EUROfusion

Thrust 1 Meeting #4

WPTE Program 2023-2024

Experimental program and modelling needs

N. Vianello on behalf of the WPTE TFLs
M. Wischmeier, M. Baruzzo, D. Keeling, A. Hakola, B. Labit, E. Tsitrone and N. VianelloEUROfusion Tokamak Exploitation Team

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.

WPTE Research Topic Structure

Thrust 1: 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

Mission 1

Mission 2

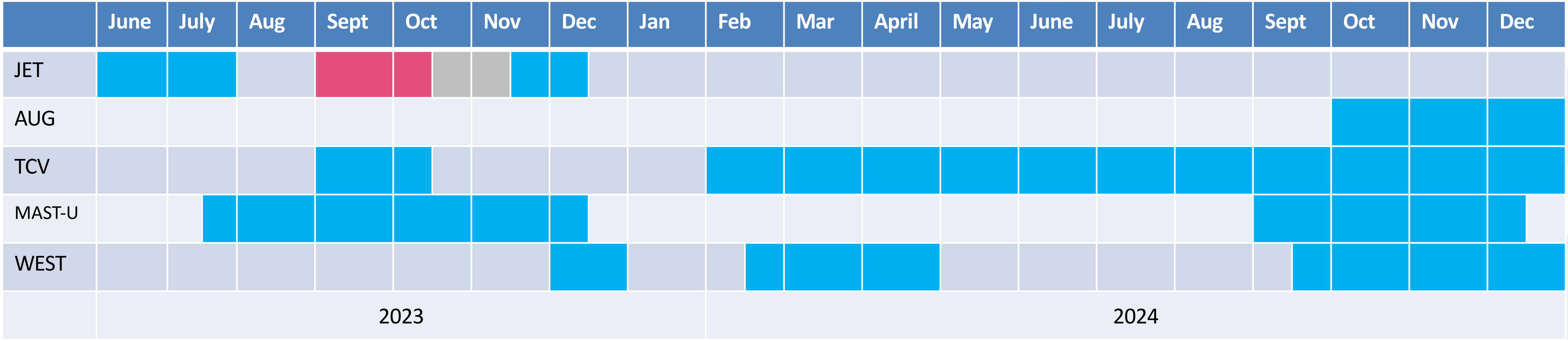
RT09: Physics of energetic particles

RT07: Alternative divertor configuration

PEX

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

Timeline of the experimental time from last Thrust 1 meeting to end of 2024

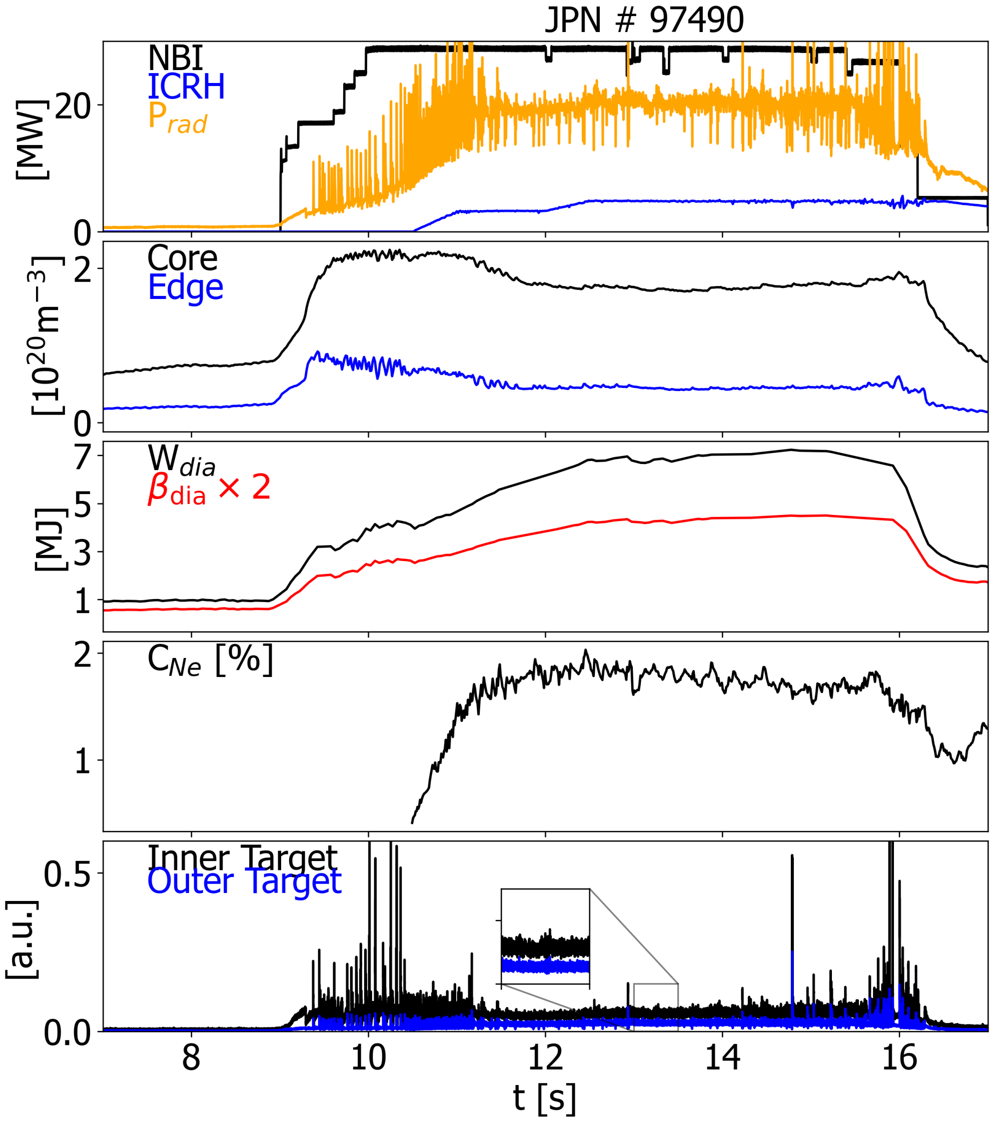


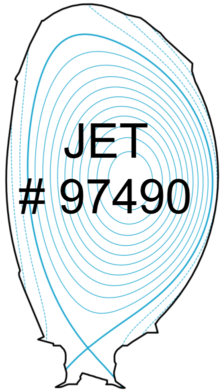
RT01: Core-Edge-SOL integrated H-mode scenario compatible with exhaust constraints in support of ITER

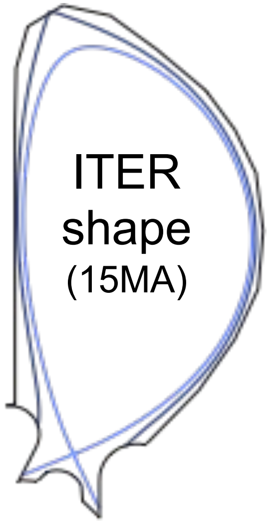
#	Scientific Objectives
D1	Develop stationary high power H-mode scenario at low core and pedestal collisionalities compatible with detached divertor
D2	**Provide physics-based cross-field transport coefficients to TSVVs (1, 3, 4 and 11) for turbulence modelling**
D3	Determine the impact of different 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

