Progress and Innovations in the TCV Tokamak Research Programme

Christian Theiler for the TCV team

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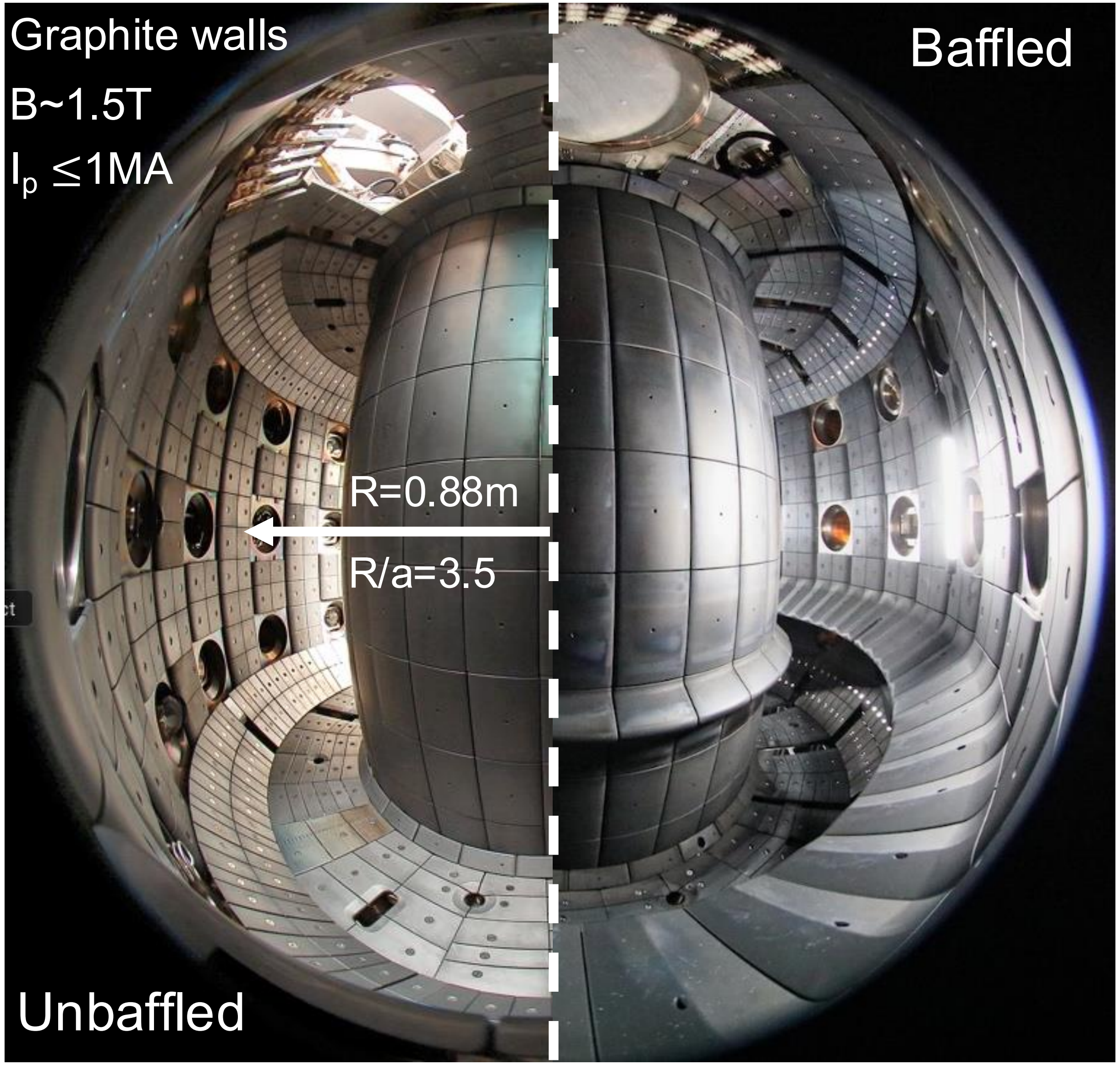
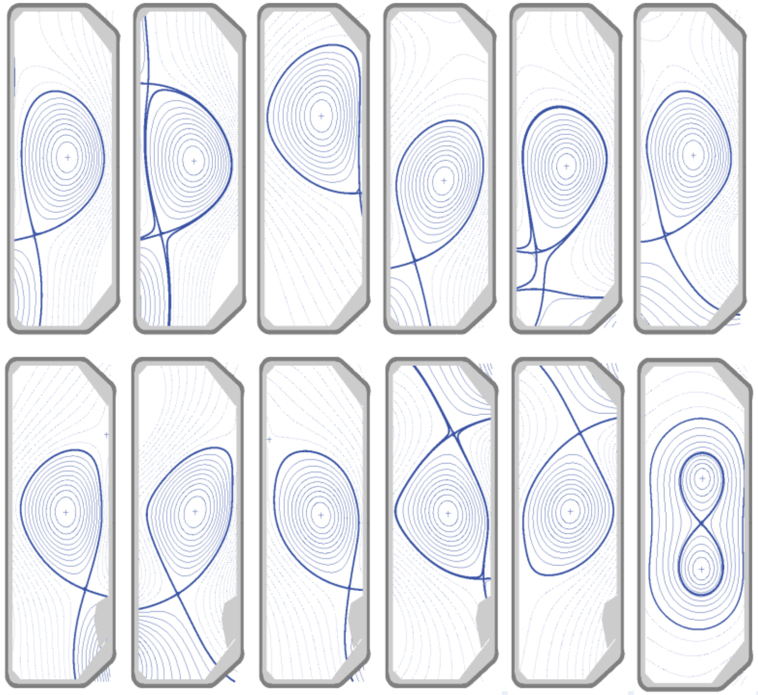
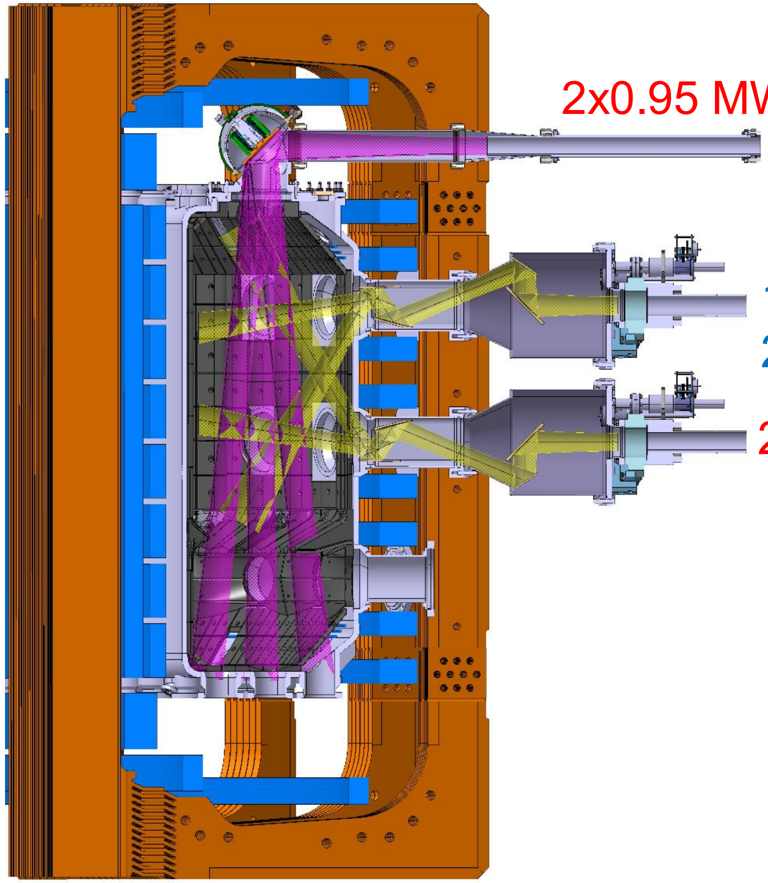
Tokamak à Configuration Variable (TCV)



- High operational flexibility
- Extensive set of diagnostics
- Modern control system
- Versatile heating
- Unique magnetic shaping



TCV's versatile heating system

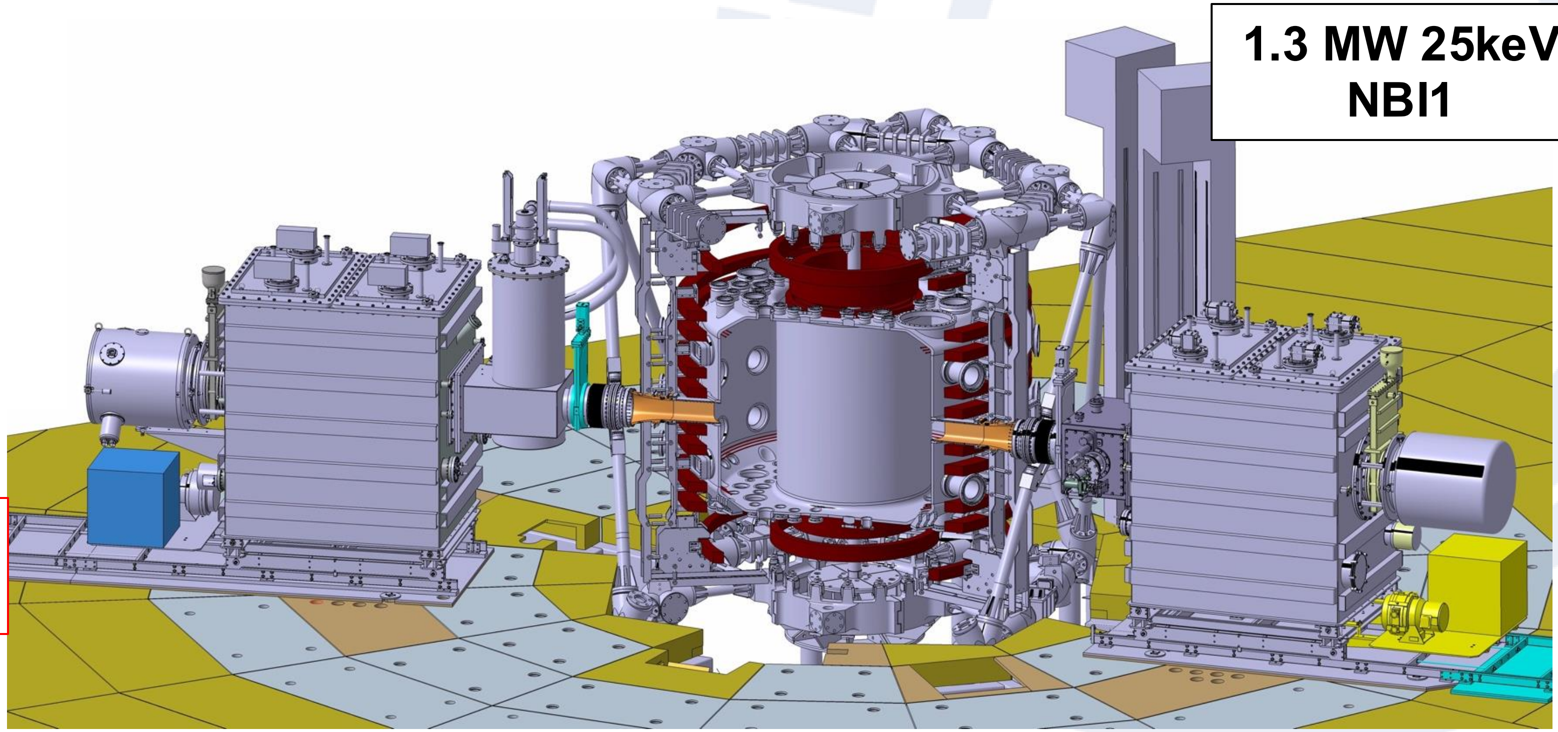


2x0.95 MW X3 (126 GHz)

1x0.7 MW (82.7 GHz) +
2x0.95 MW X2 (84 GHz)

2x0.45 MW X3 (118 GHz)

- ECRH and NBH power real-time controllable
- ECRH angles also real-time adjustable



1.3 MW 25keV NBI1

1.3 MW 55keV NBI2

Outline

Highly productive campaings in 2024 and 2025 with a record of 3’517 successful discharges in 2024, further strengthened international collaborations, and preparations for various upgrades - can only cover some of the highlights here!

- ITER baseline and non-inductive scenarios
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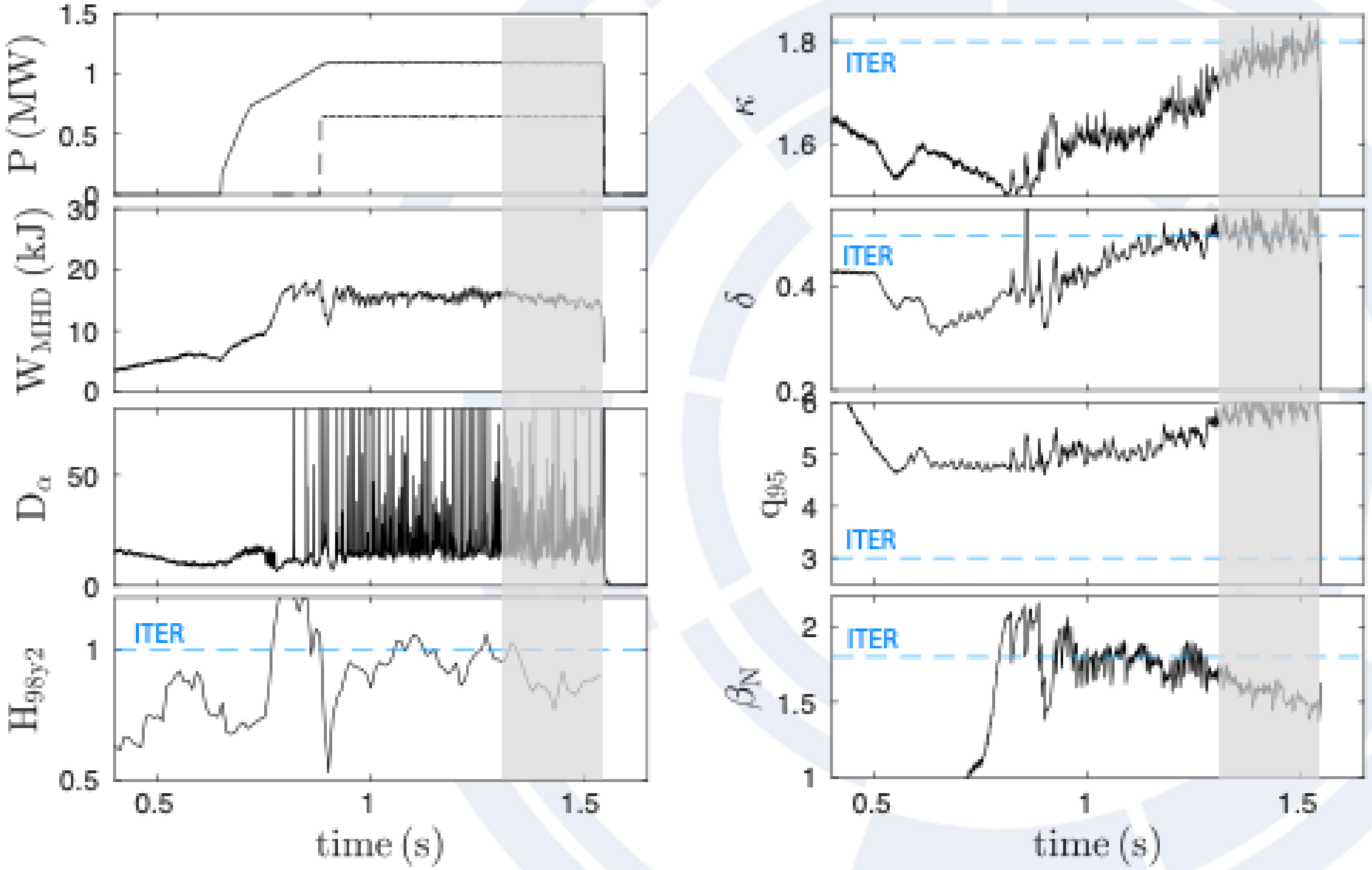
ITER baseline scenario extended to full shaping and core-edge integration

