MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

ASDEX Upgrade

Overview of ASDEX Upgrade results

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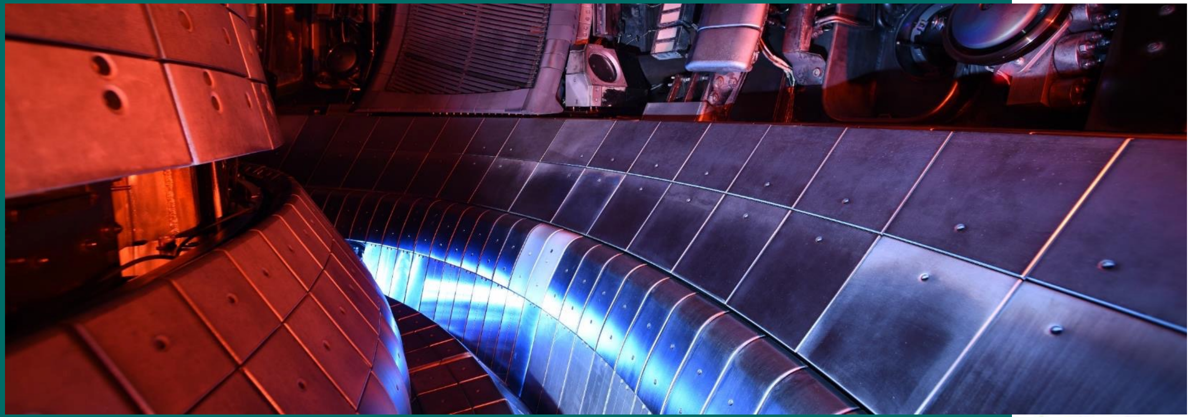

Presented at the 30th IAEA Fusion Energy Conference, Chengdu, China, 14th of October 2025

EUROfusion

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.

Outline

- **Upper divertor upgrade in AUG**
- **Alternative divertor configurations (ADCs) explored**
- **Supporting the full-W ITER**
    - Boronizations and their effect
    - ELM-free and small ELM regimes
    - Impurity transport
    - Model-based predictions
    - Tailoring of the current quench
- **Summary**

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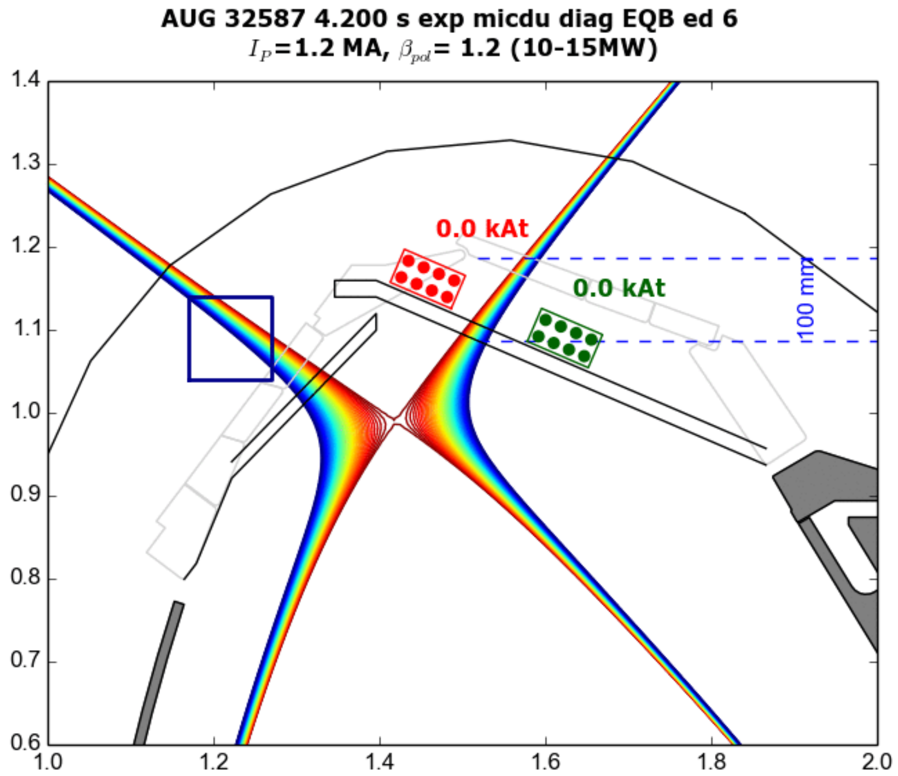
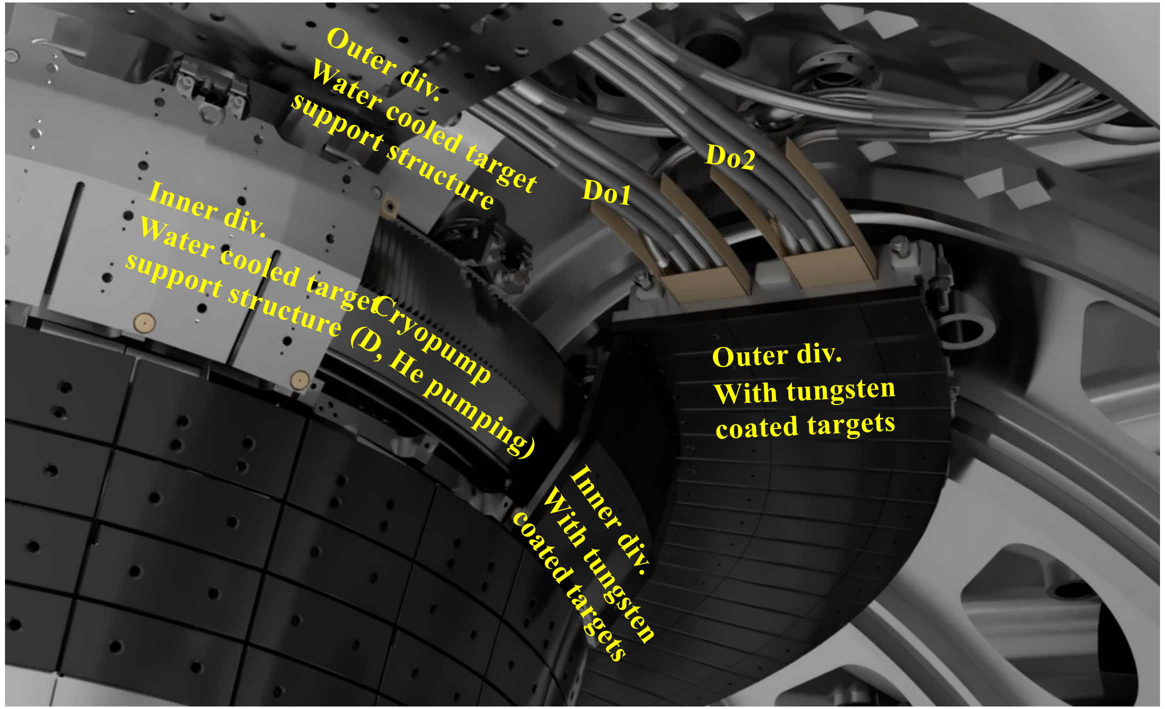
Long shutdown for installation of new upper divertor (DivIIo)