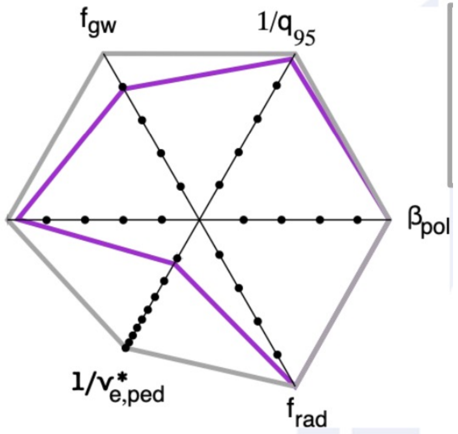
High performance Plasmas compatible with Exhaust Solution 1/

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

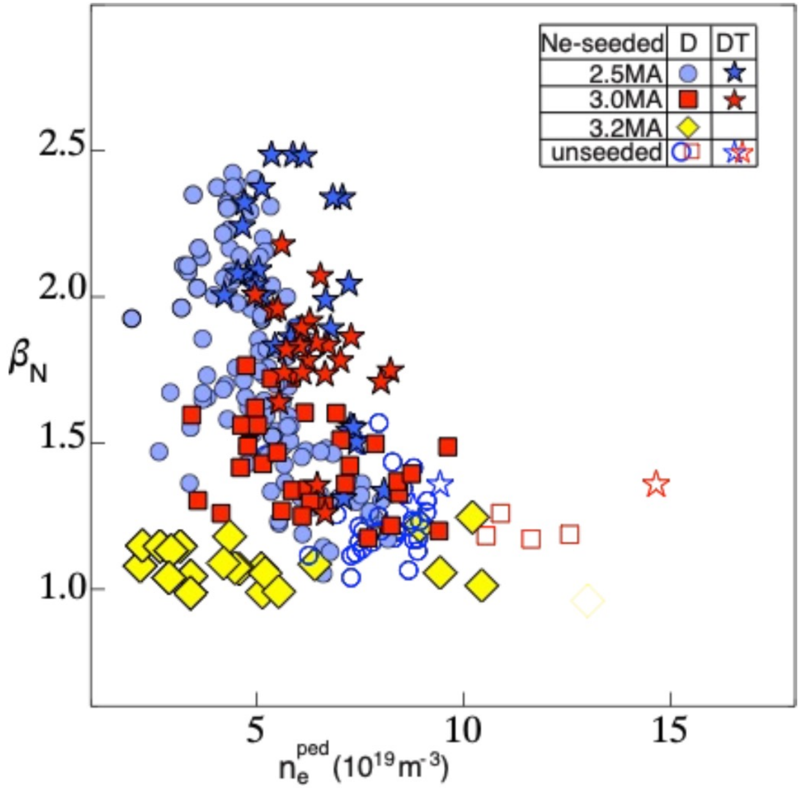


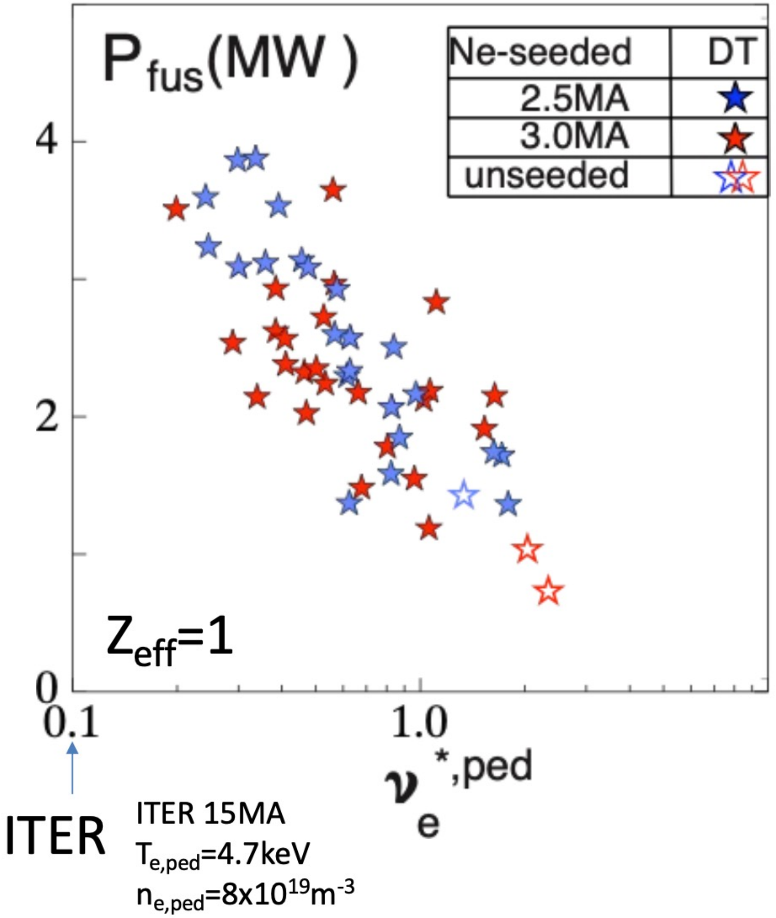






High performance Plasmas compatible with Exhaust Solution 2/





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

- 3MA stationary DT H-mode scenario in partial detachment achieved
- Low pedestal collisionality in seeded partial detachment