- Exact ITER shape (κ=1.8, δ=0.5) achieved for several τ_E with H_{98}=1 and β_N=1.6, but at large q_{95}

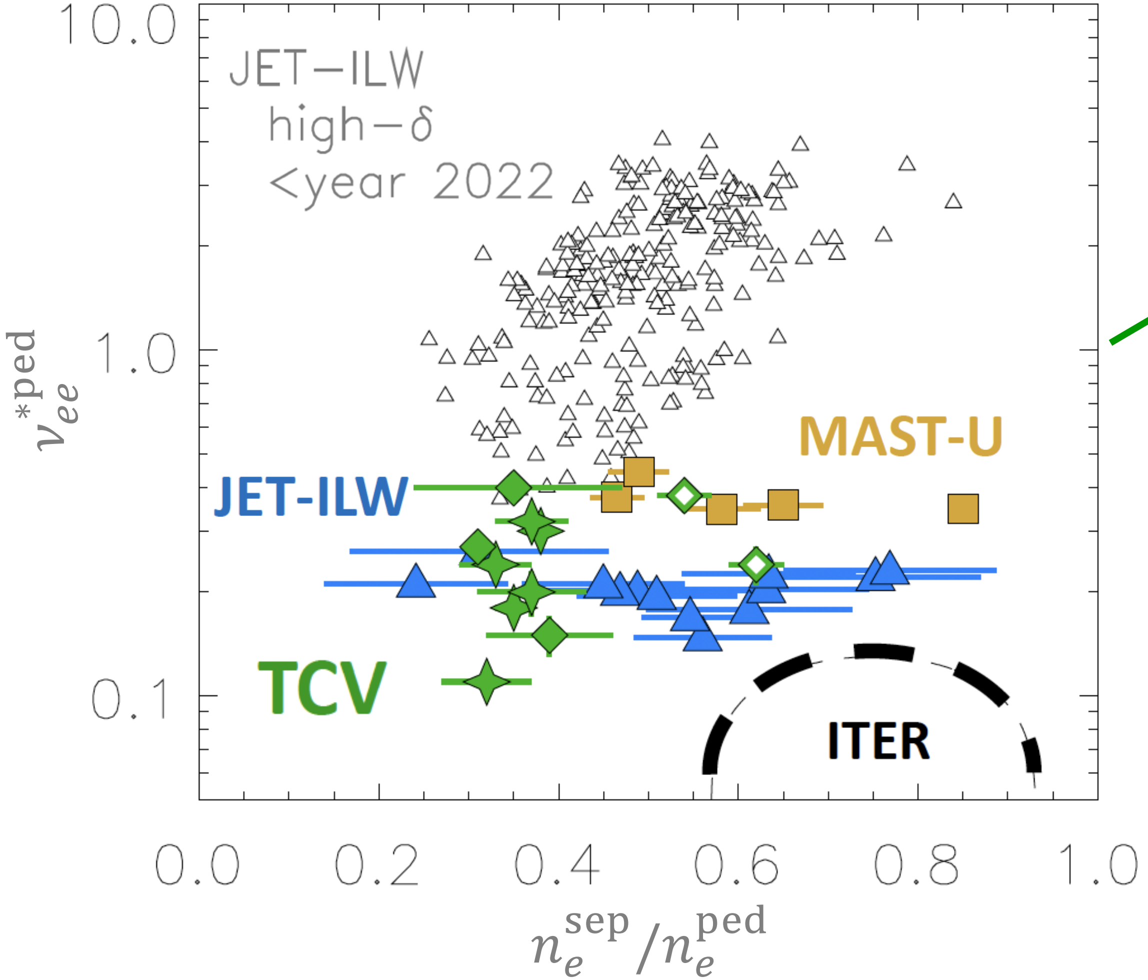
- First attempts of core-edge integration at reduced shaping but q_{95}~3.4 with N_2 seeding
  - ➢Pedestal degraded and ELMs reduced, but good confinement is kept



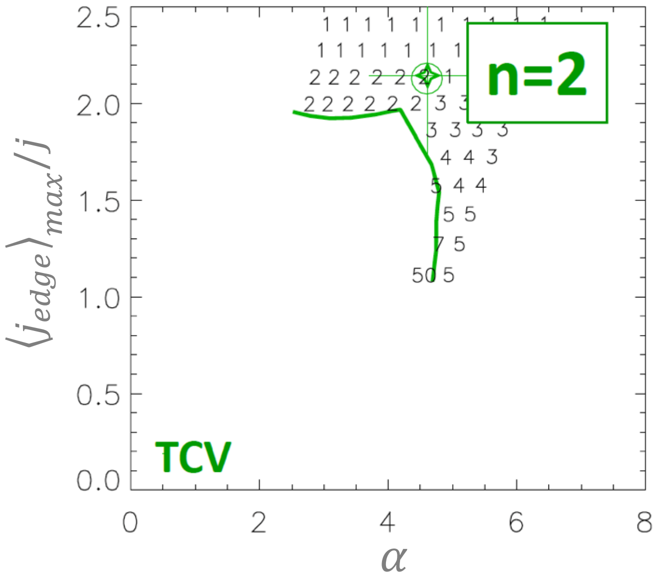
[B. Labit et al., NF 2024]

Access to ITER-relevant pedestal collisionalities

Multi-device study approaching ITER collisionalities



Low-n mode unstable; near peeling boundary



- High δ
- q_{95}=5.0
- P_{NBI}=1MW, P_{ECRH}=1.1MW
- Gas puff scan

[L. Frassinetti et al., this conference]

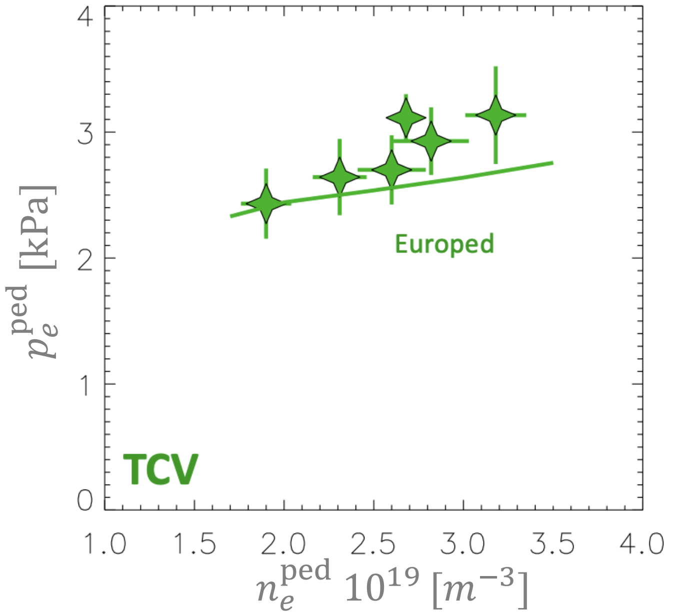
Beneficial pedestal behavior at increased density

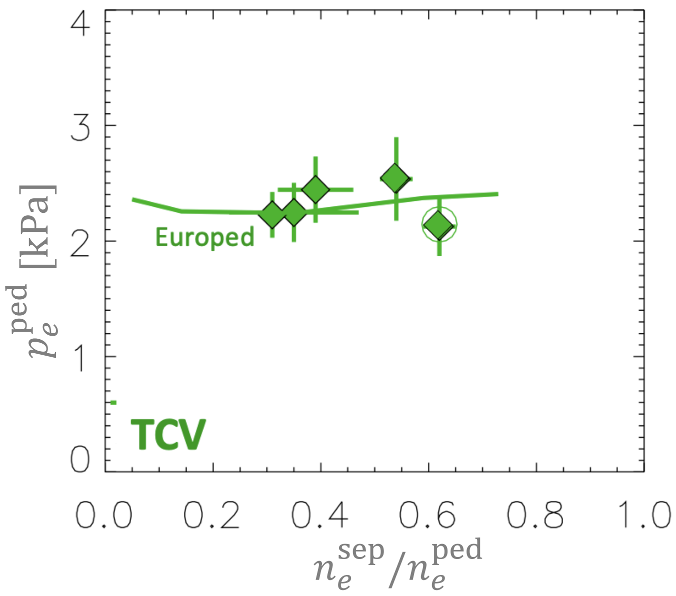
Contrary to ballooning limited pedestals, and in qualitative agreement with Europed:

- P_e^{ped} increases with density
- P_e^{ped} does not degrade with n_e^{sep}/n_e^{ped}

- Multi-device study overall points to promising behavior in view of ITER

- **See L. Frassinetti, Saturday 9:30**

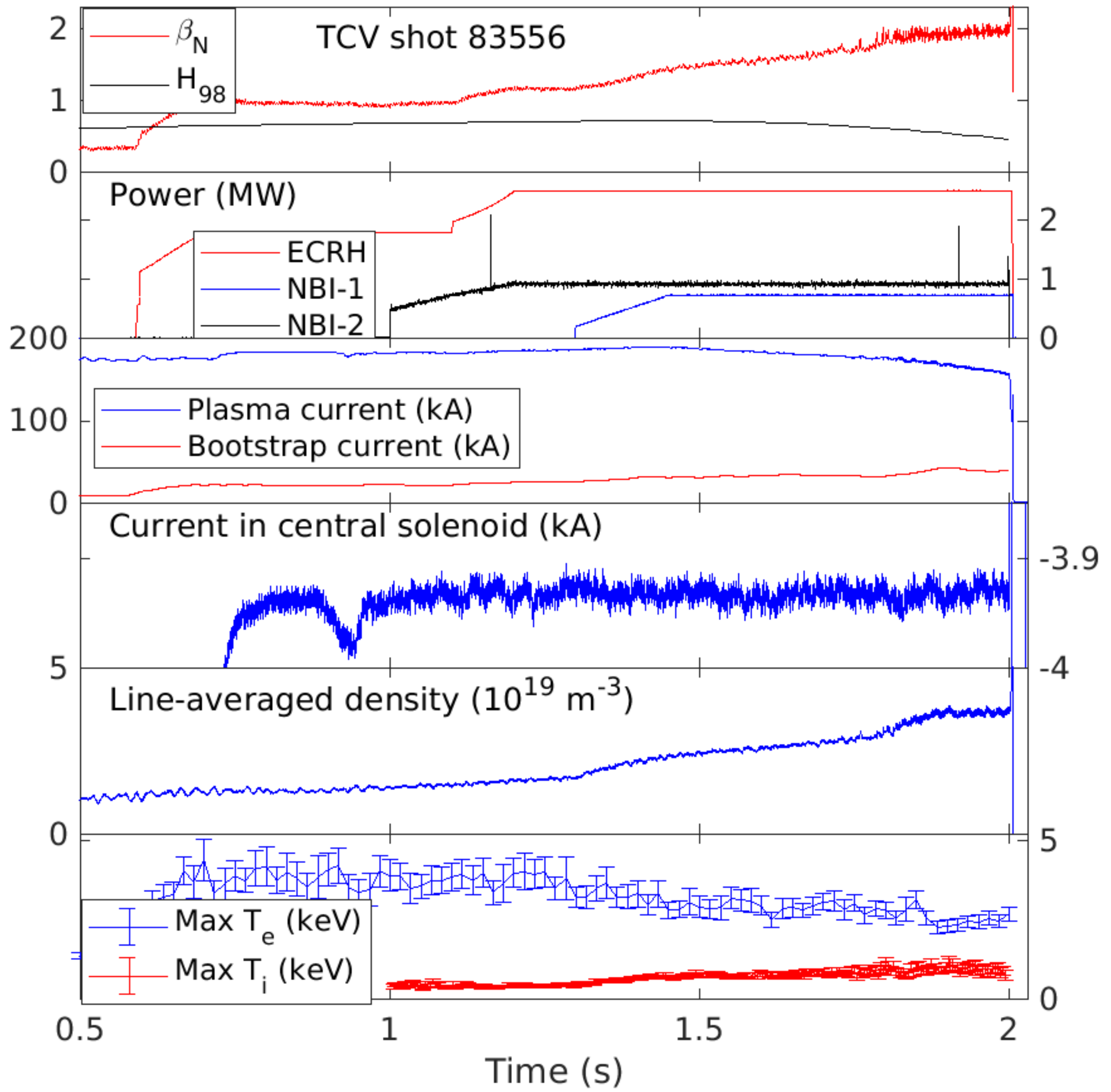




Towards steady-state, non-inductive advanced scenarios

TCV's extensive history of steady-state, non-inductive scenarios extended in preparation of long-pulse experiments in JT-60SA and ITER

- Off-axis ECCD for non-inductive operation
- NBI-1 and NBI-2 for more balanced T_e vs T_i

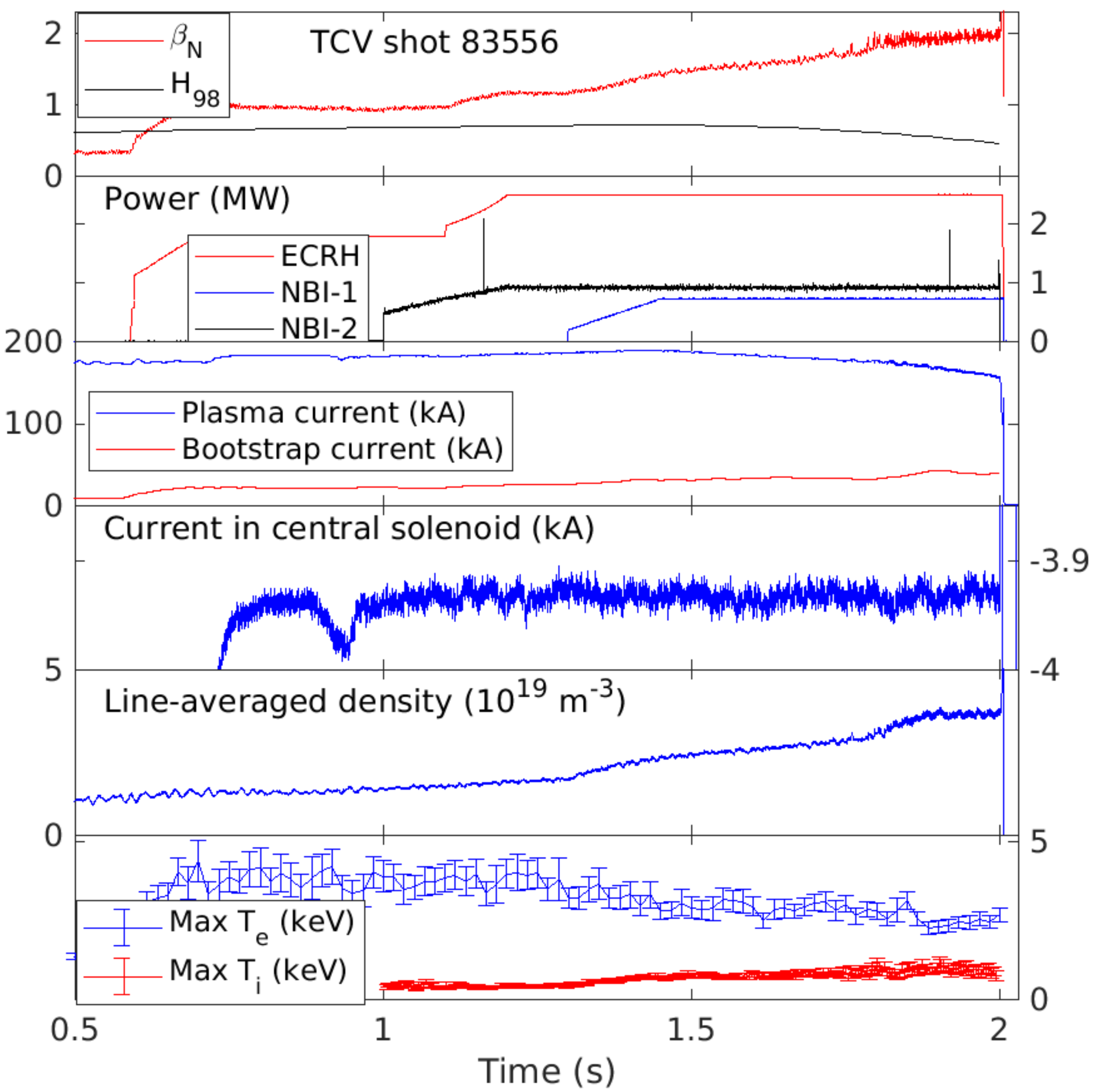


[S. Coda et al., this conference]

