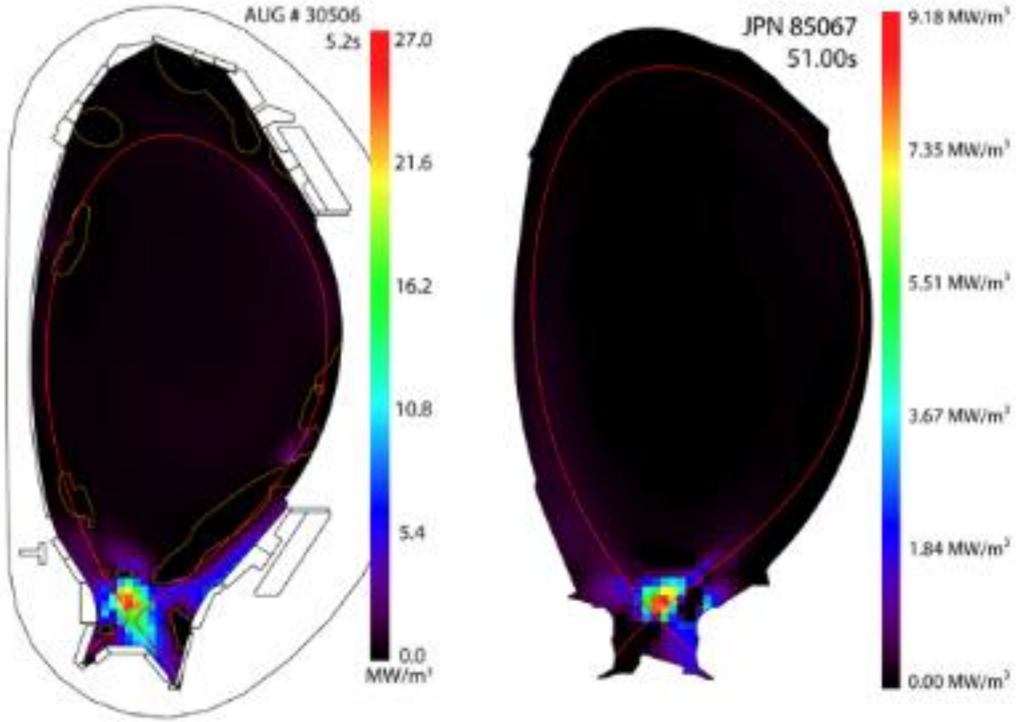
# Modelling needs

- Edge modelling, including turbulence effects (GRILLIX/SOLEDGE3X)
- Plasma background for evaluation of first wall erosion
- Pedestal GK transport (in view of what done for AUG) including isotope effects

# 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 Control schemes for radiative detachment, transferable to DEMO/ITER |
| D3 | Quantify edge-SOL particle and heat transport in detached conditions |
| D4 | Characterize the interaction between plasma transport, neutral and molecules and the impact of baffling |
| 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) |

