Progress and Innovations in the TCV Tokamak Research Programme

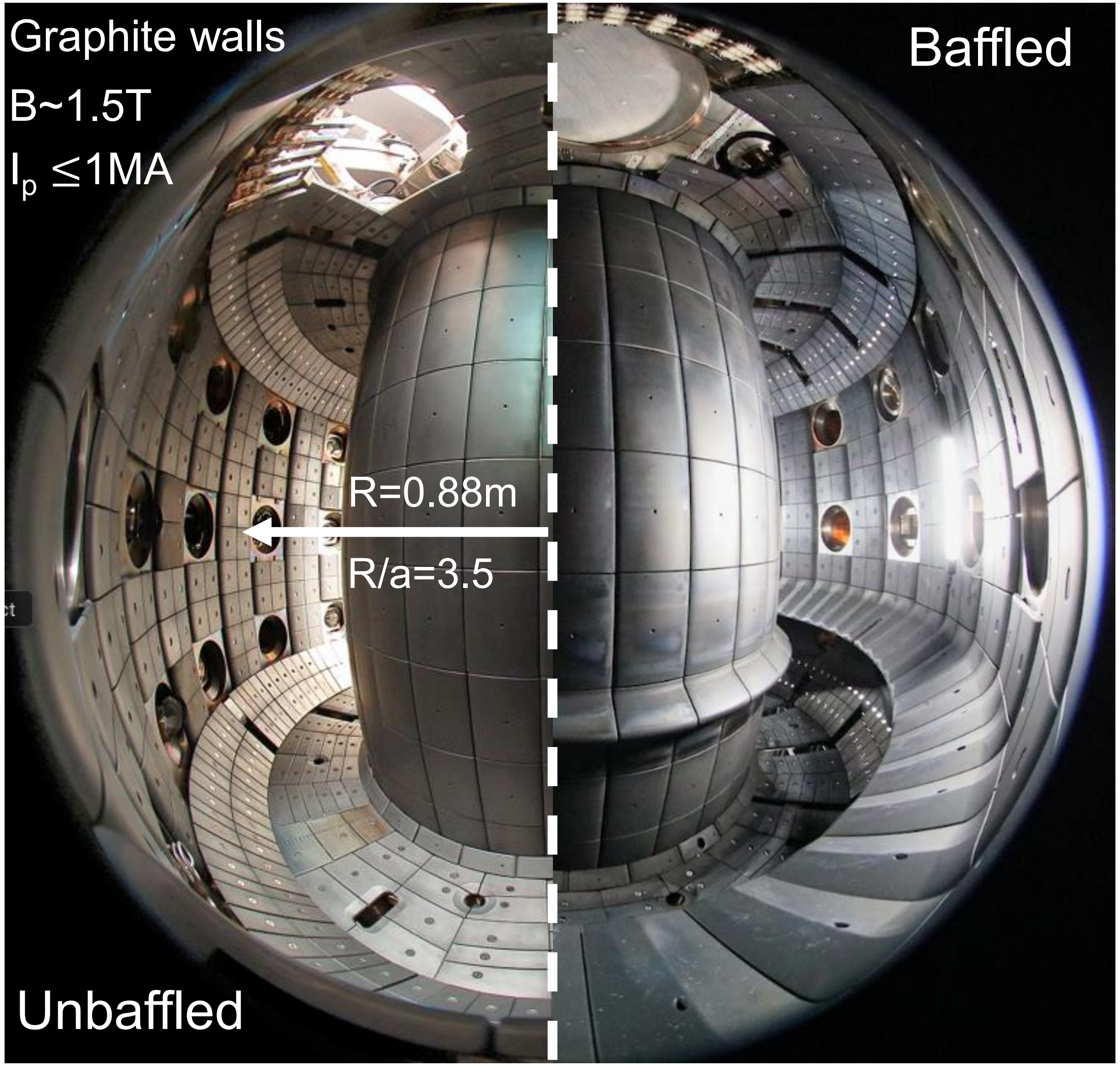
Christian Theiler for the TCV team

30th IAEA Fusion Energy Conference

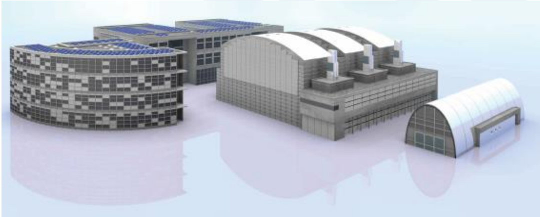
Chengdu, People's Republic of China, Oct. 13-18 2025

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.

Tokamak à Configuration Variable (TCV)

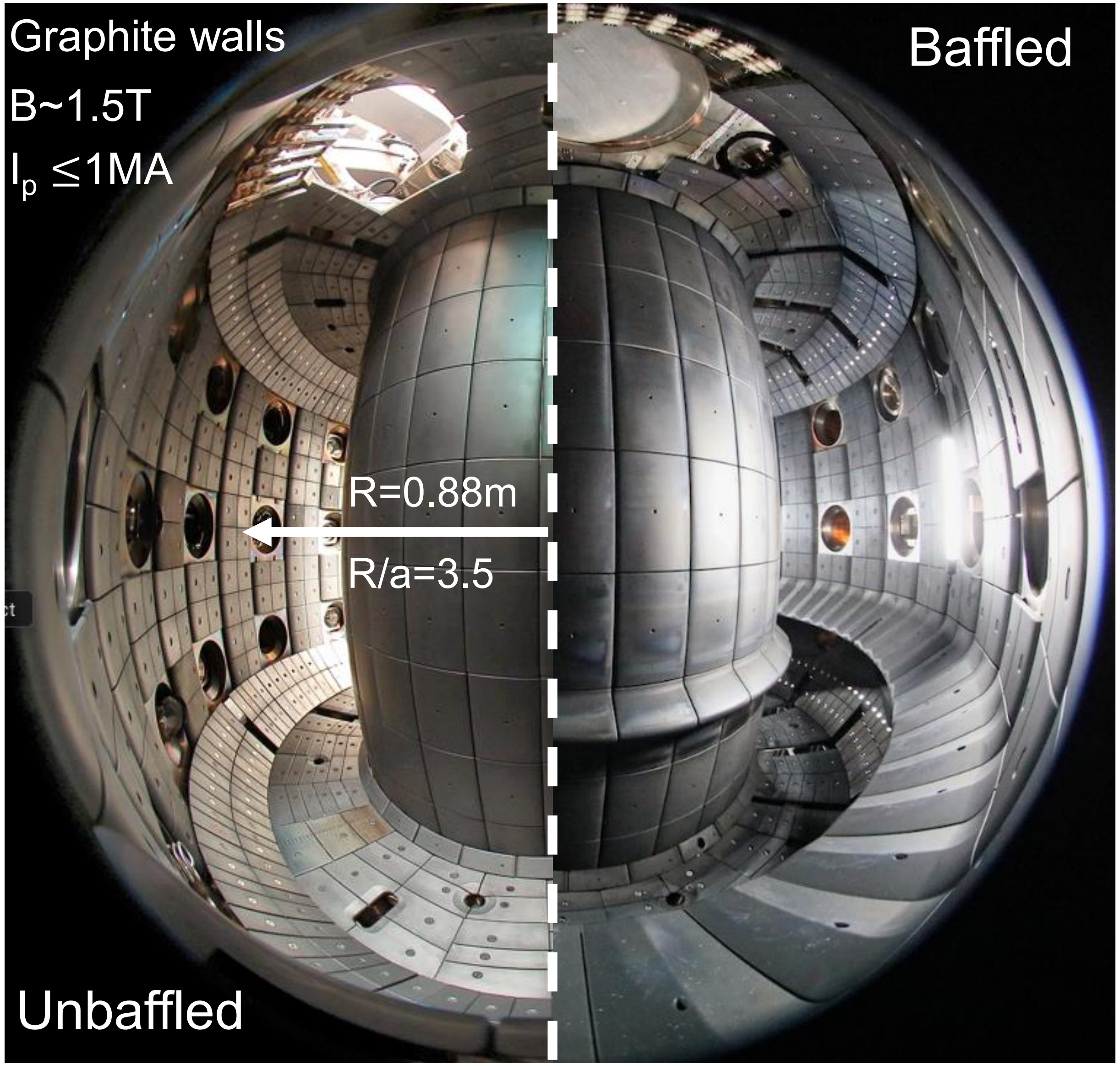


- High operational flexibility
- Extensive set of diagnostics
- Modern control system
- Versatile heating
- Unique magnetic shaping

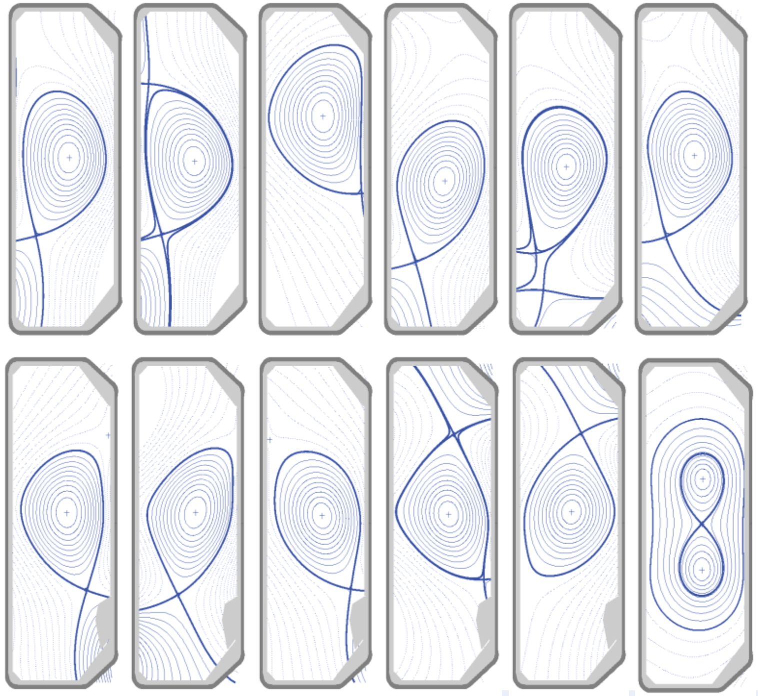


SWISS PLASMA CENTER

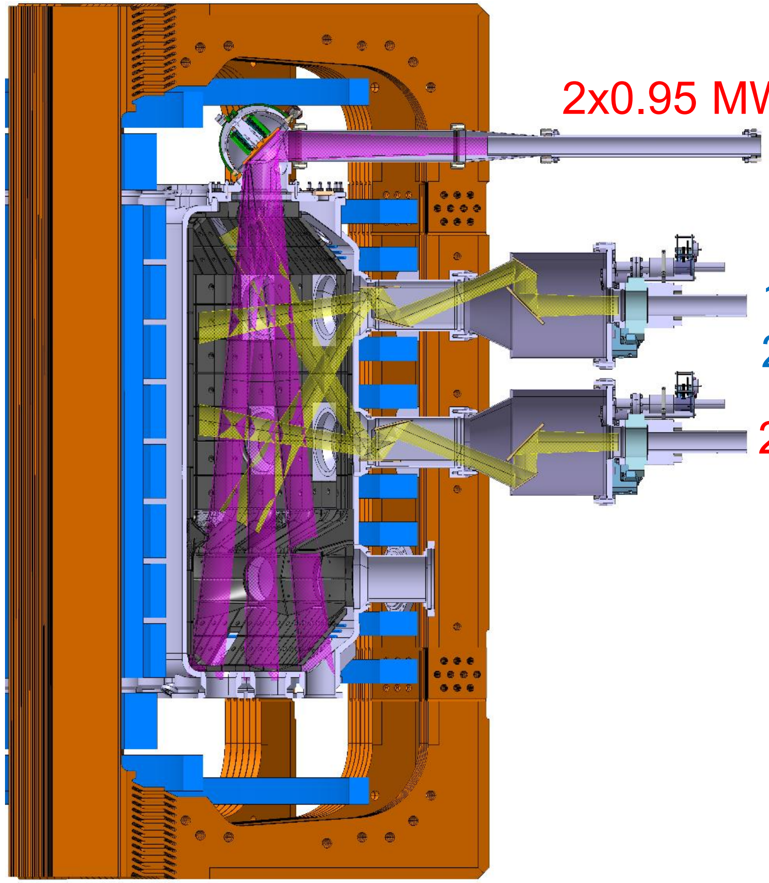
Tokamak à Configuration Variable (TCV)



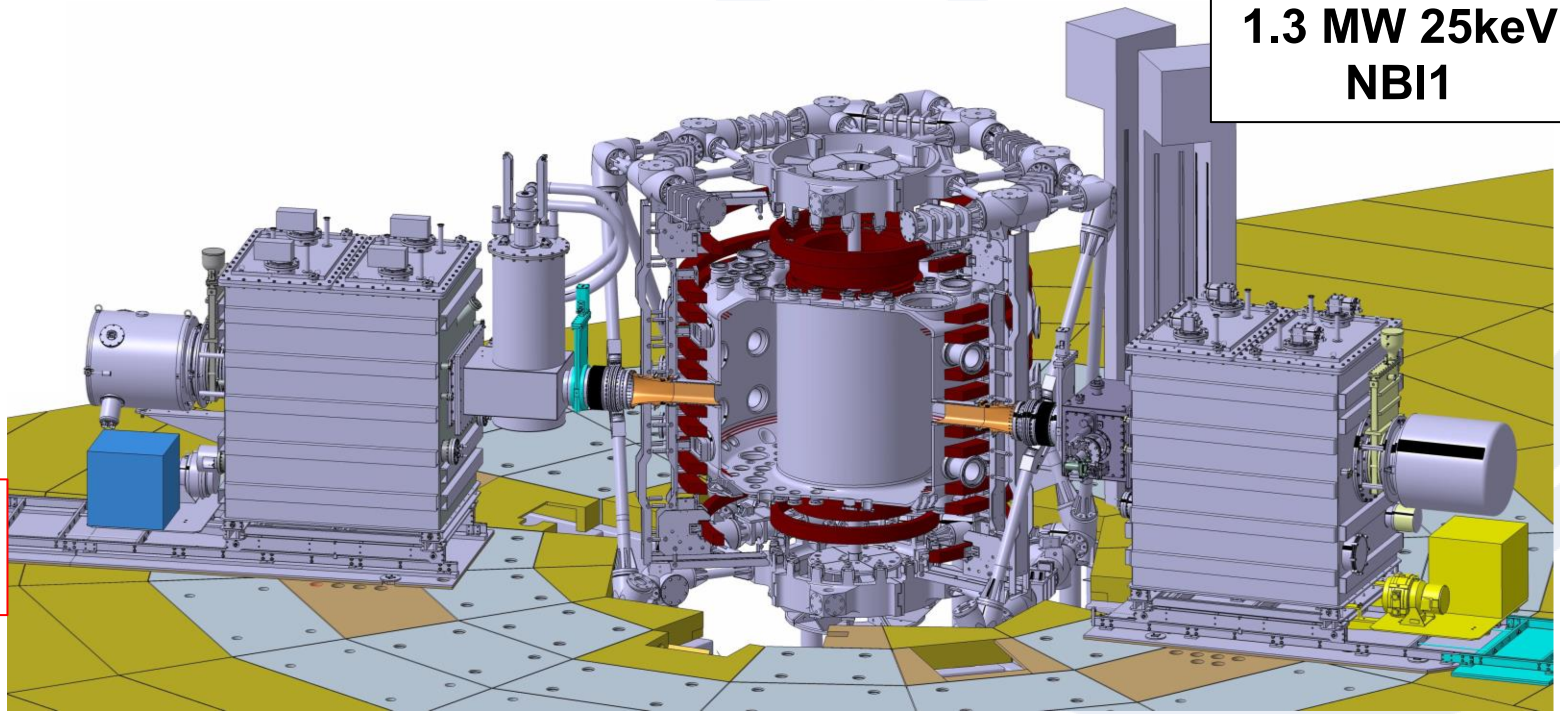
- High operational flexibility
- Extensive set of diagnostics
- Modern control system
- Versatile heating
- Unique magnetic shaping



TCV’s versatile heating system



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



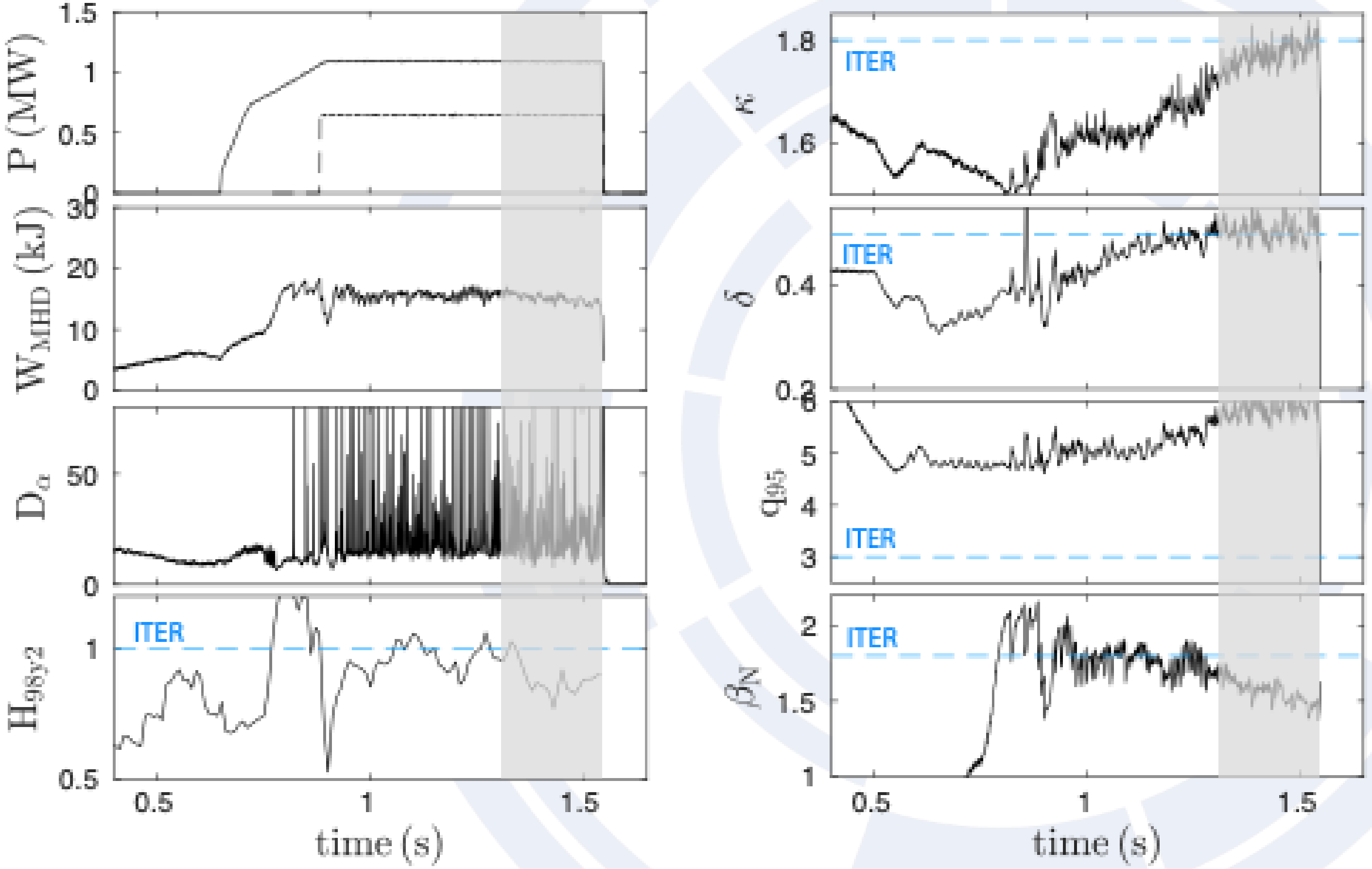
Outline

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

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}

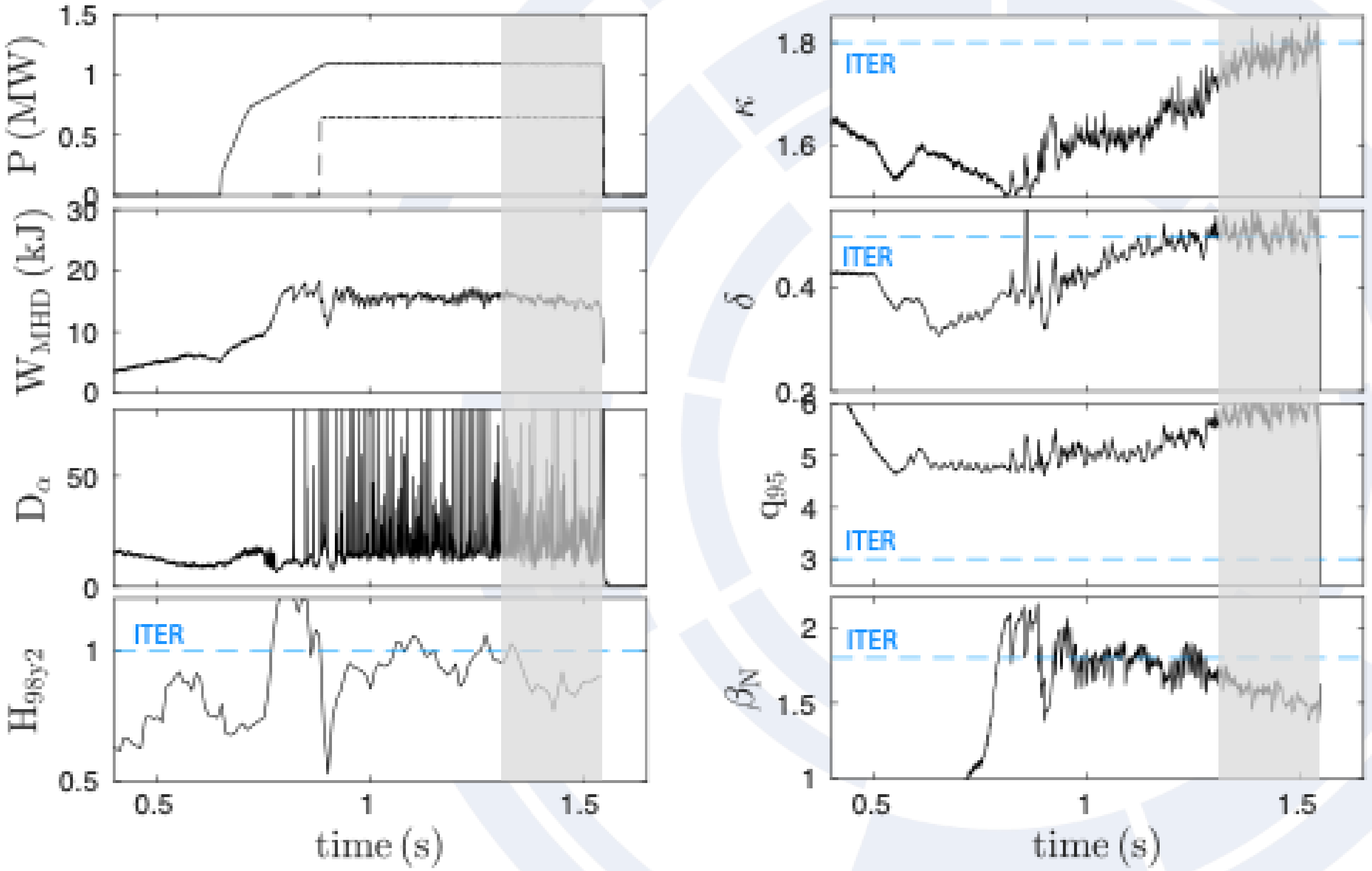


[B. Labit et al., NF 2024]