Towards steady-state, non-inductive advanced scenarios

Achieved scenario:

- Fully non-inductive
- Semi-stationary, β_N~2
- Reversed shear
- $T_i/T_e \rightarrow$ 30%
- Increased gradients at mid-radius and near edge, yet
  - No strong ITB or ETB
  - Bootstrap current fraction ~30%

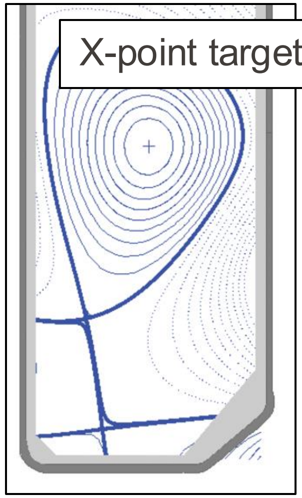


[S. Coda et al., this conference]

Towards steady-state, non-inductive advanced scenarios

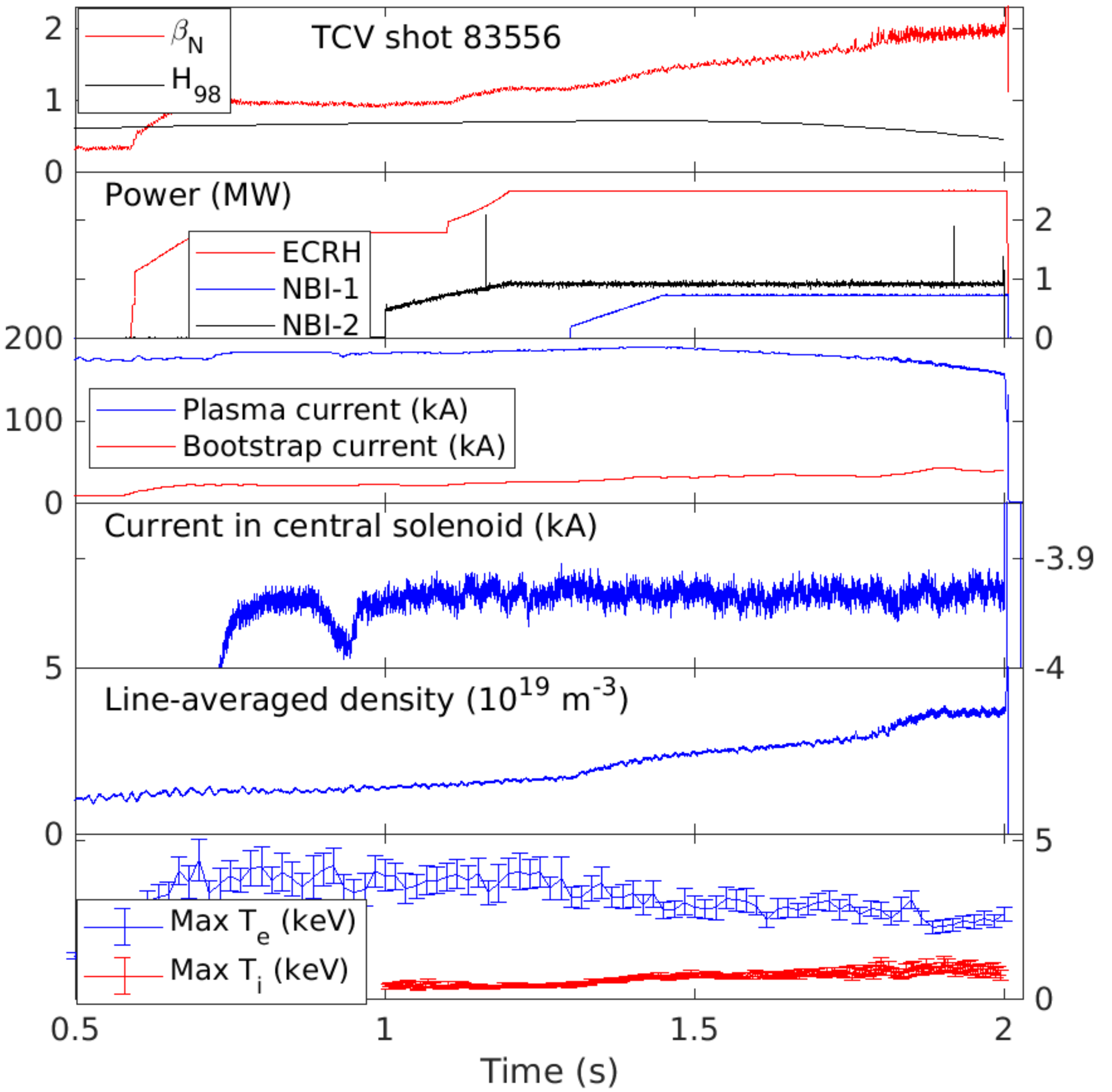
With more central heating in 2026:

- Realistic prospect for fully stationary, high β_N, high bootstrap fraction non-inductive, NBI-heated operation
- Combination with divertor solution ongoing



+ baffles

- **See S. Coda, Thursday AM**



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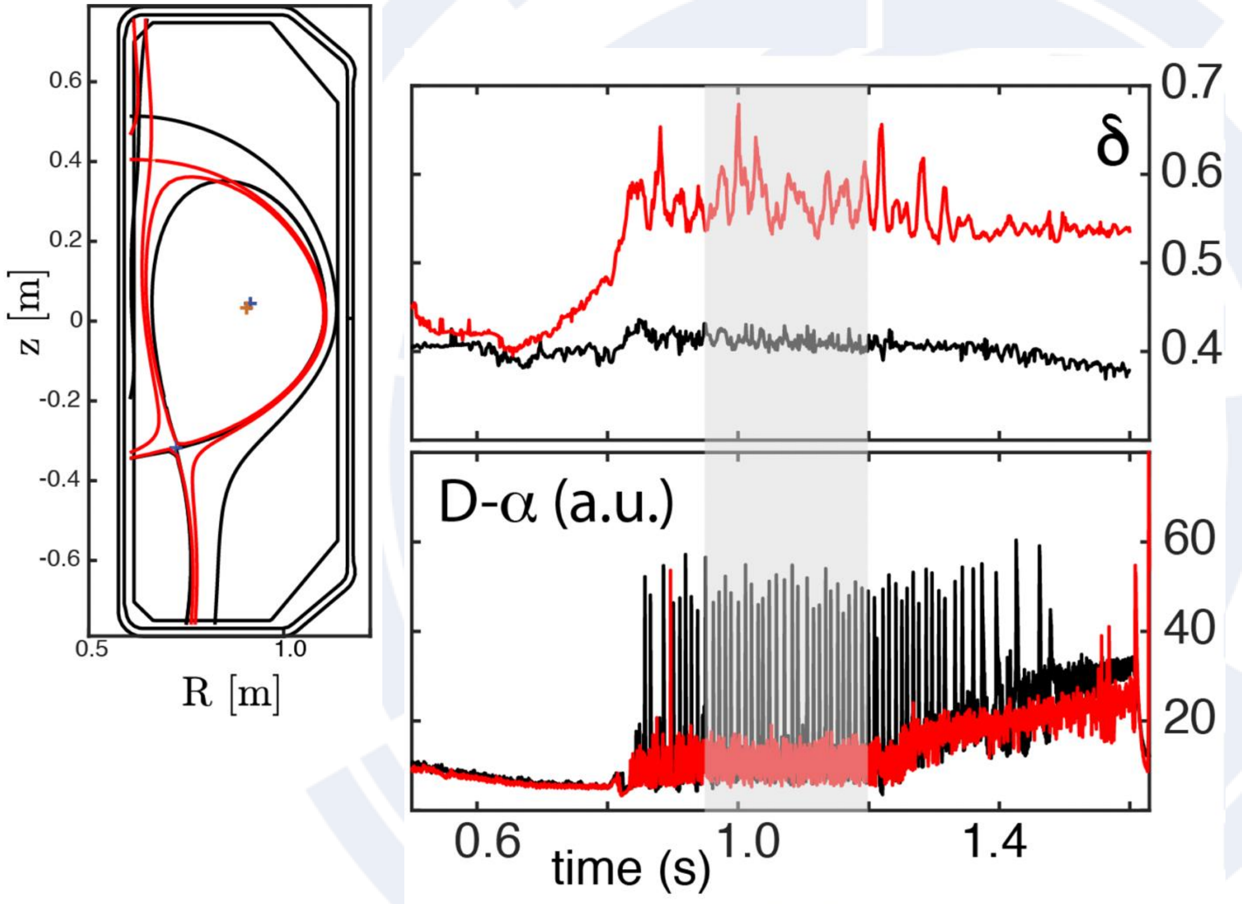
Quasi-cont. exhaust (QCE): Step-ladder approach towards ITER

QCE a promising ELM-free reactor regime

- ➢ Step-ladder approach (TCV, AUG, JET) led to QCE development in JET
- ➢ Minimum separatrix density for QCE extrapolates favorably to ITER

➢ See M. Dunne, Wednesday 16:30



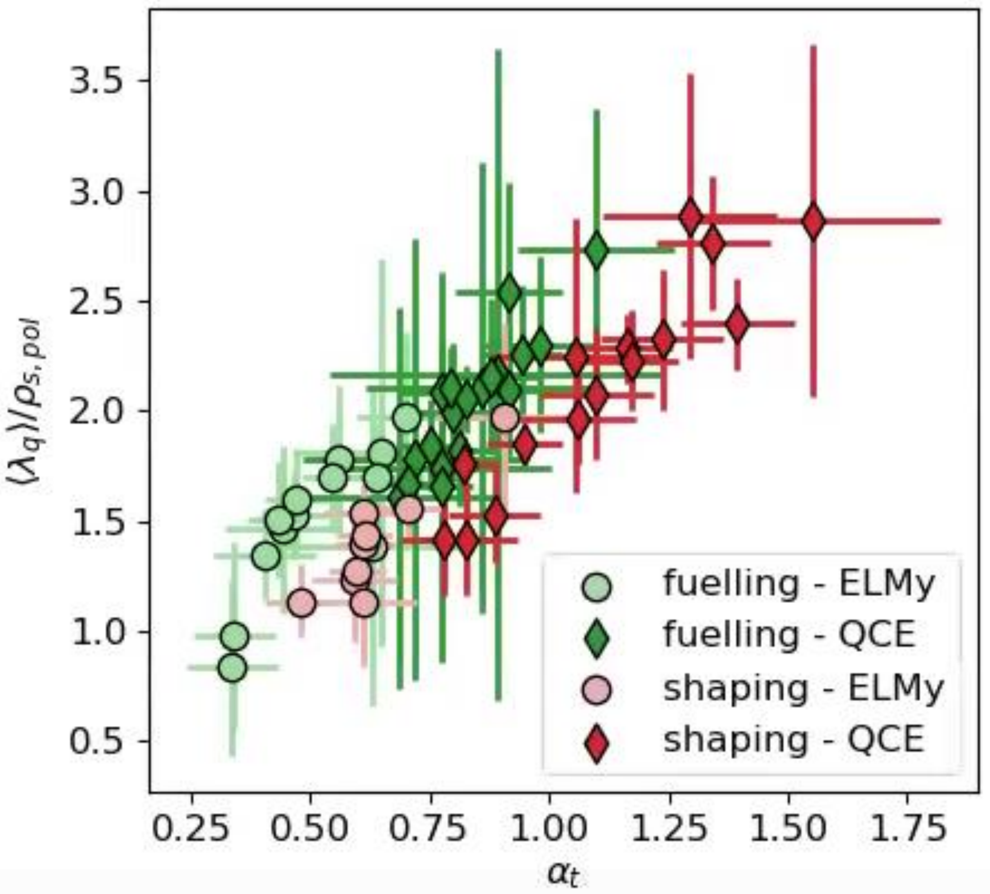
[B. Labit et al., NF 2019]

Larger λ_q and density shoulder in the QCE

- SOL power width larger in QCE than in Type-I ELMy H-mode
  - ➢ Increase correlates with turbulence parameter α_t

$$\alpha_t = KRq_{cyl}^2 \frac{n_{e,sep}}{T_{e,sep}^2} Z_{eff} \propto q_{cyl} \nu_{ei}^*$$

- Large α_t values and QCE associated with density shoulder
  - ➢ Implications for first-wall loads?

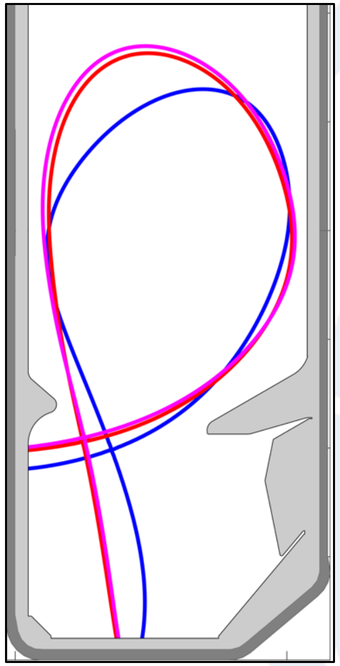


[A. Stagni et al., NF 2024]

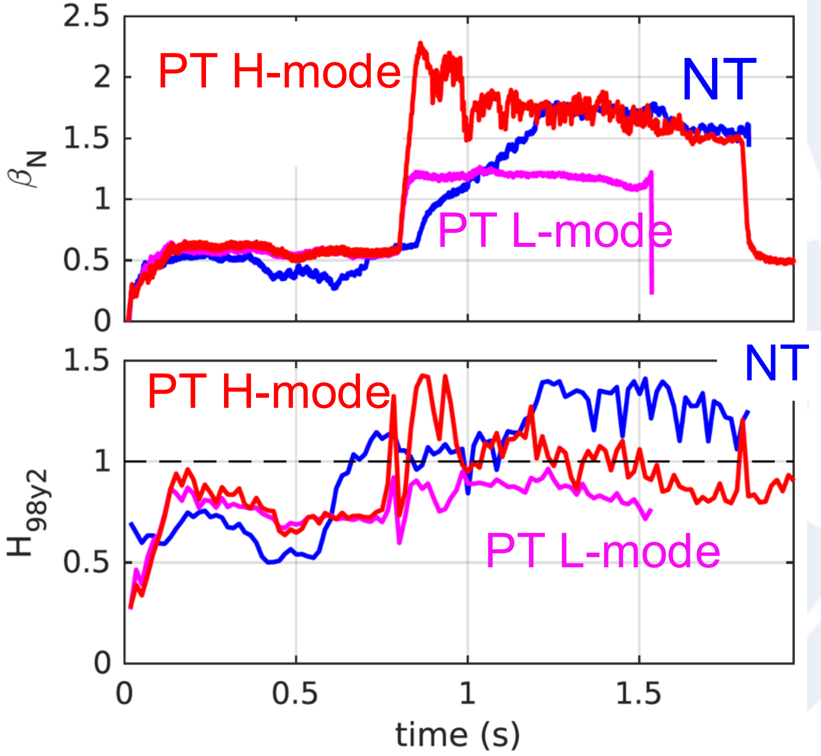
Towards core-edge integration in Negative Triangularity (NT)

NT a promising solution for high confinement, without drawbacks of H-mode

- NT more challenging to detach. [O. Février PPCF 2024, G. Durr-Legoupil-Nicoud 2025]
- Partly due to smaller λ_q at negative top δ [K. Lim PPCF 2023, R. Morgan NF 2025]