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



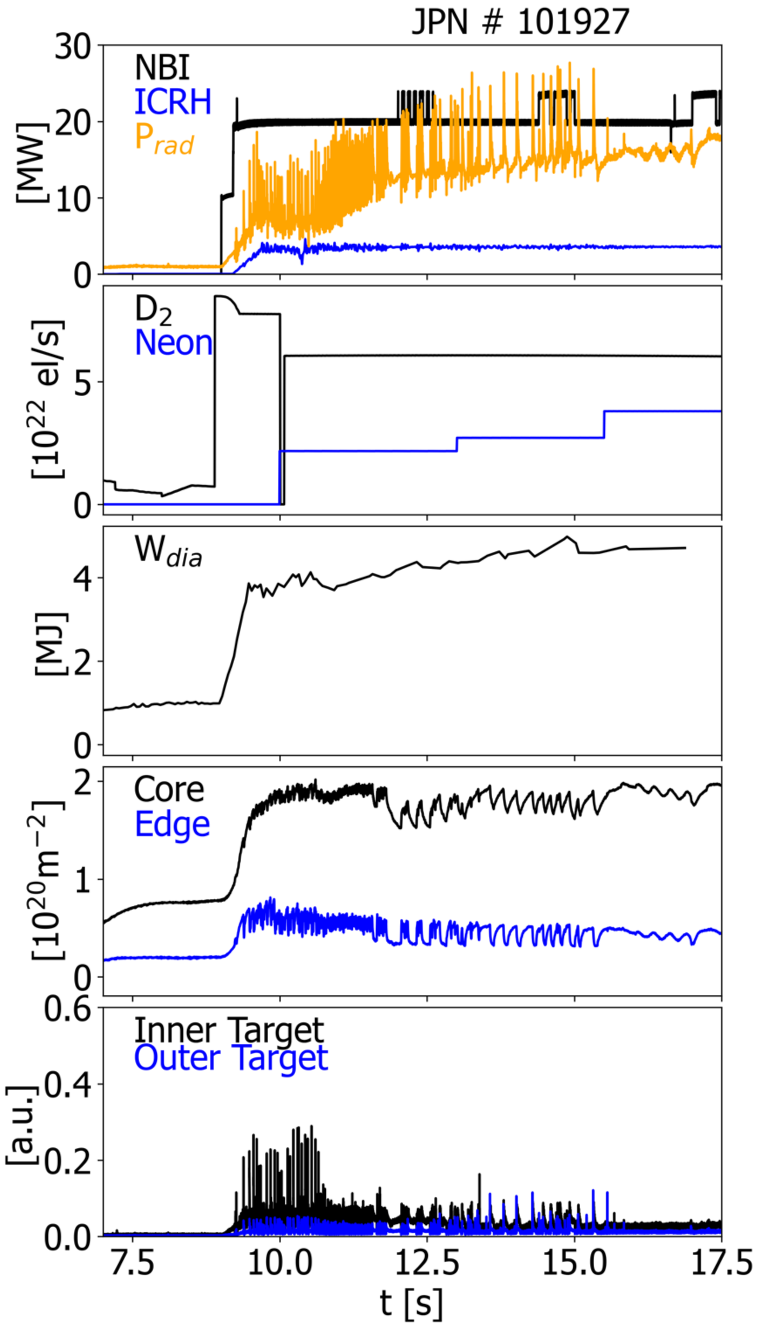
(a) AUG (b) JET

- DEMO or any next step device will need to operate in full detachment with up to 90% of the power dissipated before crossing separatrix
- Detachment should be **robust and resilient to transients** as power cuts/variations as well as (eventually) ELM burnthrough
- **A viable solution found in the so-called X-Point Radiator Regime (XPR)**
- Characterized by a small region of high radiation, low temperature and high density inside the confined region at/above the X-point
- The scenario is **stable**, offer **access to full detachment** and **can provide ELM suppression**

# The Differences between extrinsic impurities

Low-**δ** 2.5 MA/2.6T plasma
With Ne seeding as single extrinsic impurity only
different phases observed:

- Strong dithering (H/L/M-mode) independently on the power (link to Ne transport)
- Last phase without dithering, ELM-free & detached