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}

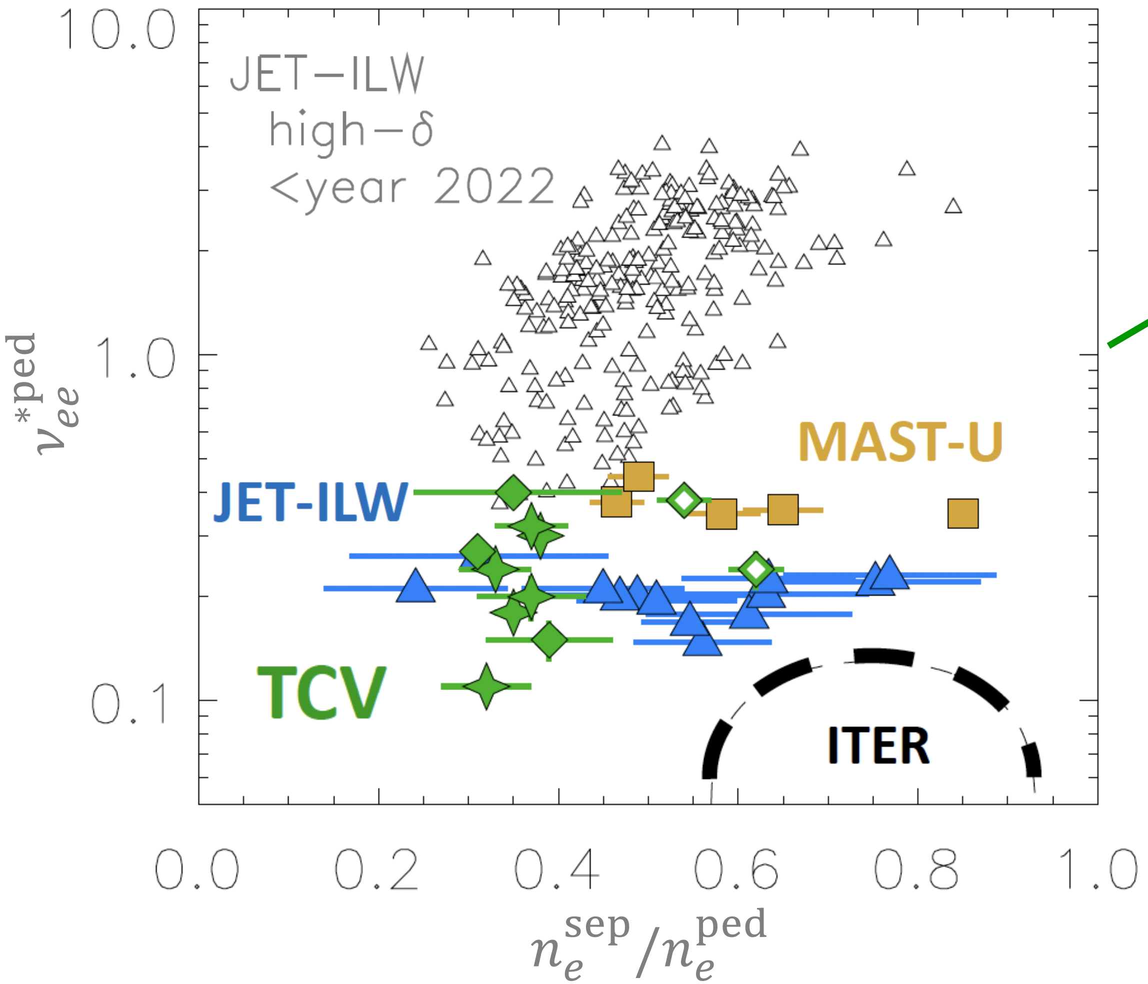
- First attempts of core-edge integration at reduced shaping but q_{95}~3.4 with N_2 seeding
  - ➢Pedestal degraded and ELMs reduced, but good confinement is kept



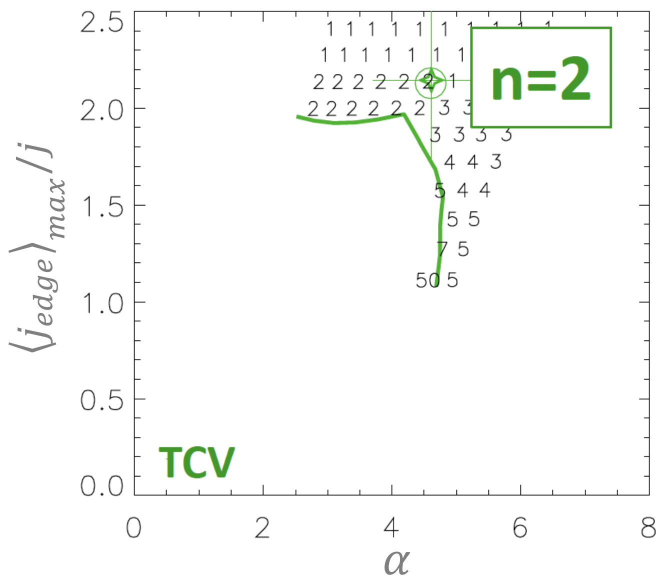
[B. Labit et al., NF 2024]

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]

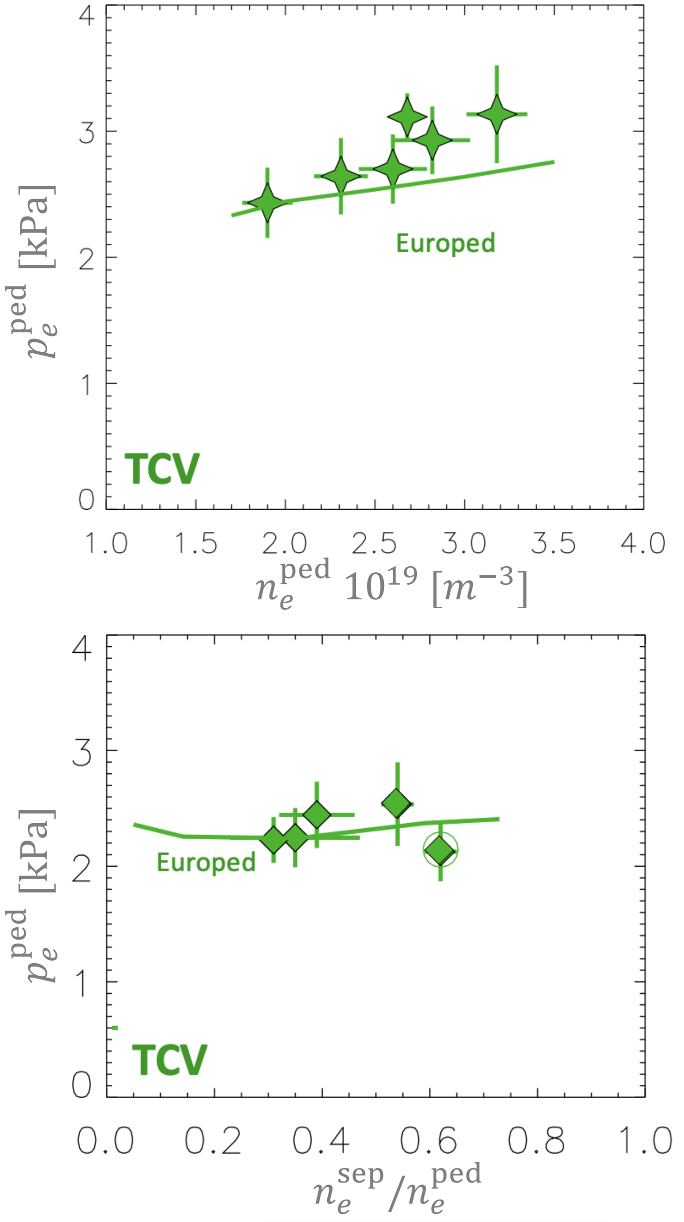
Beneficial pedestal behavior at increased density

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

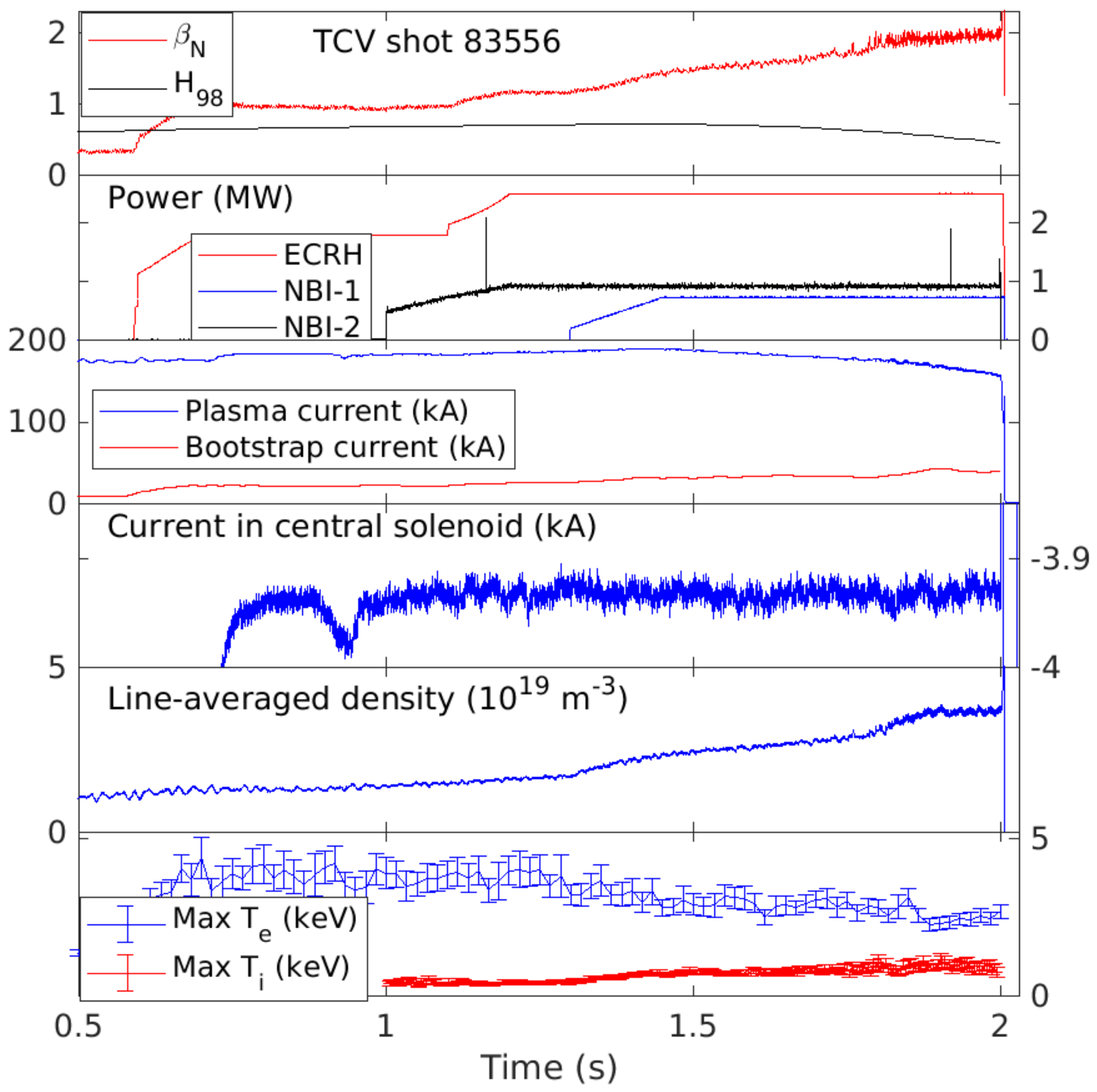
- **See L. Frassinetti, Saturday 9:30**



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

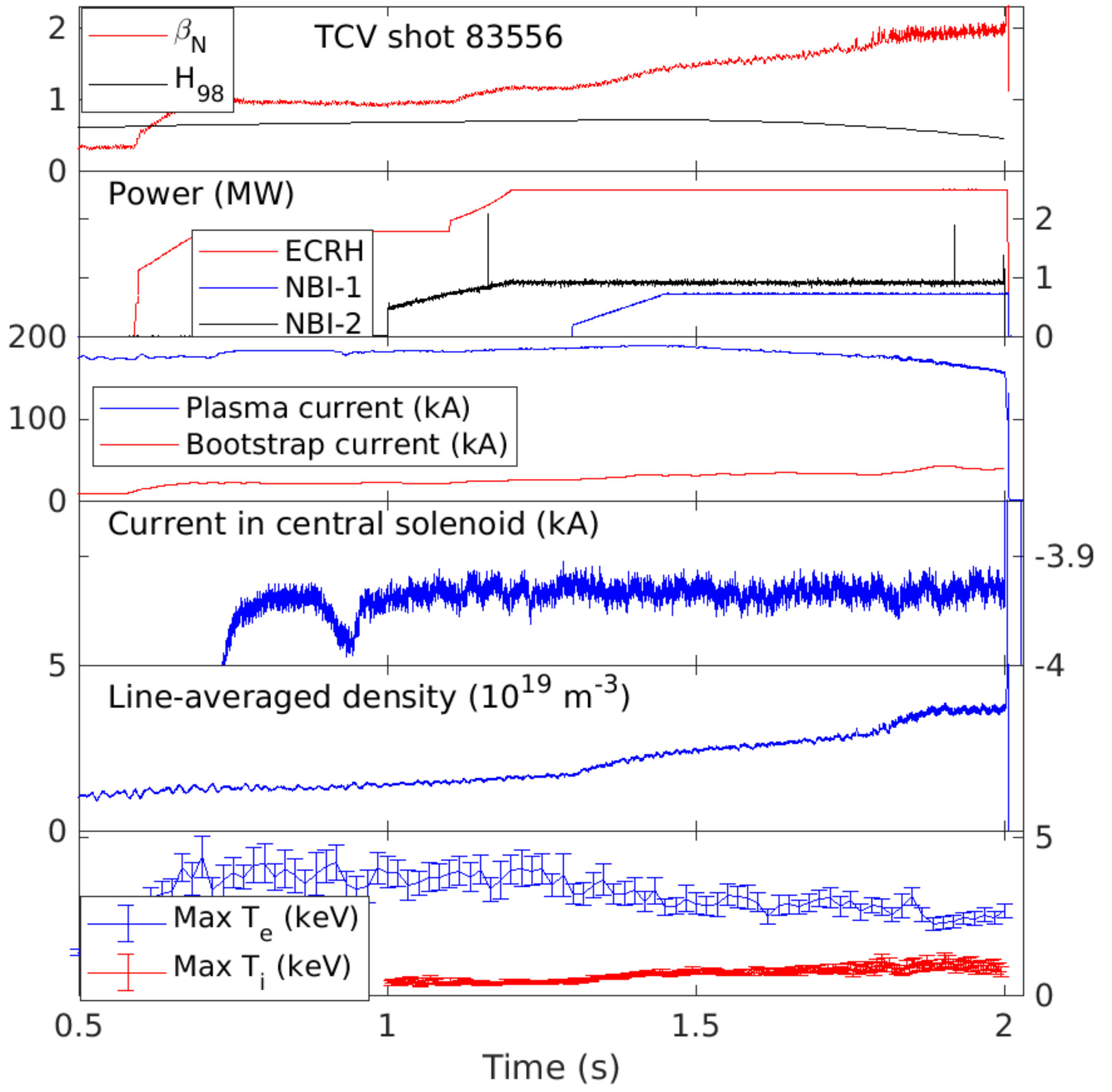


[S. Coda et al., this conference]

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%



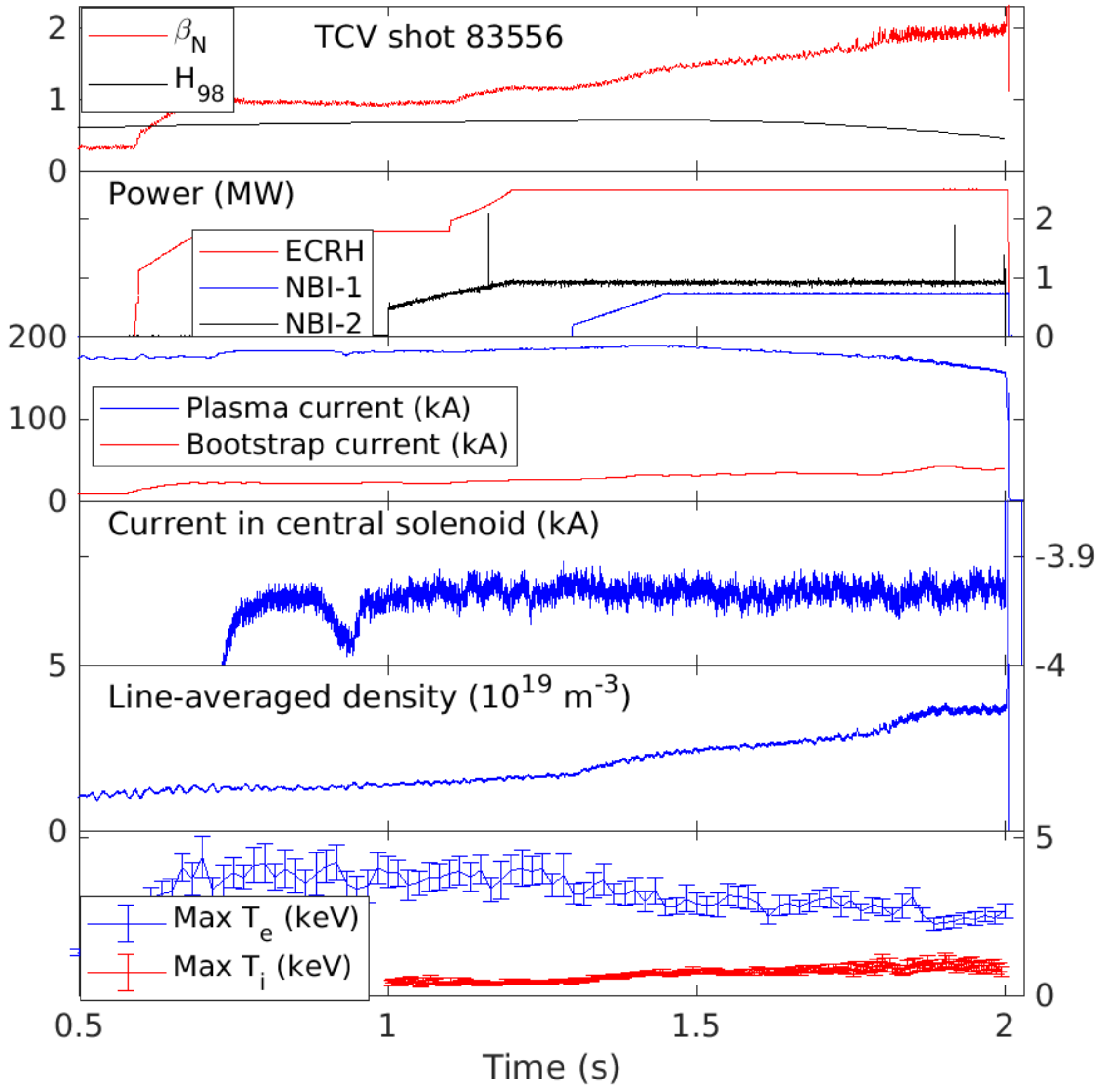
[S. Coda et al., this conference]

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

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



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!