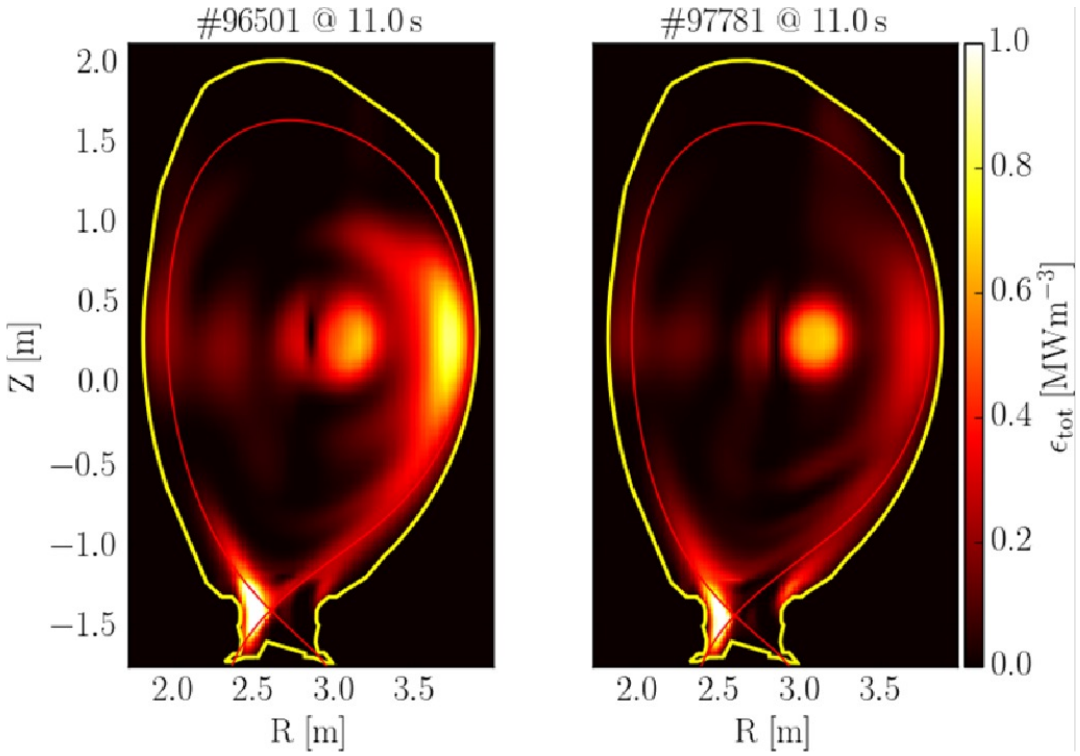
High performance Plasmas compatible with Exhaust Solution 3/

- 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 and others)
  - Interest from US colleagues (BOUT ++) 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