M. Bernert, D. Brida, H. Reimerdes, N. Fedorczak

➢ M. Bernert et al, PSI 2024

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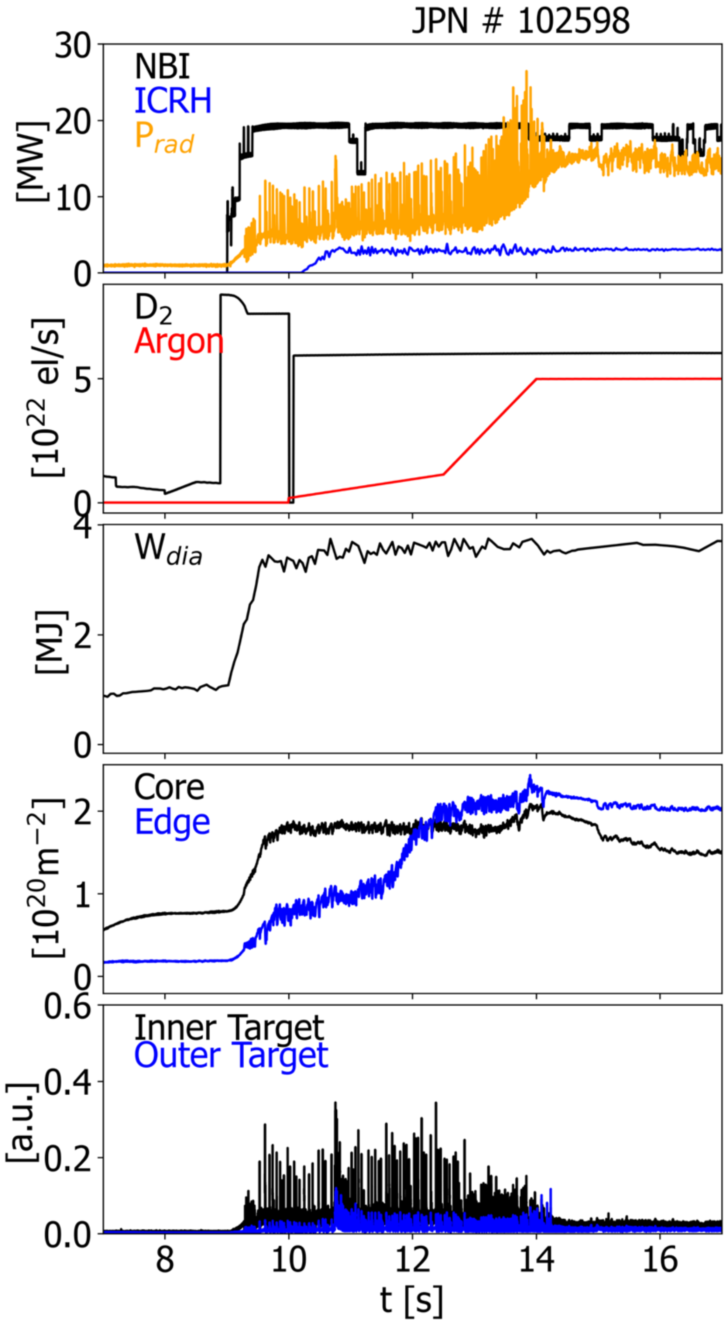
Low-**δ** 2.5 MA/2.6T plasma
With Ne seeding as single extrinsic impurity only
different phases observed:

- Strong dithering (H/L/M-mode) independently on the power (link to Ne transport)
- Last phase without dithering, ELM-free & detached

With Ar seeding as single extrinsic impurity only
different phases observed:

- Quite evident and robust XPR
- ELMs disappear
- Strong fluctuations with frequent HL dithering
- Suggestion of different SOL transport