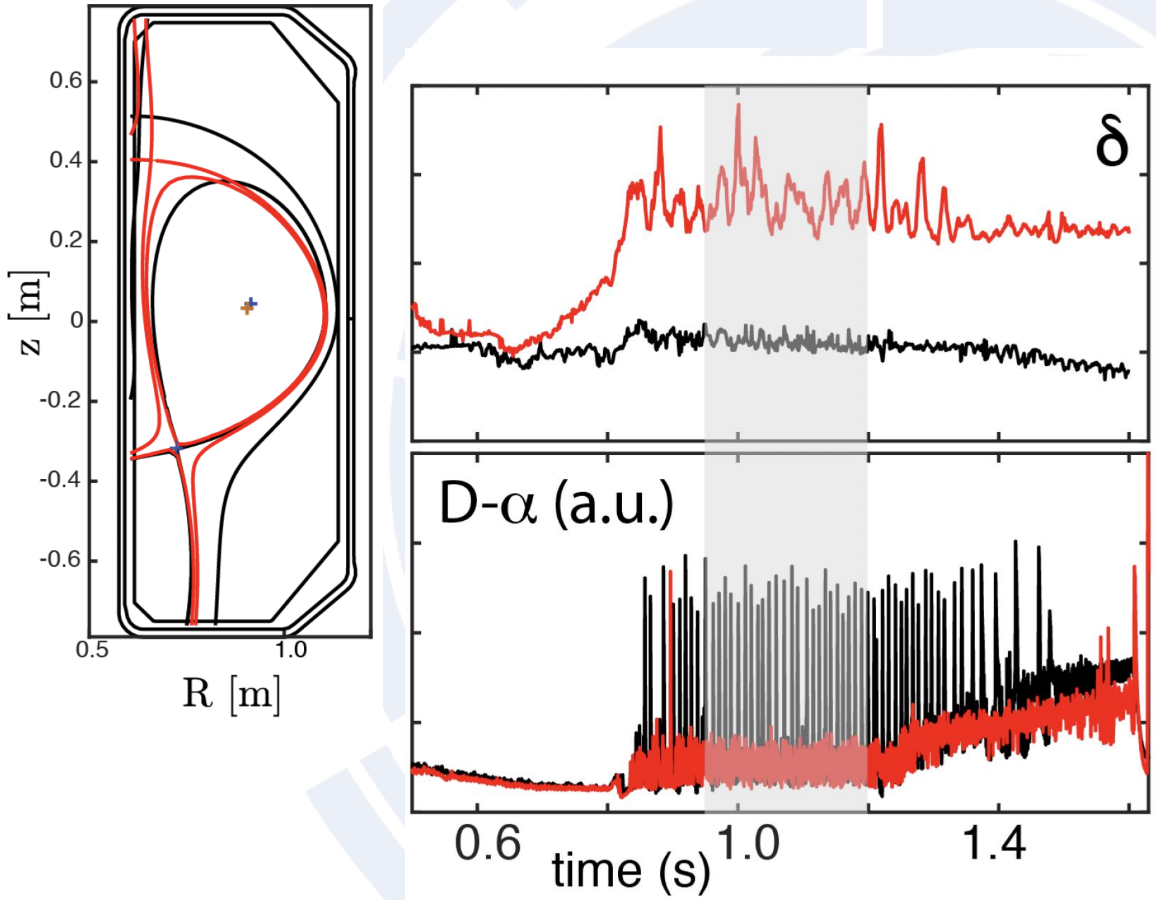
- ITER baseline and non-inductive scenarios
- Alternative ELM-free scenarios
- Fast particle physics
- Edge and divertor physics
- Plasma control
- Outlook

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**

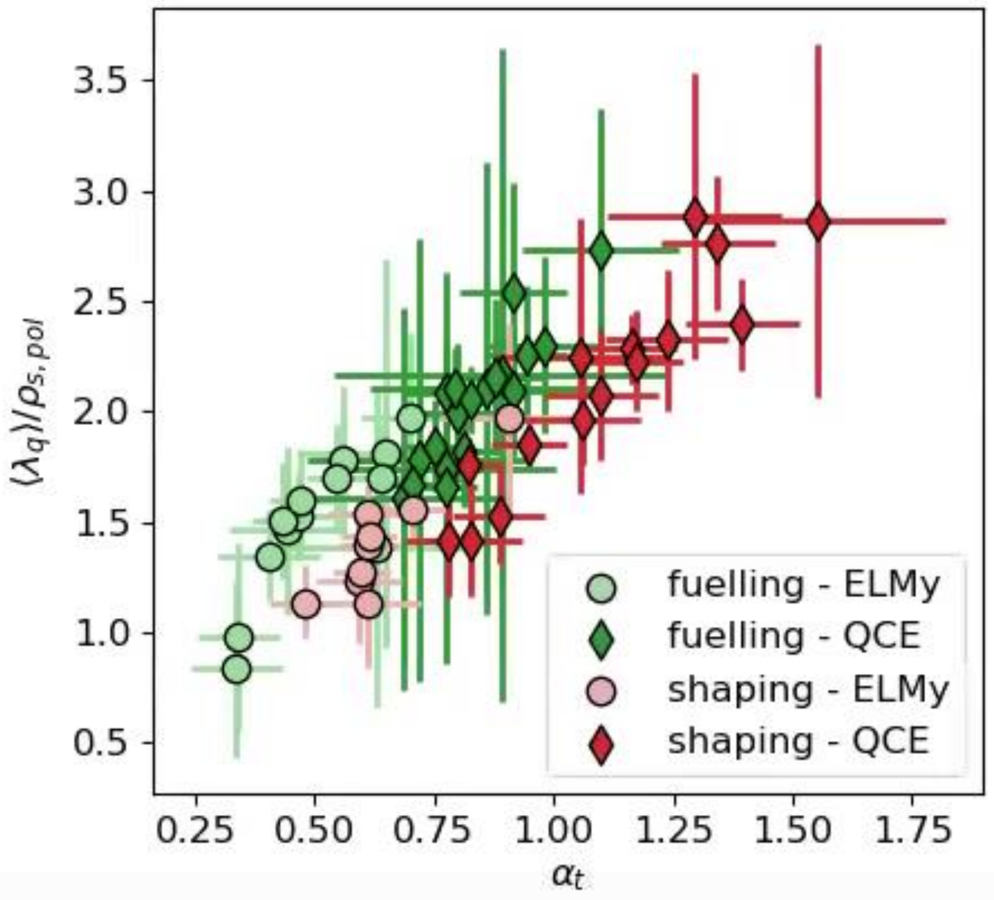


[B. Labit et al., NF 2019]

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

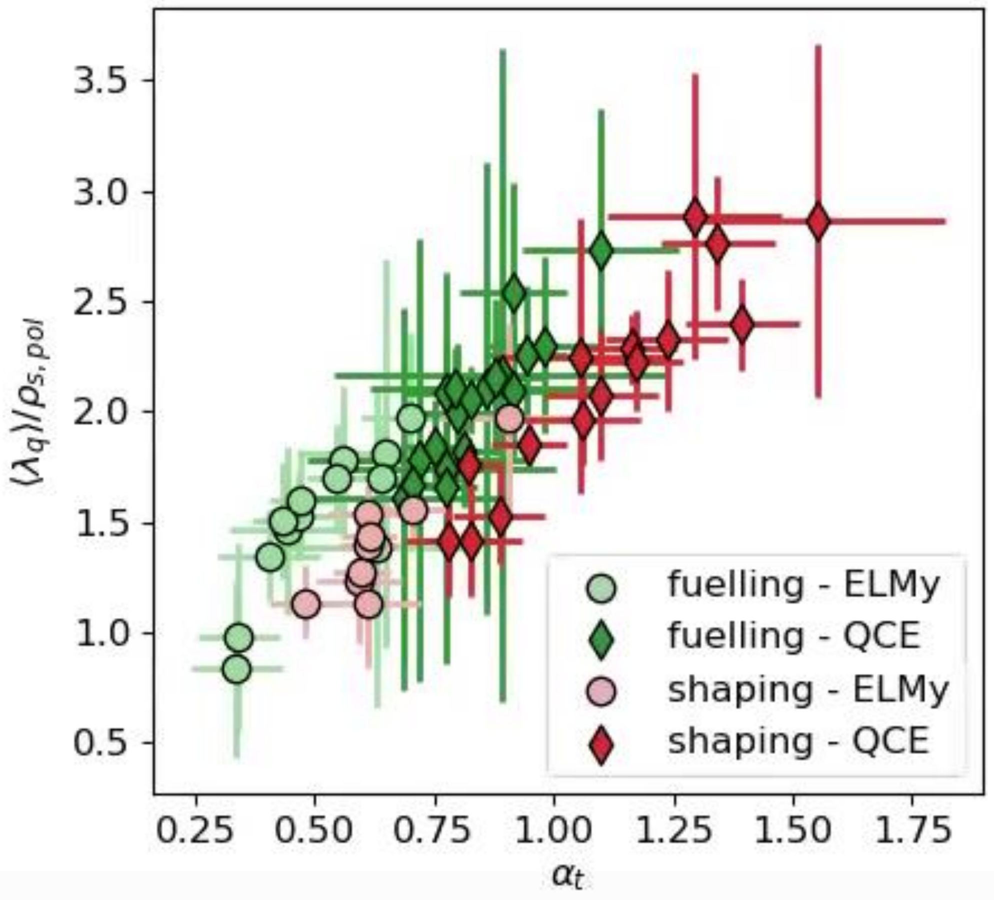
$$\alpha_t = KRq_{cyl}^2 \frac{n_{e,sep}}{T_{e,sep}^2} Z_{eff} \propto q_{cyl}\nu_{ei}^*$$



[A. Stagni et al., NF 2024]

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

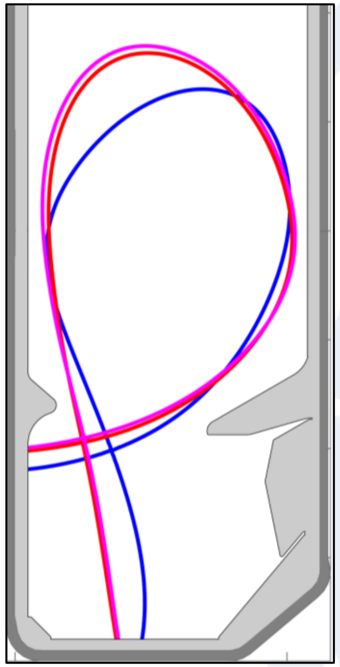


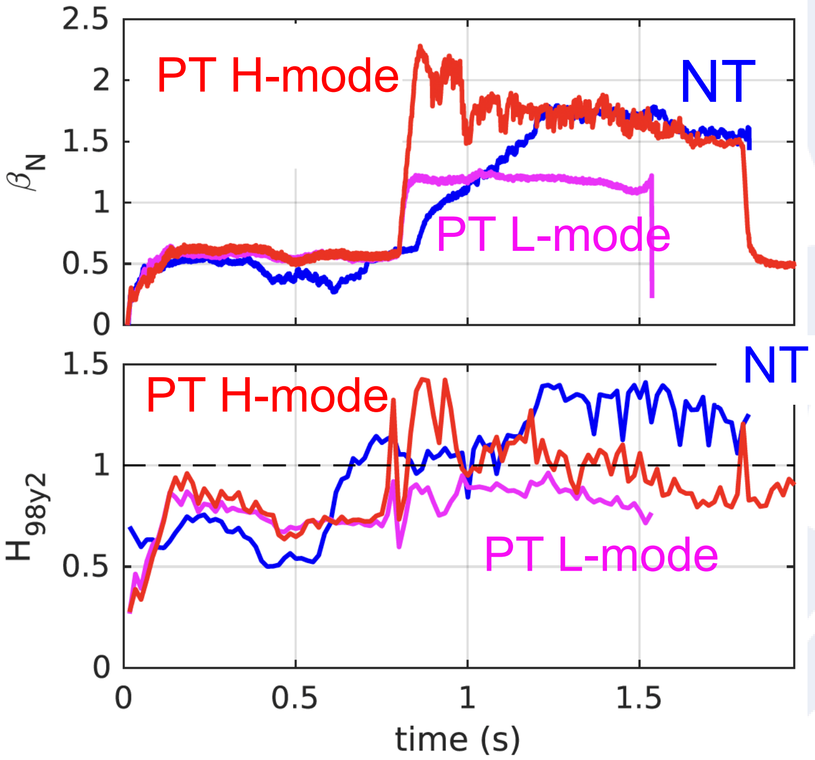
[A. Stagni et al., NF 2024]

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]





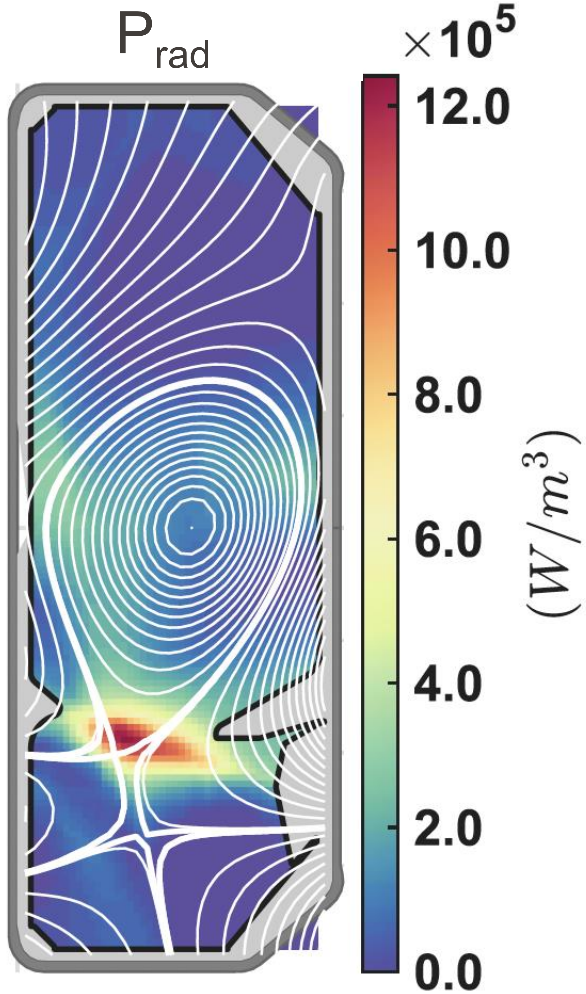
[O. Février et al., this conference]

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

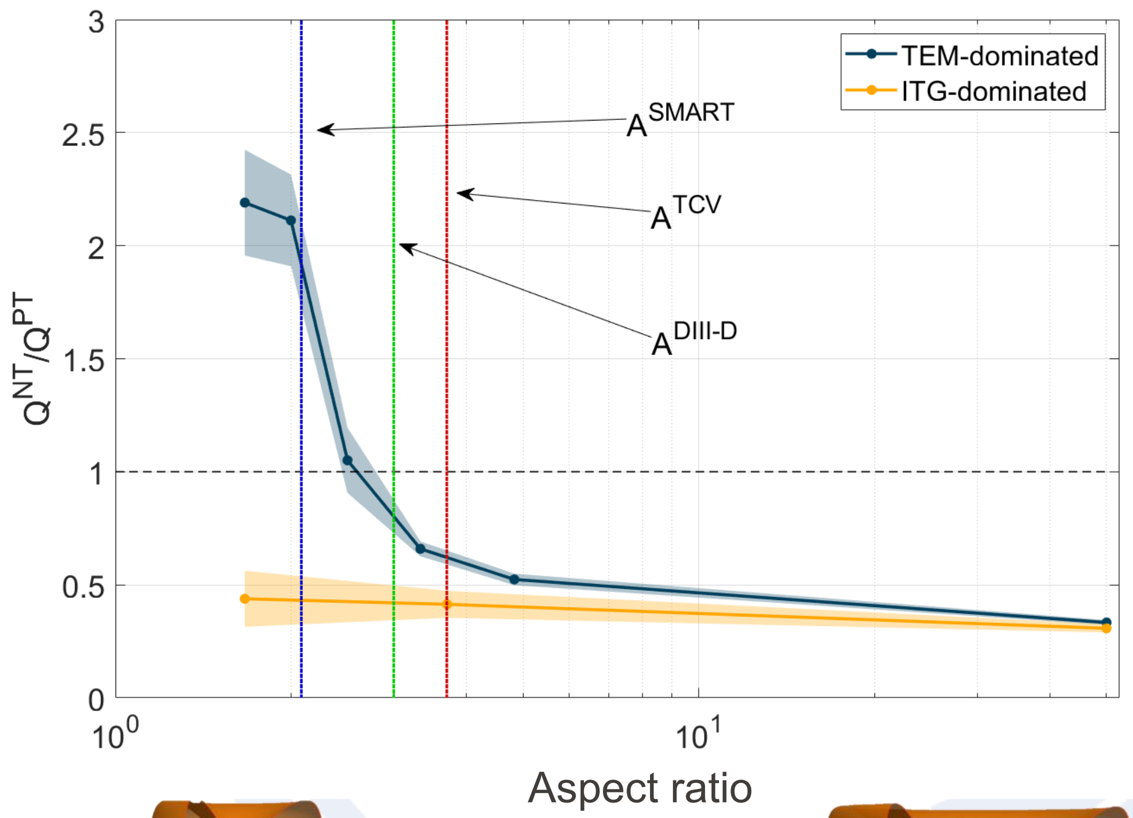
➢ **See O. Février, Wednesday PM**

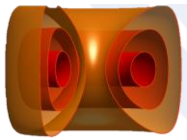


[G. DLN et al., EPS 2025]

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]





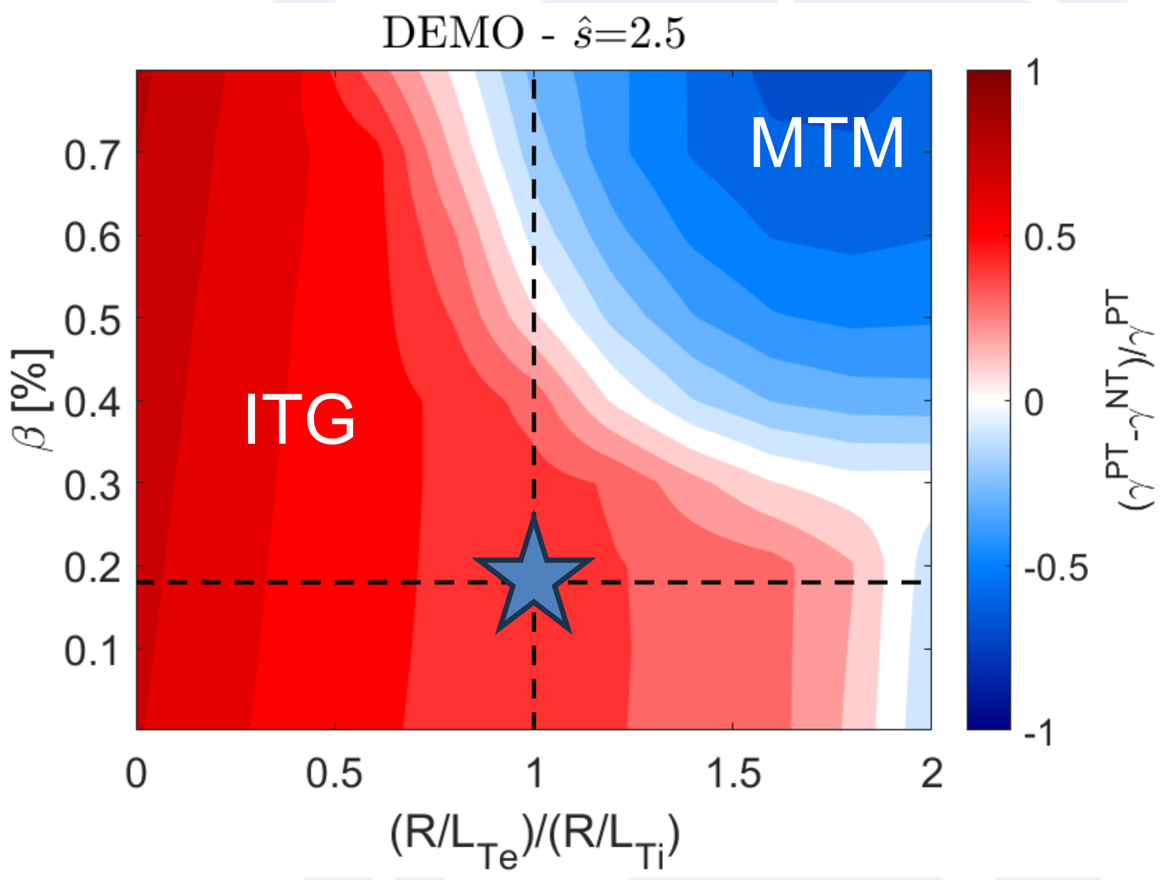
[A. Balestri et al., PPCF 2024]