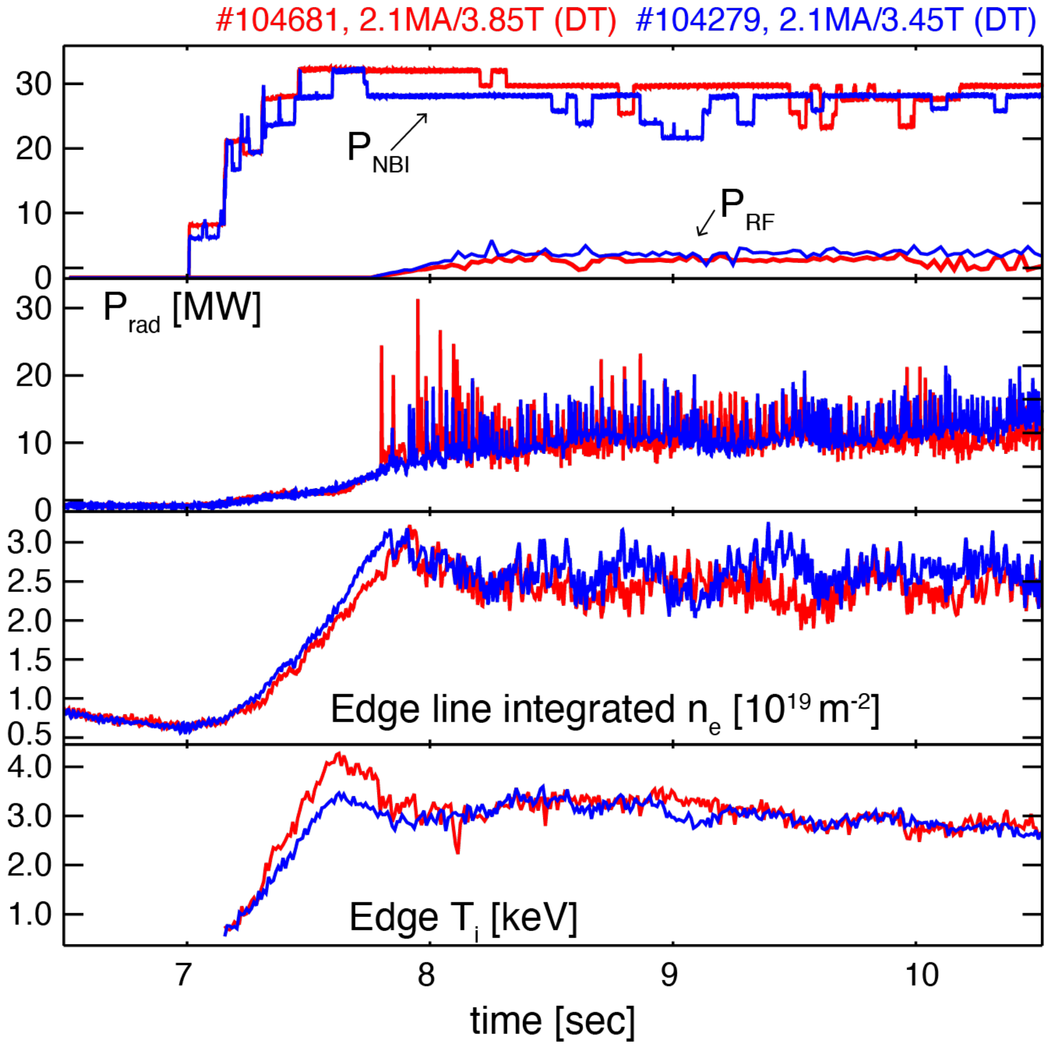
high ∇Ti → peripheral screening



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/

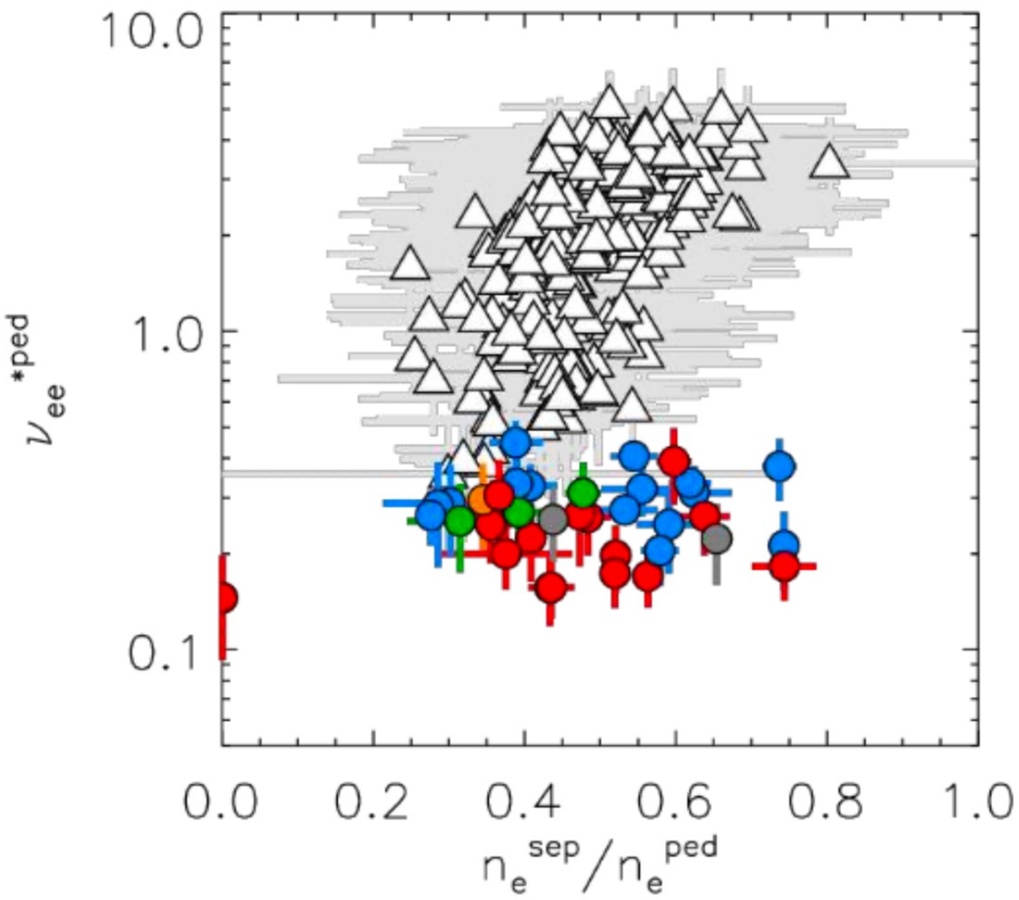


- W screening with high ion temperature gradient confirmed in hybrid scenarios in DD operation (A. Field, NF 2023)
- DTE2 results confirmed deuterium observation, although data quality hampered by non-optimal diagnostic compatiblity with hybrid scenarios (J. Hobirk NF 2023)
- DTE3 improved diagnostic 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 $\Omega_{\boldsymbol{\phi}}$ in such pulses;
- Open question – Does turbulent particle transport play a significant role in screening out the W across the pedestal?

Peeling limited pedestal in metallic devices 1/



△ high-d JET-ILW database (till 2020)

- high-**δ** JET-ILW new data 1.4MA/1.7T 25MW
- high-**δ** JET-ILW new data 1.4MA/2.2T 25MW
- high-**δ** JET-ILW new data 1.4MA/2.8T 25MW
- high-**δ** JET-ILW new data 1.4MA/3.4T 25MW
- high-**δ** JET-ILW new data 1.4MA/3.8T 25MW

Reached an unexplored corner of the ν^*-n_e^{sep}/n_e^{ped} operational space
in type I ELMy H-modes

- On-going modelling handle by internal resources B. Chapman -> strong link with TSVV1

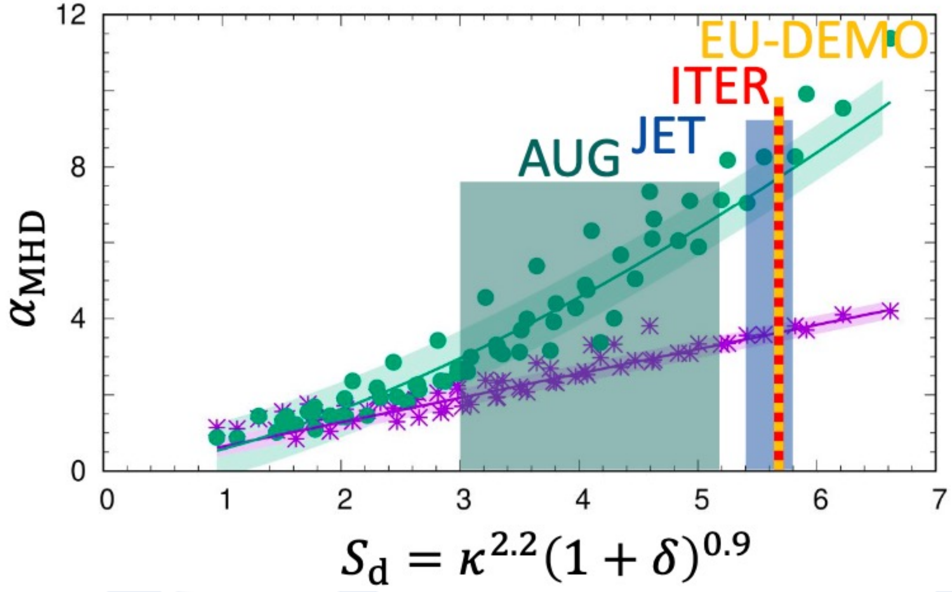
RT02 - Physics understanding of alternatives to Type-I ELM regime

#	
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

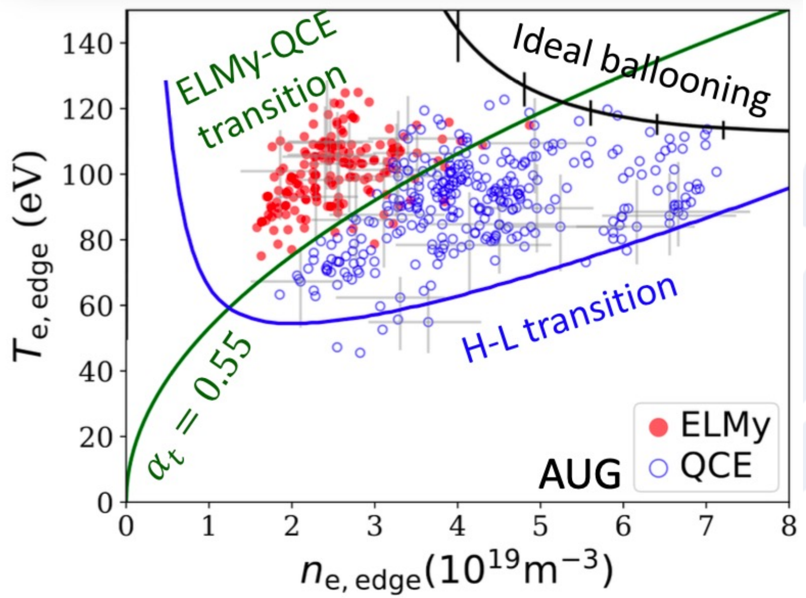
RT02-Small ELM scenario for DEMO

The quasi-continuous exhaust (QCE) regime is
a stationary H-mode regime

- at high plasma shaping
  - Elongation, triangularity and closeness to double null
- with high density
- with high confinement
- without type-I ELMs