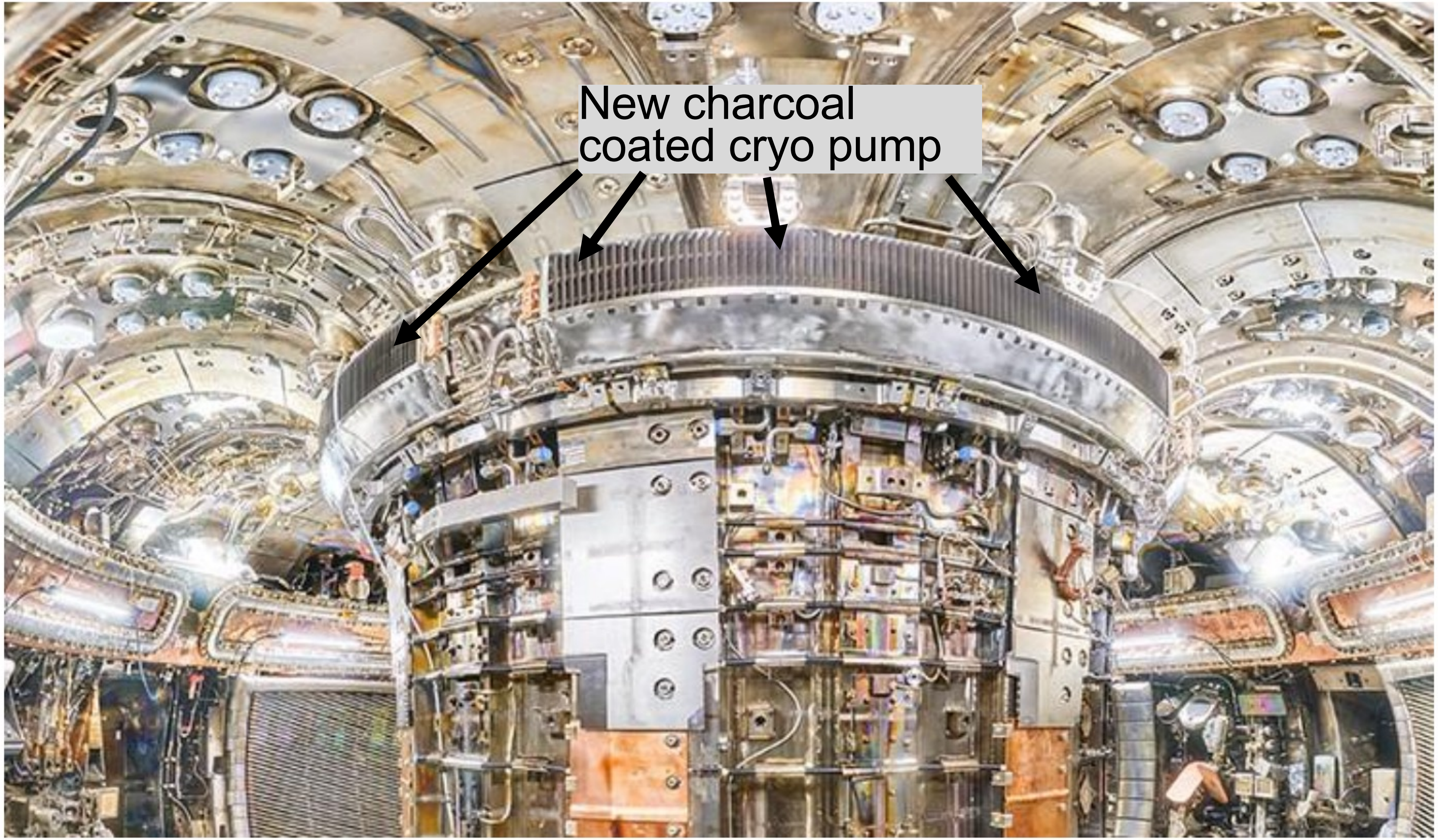




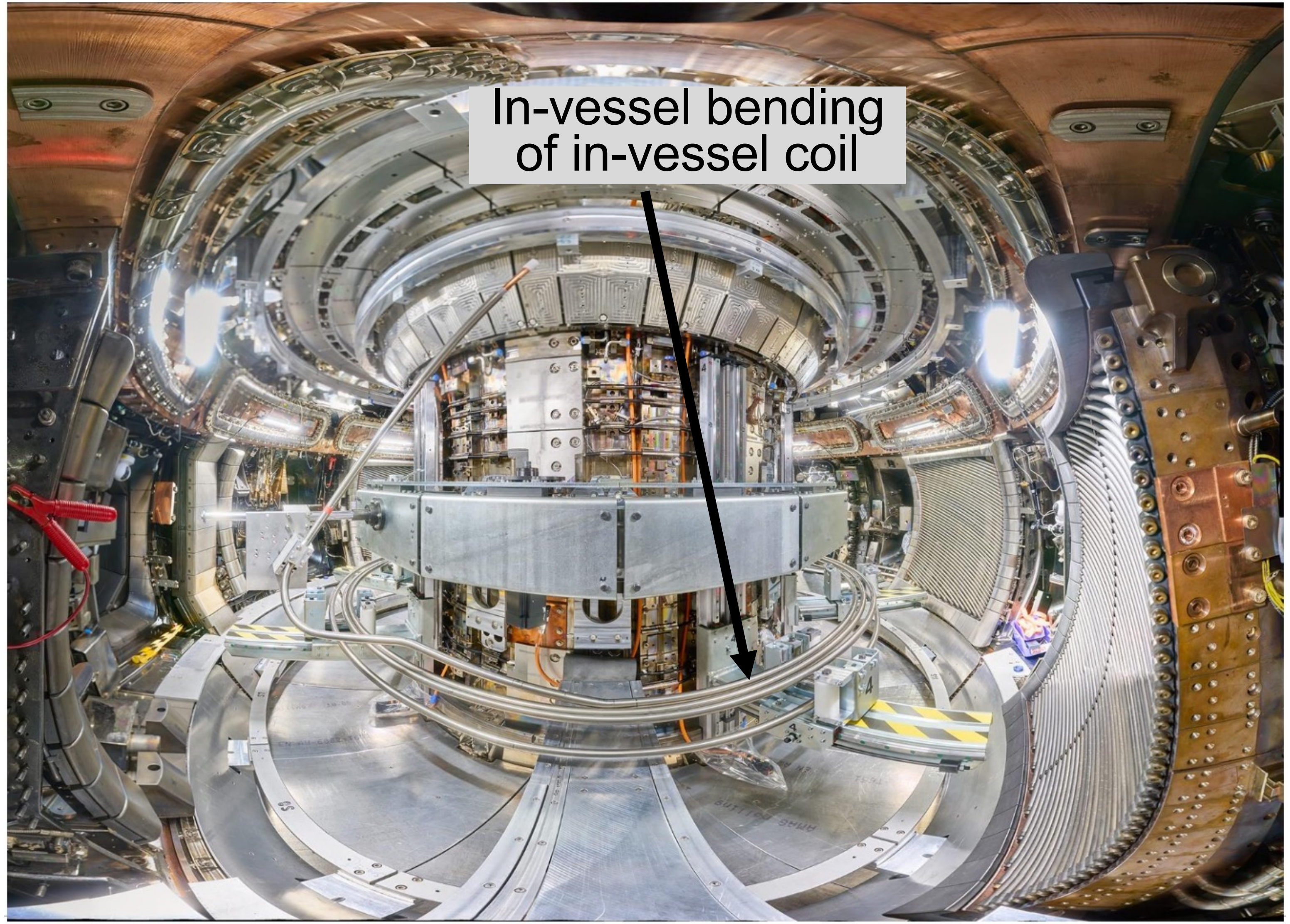
ASDEX Upgrade went through a ~2 yr shutdown for installation of the new divertor