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]

Promising reactor predictions

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



[A. Balestri et al., EPS 2025]

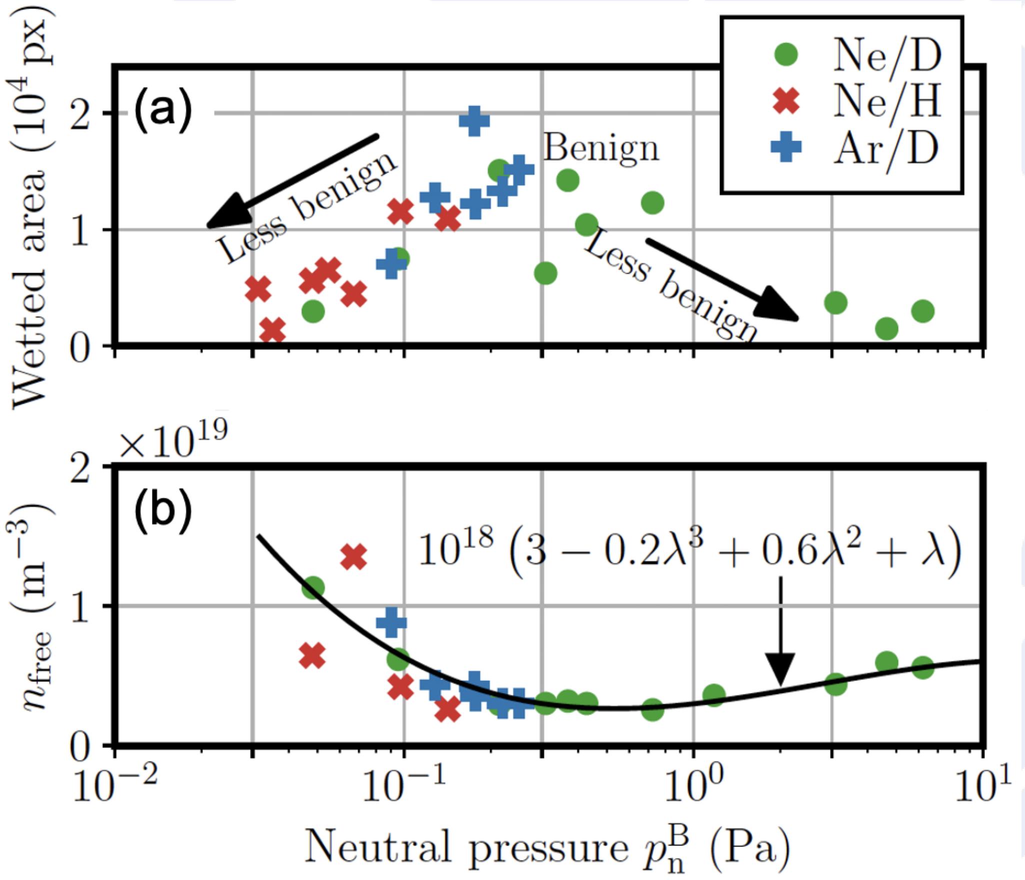
Outline

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

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

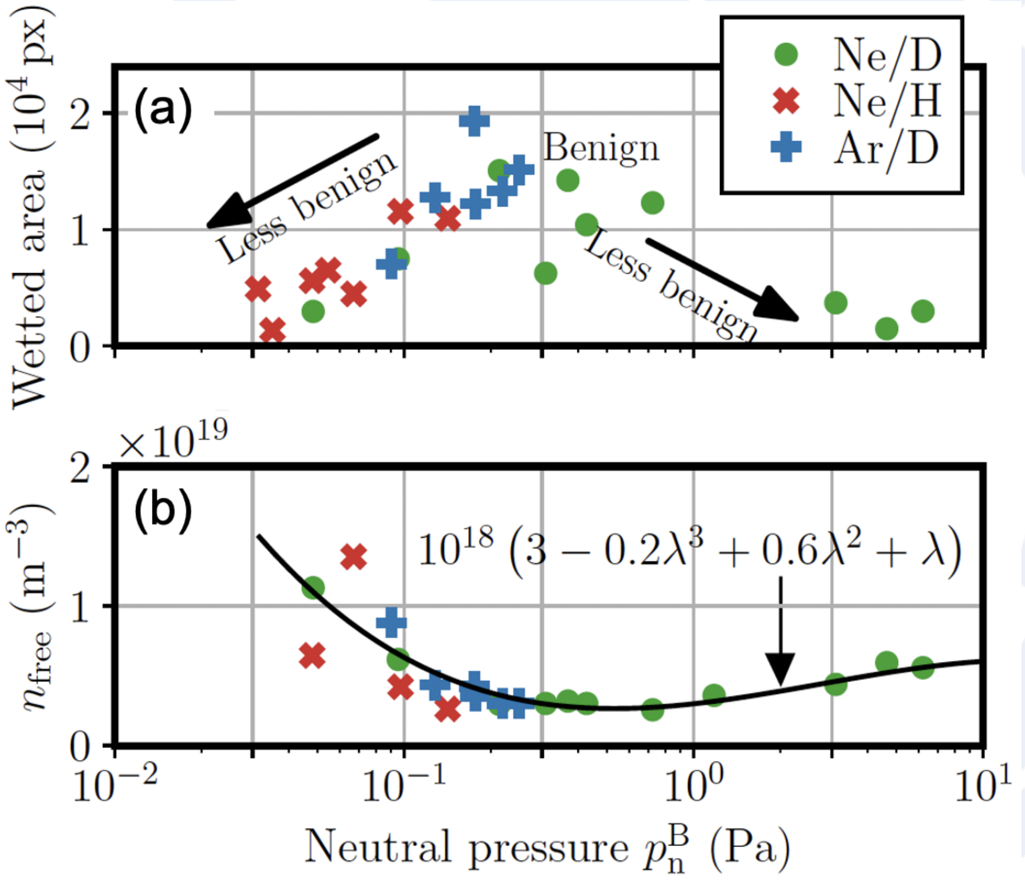


[M. Hoppe et al., PPCF 2025]

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**

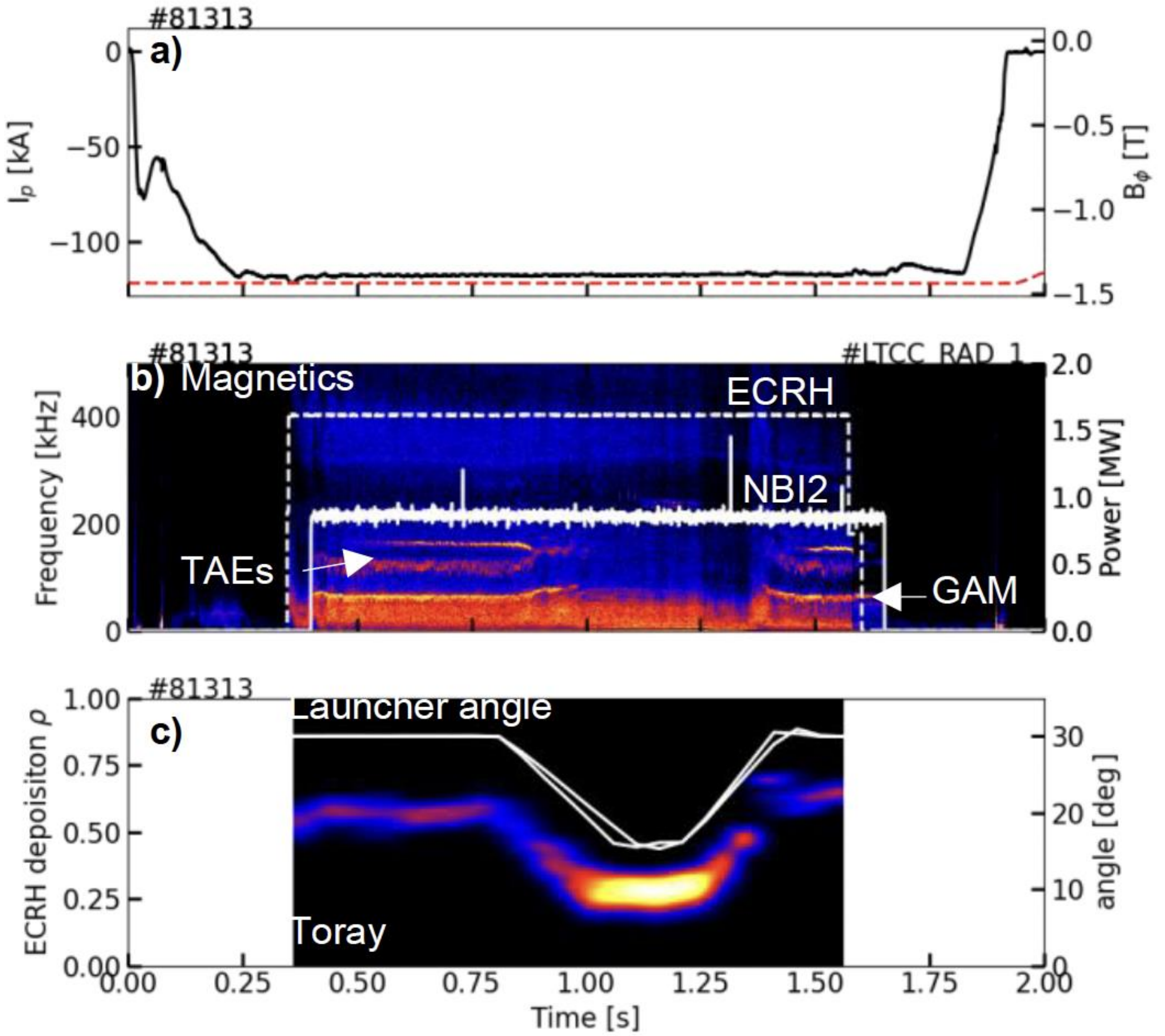


[M. Hoppe et al., PPCF 2025]