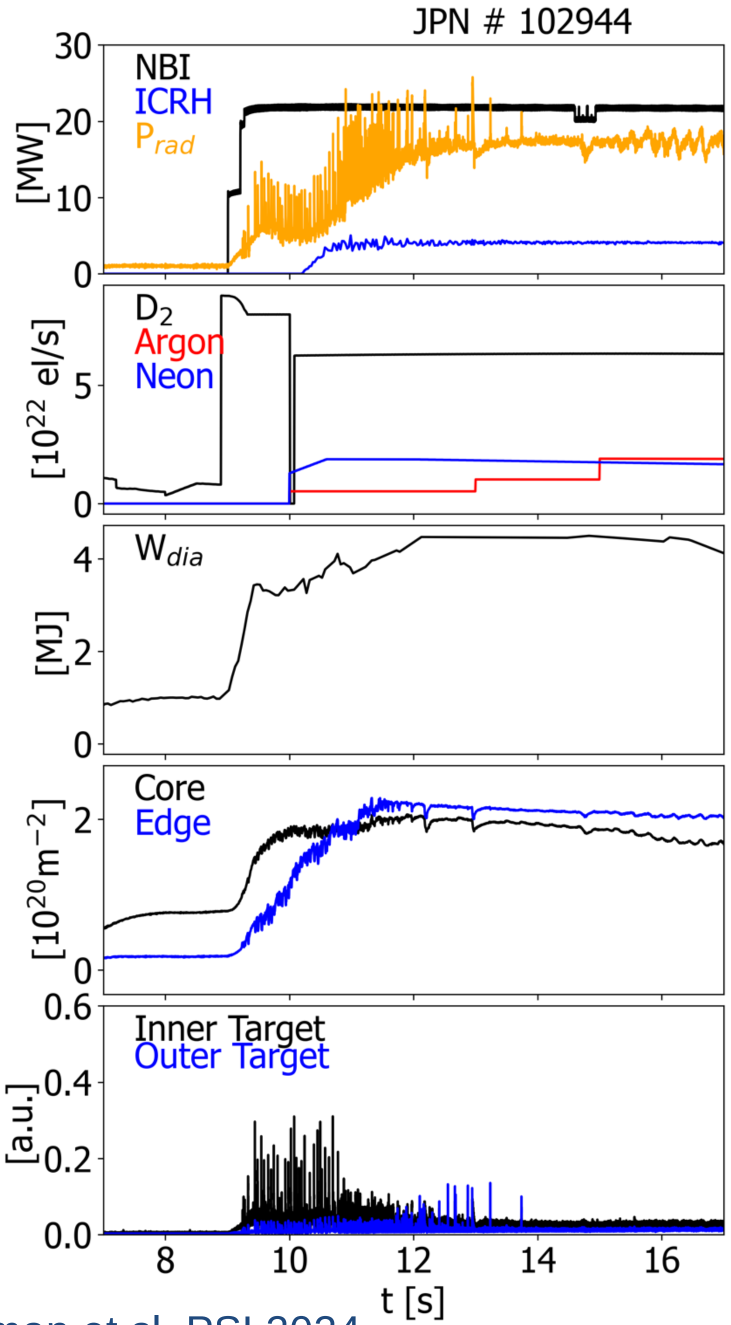



M. Bernert, D. Brida, H. Reimerdes, N. Fedorczak

➢ M. Bernert et al, PSI 2024

# The benefit of Mixed impurities

- The mixed impurity  exhibit stronger stability (Zeff ~ 3.1 → $C_{Ar}$ ~ 0.6% and $C_{Ne}$ ~ 0.5%)
- The Neon dominated plasma still exhibit L-H-L dithering but **Ar dominated plasmas stable with clear access to no-ELM and full detachment**
- Implementation of Real time control with diagnostic and actuators compliant with ITER constraints