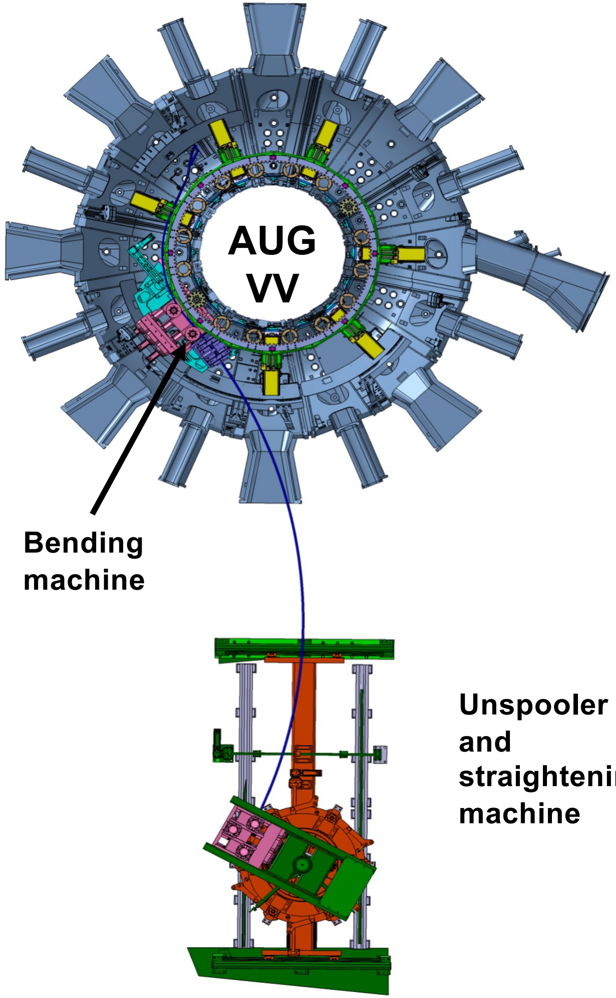
- installation of 2 divertor coils inside the vessel, a cryopump and a new set of flat tiles
- aim is to study the physics element of alternative divertors (SF, X-divertor, sCRD)