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

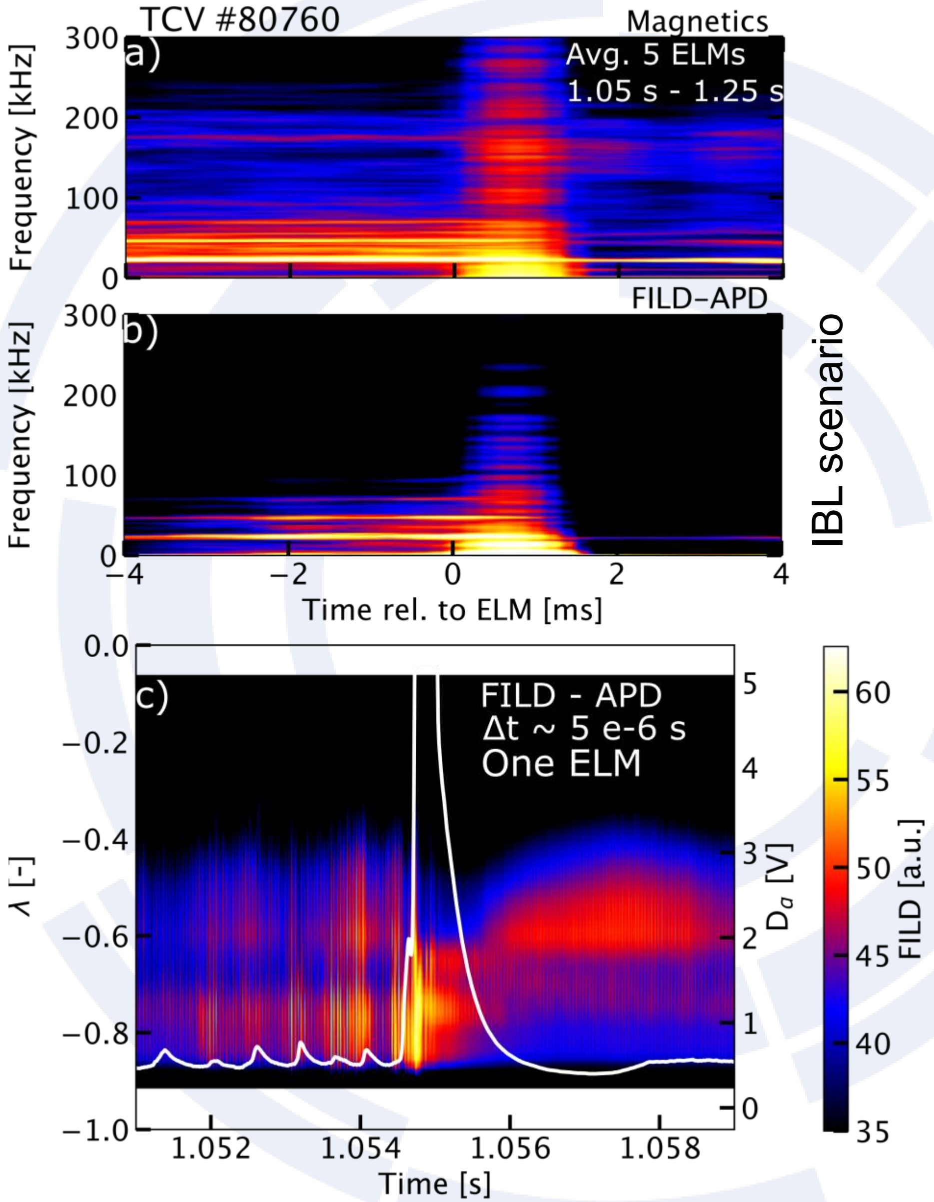
➢ **See A. Van Vuuren, Thursday PM**



[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

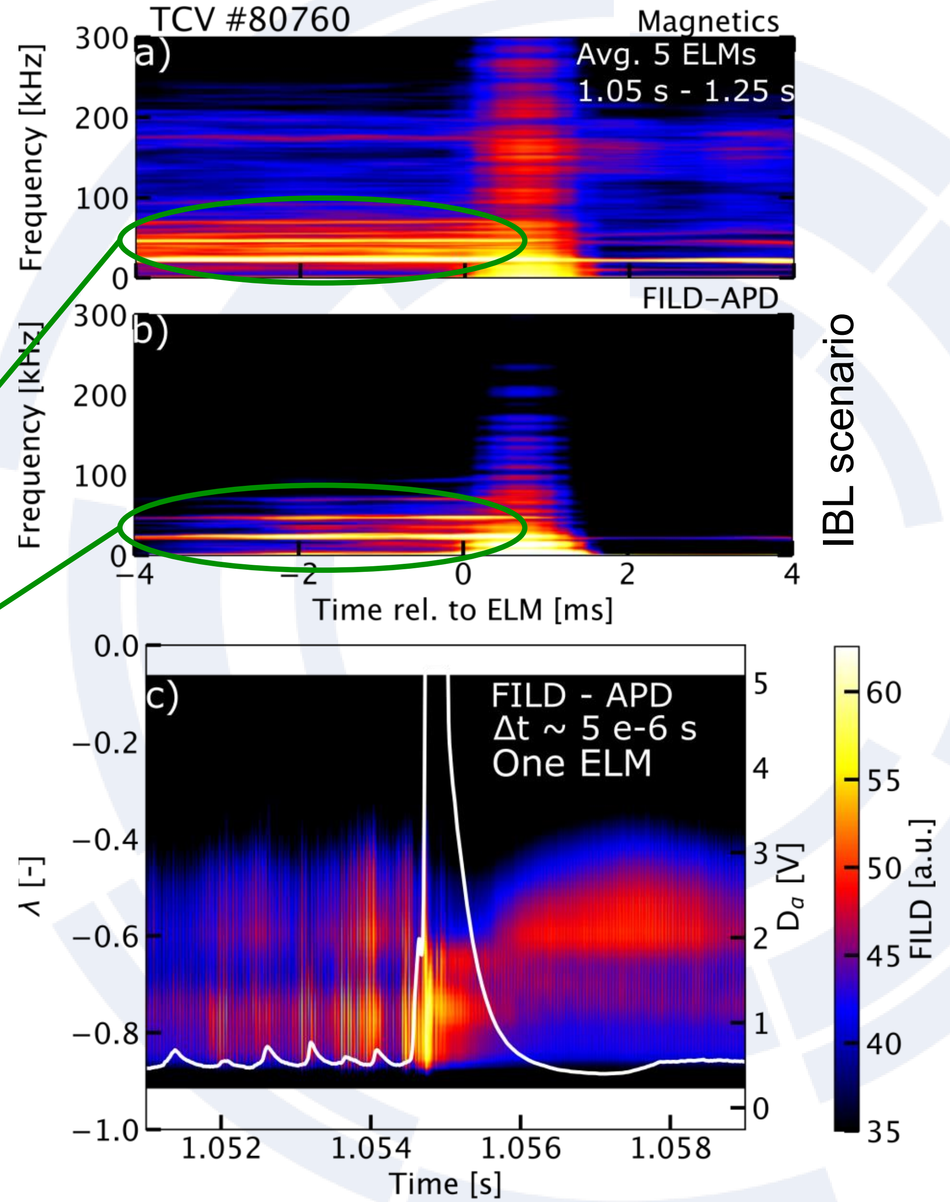


Elucidating inter- and intra-ELM Fast-Ion (FI) losses

- 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

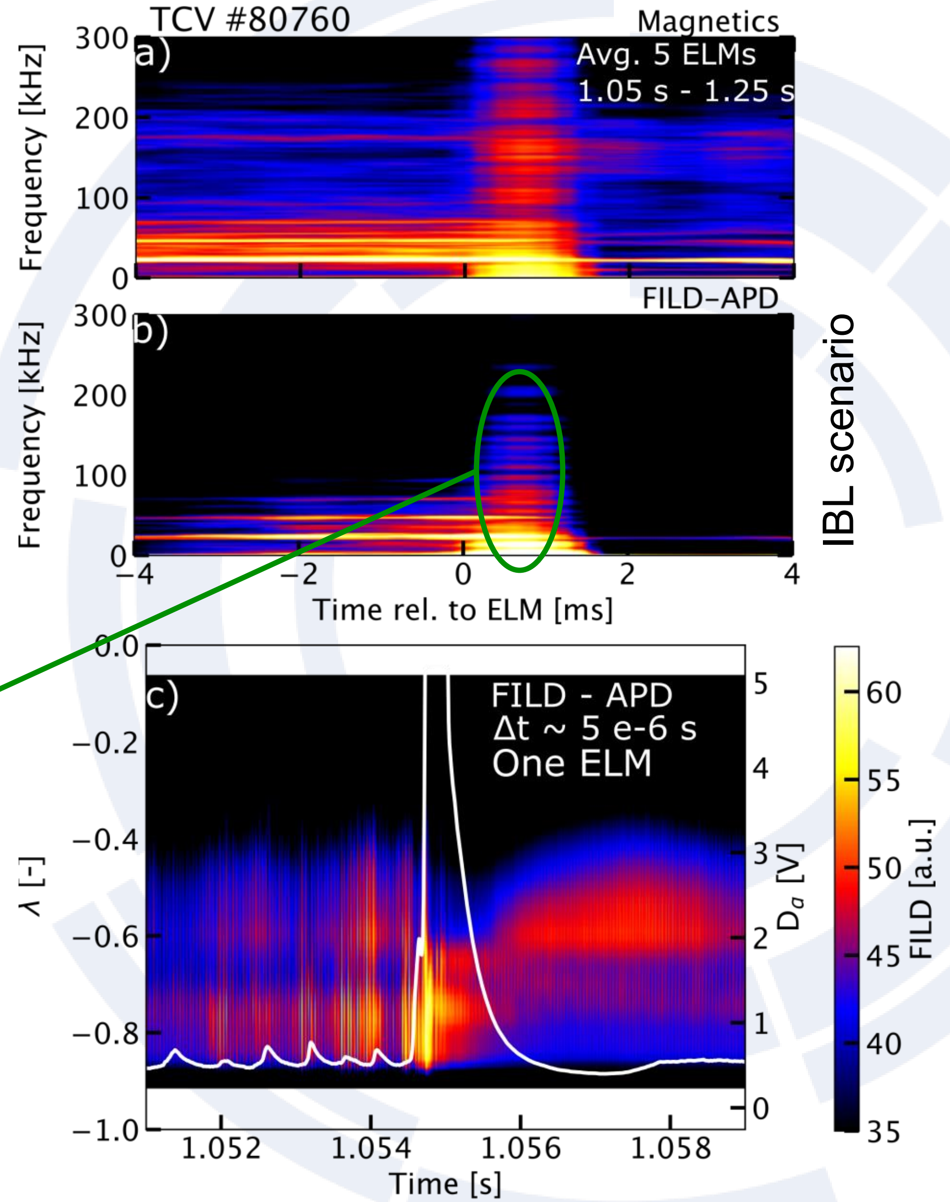


Elucidating inter- and intra-ELM Fast-Ion (FI) losses

- 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

Broad FI loss spectrum during ELM



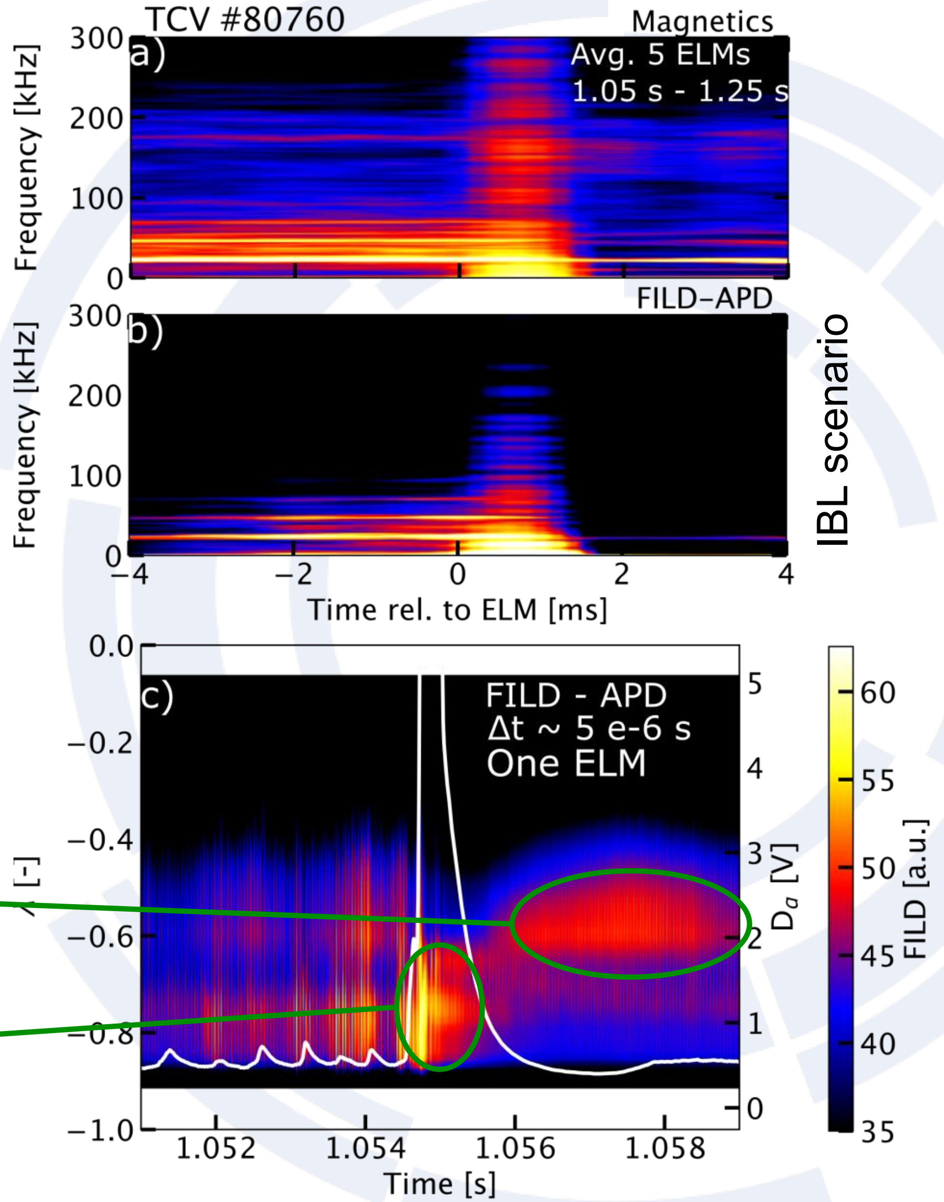
Elucidating inter- and intra-ELM Fast-Ion (FI) losses

- 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

Neoclassical losses (ASCOT5)

Anomalous losses

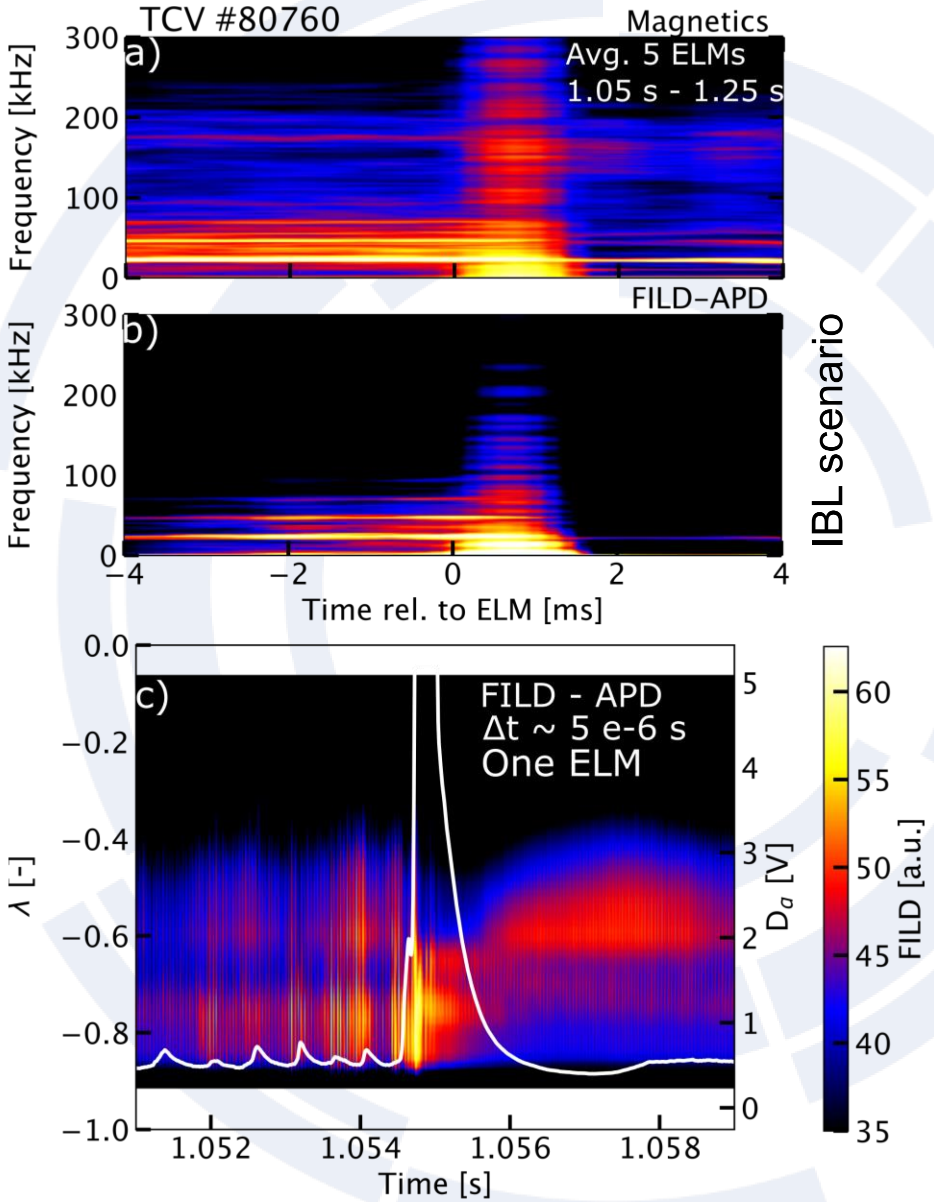


Elucidating inter- and intra-ELM Fast-Ion (FI) losses

- 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

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



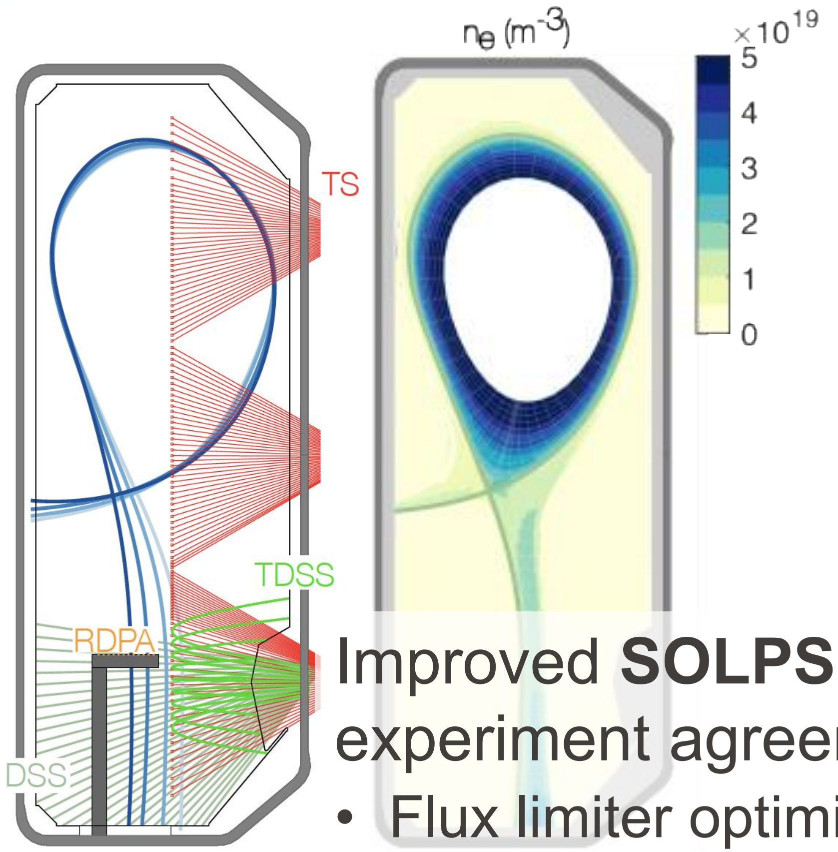
Outline

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

TCV as a continued testbed for boundary code validation

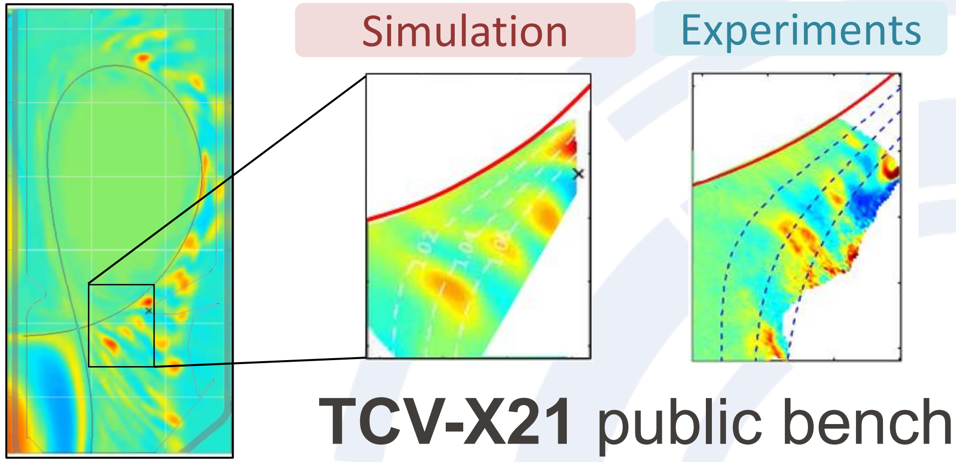
EPFL



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

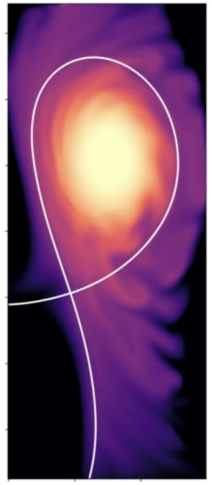
- Flux limiter optimization
- Improved sputtering model
- Core coupling via JINTRAC

➢ **See E. Tonello, Wednesday 15:20**



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

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

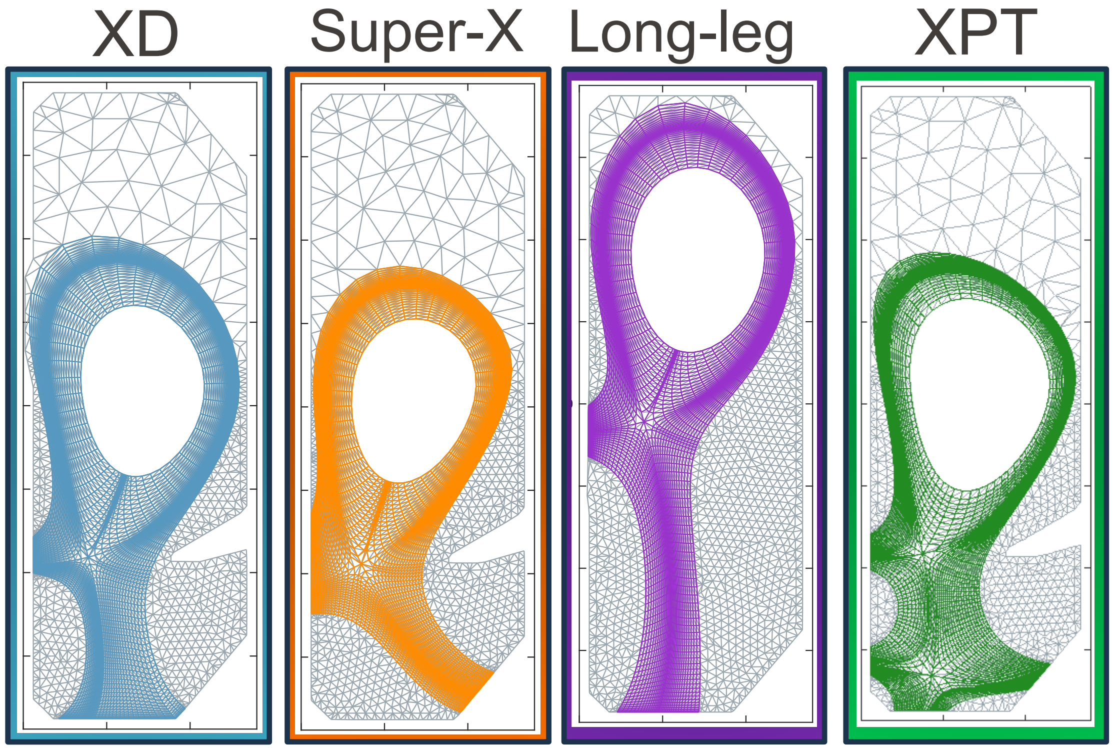


TCV-X23 → detachment with **GBS** [Mancini EPS 2025]

➢ **See P. Ricci, Wednesday AM**

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

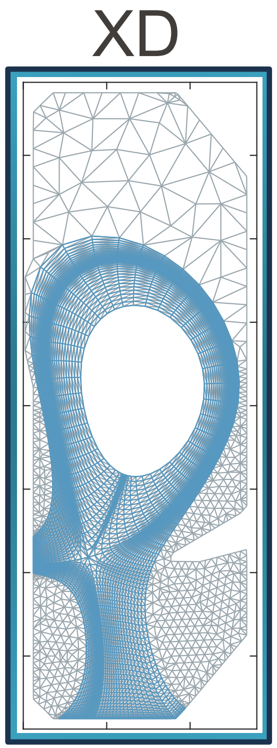
Assessment of individual alternative divertor features and interpretation with SOLPS-ITER

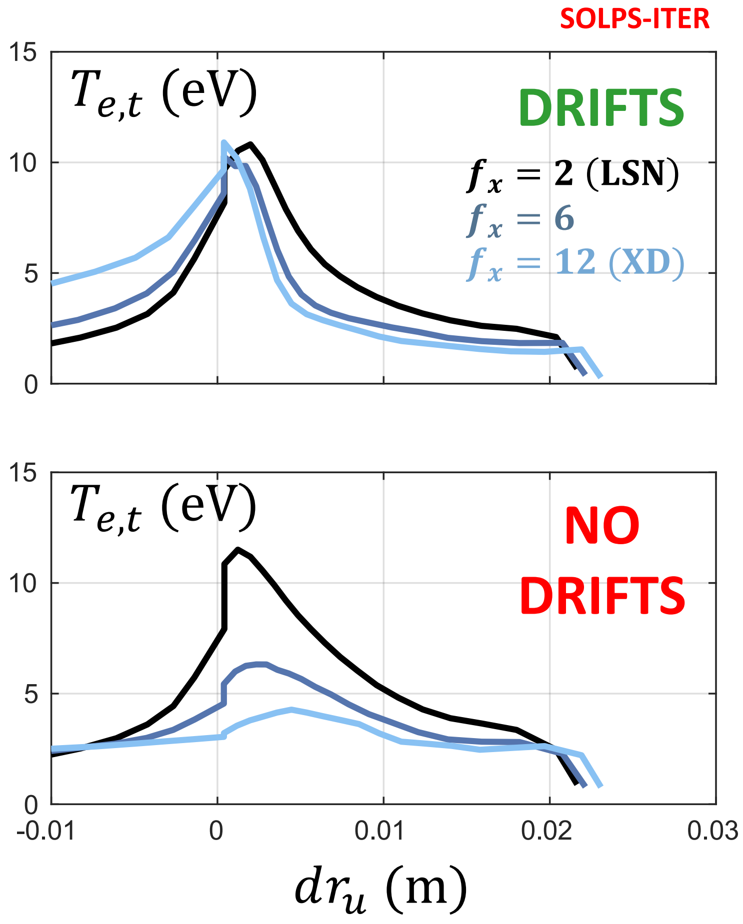


[M. Carpita et al., AAPPS 2025]

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

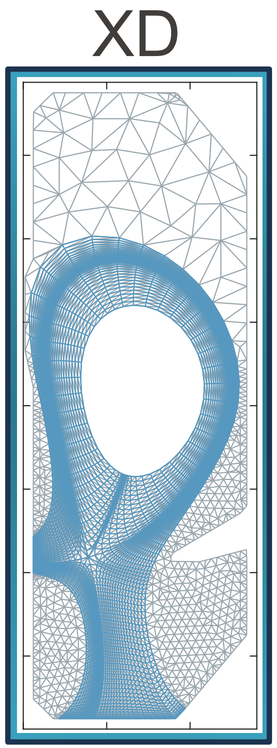
Assessment of individual alternative divertor features and interpretation with SOLPS-ITER

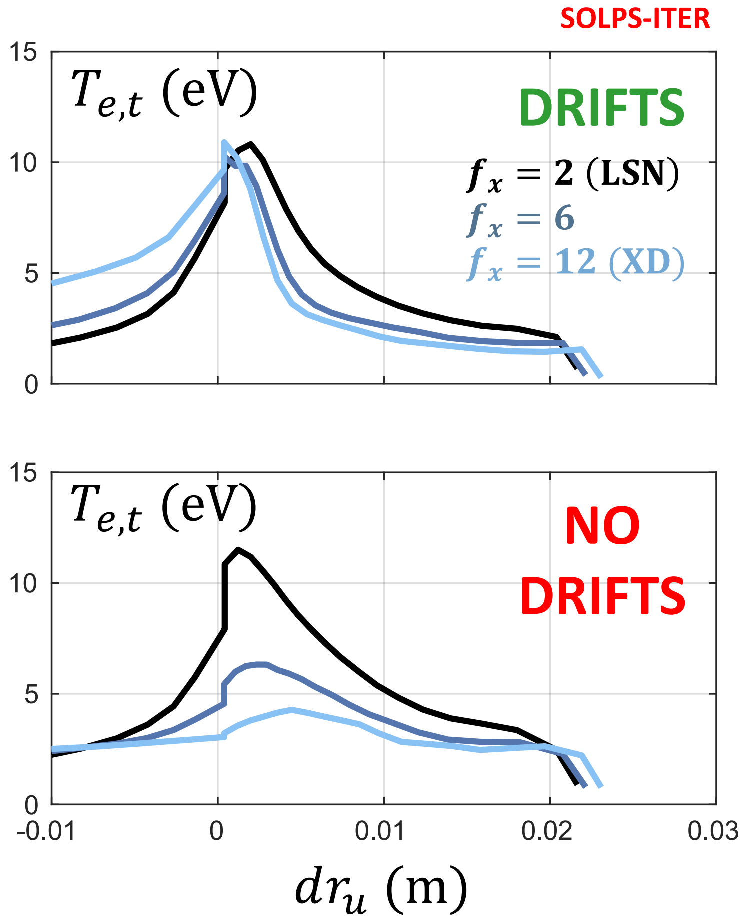




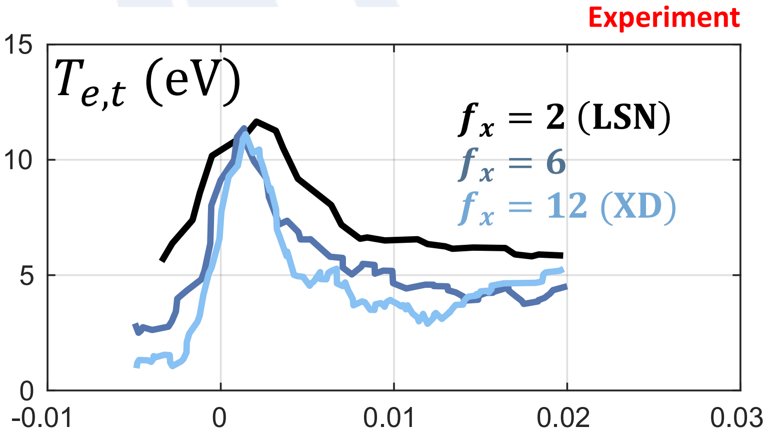
- Alternative divertors simulated routinely with SOLPS-ITER – drifts fully included [M. Carpita NF 2025]
- Simulations qualitatively reproduce most of the experimental results