NBI-heated NT and PT plasmas



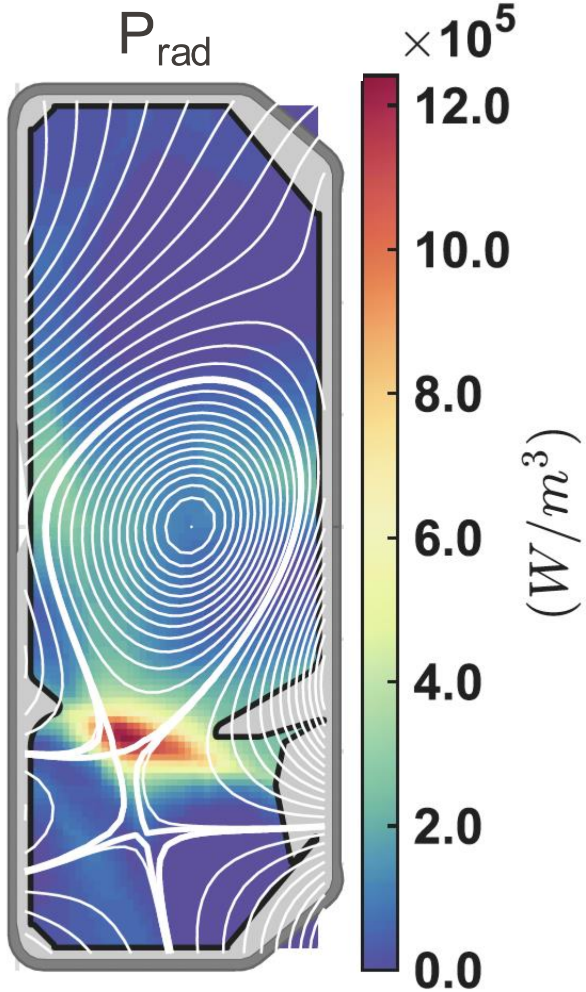
[O. Février et al., this conference]

Towards core-edge integration in Negative Triangularity (NT)

NBI-heated, high-performance NT scenario successfully detached with N_2 seeding

- Formation of an X-point radiator
- Detached outer and strongly cooled inner divertor
- Only modest reduction in performance
- Further improved power exhaust if combined with Snowflake divertor

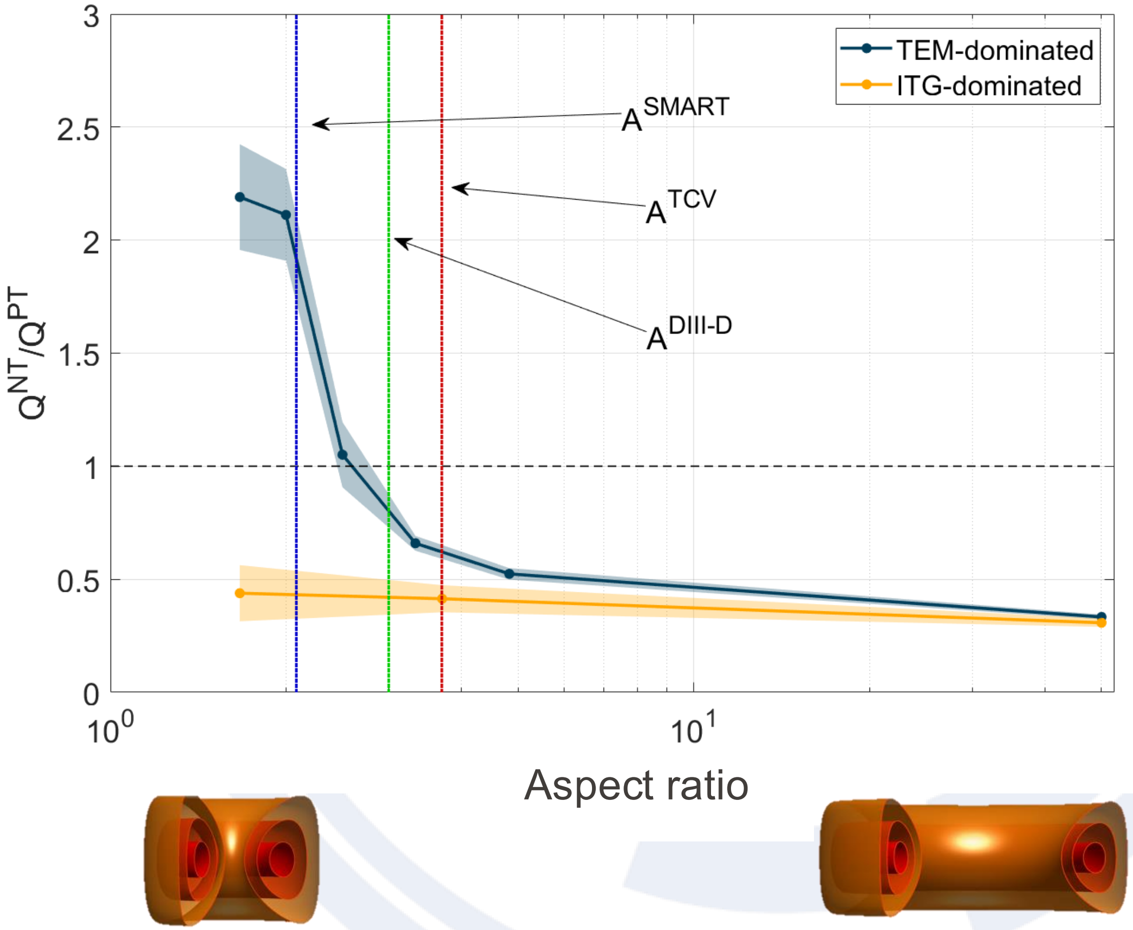
➢ **See O. Février, Wednesday PM**



[G. DLN et al., EPS 2025]

Improved understanding and extrapolations of NT

- Nonlinear GENE: at conventional and large R/a and $\kappa > 1$, ITG and TEM more stable in NT [A. Balestri PPCF 2024]



[A. Balestri et al., PPCF 2024]

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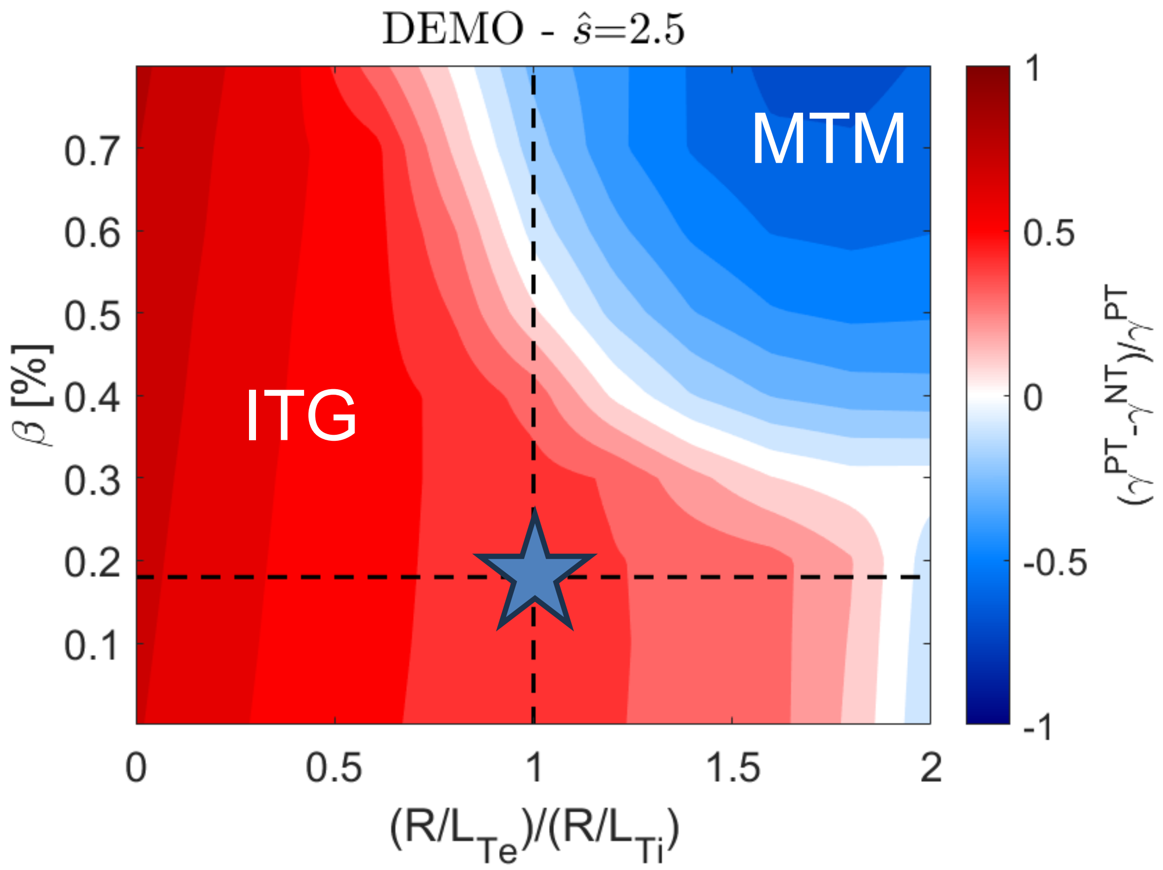
Promising reactor predictions

- e.s. ORB5: no ρ^* degradation of NT benefits [G. Di Giannatale, PPCF 2024]
- GENE: turbulence stabilized at high β in NT, unless MTMs dominate (potential issue for spherical tokamaks) [A. Balestri, EPS 2025]



[A. Balestri et al., EPS 2025]

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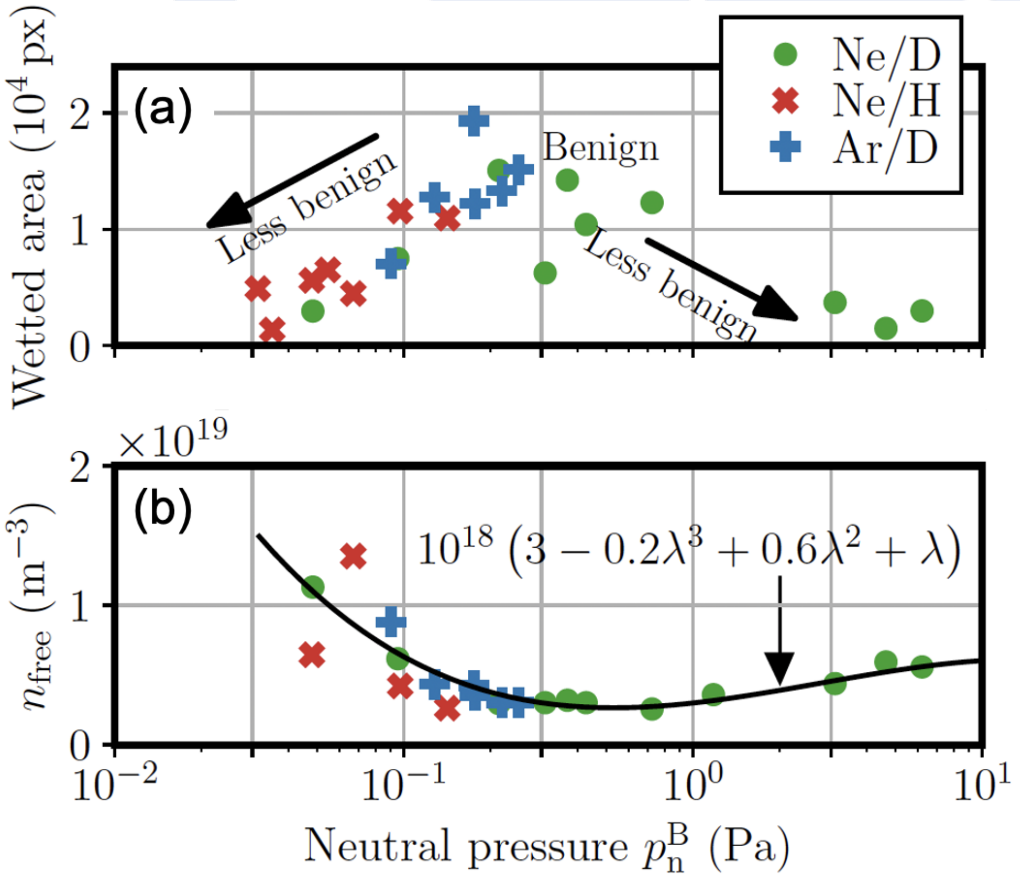
Mitigating Runaway Electron (RE) beam risks

- Expulsion of RE seed population with ECRH can prevent beam formation [J. Decker NF 2024]
- If RE beam forms, low-Z Benign Termination could mitigate it [U. Sheikh PPCF 2024]
  - ➢Requires low density companion plasma, for fast MHD instability expelling REs over broad wetted area
  - ➢Low density achieved in specific neutral pressure range

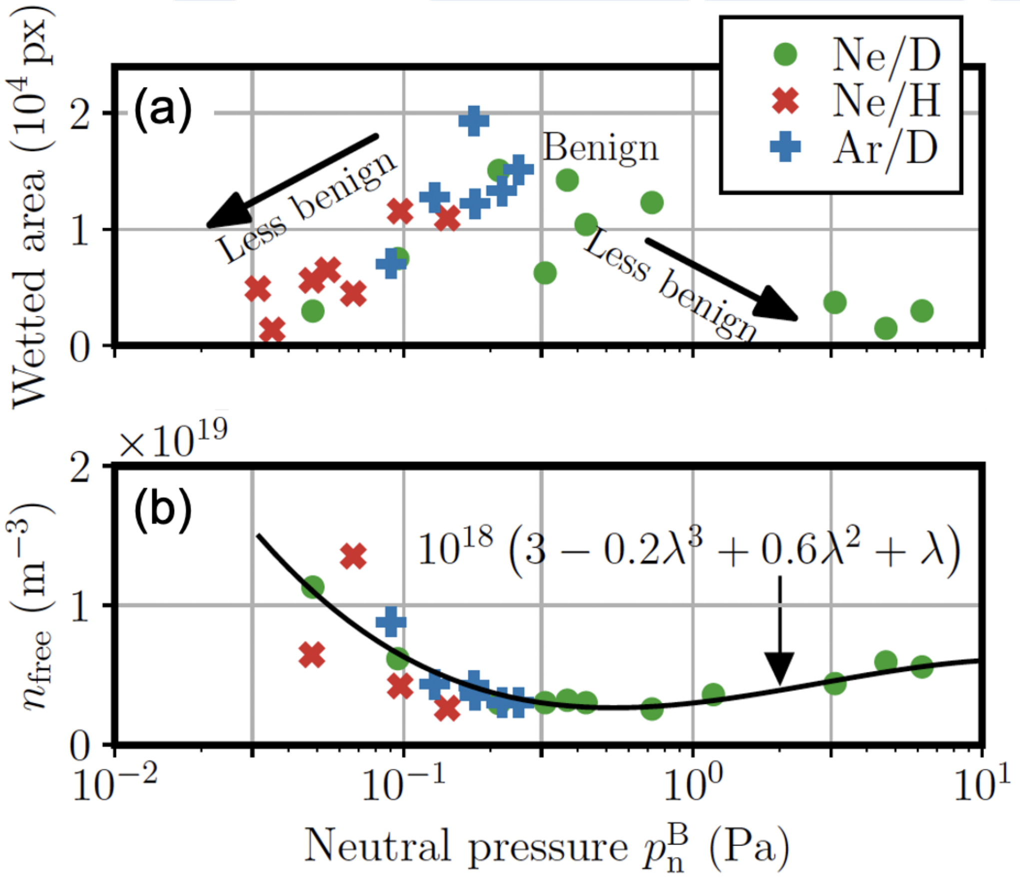


[M. Hoppe et al., PPCF 2025]

Mitigating Runaway Electron (RE) beam risks

- Lower neutral pressure limit reproduced with SOLPS-ITER [E. Tonello in prep.]
- Upper limit partly explained by increasing rate of RE impact ionization [M. Hoppe PPCF 2025]
- Multi-device study indicates a pressure range of 0.2 Pa - 1.5 Pa for ITER
  - ➢ Challenging for current staggered injection scheme