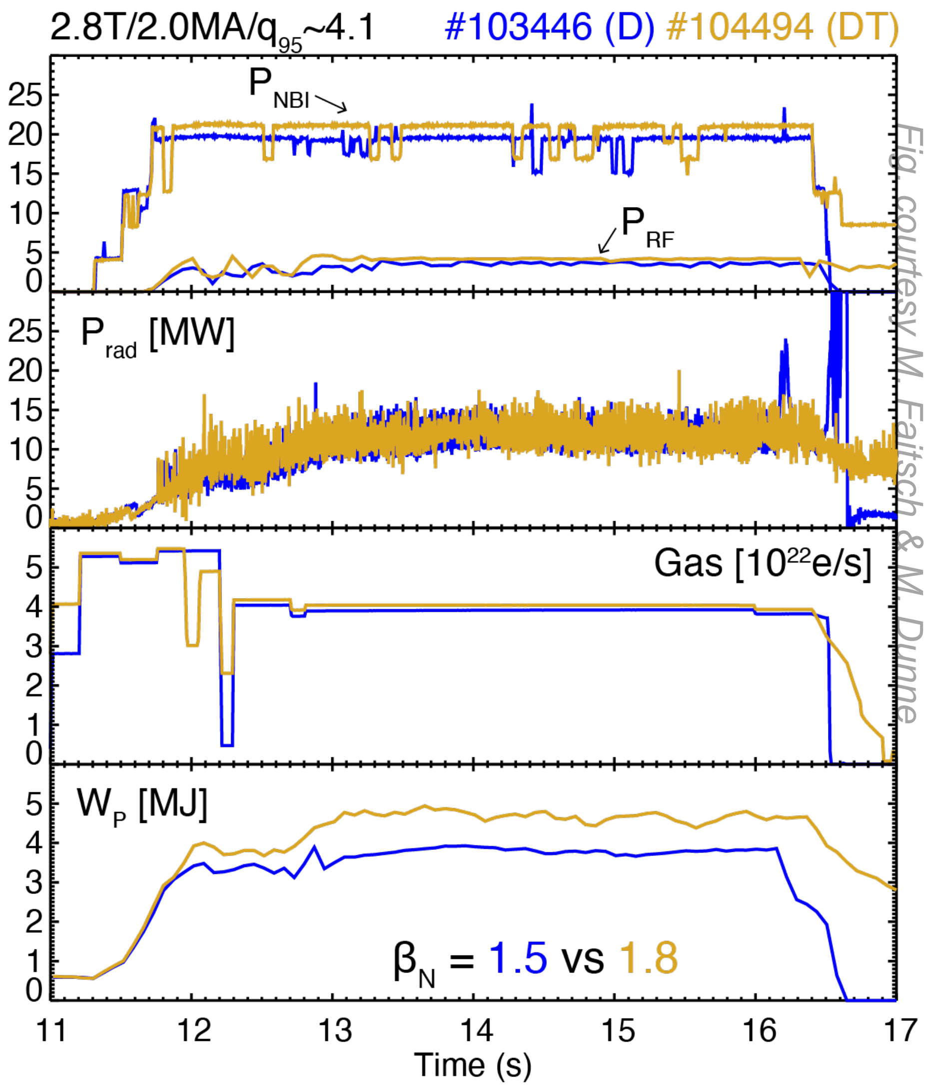
- According to shaping a stability region exhists within global peeling mode (located at region of maximum gradient) and infinite local balloning (close to the separatrix) → QCE operational space opens with S_d > 3
- Fueling dependence might have different explanation
  - Ideal MHD (local pressure gradient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



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



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

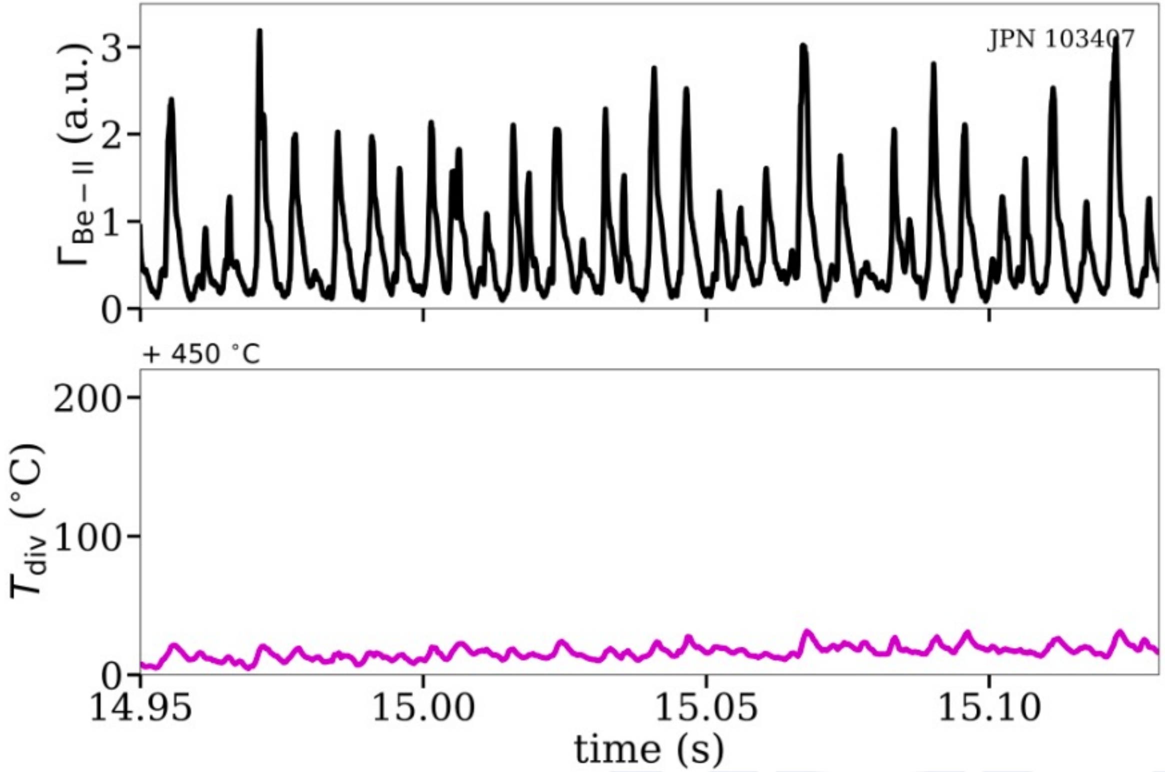
➢ M. Faitsch et al, PSI 2024; M. Dunne et al , EPS 2024

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 Prad: 6 MW → 11 MW [Pheat ≈ 21MW]
  - Decreased ΔT div: 130 T °C/s → 40 T °C/s
  - Increased Zeff,edge, recycling, … ?