Upper divertor upgrade



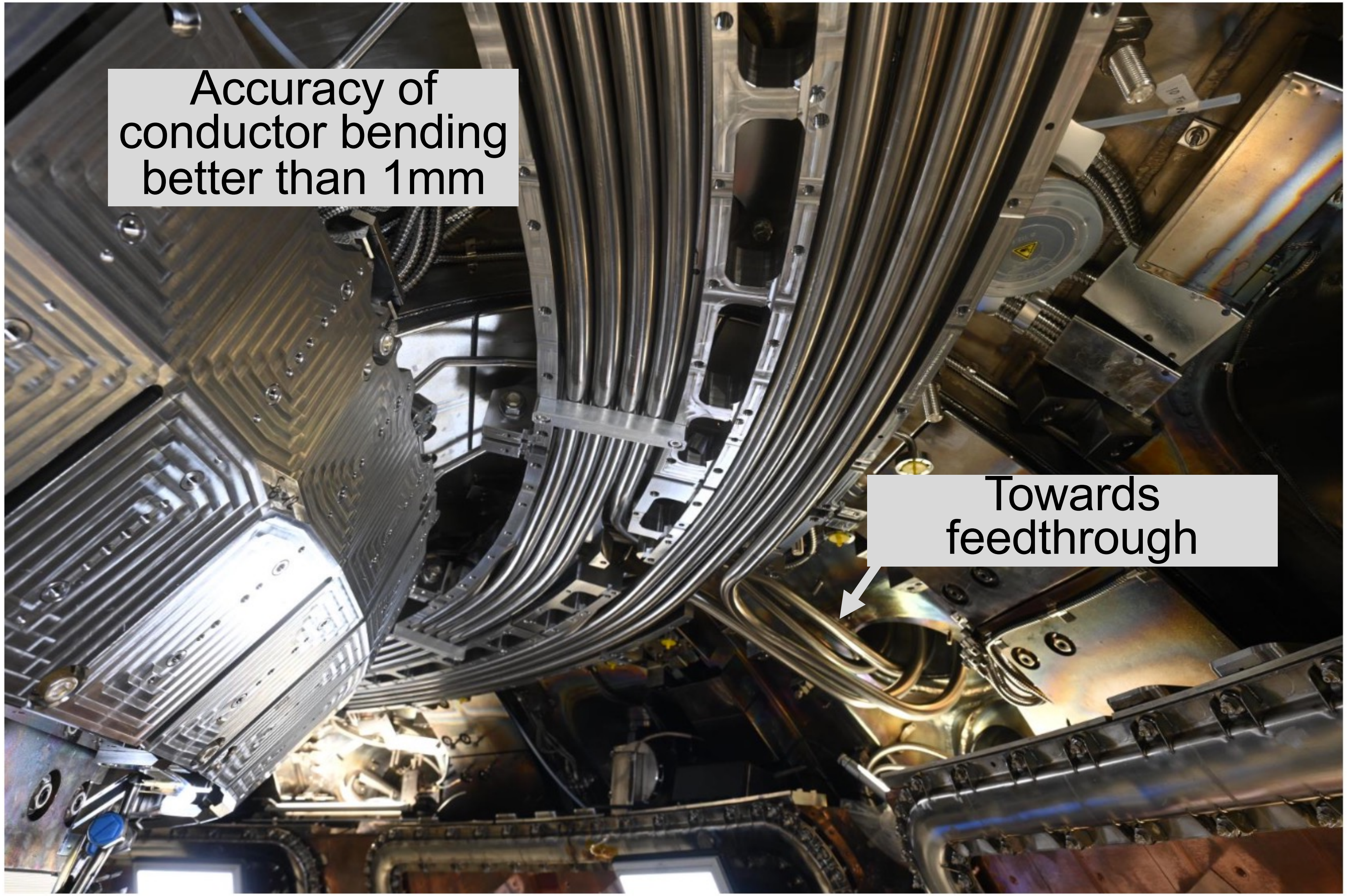
Upper divertor upgrade



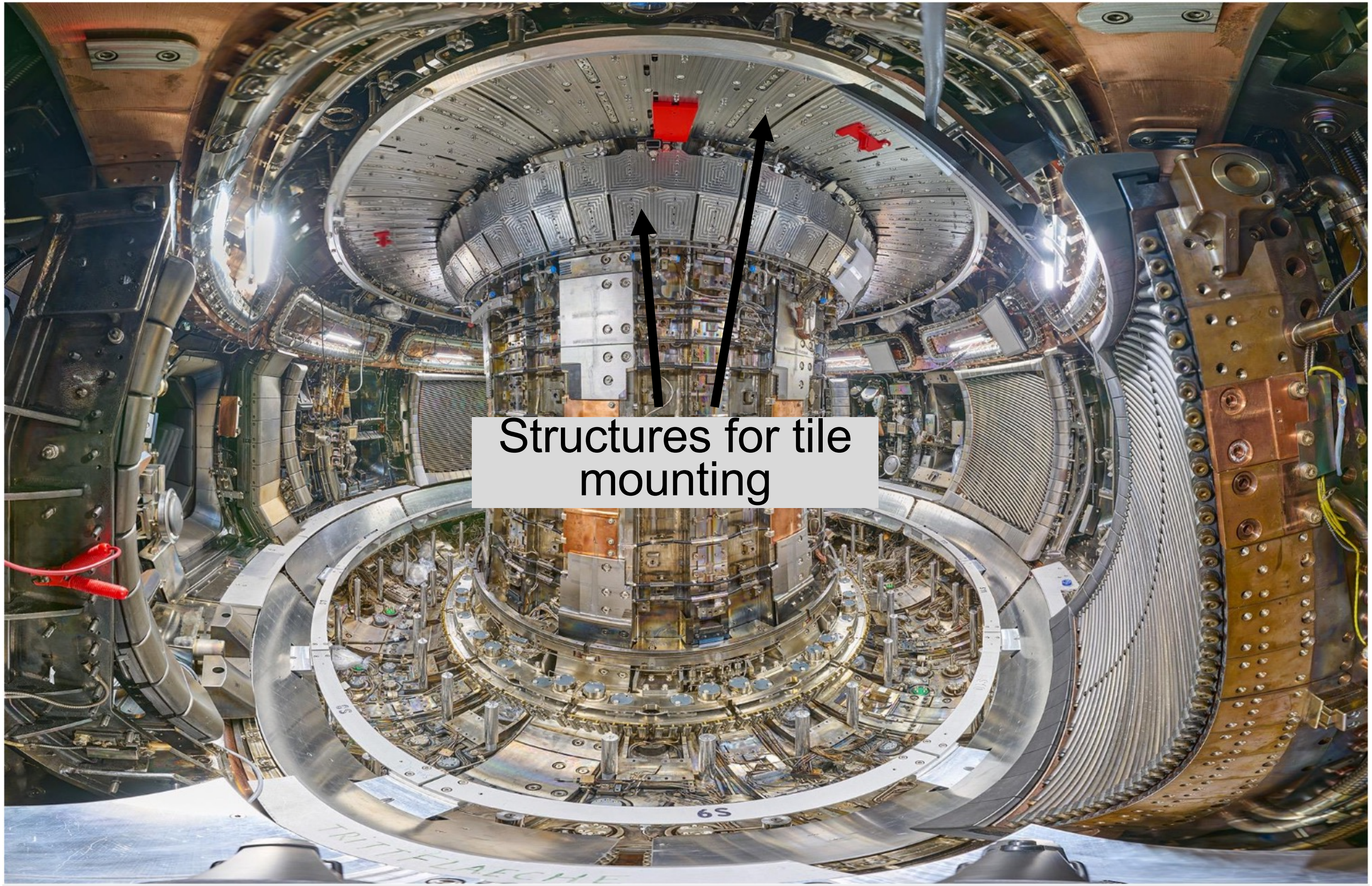


I. Zammuto SOFE 2025

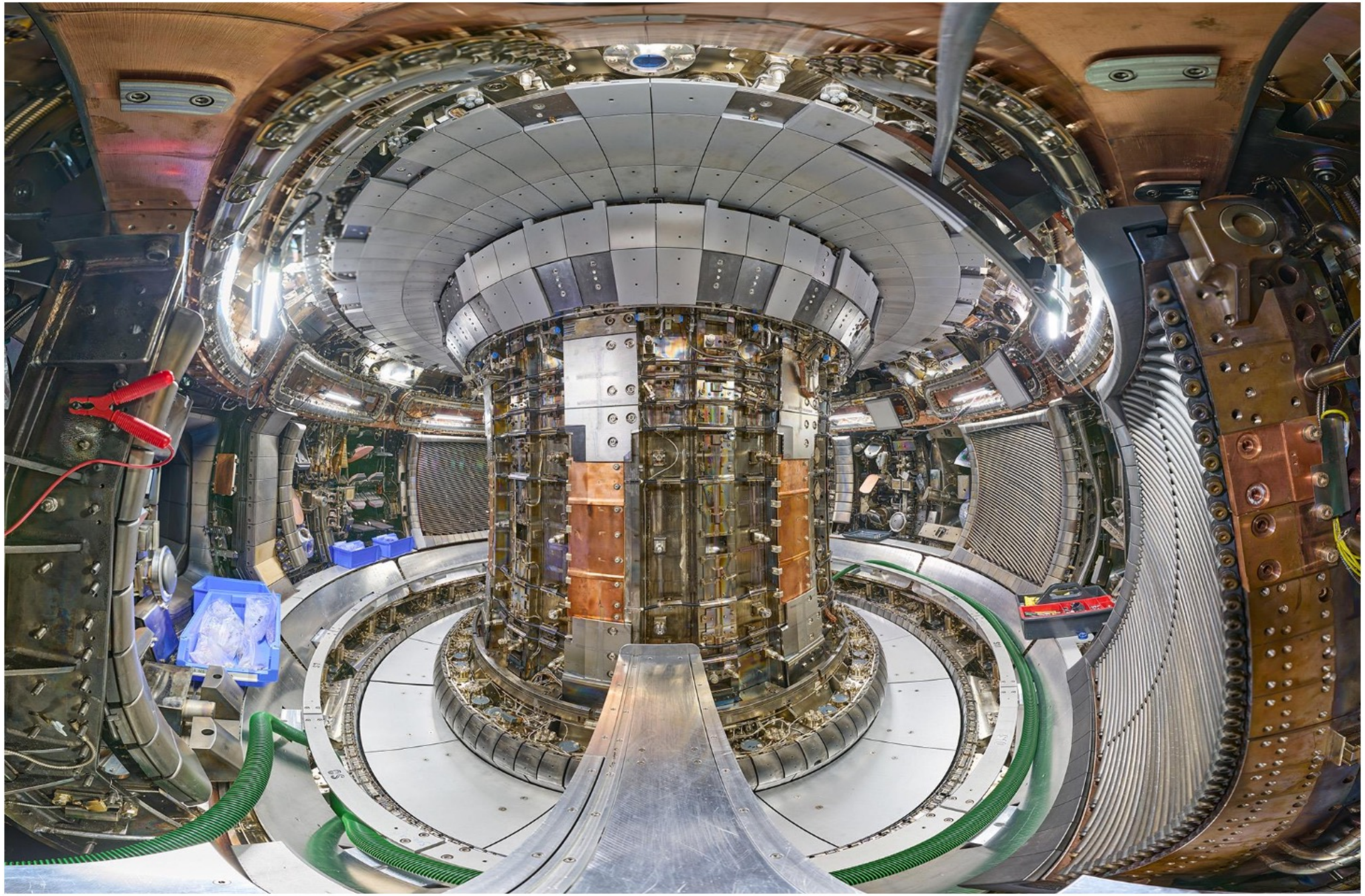
Upper divertor upgrade



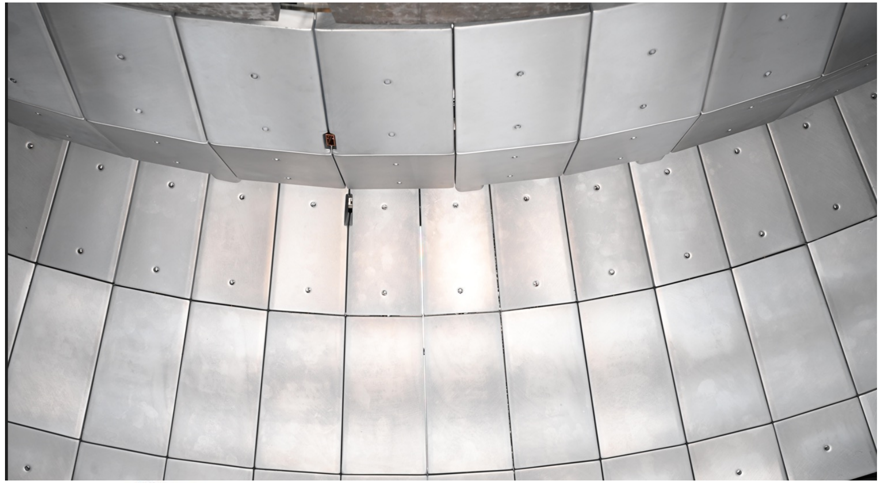
Upper divertor upgrade

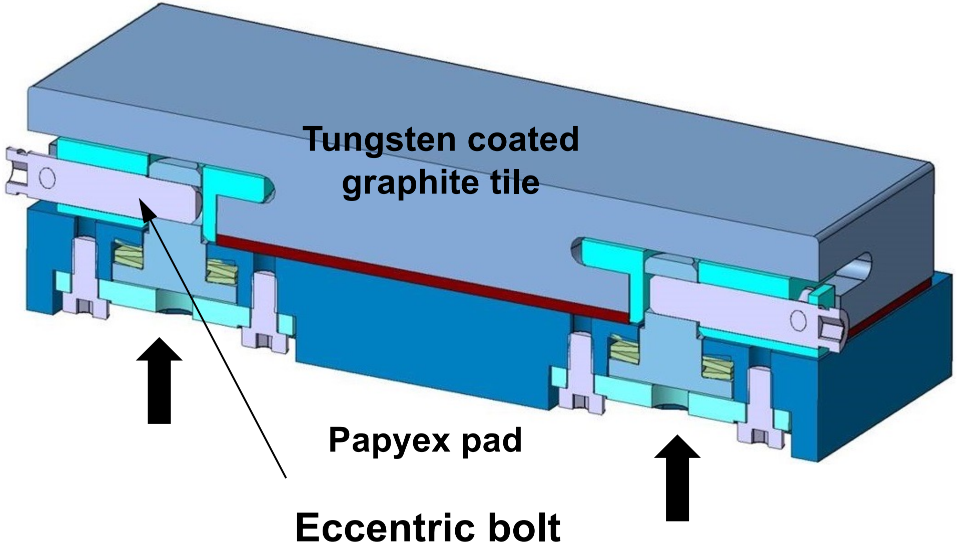


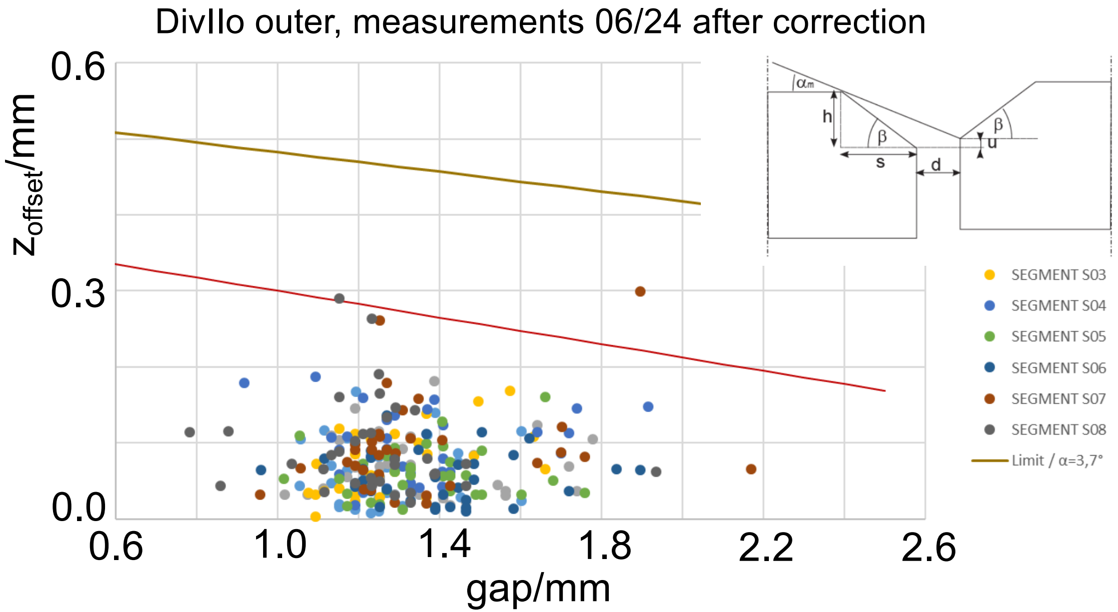