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



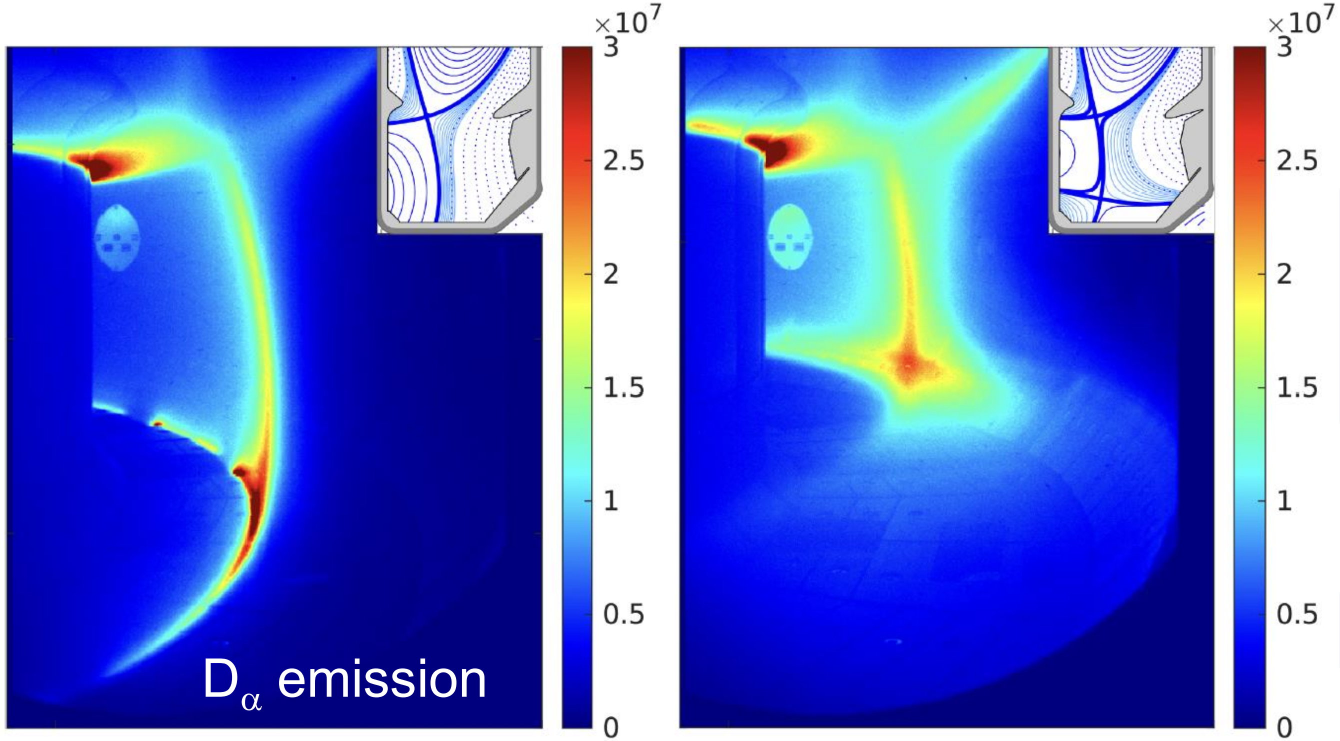


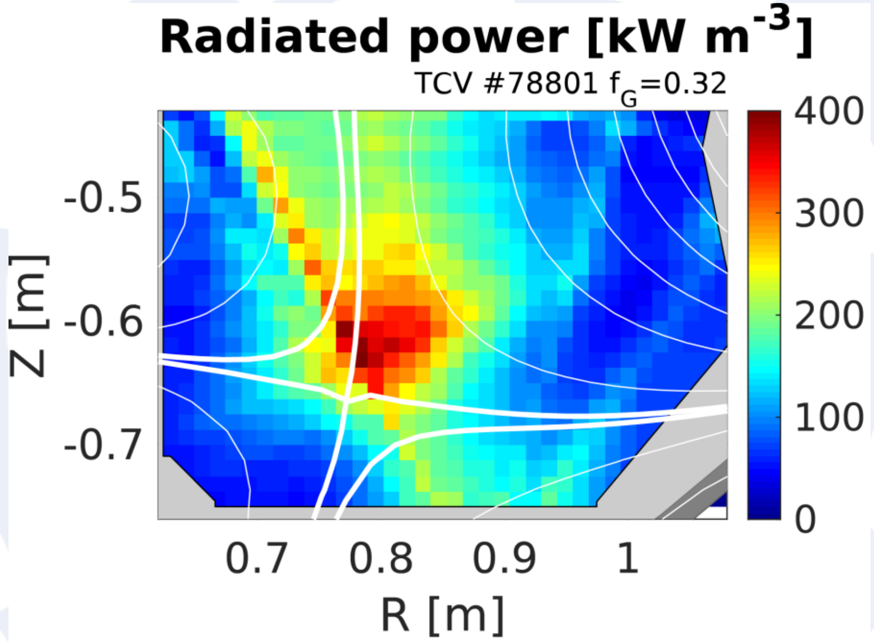
- Alternative divertors simulated routinely with SOLPS-ITER – drifts fully included [M. Carpita NF 2025]
- Simulations qualitatively reproduce most of the experimental results, **but inclusion of drifts is key!** [M. Carpita AAPPS 2025]



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

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



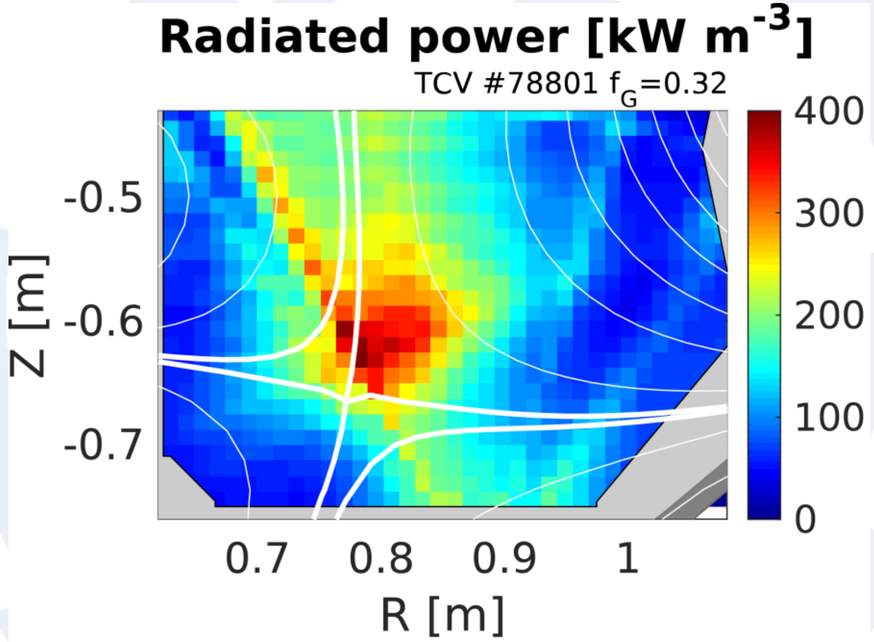


[K. Lee et al., PRL 2025]

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

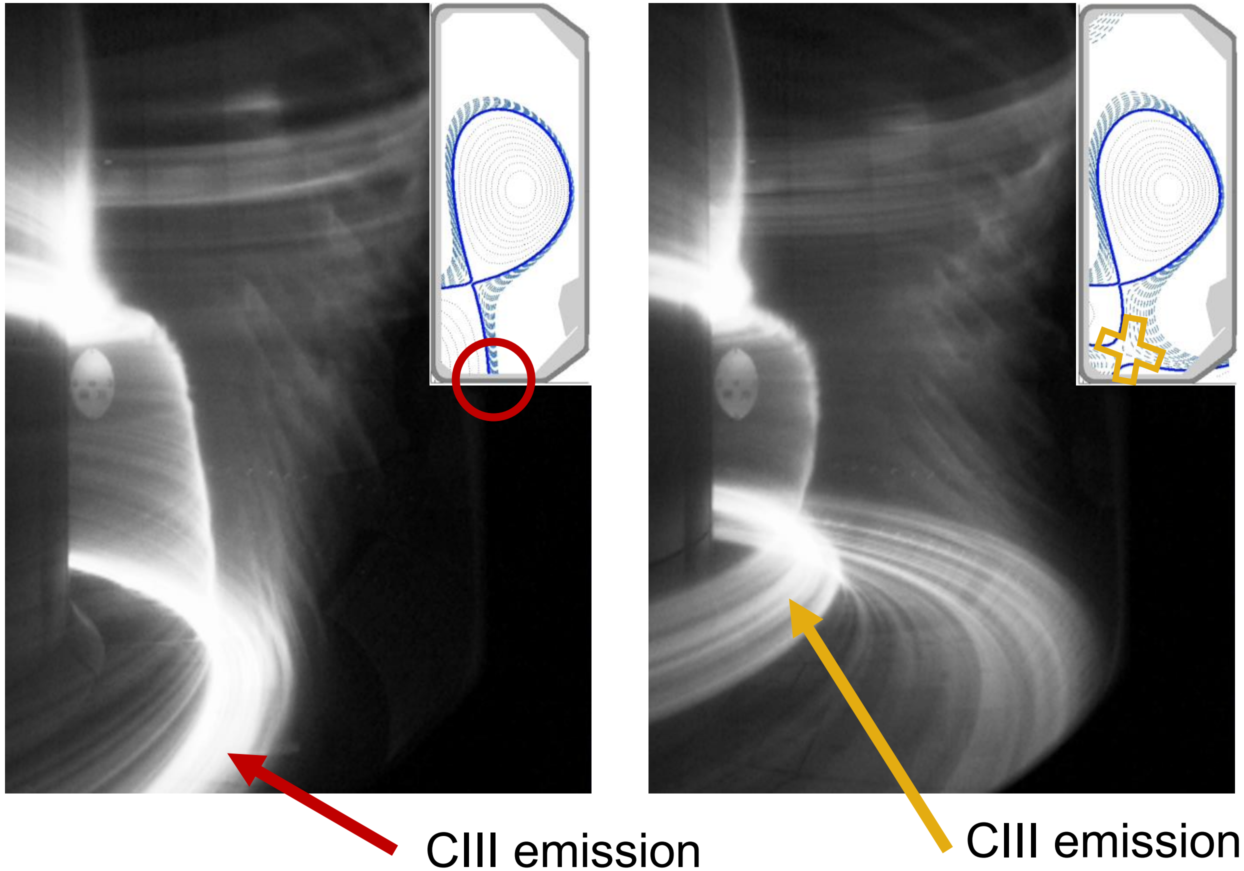
➢ Novel power exhaust concepts where edge cooling can be avoided during divertor detachment



[K. Lee et al., PRL 2025]

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

FastCam CIII frame during Type-I ELM

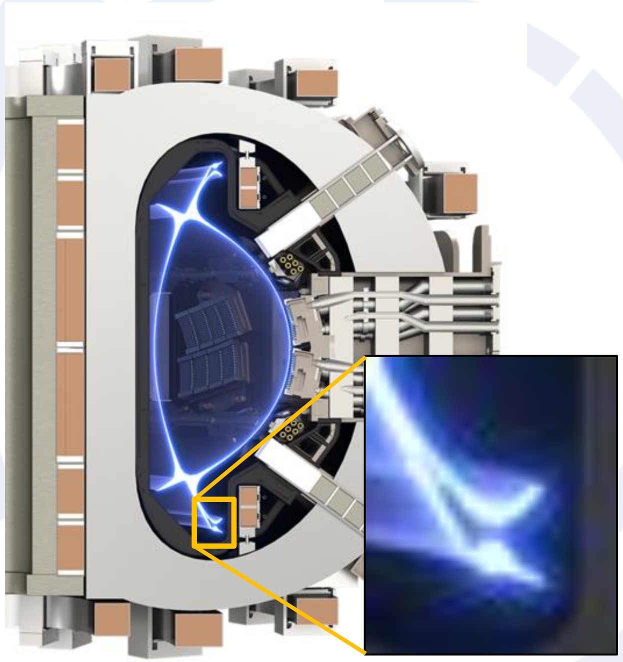


CIII emission during ELMs is strong at target

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**

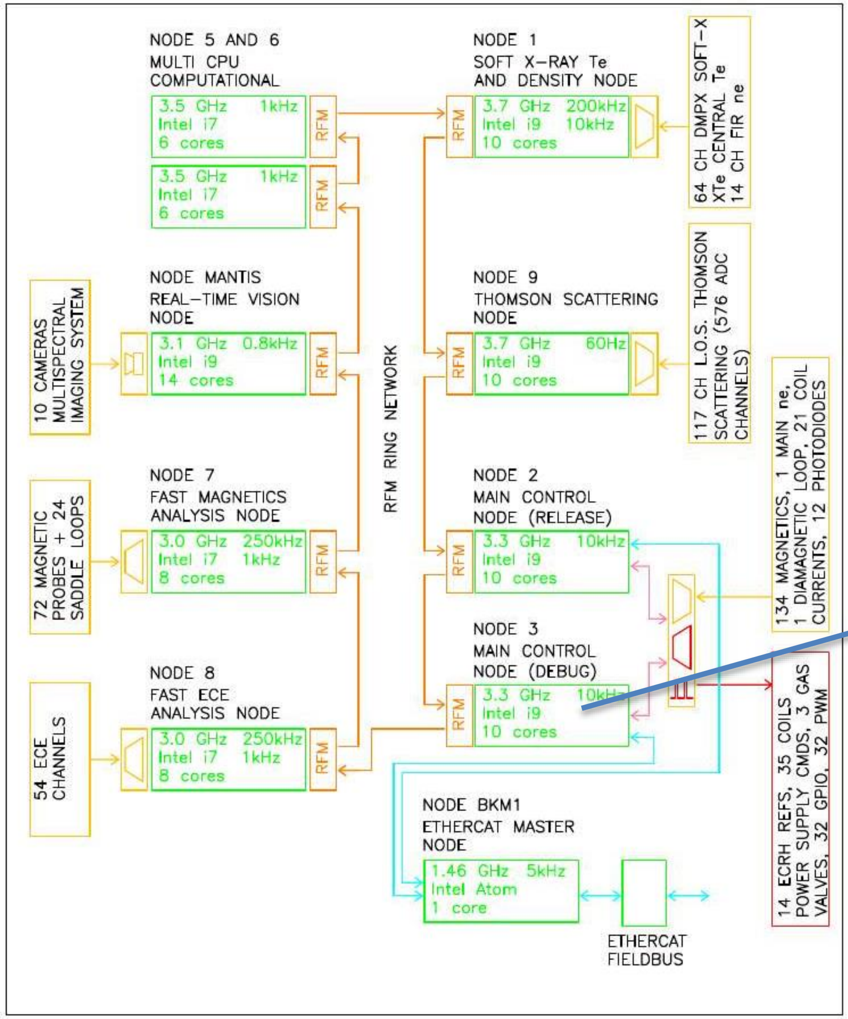
Outline

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!

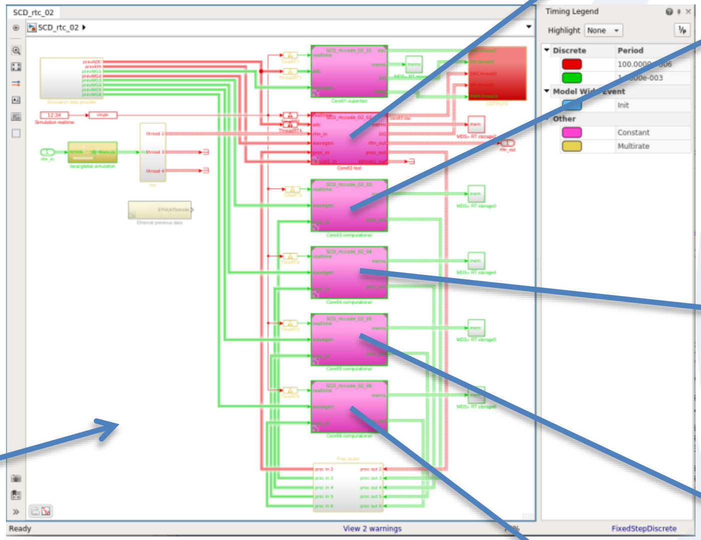
- ITER baseline and non-inductive scenarios
- Alternative ELM-free scenarios
- Fast particle physics
- Edge and divertor physics
- Plasma control
- Outlook

TCV digital distributed control system (SCD)

Hardware layout



[C. Galperti et al., FED 2024]



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

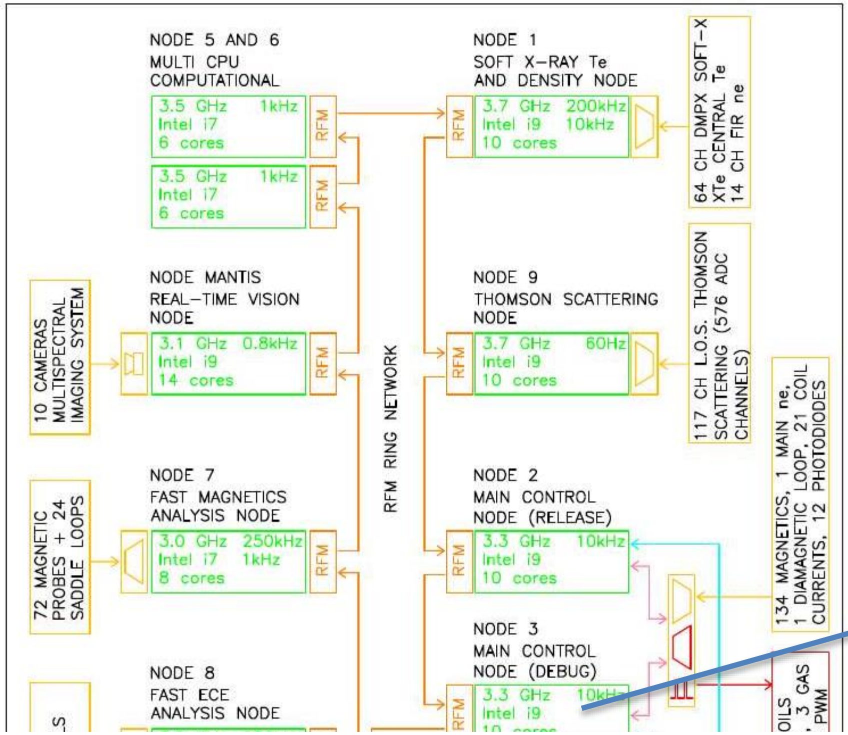
CPU#3
- Actuator manager and pulse scheduler (SAMONE)

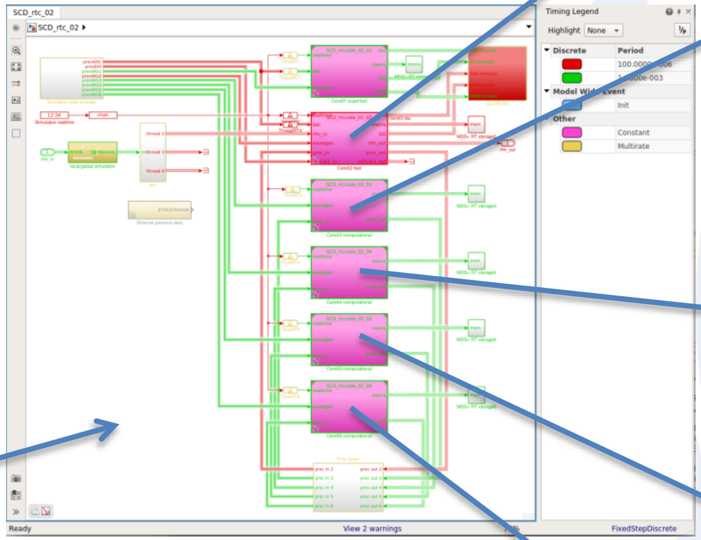
CPU#4
- RAPTOR (real-time heat transport and current diffusion simulator)

CPU#5
- RAPDENS (real-time model-based electron density observer)