➢ **See U. Sheikh, Wednesday AM**

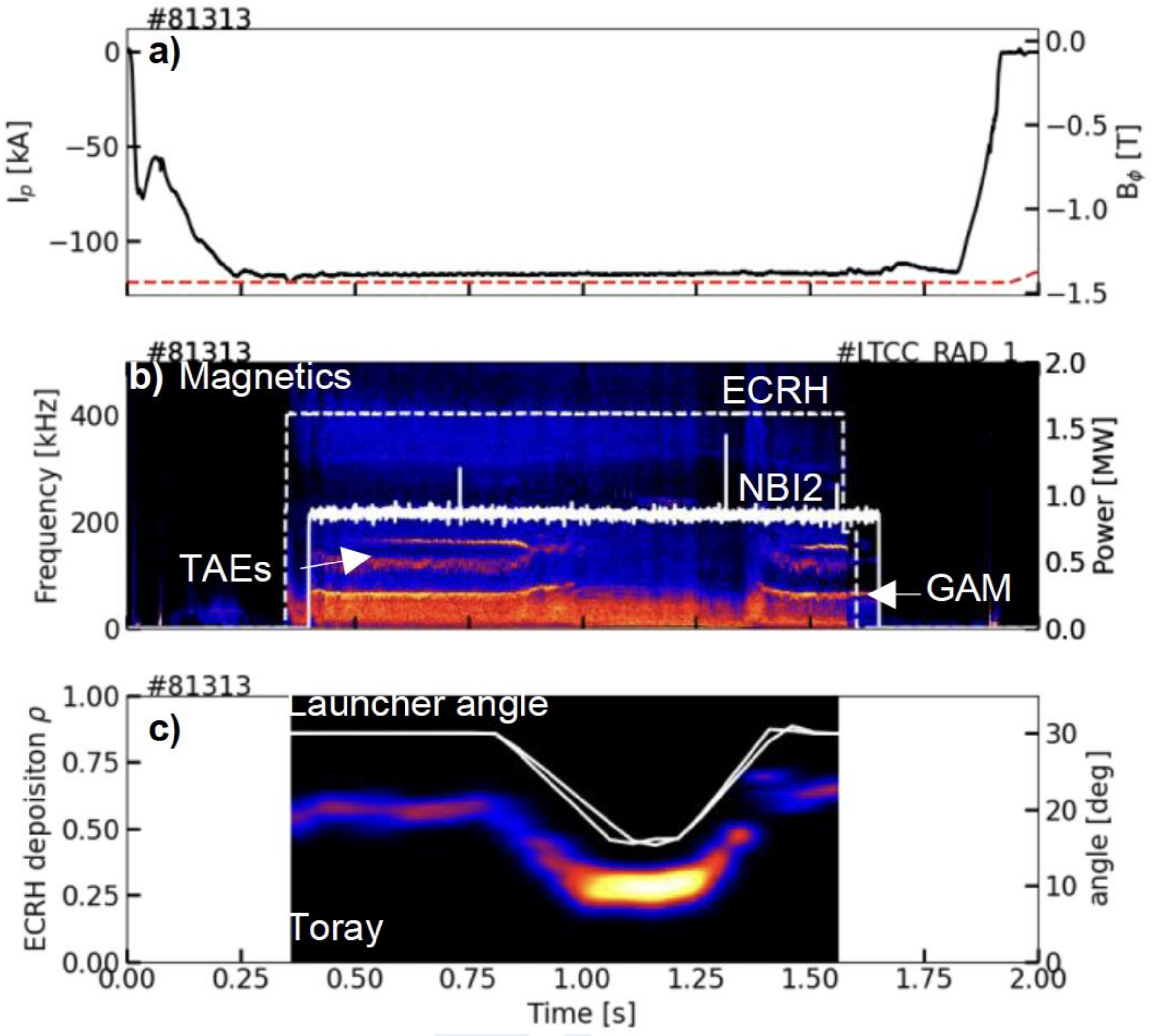


[M. Hoppe et al., PPCF 2025]

Alfvén Eigenmode (AE) excitation and suppression

- AEs routinely excited by counter-NBI
- Robust stabilization by on-axis ECRH
- Stabilization with ECCD, more efficient in counter-I_p
- Mitigation by negative triangularity

➢ **See A. Van Vuuren, Thursday PM**



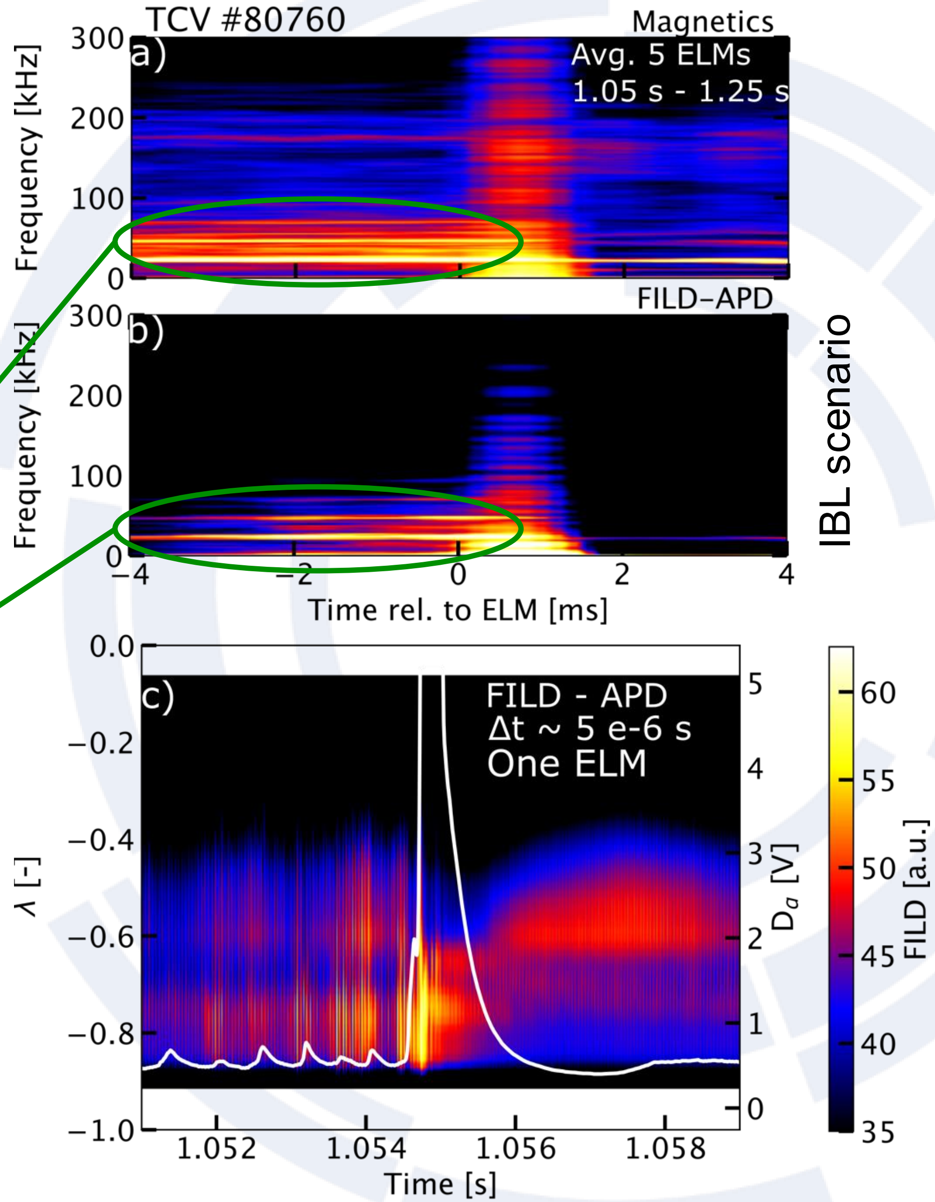
[A. Van Vuuren et al., this conference]

Elucidating inter- and intra-ELM Fast-Ion (FI) losses

- FI loss studies in ITER-baseline and low-ν* scenarios
  [J. Poley NF 2025, J. Poley in prep.]
- Significant FI losses due to NTMs and AEs, respectively

First-time, μs and velocity-space resolved FI loss measurements

Low-frequence NTMs drive FI losses



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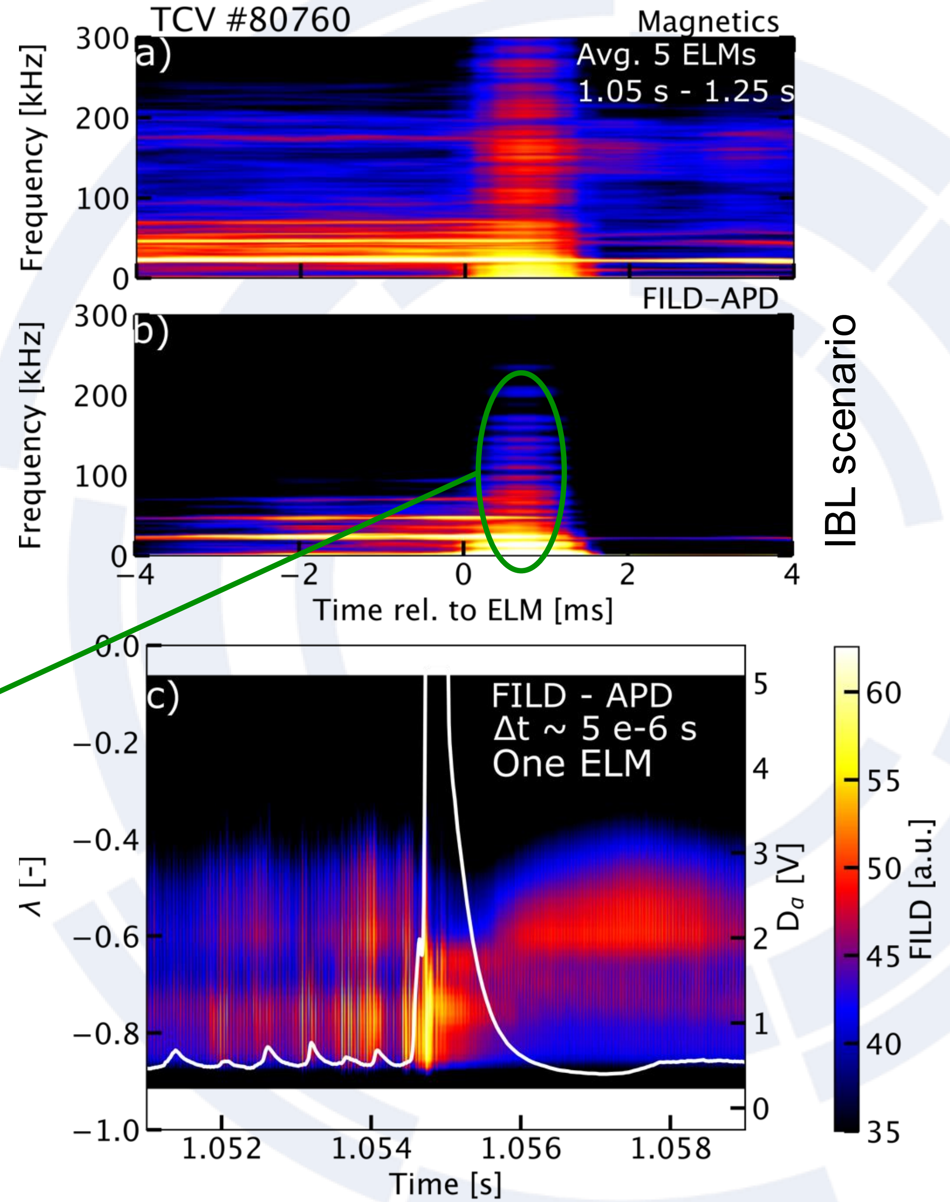
First-time, μs and velocity-space resolved FI loss measurements

Broad FI loss spectrum during ELM



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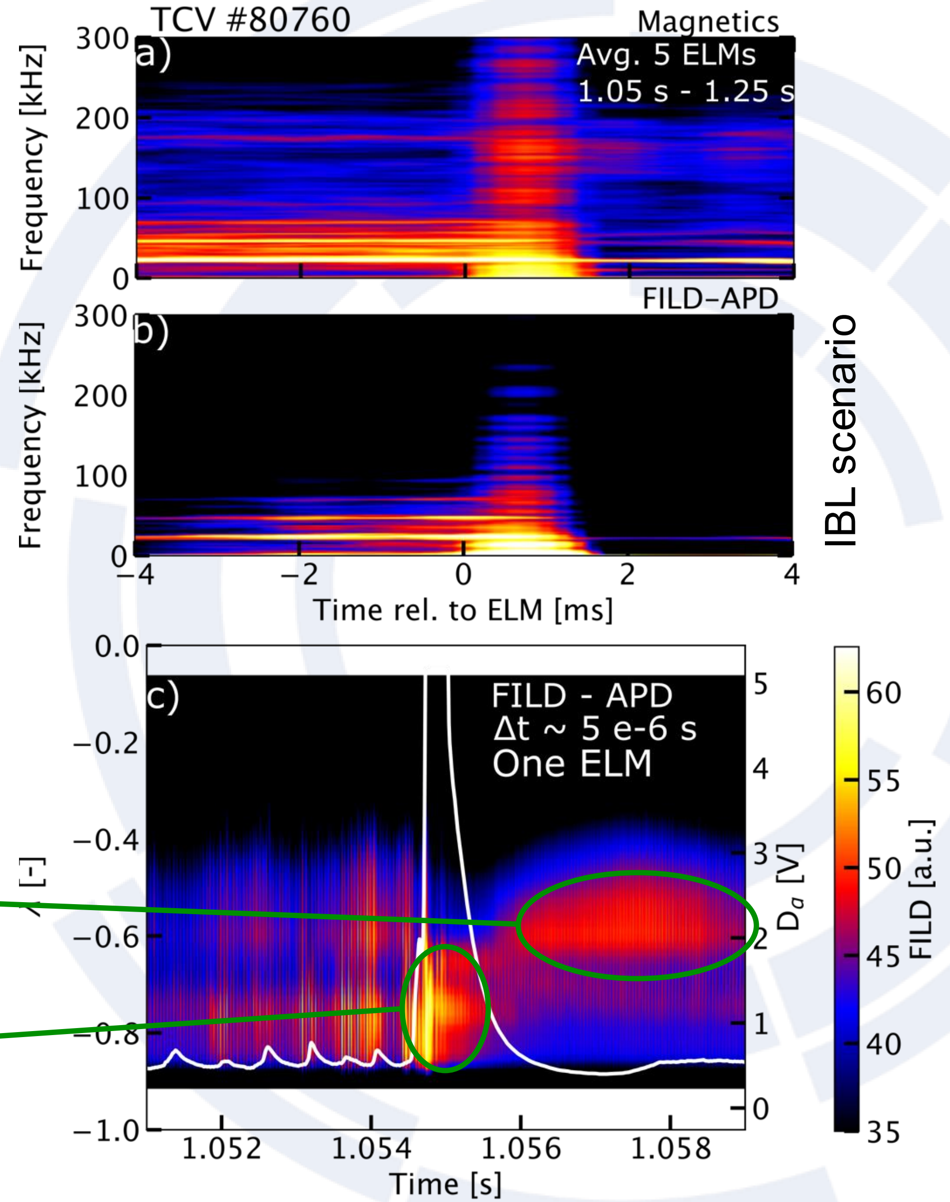
First-time, μs and velocity-space resolved FI loss measurements

Neoclassical losses (ASCOT5)