Upper divertor upgrade



Flat tile target in the upper divertor fulfills tolerances





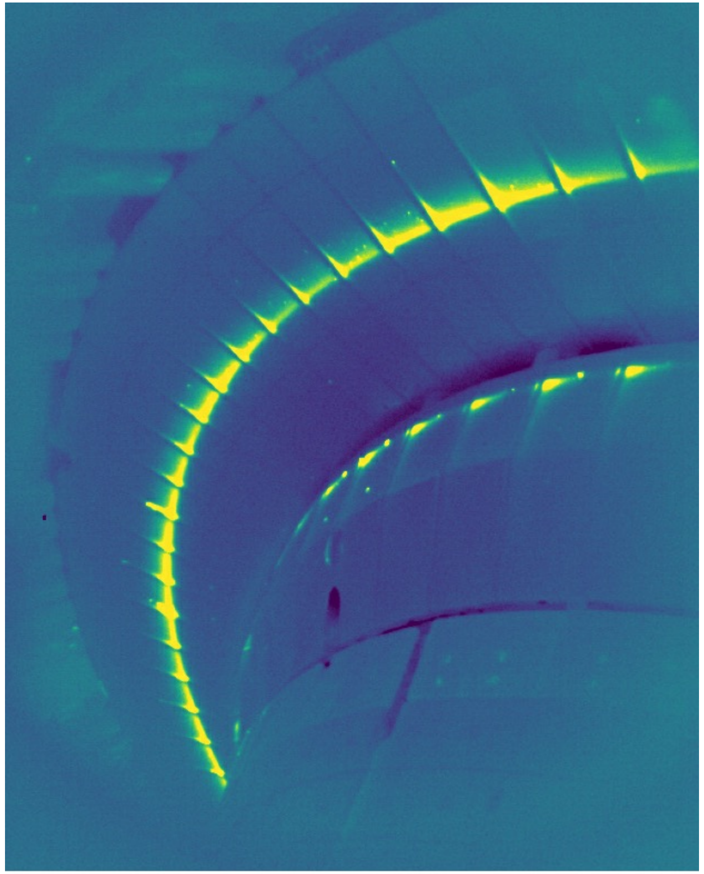


Strict tolerance requirements to avoid leading edges

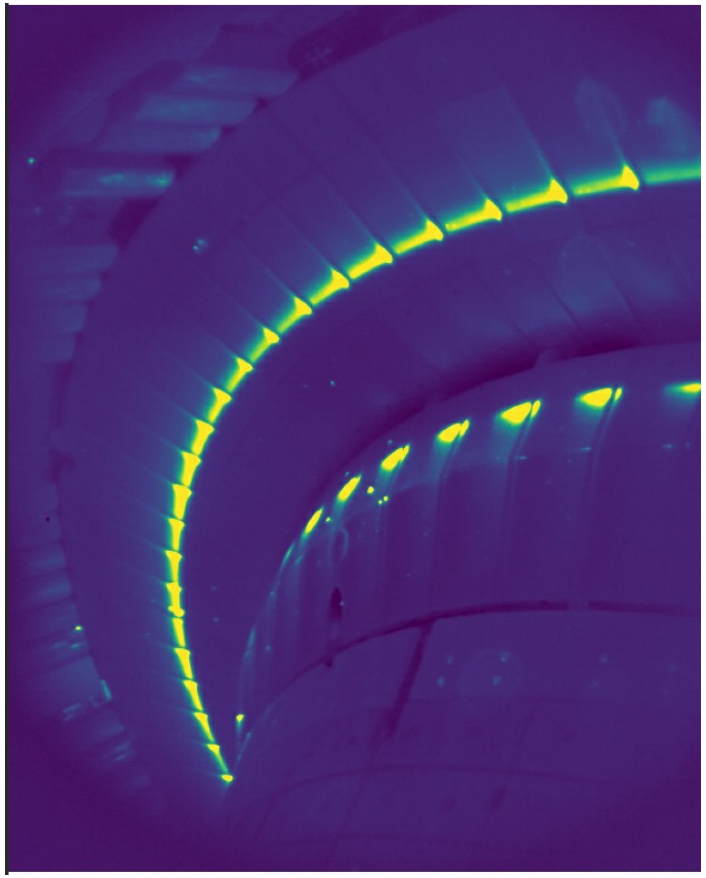
- alignment of most exposed tiles by excentric bolts on the lower side
- height offsets below 300 μm were met