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

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

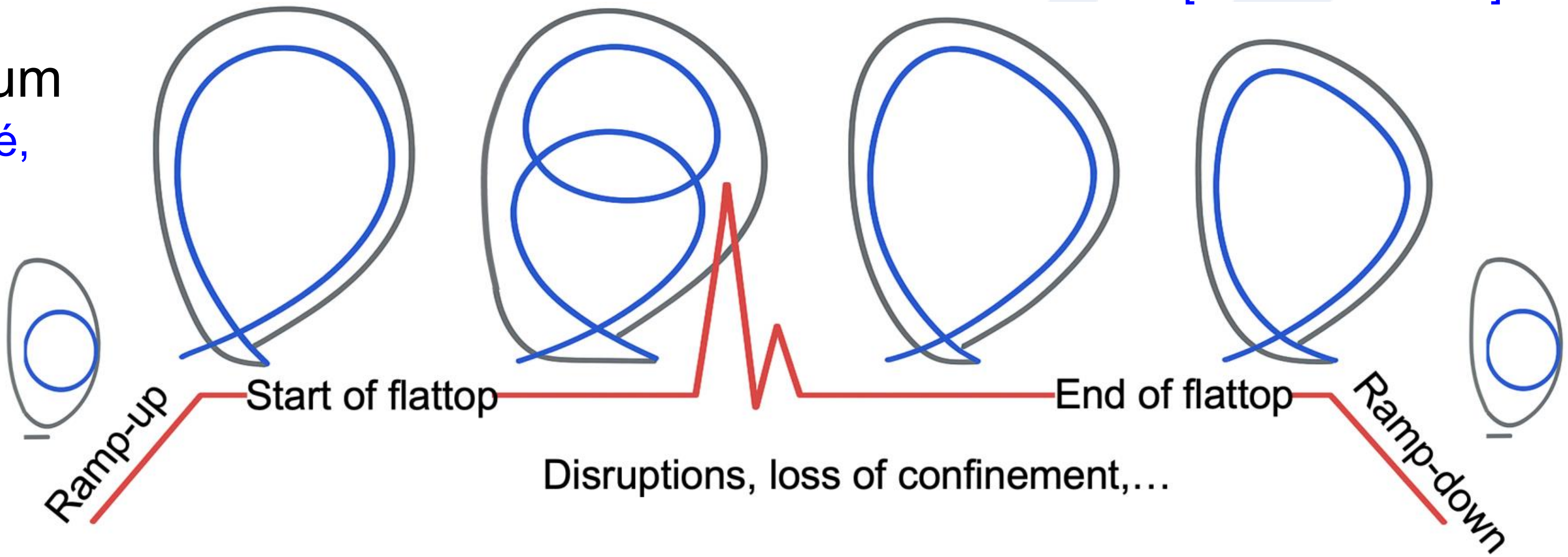
A glimpse of recent advances in tokamak control on TCV

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]

…

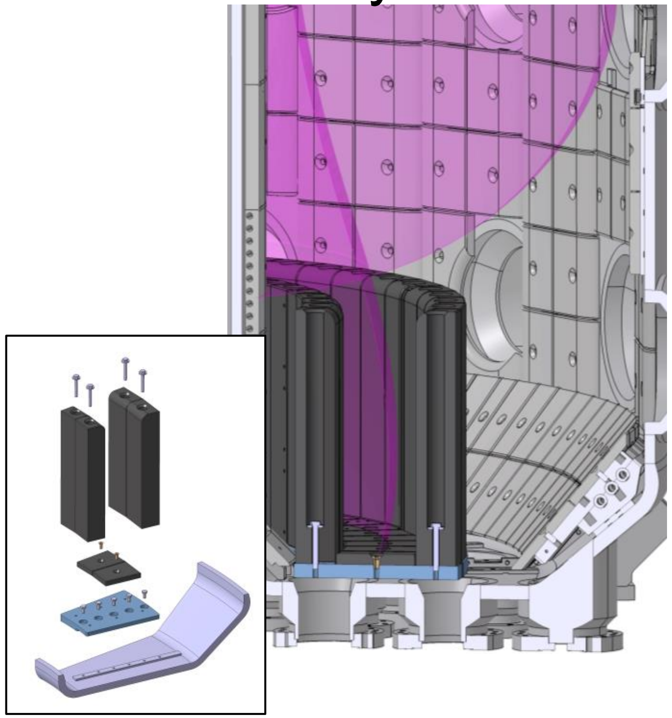
Outline

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

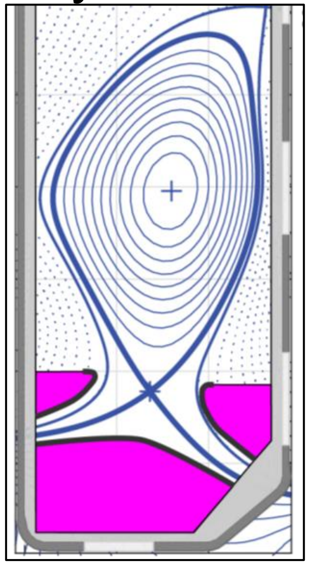
by 2026



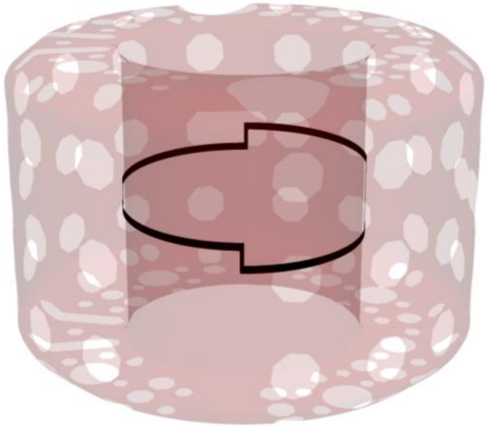
- Test of the Tightly-Baffled Long-Legged Divertor (TBLLD), a novel concept combining key exhaust features with minimum added complexity

➢ **See H. Reimerdes, Wednesday PM**

by 2028



by 2026

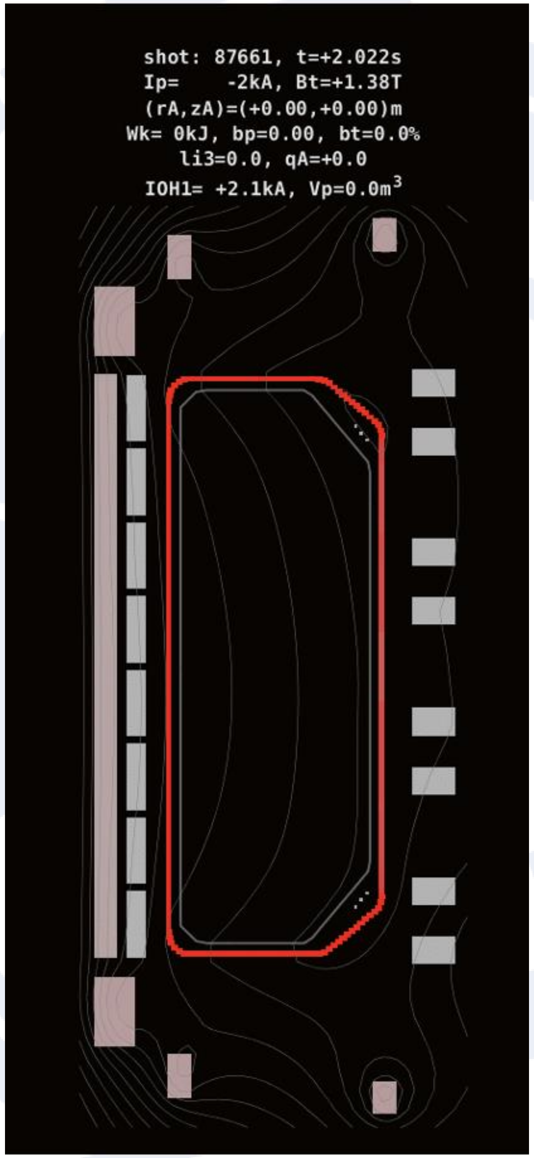


[U. Sheikh 2025]

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

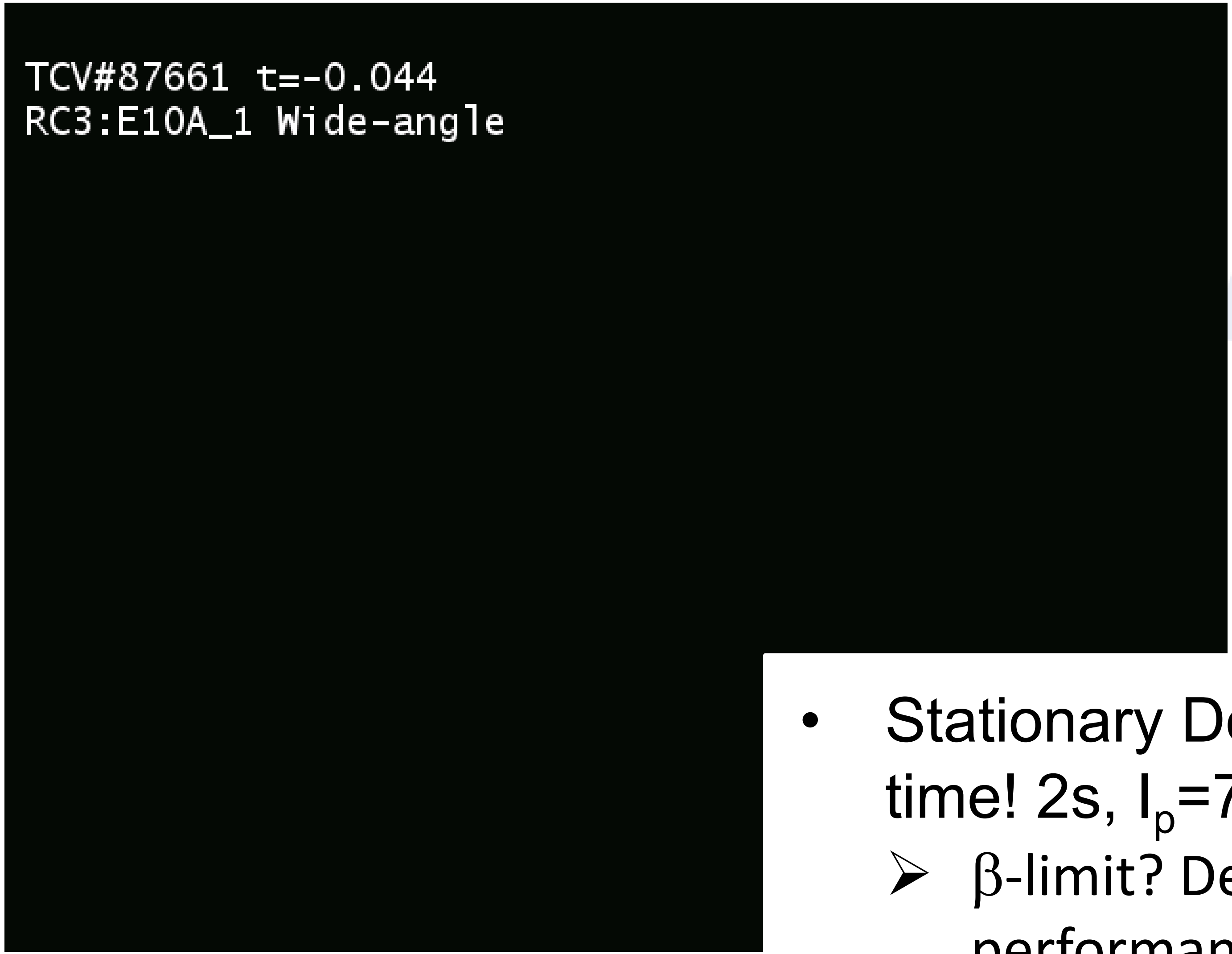
- Installation of two additional 1MW, dual-frequency gyrotons (2026 and 2027)

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

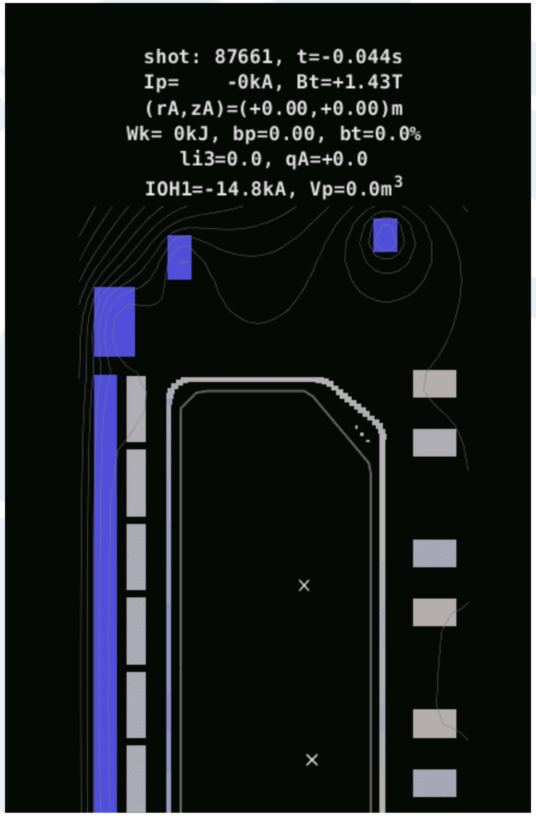


[C. Heiss APS 2025]

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



[C. Heiss APS 2025]



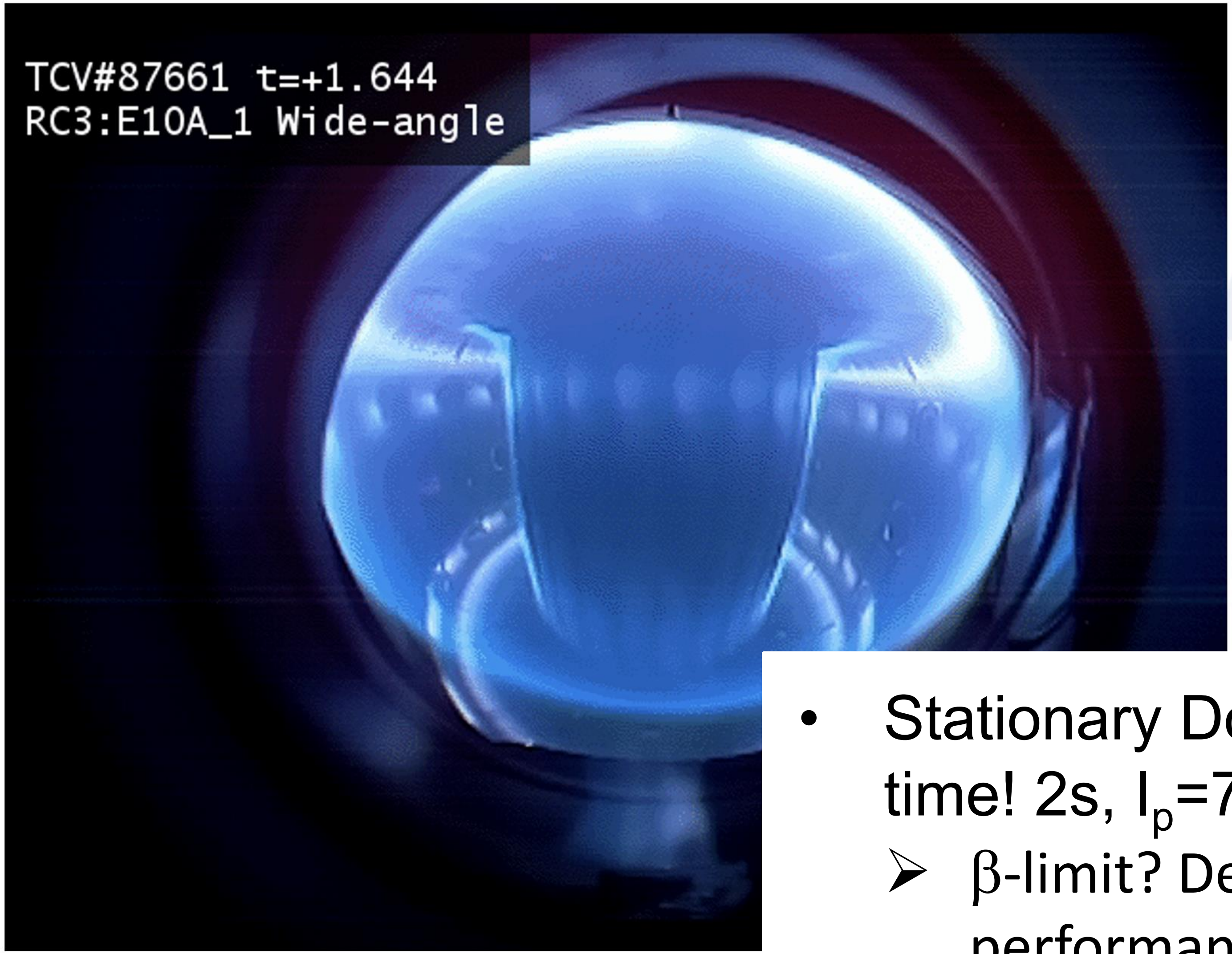
- Stationary Doublets achieved for the first time! 2s, I_p=700kA, κ=3.1
  - ➢ β-limit? Density limit? Confinement? Exhaust performance (radiative mantle)?…

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

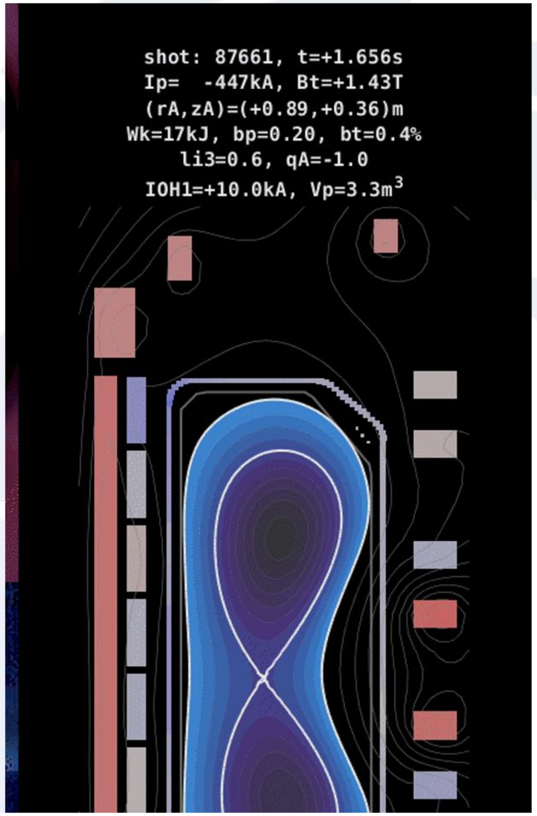
+ many more!

We are always open for collaborations!

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



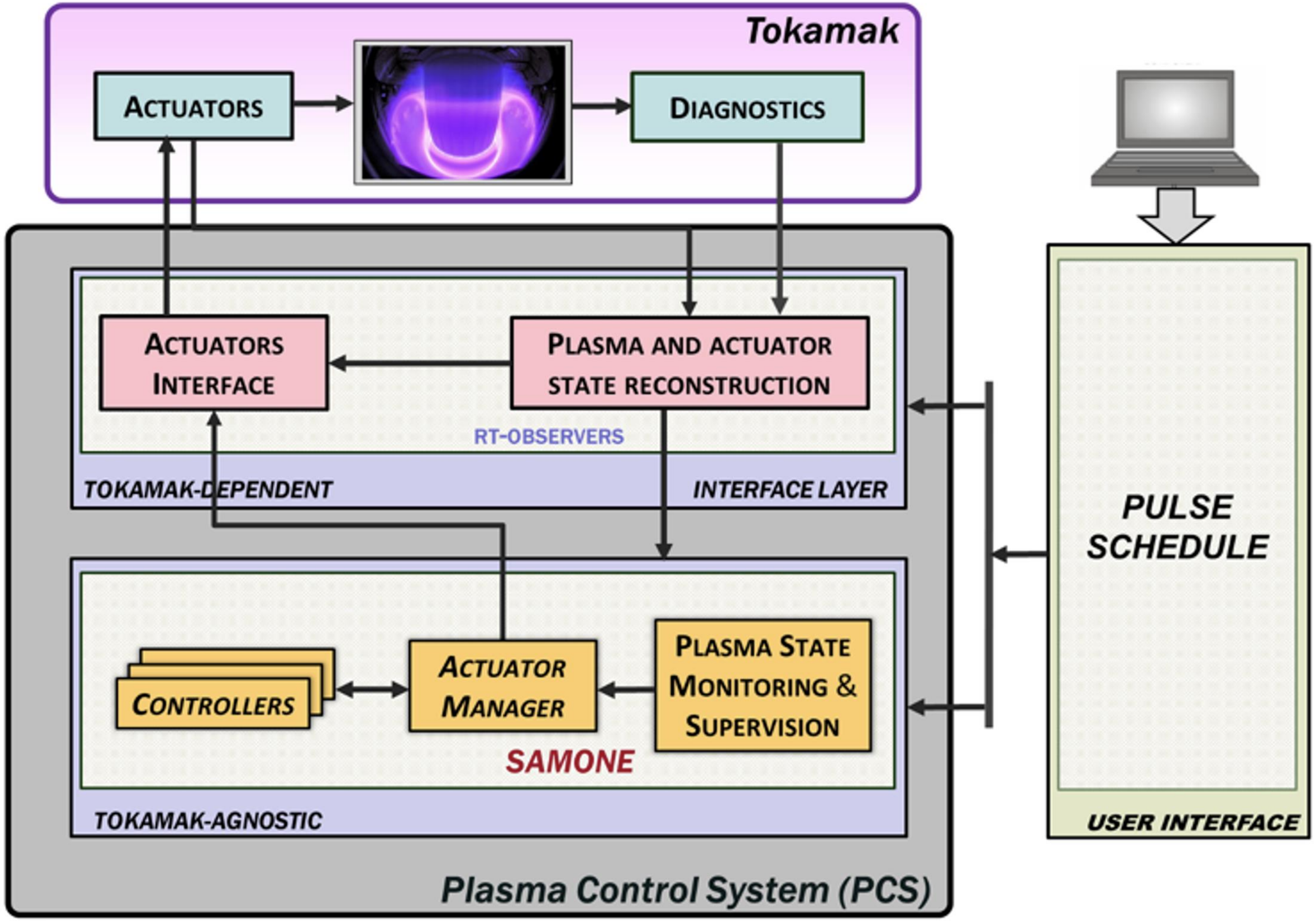
[C. Heiss APS 2025]