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

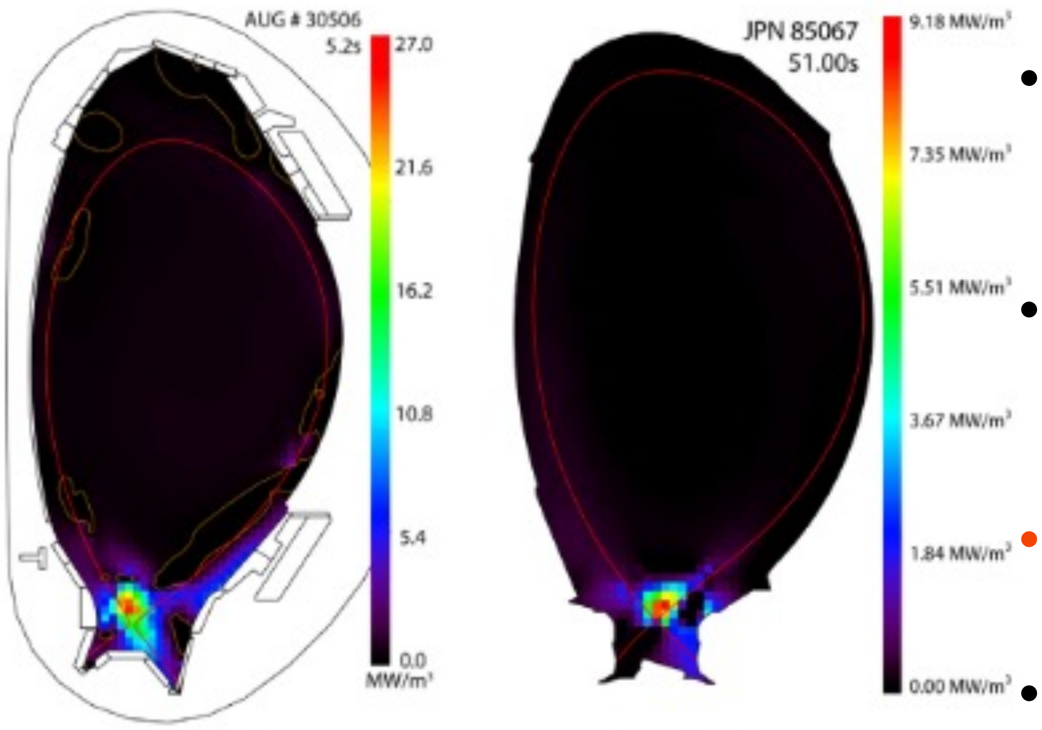
Modelling needs

- Edge modelling, including turbulence effects (GRILLIX/SOLEDGE3X)
- Plasma background for evaluation of first wall erosion
- Pedestal 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

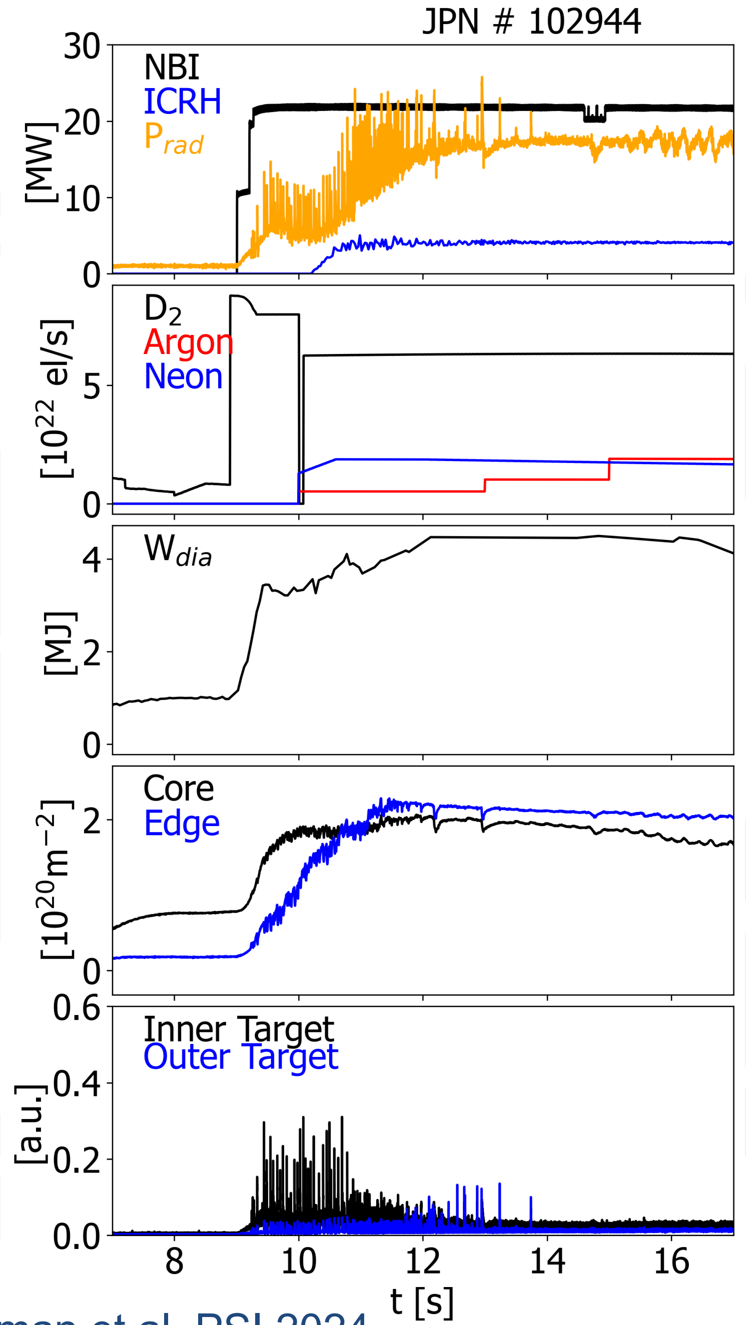


(a) AUG (b) JET

- 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 benefit of Mixed impurities

- The mixed impurity exhibit stronger stability (Zeff ~ 3.1 → C_{Ar} ~ 0.6% and C_{Ne} ~ 0.5%). Exported as well in D-T operation
- 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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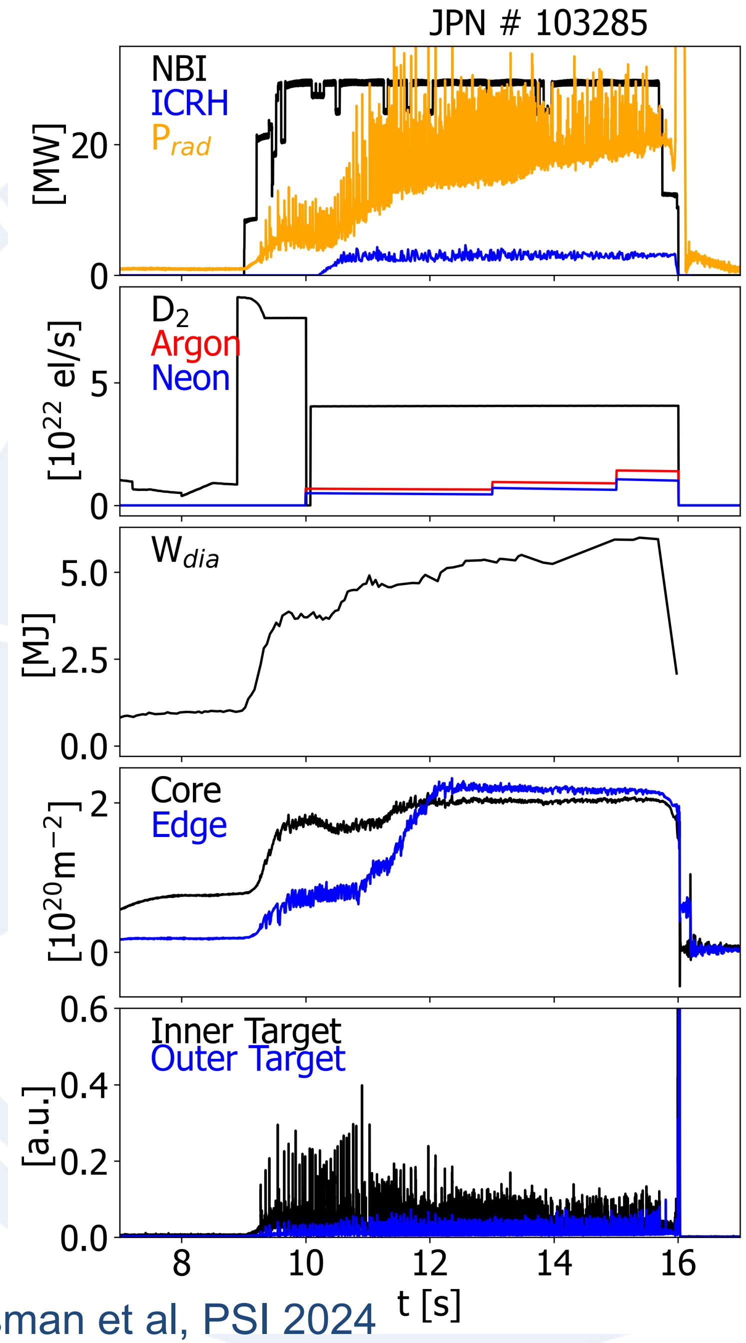
- Implementation of Real time control with diagnostic and actuators compliant with ITER constraints
- **Work at even higher power 33MW with strong ELM mitigation whenever XPR position reaches higher Z-position**