No leading edges detected for both field helicities

#41980, B_{tor} = +2.5



#41982, B_{tor} = -2.5



Both helicities with 4.5 MW ECRH heating, symmetric flat divertor tiles with no tilting

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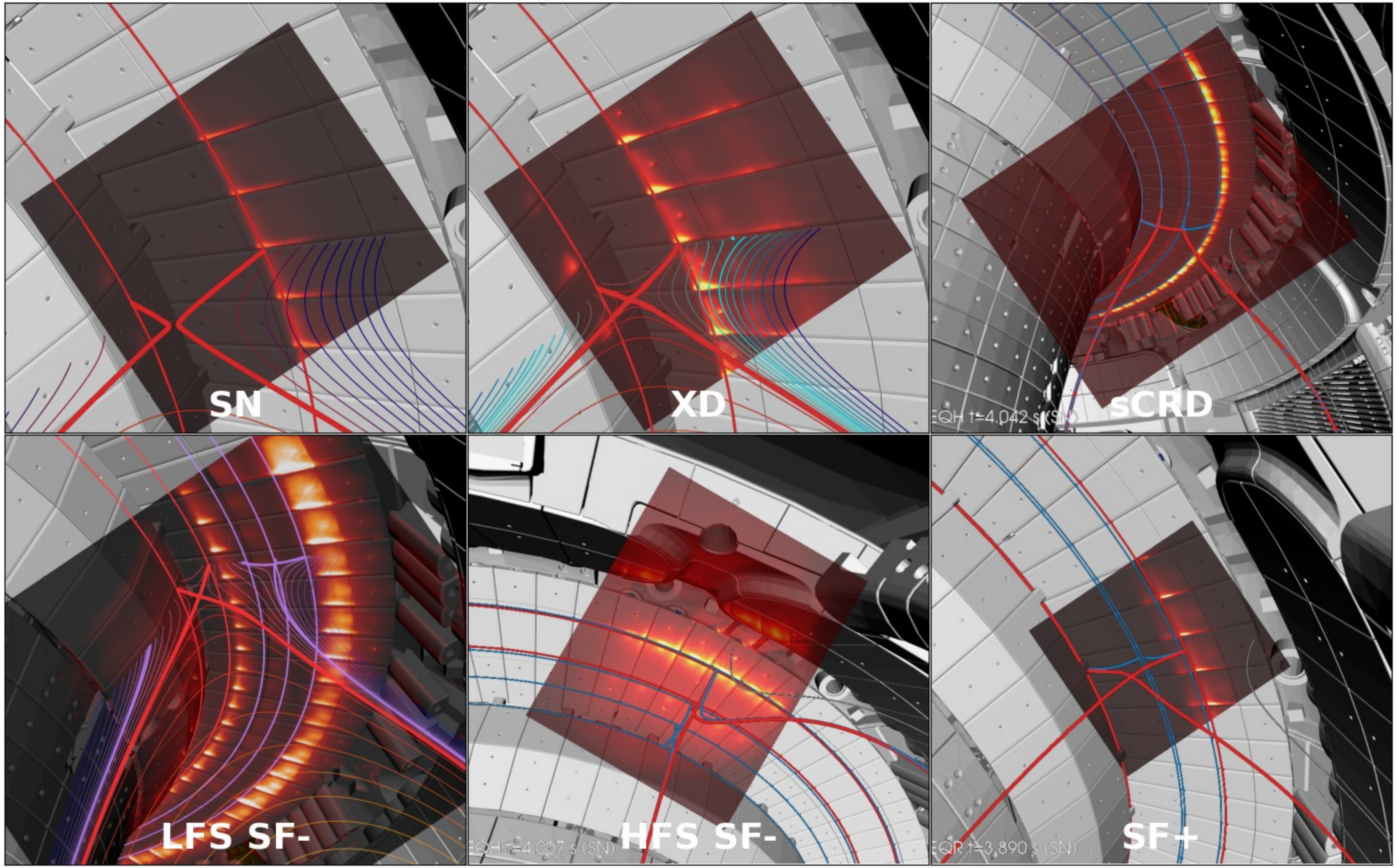
All Alternative Divertor Configurations (ADC) achieved!

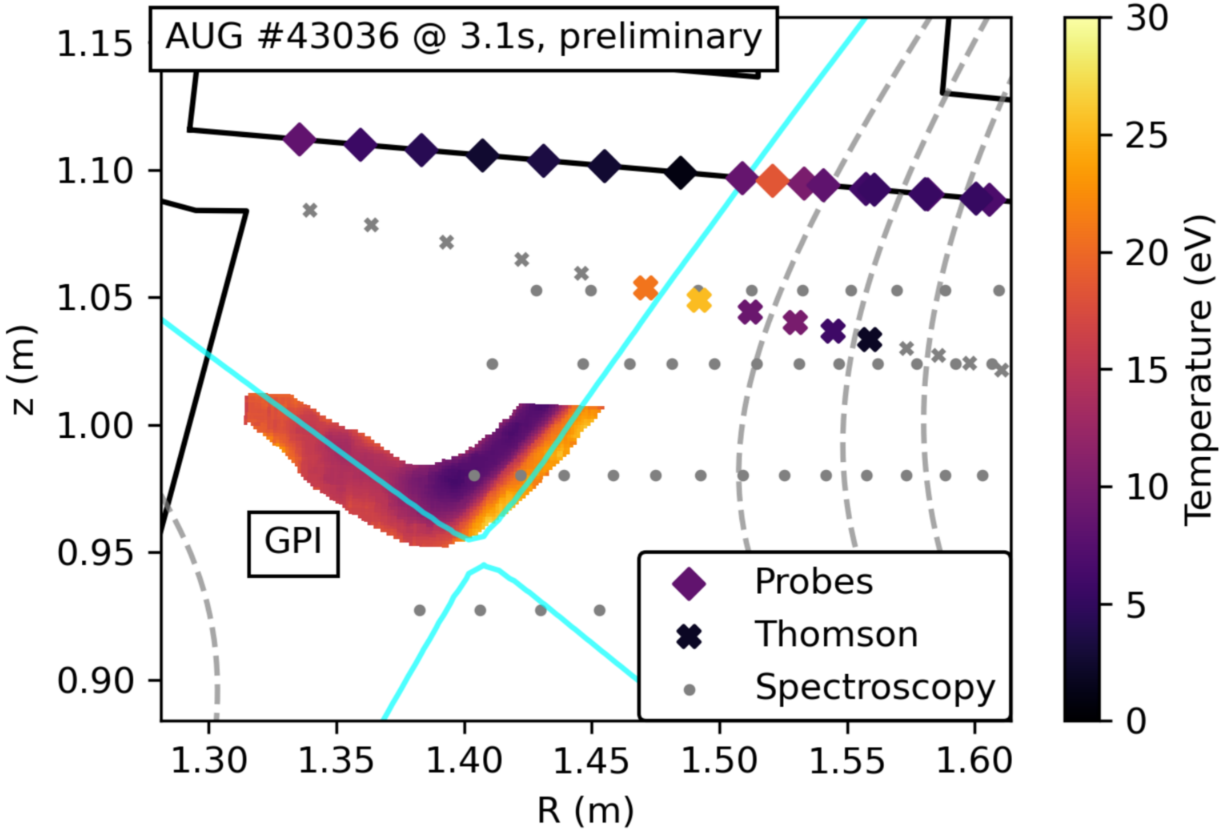
- **All envisaged configurations**
- **Up to ~20 MW of heating**
  (world record in ADC, P/R~12)
- **Ip = 0.6-1.0MA**
- **Seeding of N, Ar, Kr**
- **Detachment**