M. Bernert, D. Brida, H. Reimerdes, N. Fedorczak

- M. Bernert et al, PSI 2024
- T. Bosman et al, PSI 2024

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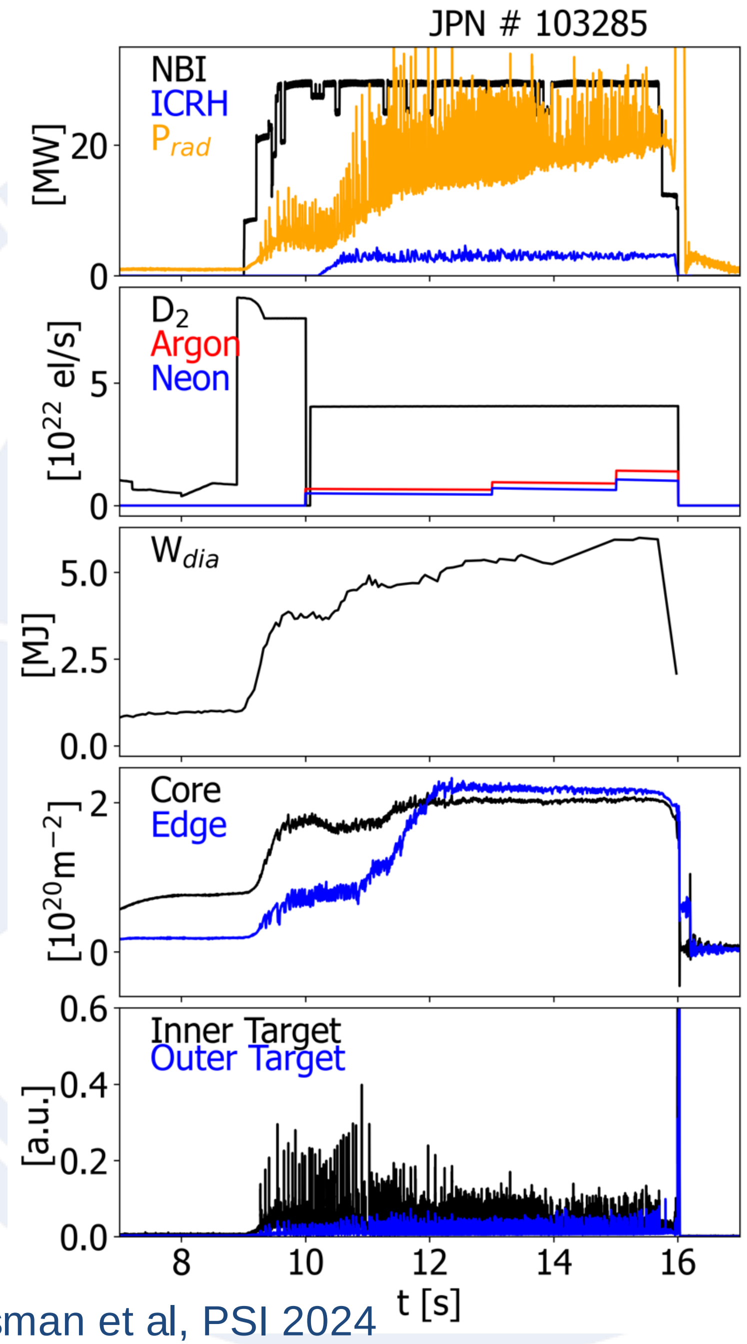
- The Neon dominated plasma still exhibit L-H-L dithering but **Ar dominated plasmas stable with clear access to no-ELM and full detachment**
- Implementation of Real time control with diagnostic and actuators compliant with ITER constraints
- **Work at even higher power 33MW with strong ELM mitigation whenever XPR position reaches higher Z-position**