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

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

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

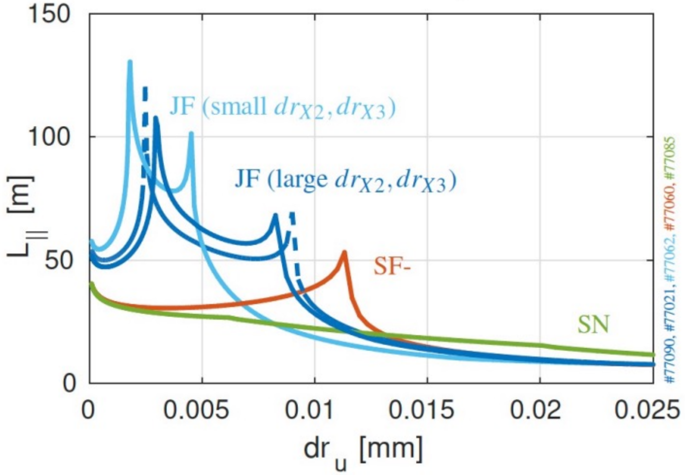
- On going SOLPS-ITER modelling
- Strong need to address the modification of transport in scenario at high gas throughput and high seeding
- Strong indication of modification causing transition to no-ELM as well as modification of SOL transport

RT07 - Physics understanding of alternative divertor configurations as risk mitigation for DEMO

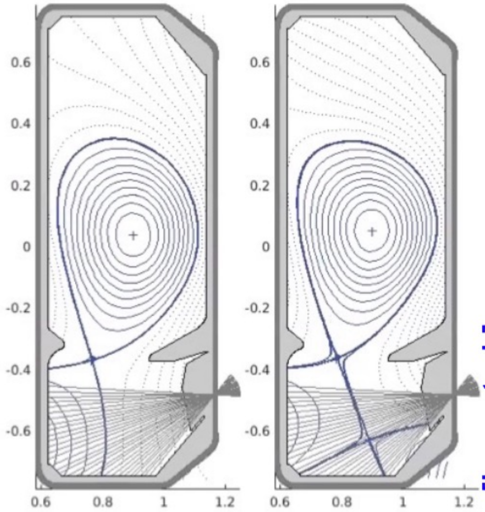
#	
D1	Determine detachment onset, radiated power fractions, and core compatibility in H-mode for the alternative divertor configurations (ADCs) and characterization of ELM activity in view of pedestal, heat flux and control in ADCs
D2	Characterize possible benefits of the snowflake configuration for X-point radiation stability and dissipated power in H-mode
D3	Quantify the degree of ELM heat load mitigation achievable by impurity seeding, investigating the dependences on relevant machine parameters
D4	Test existing reduced SOL models against ADCs

RT07 - Physics understanding of alternative divertor configurations as risk mitigation for DEMO Highlight from TCV

Assessment of effect of additional X-points and extreme $L_{||}$



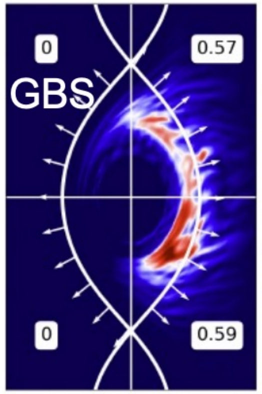
[Gorno et al., in prep.]



[Lee et al.]

Exploration of high-power (2 MW) L-mode scenario, so far not detachable in SN nor ADCs (N_2, Ne,…)

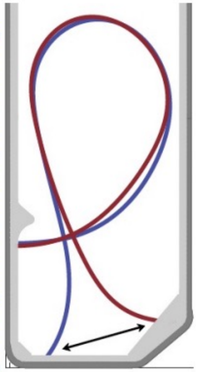
Predictive power-sharing law in DN



[Lim et al., in prep.]

Identification of reduced R_t effect due to flows

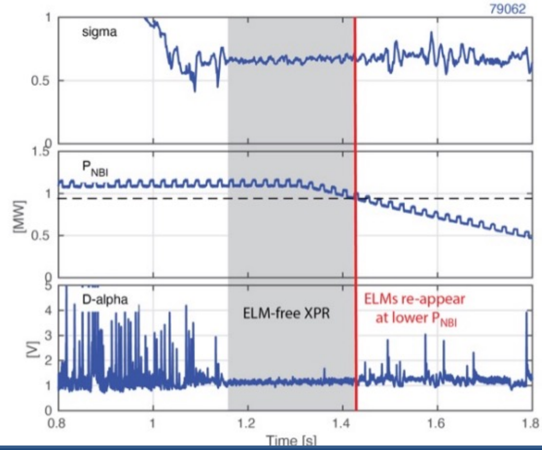
[Carpita et al., subm.]