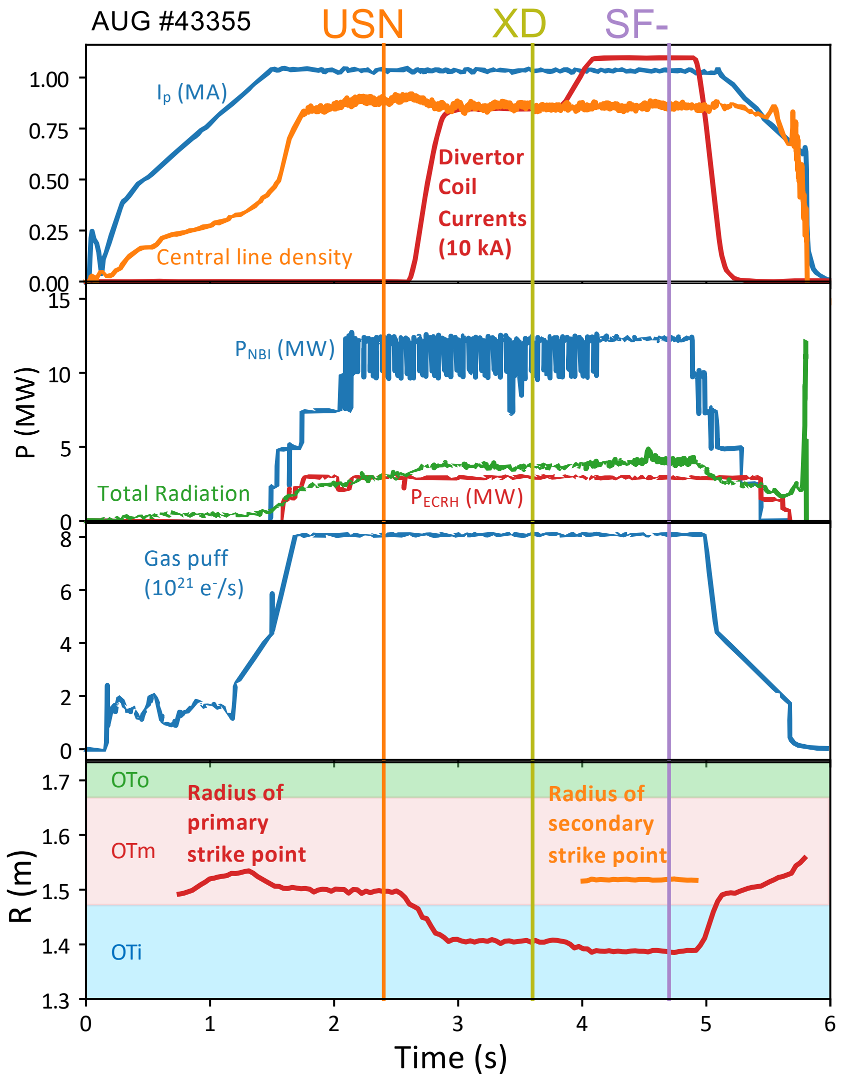
Very good Diagnostic Coverage in new Upper Divertor

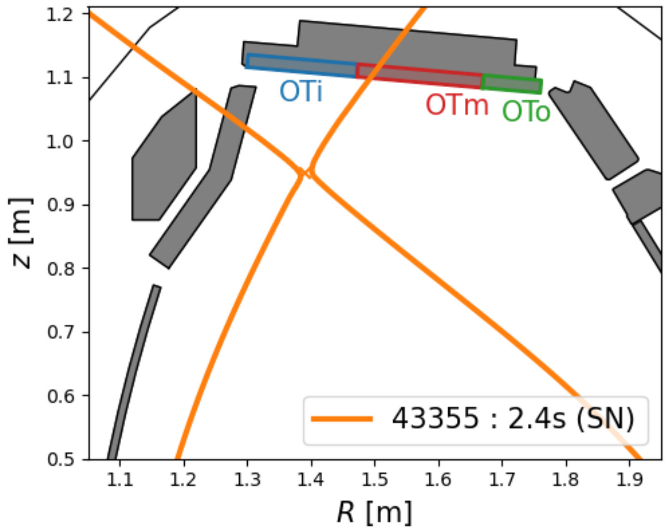
Example: electron temperature

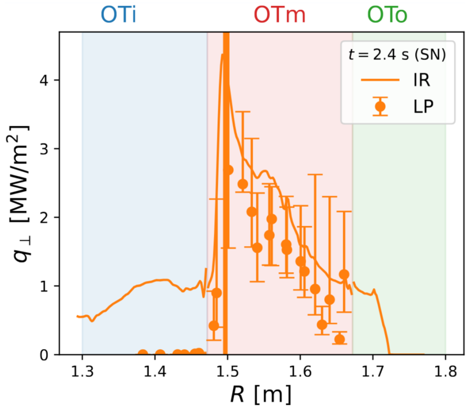
- Quantitative agreement in low density L-mode plasma between:
  - **Langmuir probes**
  - **Thomson scattering**
  - **Gas puff imaging (GPI)**
- **Spectroscopy** can replace GPI at higher densities
- Detailed comparison is **ongoing work**