Anomalous losses



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  [J. Poley NF 2025, J. Poley in prep.]
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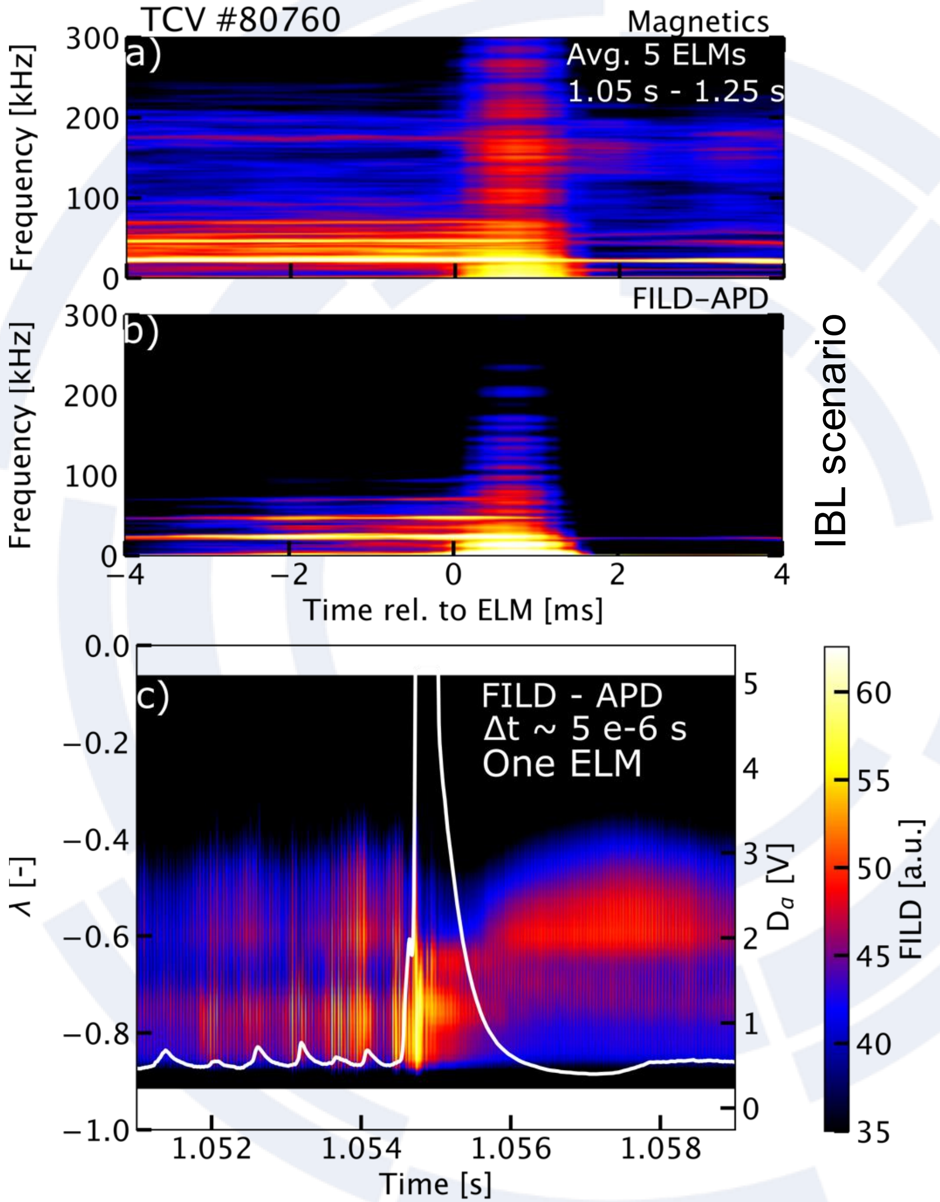
First-time, μs and velocity-space resolved FI loss measurements

- FI acceleration observed during ELMs, with FIs reaching 1.5 x NBI energy
  [J. Poley NF 2025, J. Poley in prep.]



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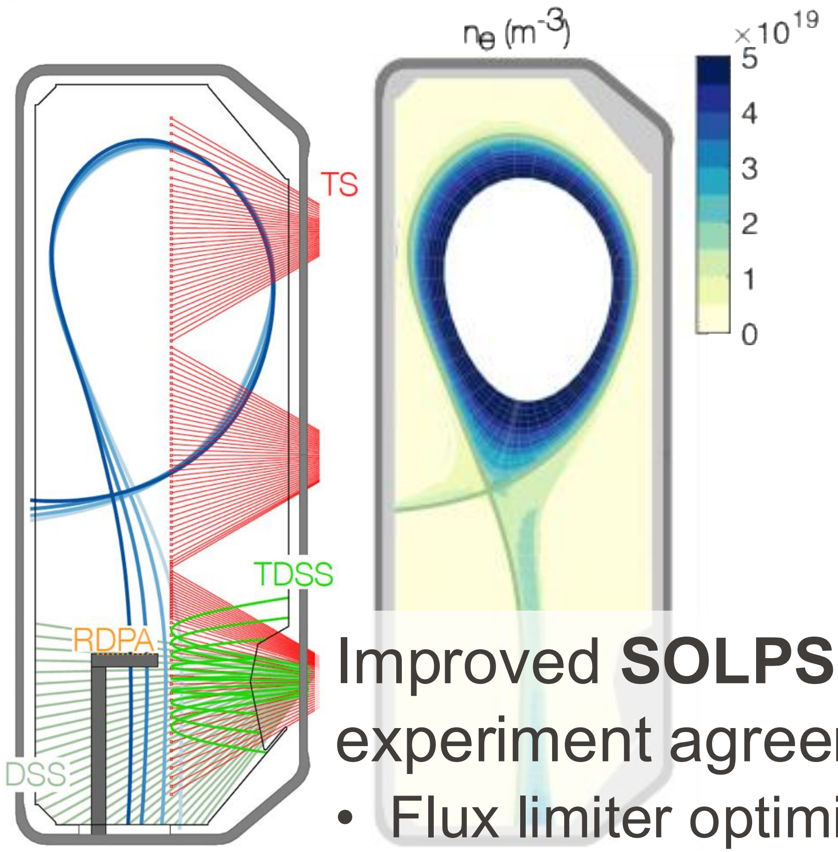
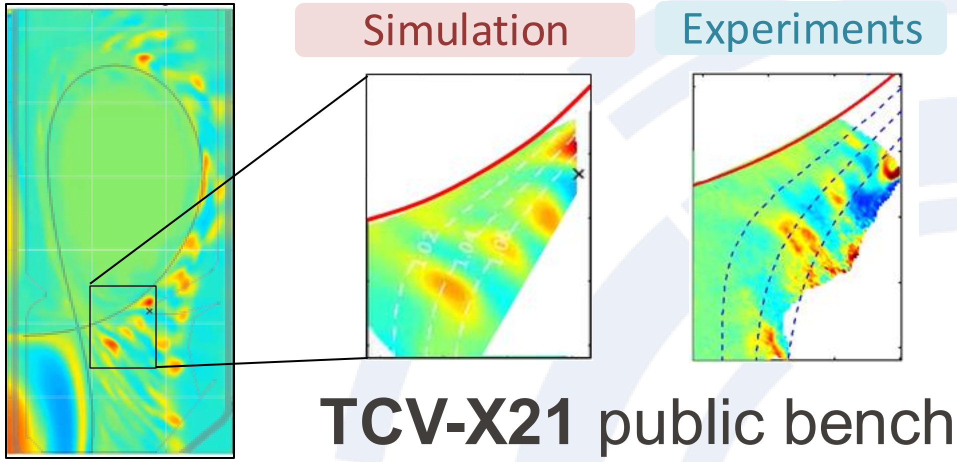
TCV as a continued testbed for boundary code validation





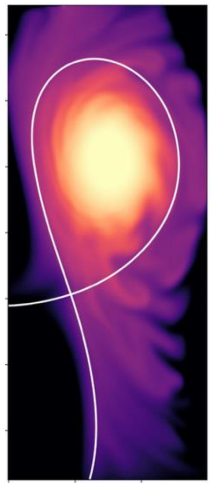
TCV-X21 public benchmark case [De Oliveira NF 2022]

- Inclusion of neutrals [Wang NF 2024]
- Filament dynamics [Wang in prep]

Improved **SOLPS-ITER** vs experiment agreement with:

- Flux limiter optimization
- Improved sputtering model
- Core coupling via JINTRAC

➢ **See E. Tonello, Wednesday 15:20**

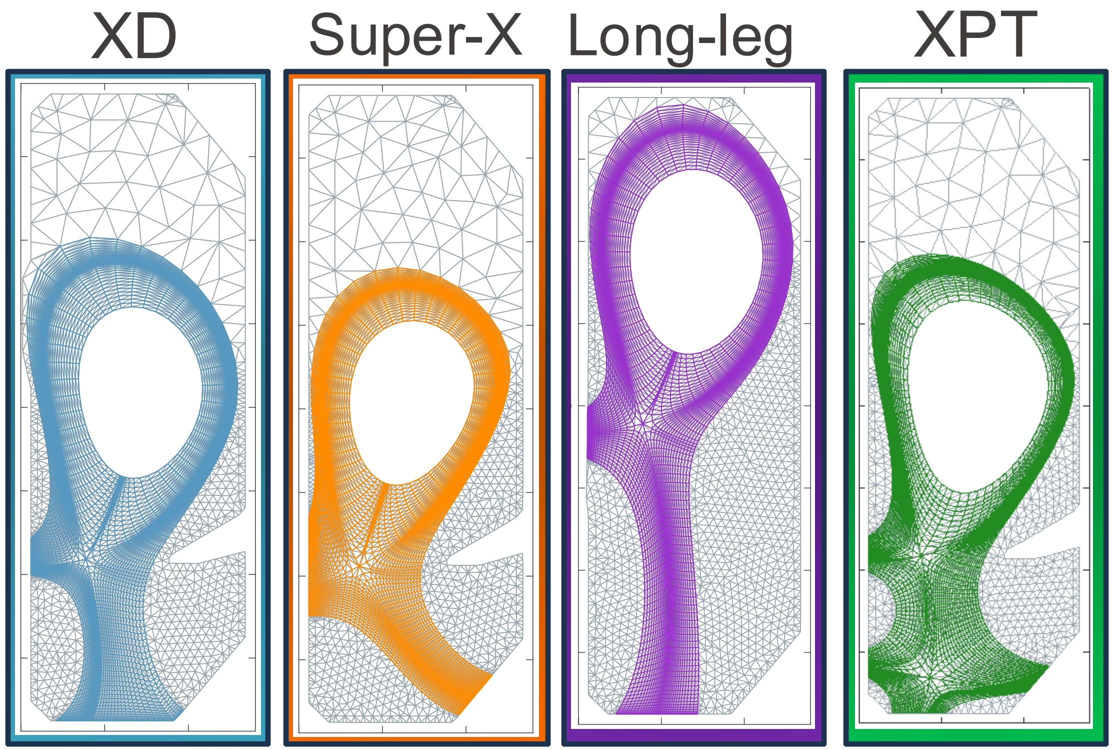


TCV-X23 → detachment with **GBS** [Mancini EPS 2025]

➢ **See P. Ricci, Wednesday AM**

ETG pedestal simulations with **GENE** [Krutkin PPCF 2025]

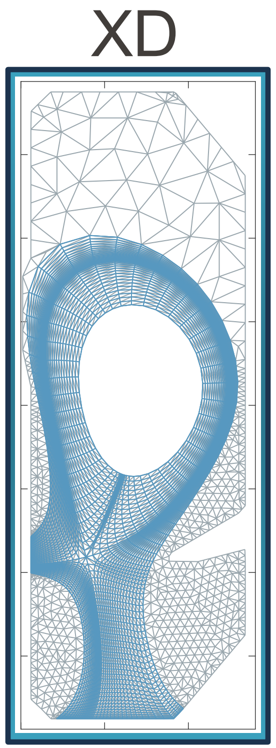
Assessment of individual alternative divertor features and interpretation with SOLPS-ITER

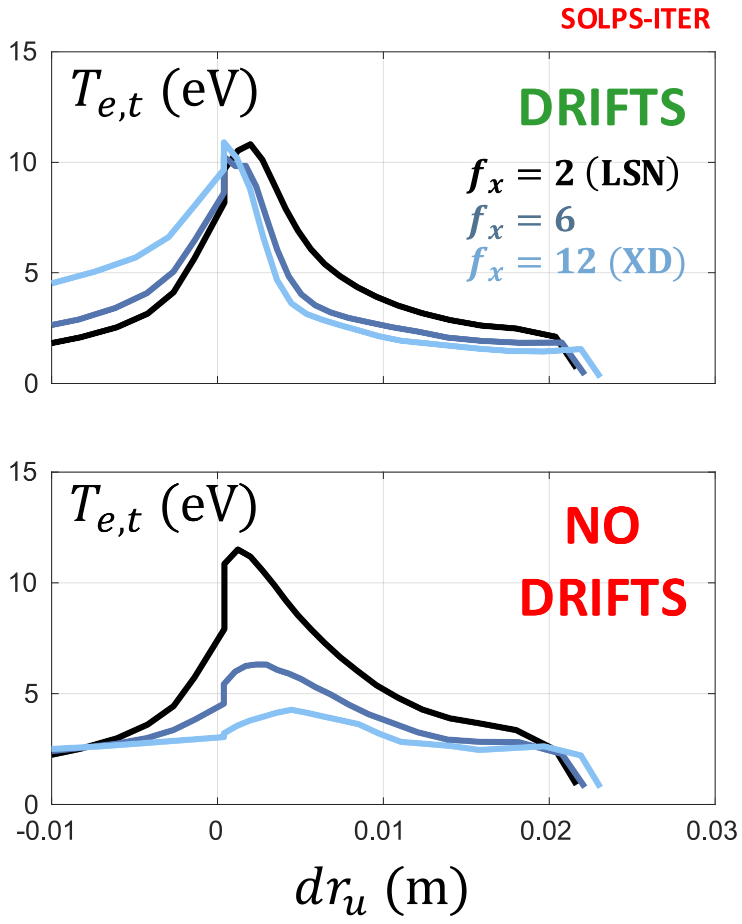


[M. Carpita et al., AAPPS 2025]

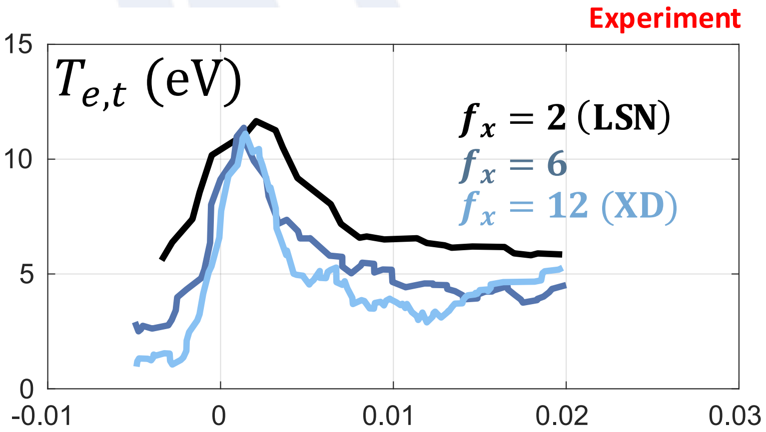
- Alternative divertors simulated routinely with SOLPS-ITER – drifts fully included [M. Carpita NF 2025]
- Simulations qualitatively reproduce most of the experimental results

Assessment of individual alternative divertor features and interpretation with SOLPS-ITER