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

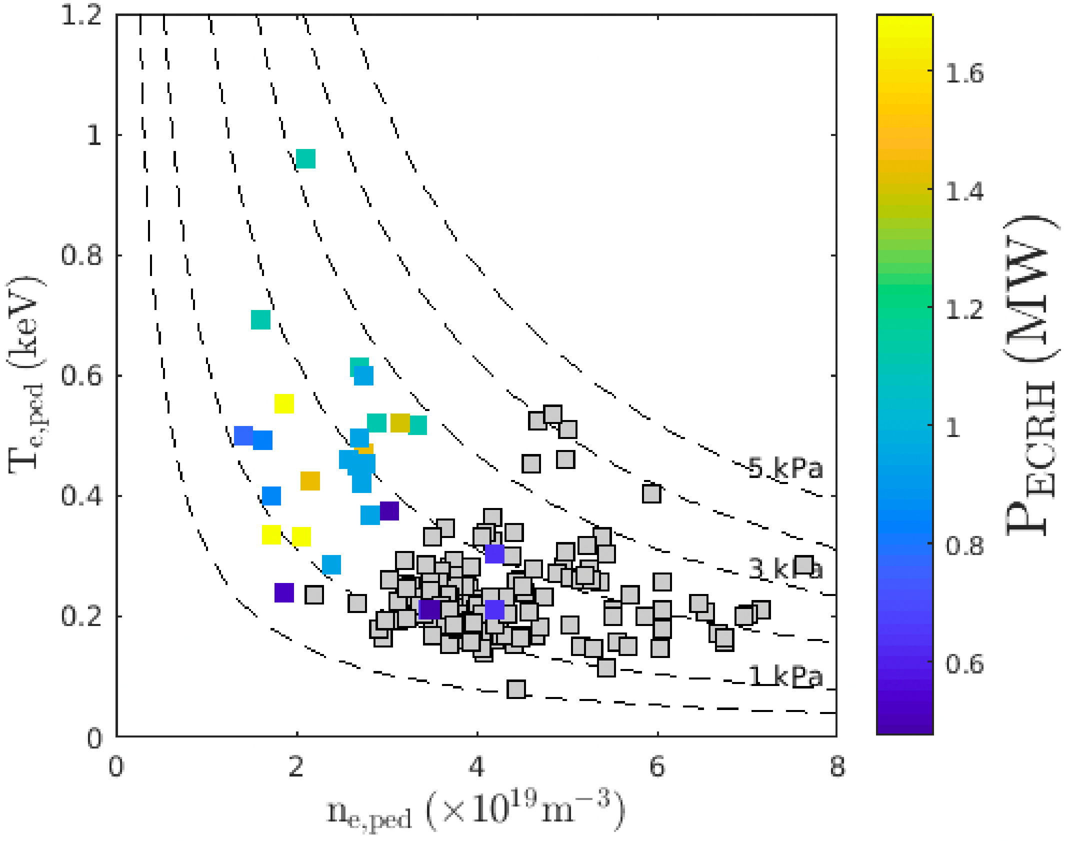
TCV's actuator manager system

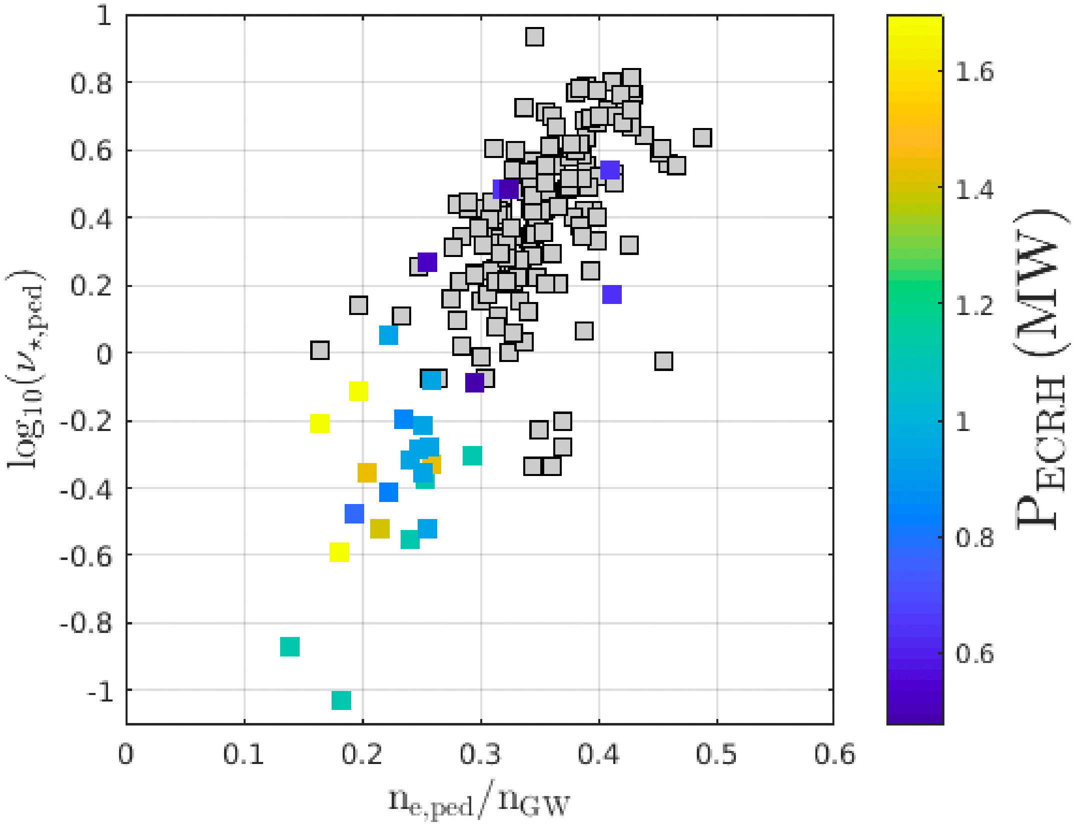
- Separation of tokamak dependent and agnostic layers
- Generic implementation
- Flexible framework allowing easy maintenance and upgrade
- Concepts of integration and portability



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

TCV H-mode operational space extended to low collisionality with additional ECRH power (X3)



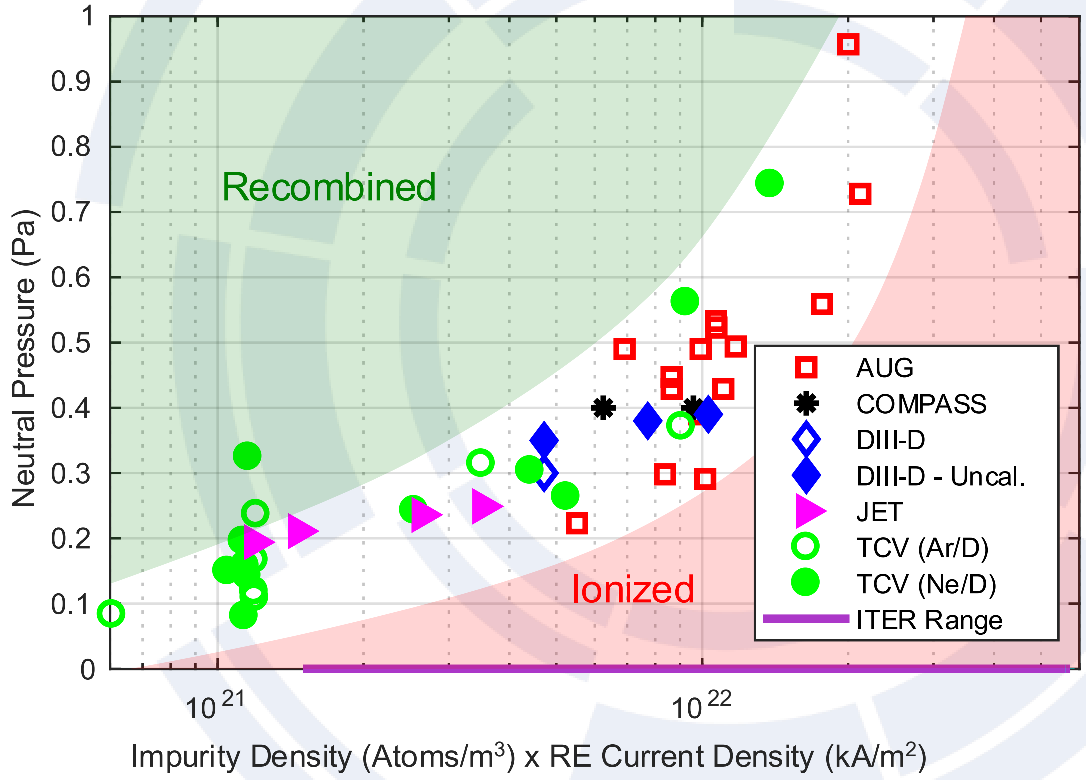


Mitigating Runaway Electron (RE) beam risks

- Lower neutral pressure limit reproduced with SOLPS-ITER [Tonello in prep.]
- Upper limit partly explained by increasing rate of RE impact ionization [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**

Experimental, lower limit for recombining companion plasma



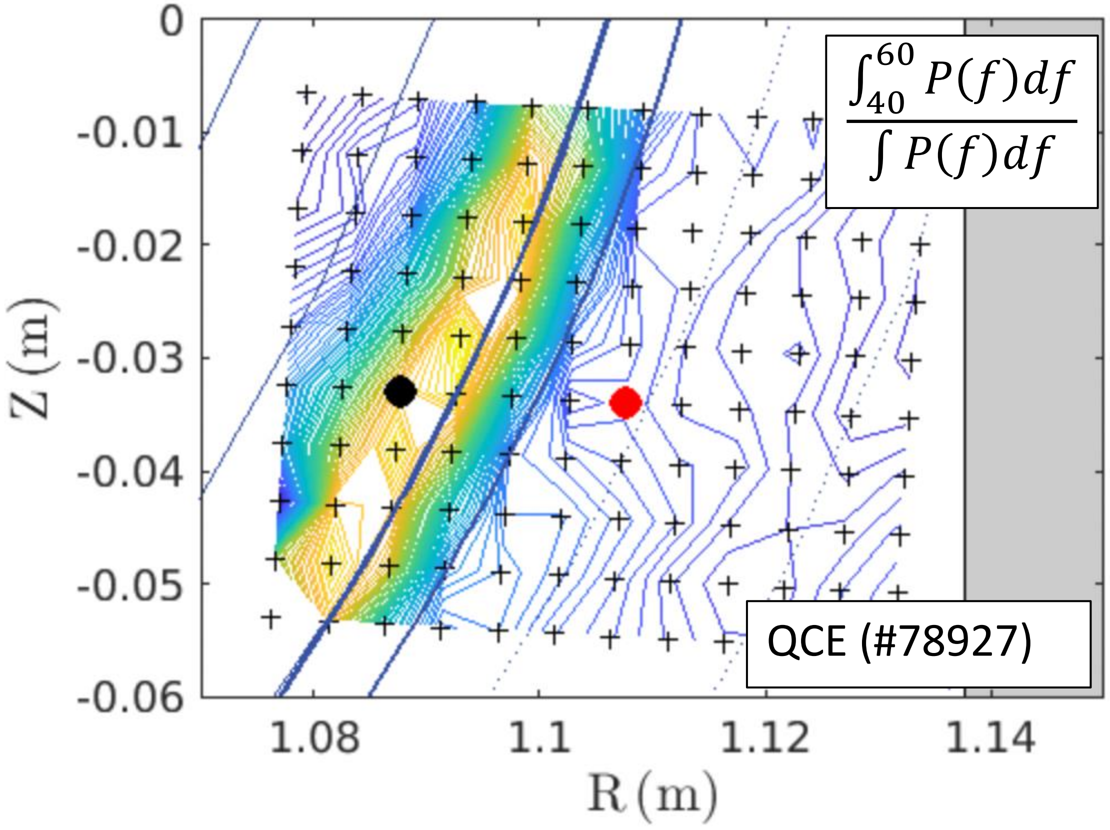
QCE edge signatures and consequences

- GPI and DBS show quasi coherent fluctuations just inside the separatrix

  f ~ 50kHz

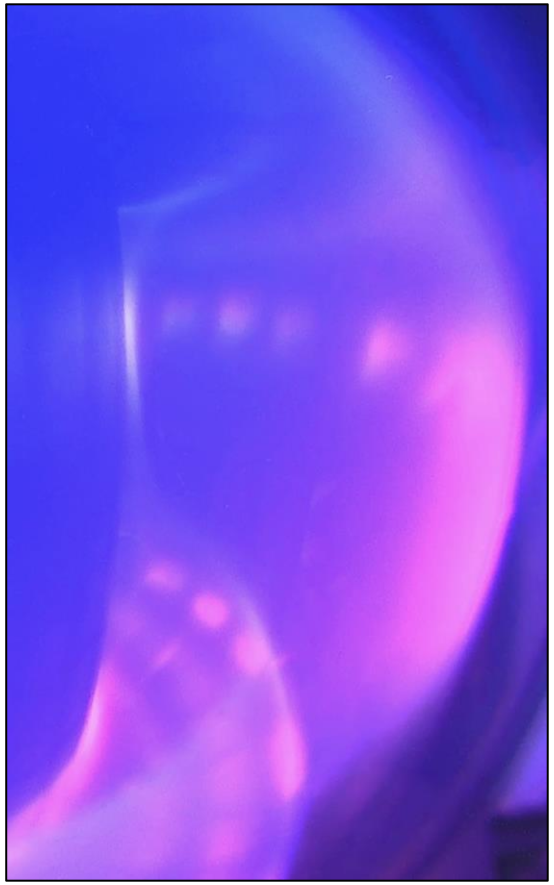
  k_θ ~100 m^{-1}

➢ Consistent with QCE triggered by unstable ballooning modes at pedestal foot

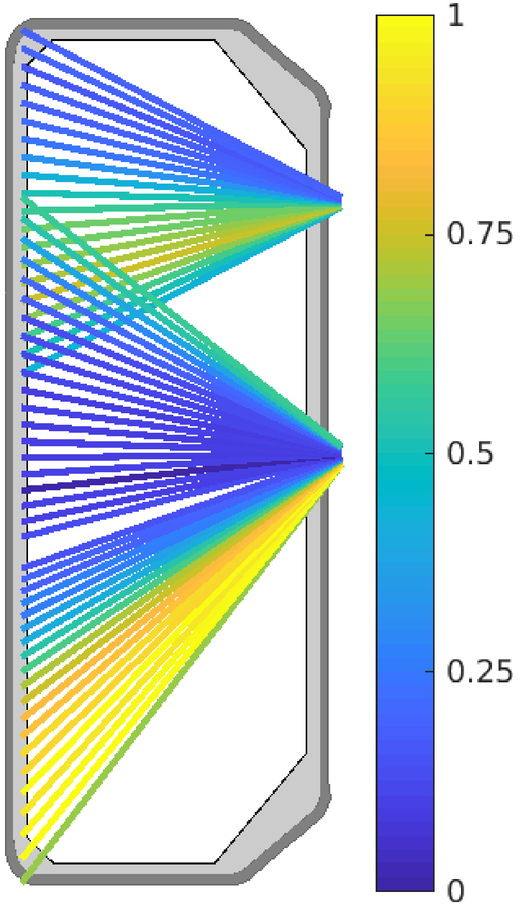


[B. Labit et al., EPS 2025]

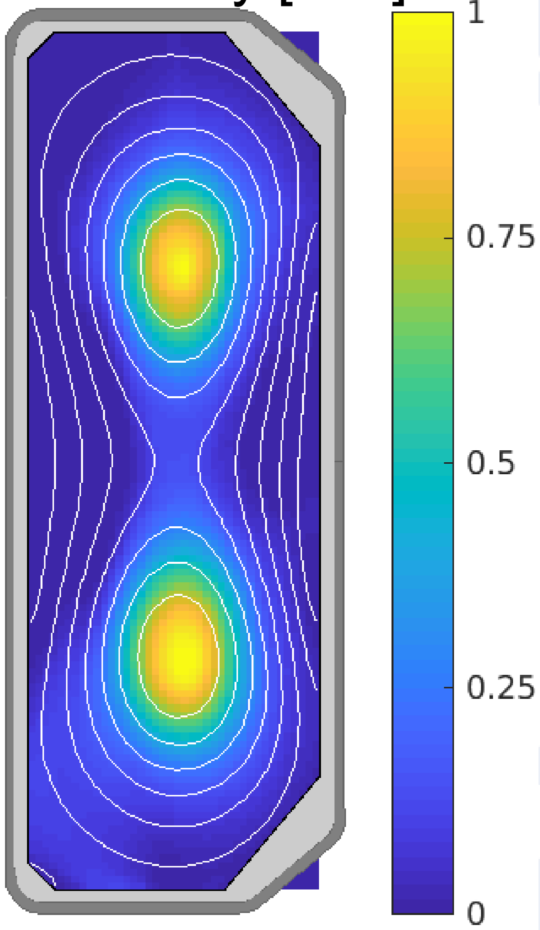
Visible imaging



Soft X-ray [a.u.]



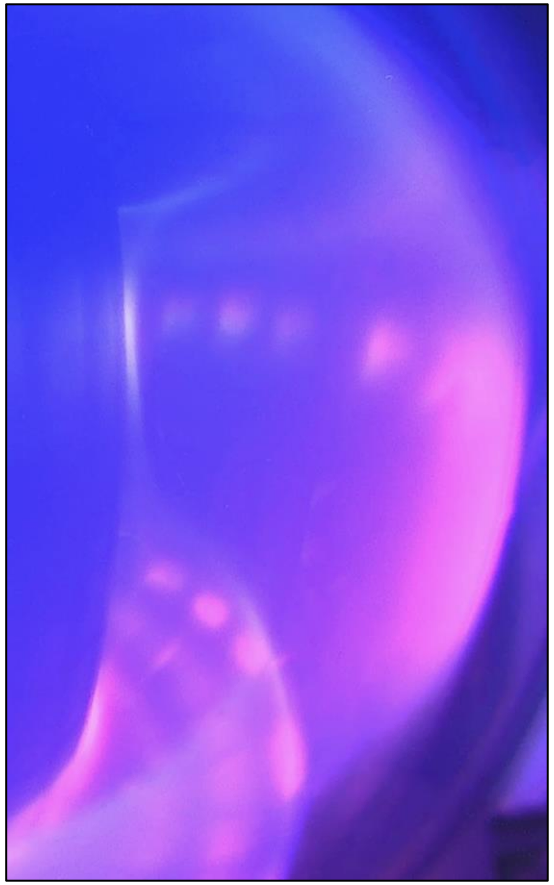
Soft X-ray [a.u.]



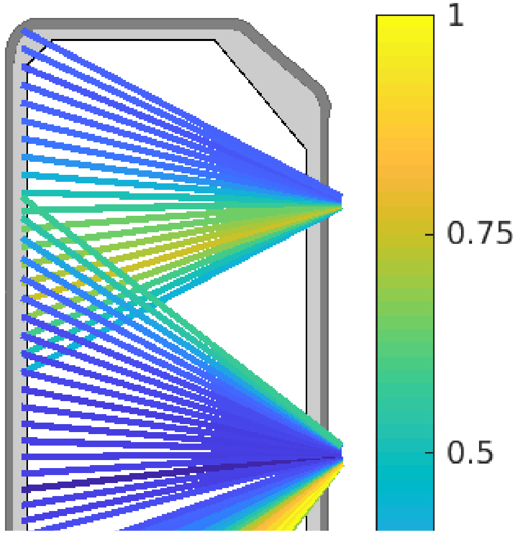
[C. Heiss APS 2025]

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

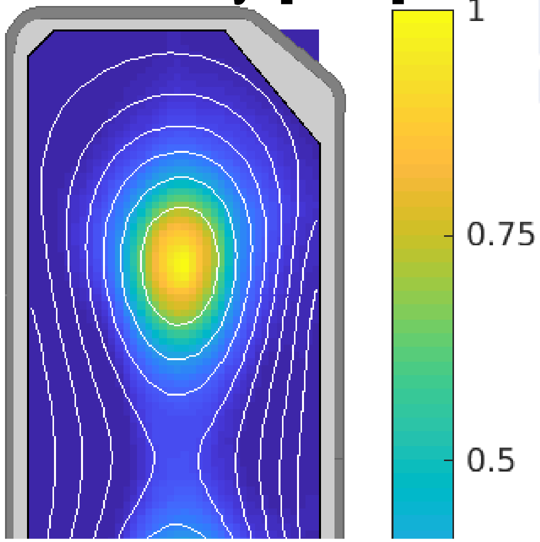
Visible imaging



Soft X-ray [a.u.]



Soft X-ray [a.u.]



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