M. Bernert, D. Brida, H. Reimerdes, N. Fedorczak

- M. Bernert et al, PSI 2024
- T. Bosman et al, PSI 2024

# X-point Radiator in D-T operation

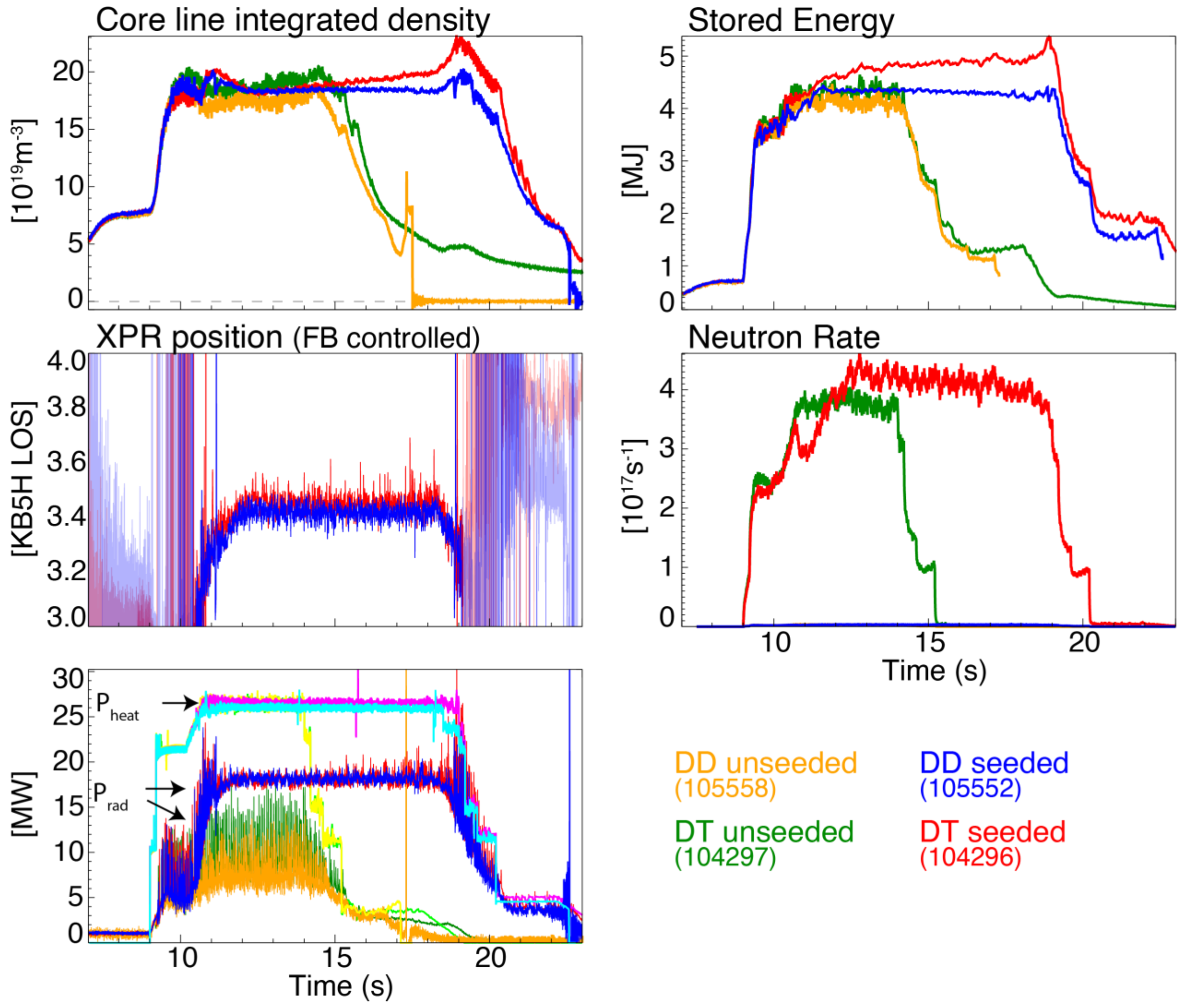



*Fig. courtesy M. Bernert*

- X-Point radiation has no detrimental effect on the confinement
- Changes between D & DT in line with expectations