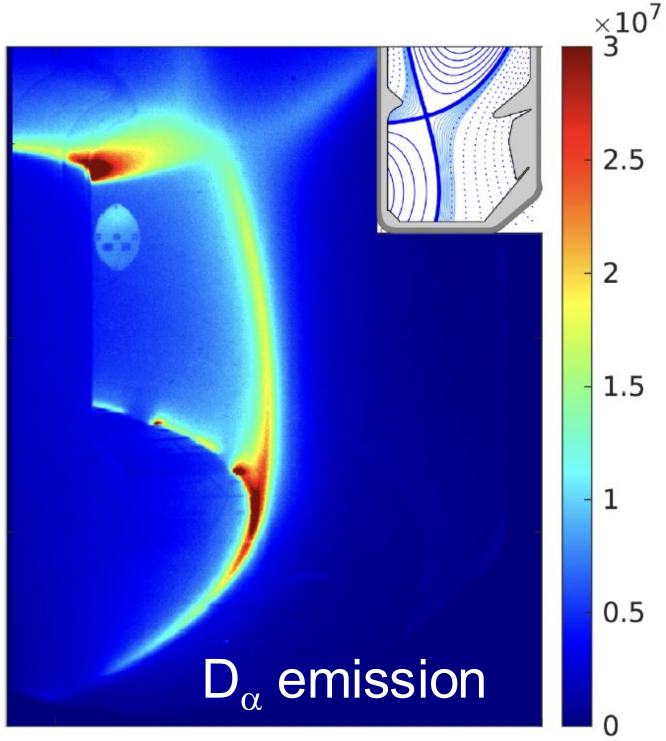


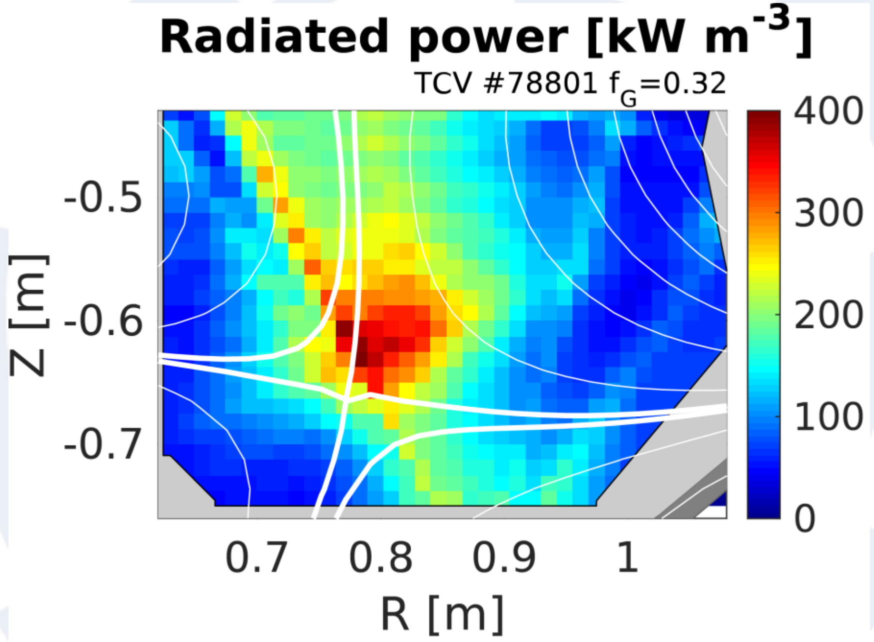
- Alternative divertors simulated routinely with SOLPS-ITER – drifts fully included [M. Carpita NF 2025]
- Simulations qualitatively reproduce most of the experimental results, **but inclusion of drifts is key!** [M. Carpita AAPPS 2025]



Discovery of the *X-point target radiator (XPTR)* regime

- Radiation localization around secondary X-point of X-Point Target (XPT) divertor identified



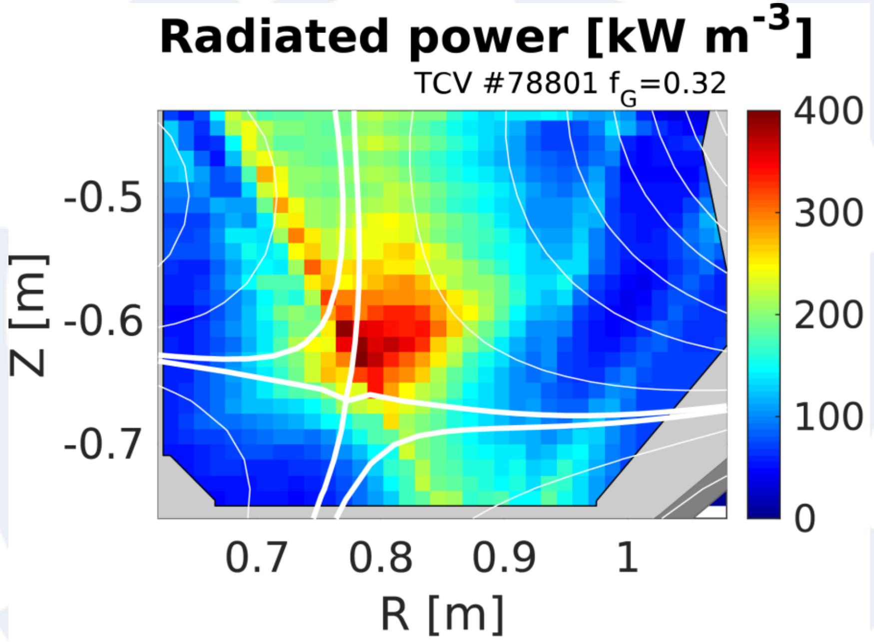


[K. Lee et al., PRL 2025]

Discovery of the *X-point target radiator (XPTR)* regime

- Radiation localization around secondary X-point of X-Point Target (XPT) divertor identified
  - Strongly facilitated detachment access
  - Significantly reduced sensitivity of the radiative front position

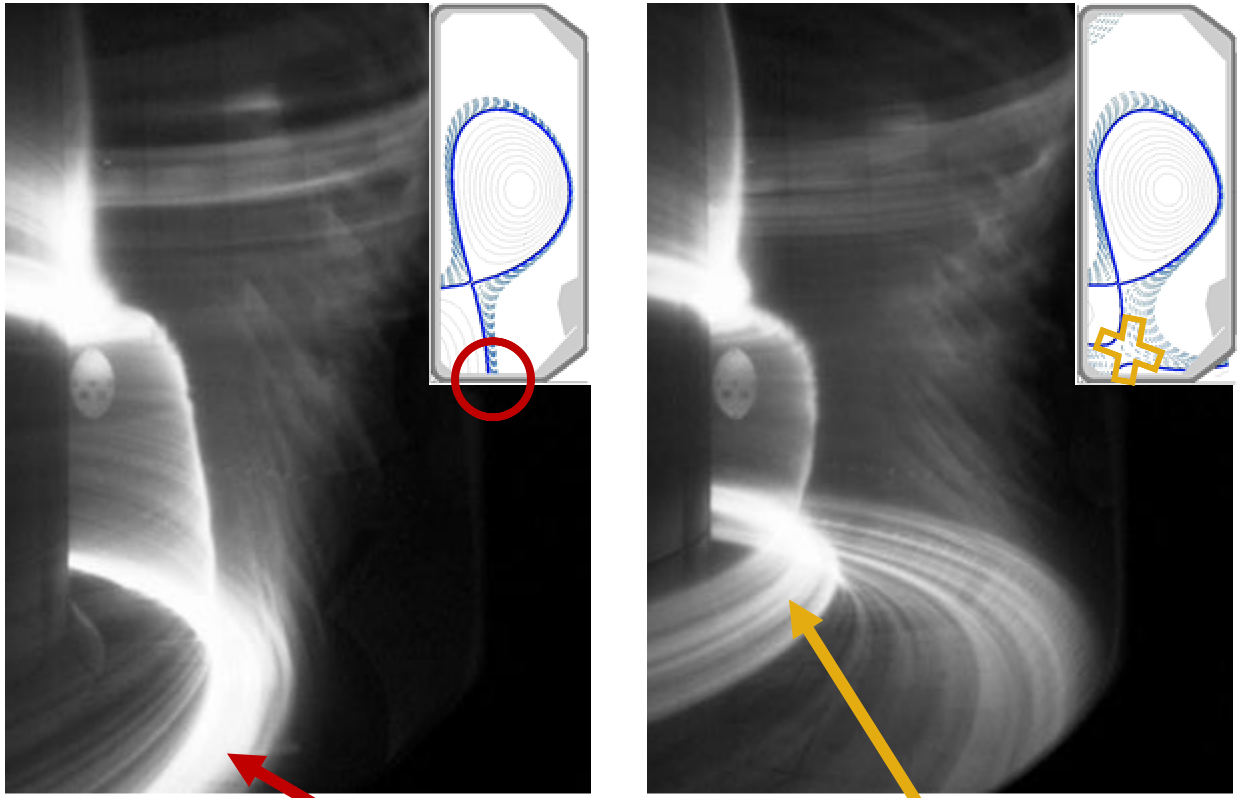
➢ Novel power exhaust concepts where edge cooling can be avoided during divertor detachment



[K. Lee et al., PRL 2025]

X-point target is able to mitigate type-I ELMs

FastCam CIII frame during Type-I ELM

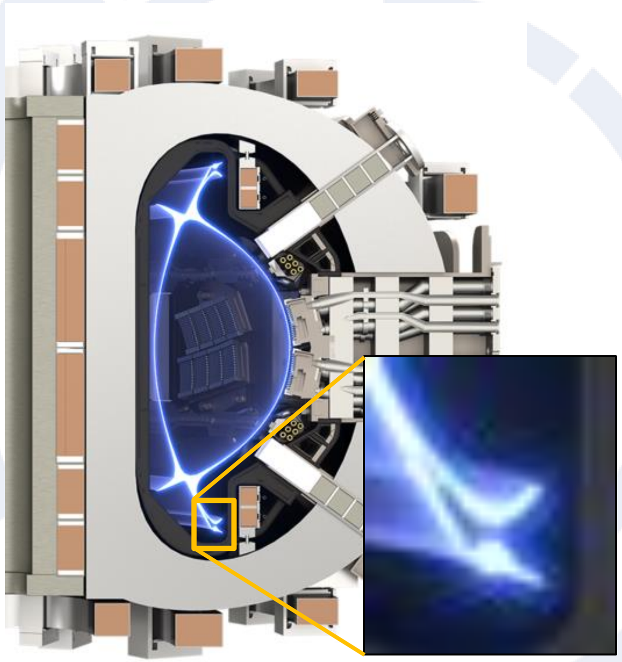


CIII emission during ELMs is strong at target

CIII emission during ELMs concentrates on 2nd X-point

[M. Zurita et al., APS 2025]

Overall, very promising results in view of SPARC!



- **E. Tonello, Wed. 15:20**
- **K. Verhaegh, Wed. 14:20**

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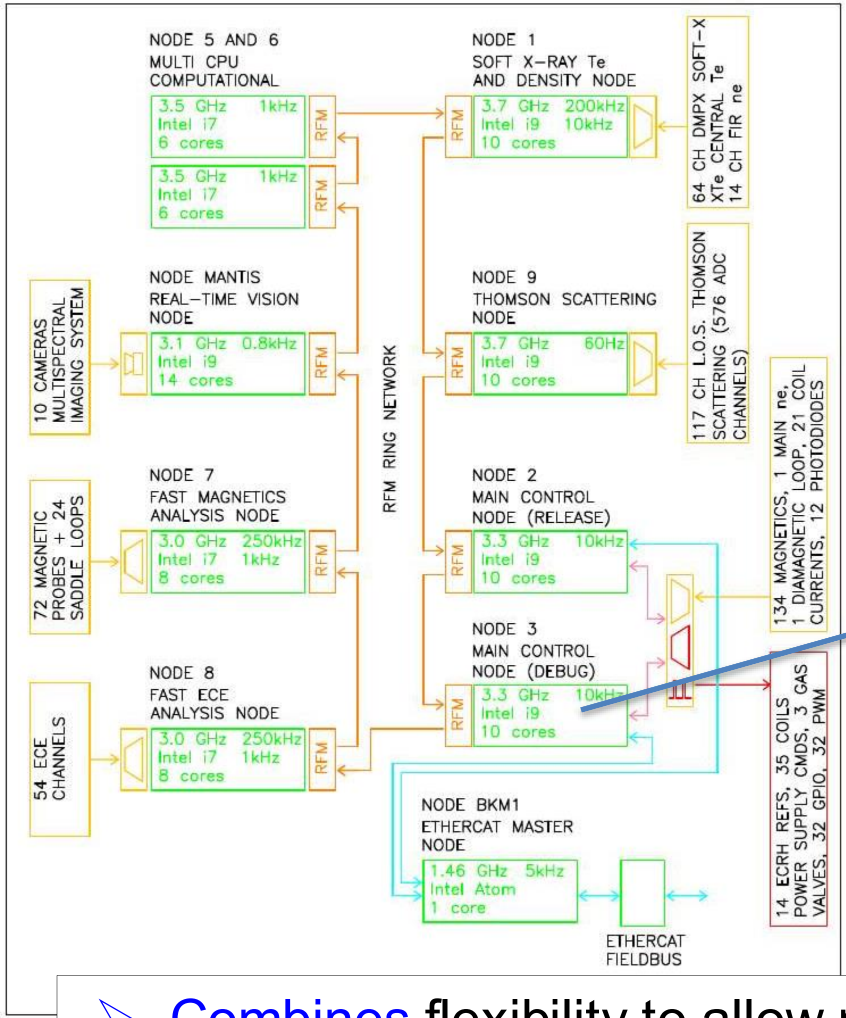
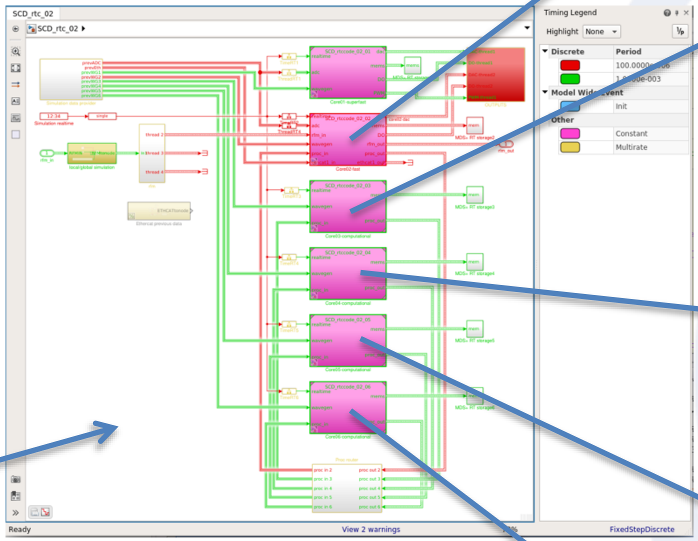
TCV digital distributed control system (SCD)

Hardware layout





CPU#1

- Main linear magnetic controller
- Fast diagnostics and actuator interfaces

CPU#2

- MEQ solver (RTLIUQE)
- Vertical growth rate estimator
- Disruption proximity estimator
- Active plasma shape controller

CPU#3

- Actuator manager and pulse scheduler (SAMONE)

CPU#4

- RAPTOR (real-time heat transport and current diffusion simulator)