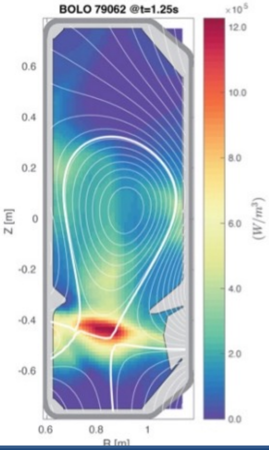


$$T_e^t \propto \left(\frac{1}{R_t}\right)^{2-\frac{2M_{eff}^2}{1+M_{eff}^2}}$$

$$n_e^t \propto \left(\frac{1}{R_t}\right)^{-2+\frac{3M_{eff}^2}{1+M_{eff}^2}}$$

Further assessment of ELM-free XPR in the Snowflake

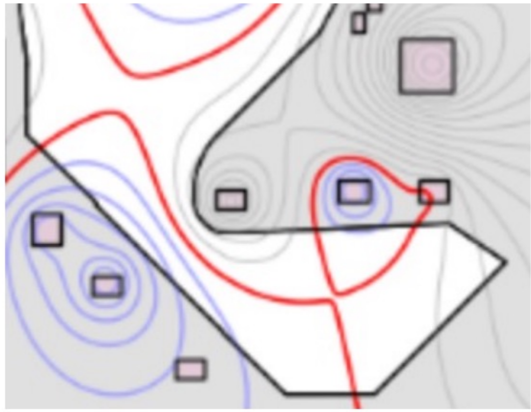




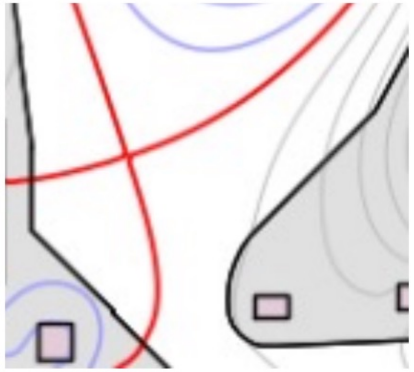
[Reimerdes et al.]

RT07 - Physics understanding of alternative divertor configurations as risk mitigation for DEMO Highlight from MAST-U

H-mode (3+ MW inj.)
X-Point Target (MU03)

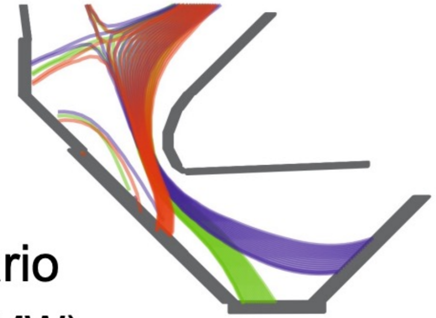


L-mode (1.5 MW inj.)
X-Divertor (MU03)



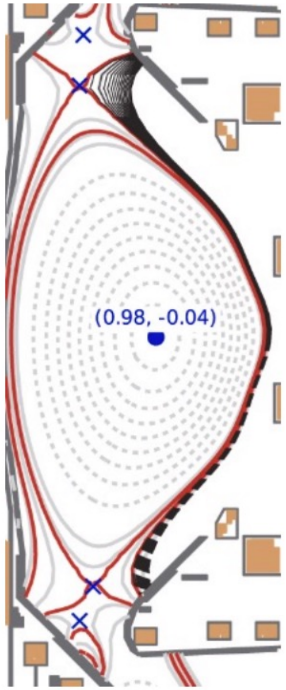
Super-X, **Conventional** &
Elongated Divertor scenario

- MU03: Ohmic L-mode (0.5 MW)
- MU03: H-mode (3+ MW inj.)
- MU02: Beam-heated L-mode (1.5 MW inj.)



[Verhaegh et al., ArXiV]

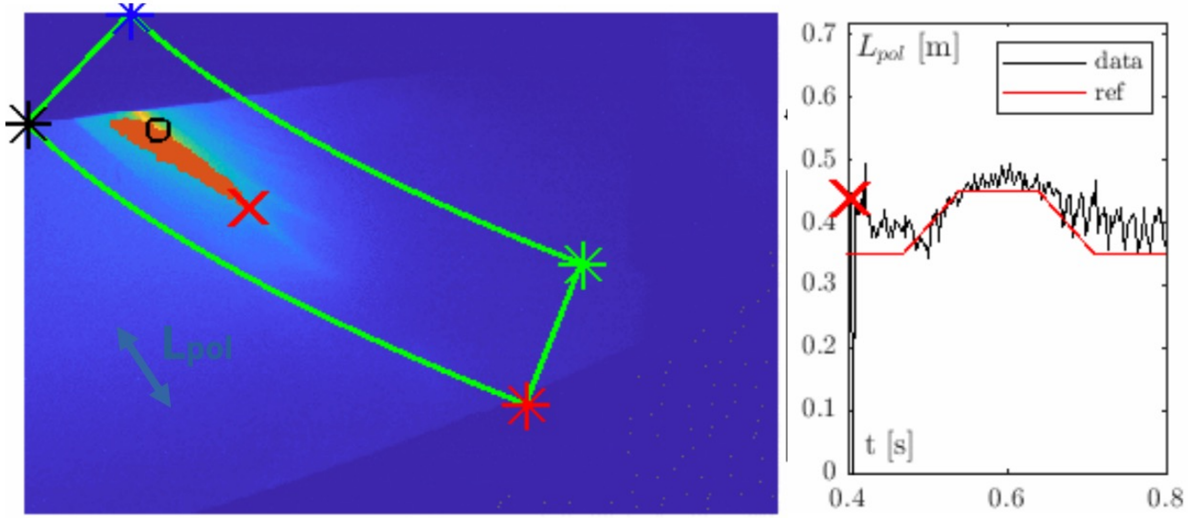
Snowflake (Ohmic)



[Soukhanovskii et al., 2022, NME]

Beam-heated L-mode)
Open Divertor (MU03)

Real-Time Detachment control in ADC (Super-X - RT05)



[Kool et al., in prep.]

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Modelling activities and needs

- SOLPS-ITER modelling (TCV): poloidal and toroidal flux expansions in different scenarios
- SOLPS-ITER modelling (TCV, MAST-U): comparing TECXY results and shifting the efforts to using SOLPS-ITER —> especially on MAST-U the resources are now thin
- SOLEDGE-EIRENE modelling for DN (TCV, MAST-U, WEST): effect of ballooning and drifts with impurities on heat fluxes
- GBS (TCV): impact of leg length in varying scenarios, turbulence in negative triangularity scenarios
- From late 2024 experiment will start on AUG and therefore a lot of modelling support will be needed once full scenario will be establish to exploit ADC in metallic environment

Conclusions

- Remarkable progress achieved including last DT operation on JET
- Activity started within Research Topics to provide interpretative modelling. Do we want these activity to be reported as well in TSVVs meeting? Further activity needed and highlighted. We really need the involvement of the TSVVs. US-groups expressed multiple time interest in our dataset but we would clearly privilege European exploitation
- Interesting papers from TSVV on the pinboard (e.g. G. Snoep: *Characterization of reduced-order turbulence models in the L-mode pedestal-forming region in JET,* L. A. Leppin *The JET hybrid H-mode scenario from a pedestal turbulence perspective*). Might be good a scientific discussion on the results within the scientific team, before coming to the publication
- Need a feedback on status of validation as well as missing dataset/diagnostics
- Action towards increasing the number of users for newly available/update codes. Should we raise the point? How? At which level?