M. Bernert, D. Brida, H. Reimerdes, N. Fedorczak

➢ M. Bernert et al, PSI 2024

# X-point Radiator in D-T operation

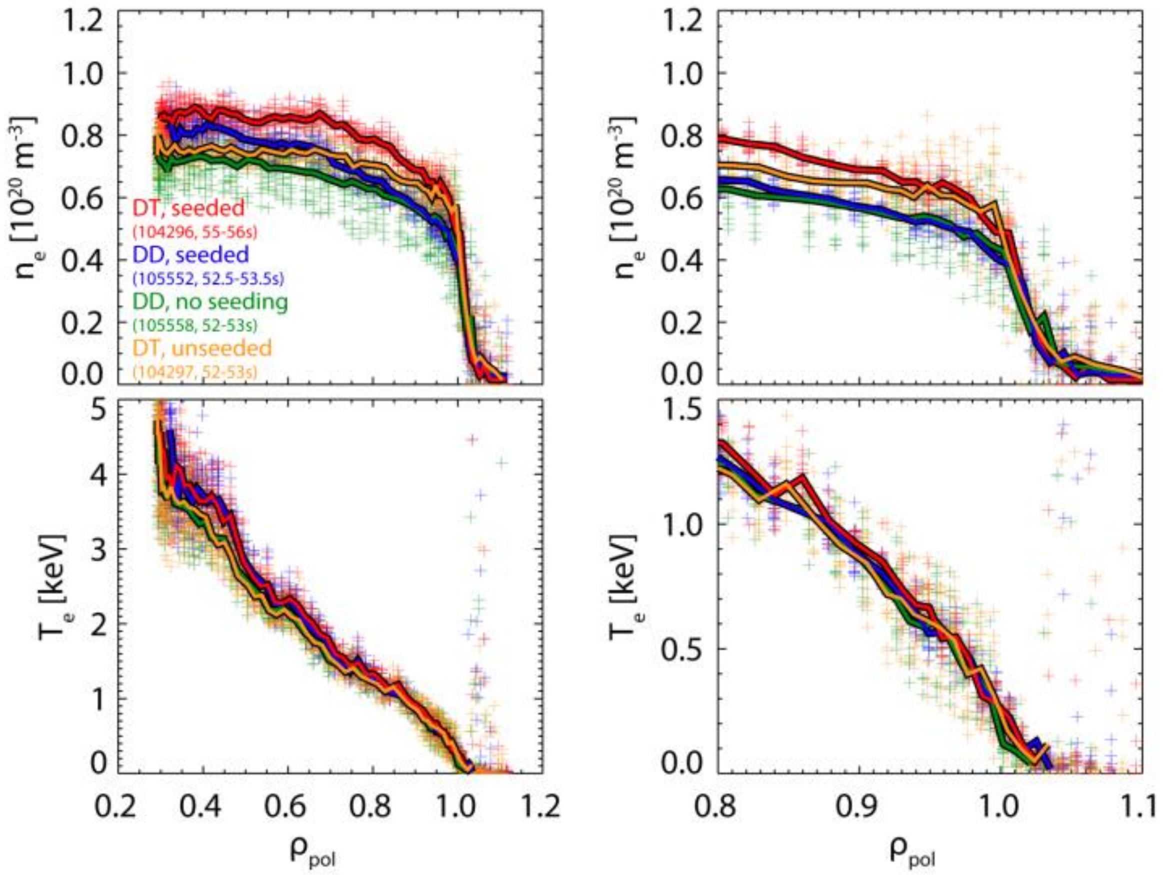



*Fig. courtesy M. Bernert*

- X-Point radiation has no detrimental effect on the confinement
- Changes between D & DT in line with expectations
- No sensible modification of edge profile but clear coredensity increase (ITG stabilisation)

M. Bernert, D. Brida, H. Reimerdes, N. Fedorczak

➢ M. Bernert et al, PSI 2024

# RT05 Physics of divertor detachment and its control for ITER, DEMO and HELIAS operation – Modelling needs

- Strong need to address the modification of transport in scenario at high gas throughput and high seeding
- Understanding of mixing impurity induced transport modification (Ar/Ne)
- Strong indication of modification causing transition to no-ELM as well as modification of SOL transport

# WPTE Next Steps

**Call for proposal 2025**

- September 2024 up to 11th of October
- Review meeting in September (23rd and 26th)

**Call for participation 2025**

- From end of October to end of November
- General Planning meeting in person 18/19 November in Garching

**2025 Campaign**

**Modelling driven experimental proposals are welcomed**
**Please do join the GPM for discussing and proposed your view/requests**

# Conclusions

- WPTE continues its ambitious program with strong emphasis on the cross-device approach
- A similar Research Topic structures will be likely maintained in 2025 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
- Quoting my presentation from last year: “TSVVs should take advantage of the wide parameter range offered by similar program runs in different devices. Some unique features (e.g. machine size scaling or isotope effects including DT plasmas) are clear opportunities” We are securing resources for some of the intepretative modelling but we are looking forward your help for proper exploitation and extrapolation