CPU#5

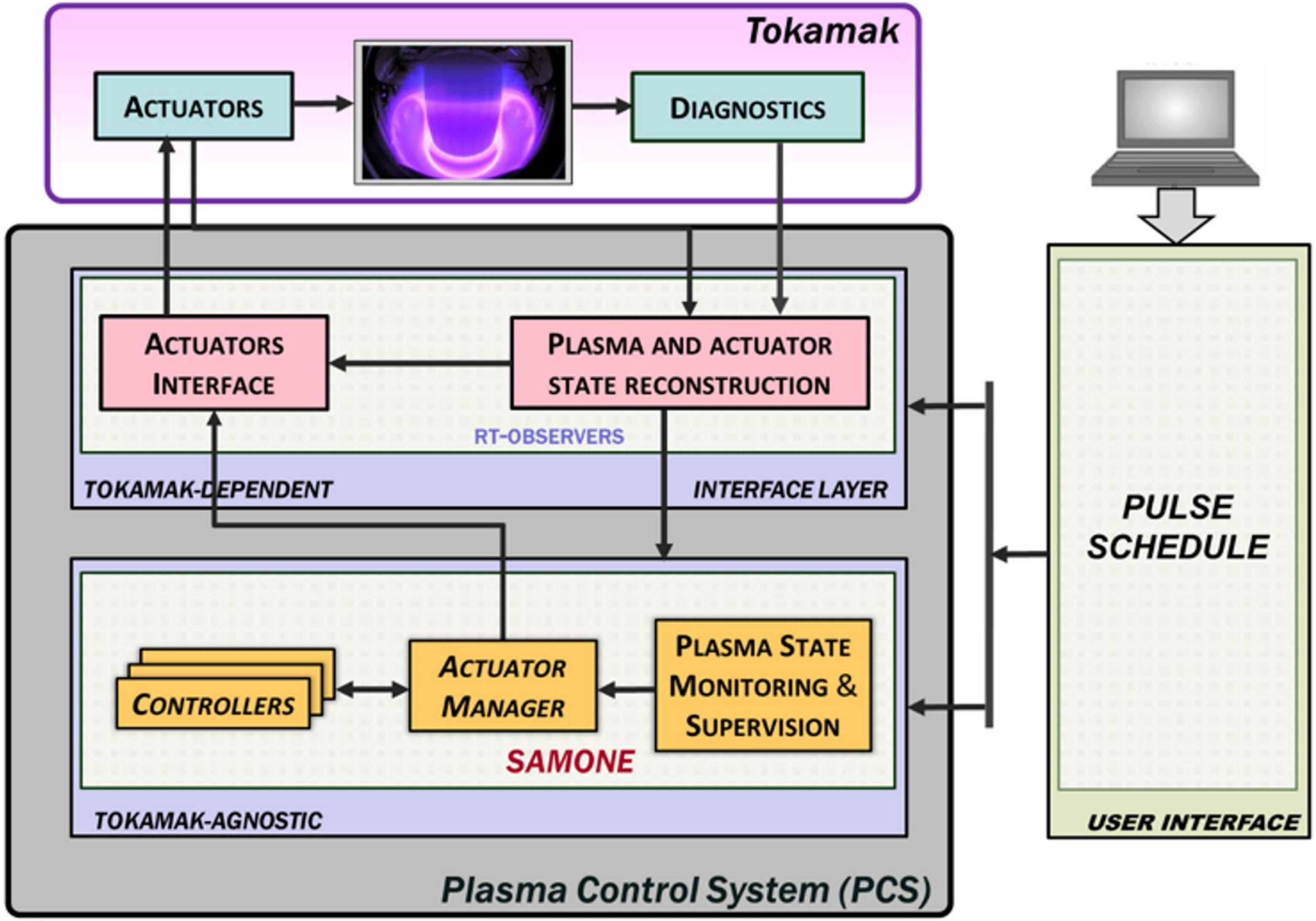
- RAPDENS (real-time model-based electron density observer)

[C. Galperti et al., FED 2024]

➢ Combines flexibility to allow rapid prototyping and implementation of new ideas with necessary rigor to ensure long-term algorithm maintenance

TCV's actuator manager system

- Separation of tokamak dependent and agnostic layers
- Generic implementation
- Flexible framework allowing easy maintenance and upgrade
- Concepts of integration and portability



[C. Galperti et al., FED 2024]
[F. Felici et al., IAEA-FEC 2021]

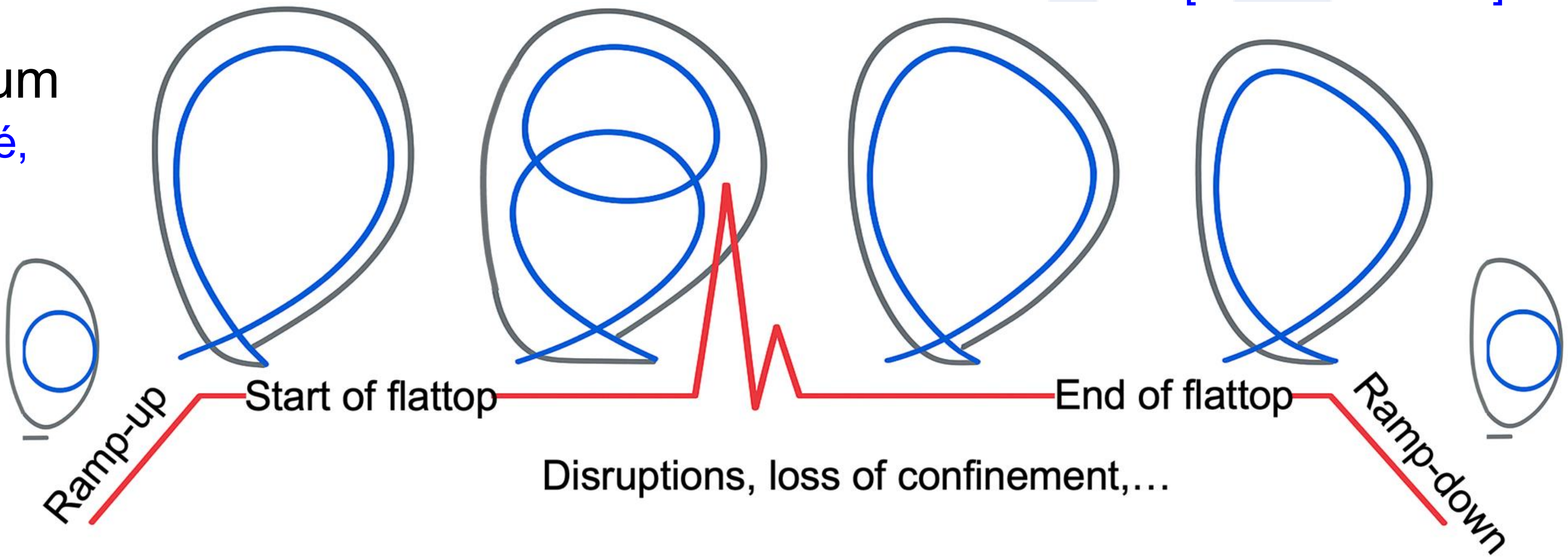
A glimpse of recent advances in tokamak control on TCV

Novel, real-time, model-predictive-control shape controller [Mele PPCF 2025]

Current limit avoidance testing for ITER [Frattolillo PPCF 2024]

Plasma state monitoring and events characterization with ML [Poels NF 2025] [Poels NF 2025]

Kinetic equilibrium prediction [Contré, in prep.]



Model-based breakdown design [di Grazia NF 2024]

Improved, model-based observers [Pastore, in prep.] [Van Mulders, subm.]

Detachment control during strikepoint seeping [Bosman, subm.]

Ramp-down trajectory optimisation with scientific ML [Wang, Pau Nat. Commun. 2025]

...

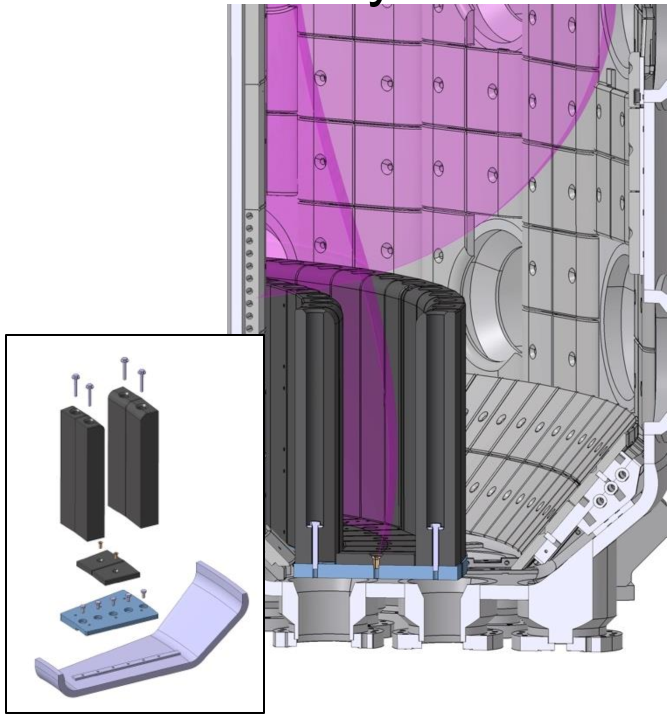
Outline

Highly productive campaings in 2024 and 2025 with a record of 3’517 successful discharges in 2024, further strengthened international collaborations, and preparations for various upgrades - can only cover some of the highlights here!

- ITER baseline and non-inductive scenarios
- Alternative ELM-free scenarios
- Fast particle physics
- Edge and divertor physics
- Plasma control
- Outlook

Outlook

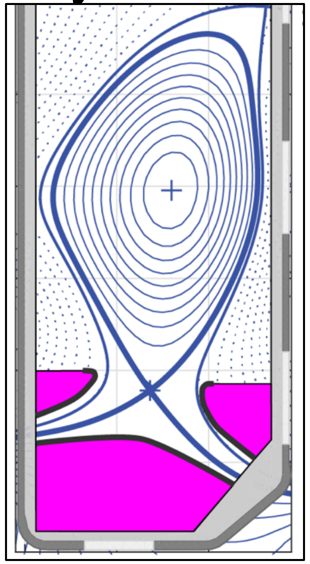
by 2026



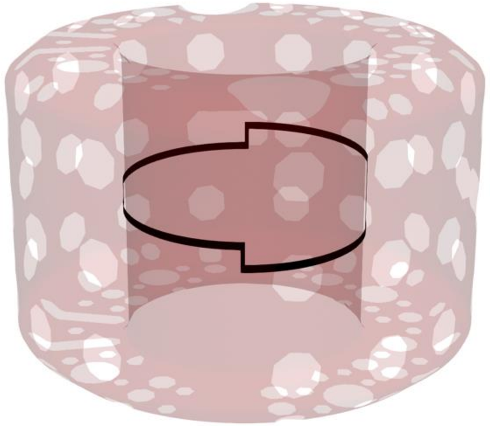
- Test of the Tightly-Baffled Long-Legged Divertor (TBLLD), a novel concept combining key exhaust features with minimum added complexity

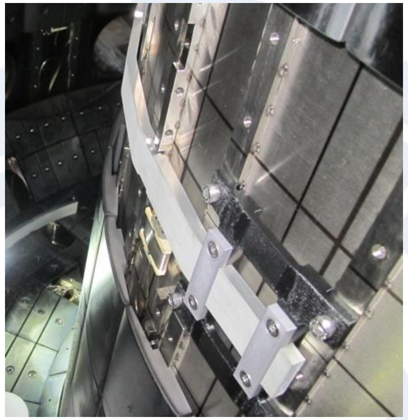
➢ **See H. Reimerdes, Wednesday PM**

by 2028



by 2026



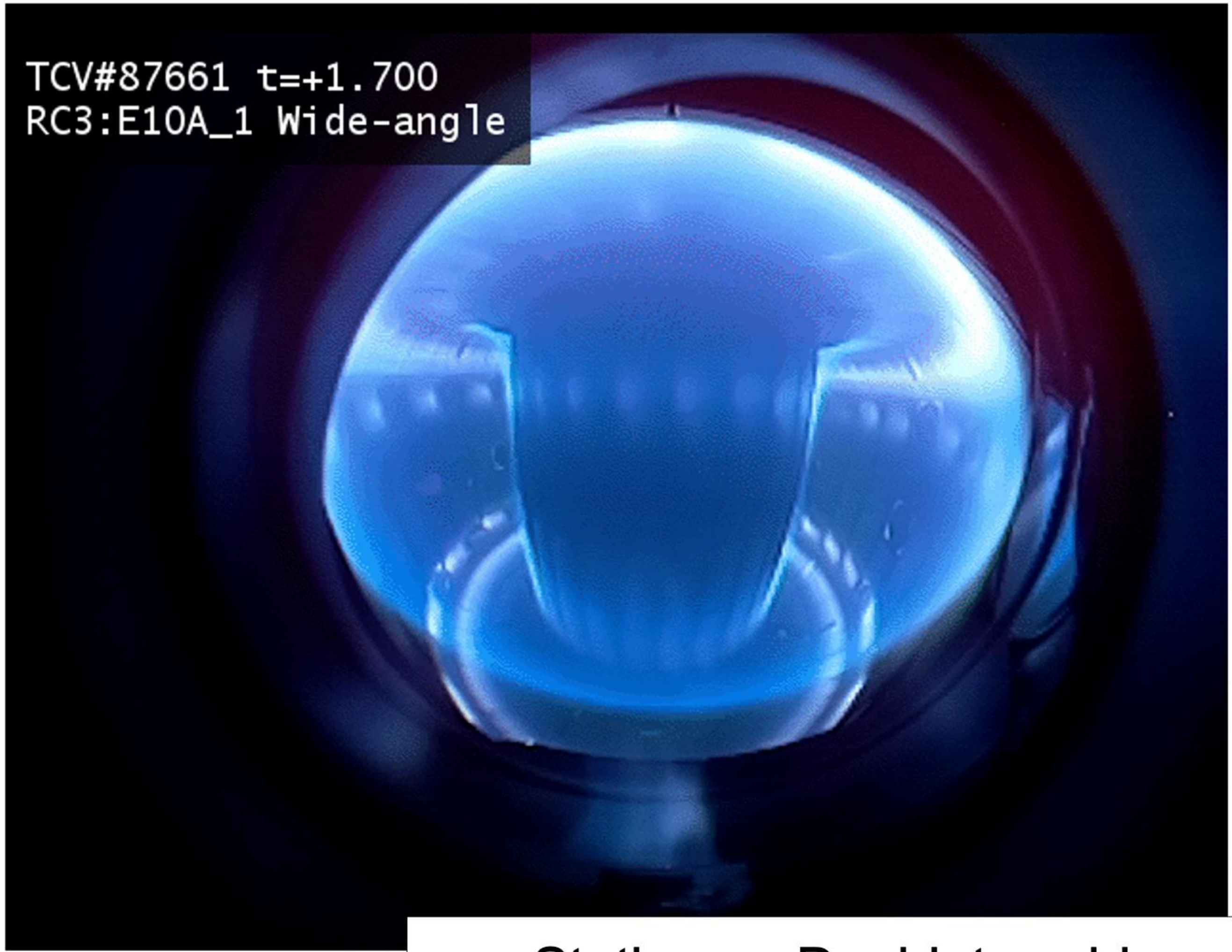


[U. Sheikh 2025]

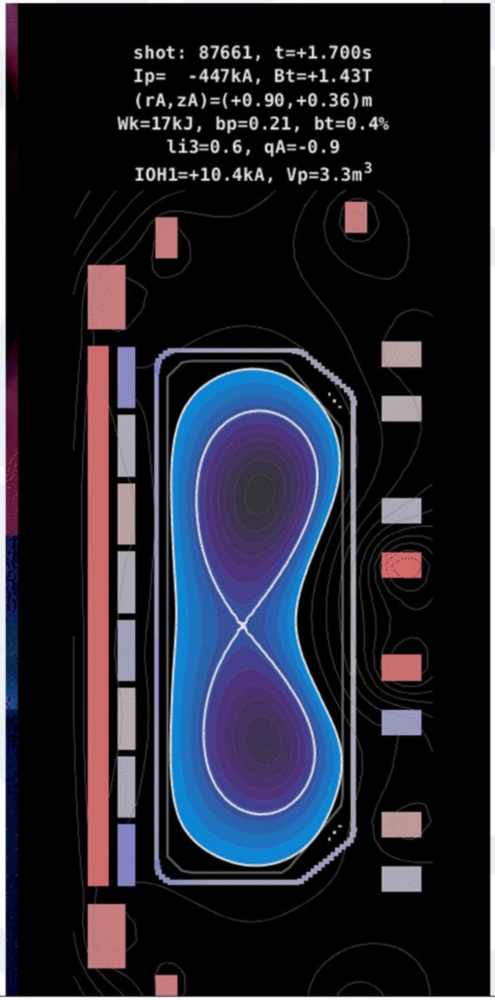
- Installation of Runaway Electron Mitigation Coil (REMC), passive in-vessel helical coil to suppress post-disruption RE beams [A. Battey in prep.]

- Installation of two additional 1MW, dual-frequency gyrotons (2026 and 2027)

A decades-long challenge overcome, opening a new research line



[C. Heiss APS 2025]



- Stationary Doublets achieved for the first time! 2s, I_p=700kA, κ=3.1
  - ➢ β-limit? Density limit? Confinement? Exhaust performance (radiative mantle)?...

Thank you to our collaborators in the public and private sectors!

+ many more!

We are always open for collaborations!