Evolution SN → XD → SF- confirms Power Spreading

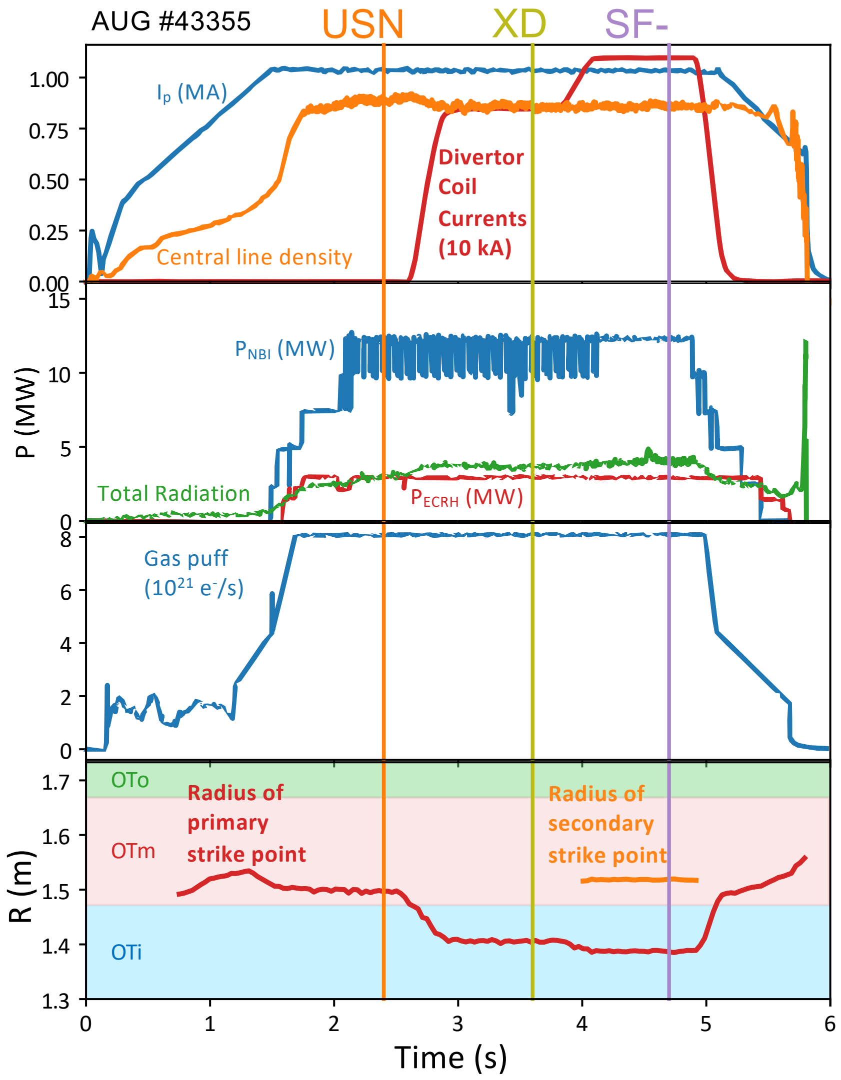


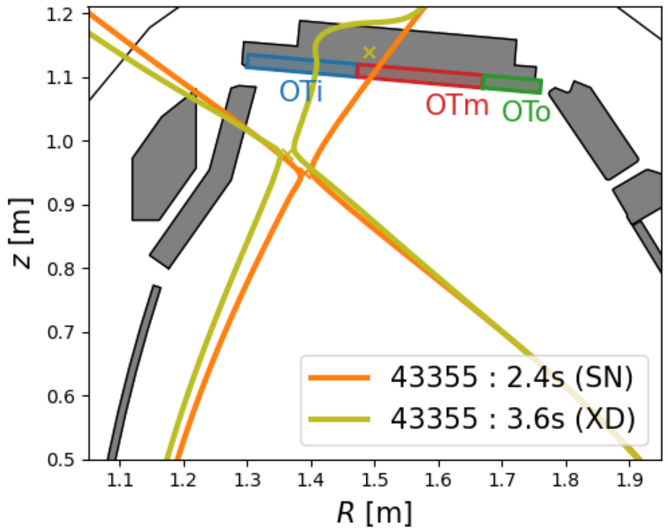


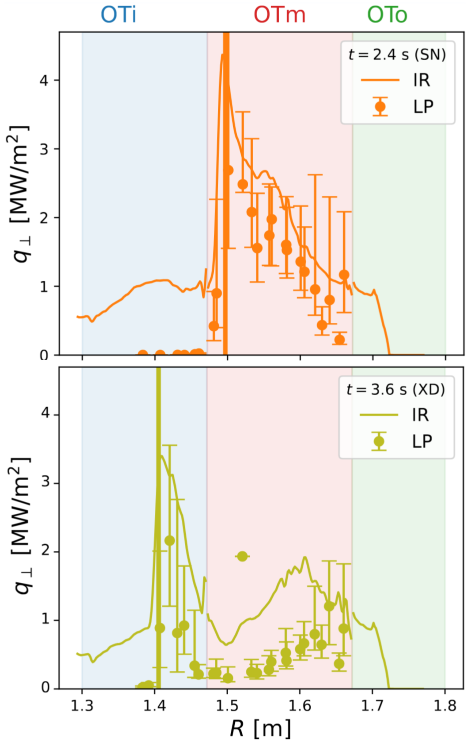


- Discharge going through various divertor configurations

Evolution SN → XD → SF- confirms Power Spreading

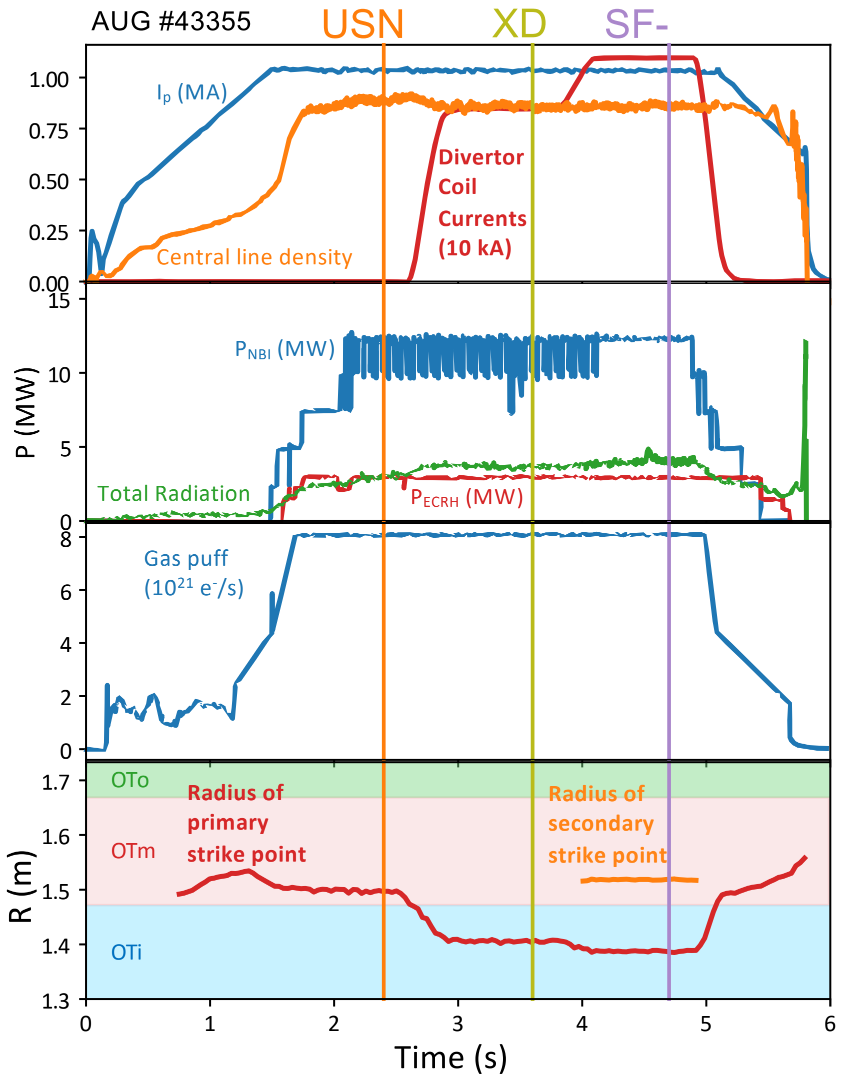


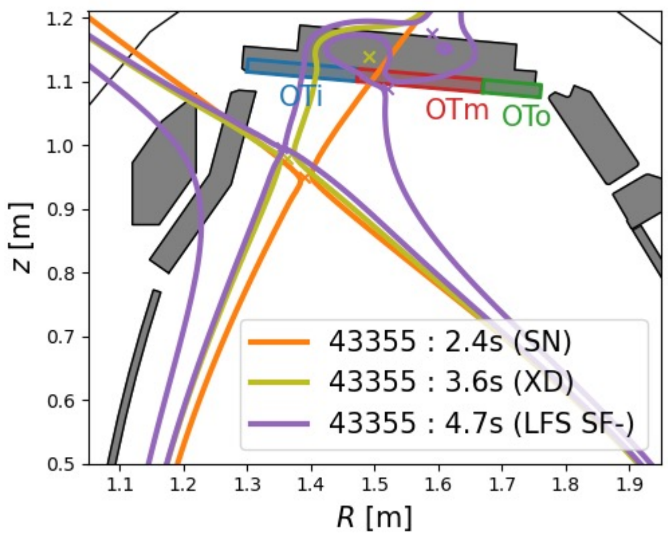


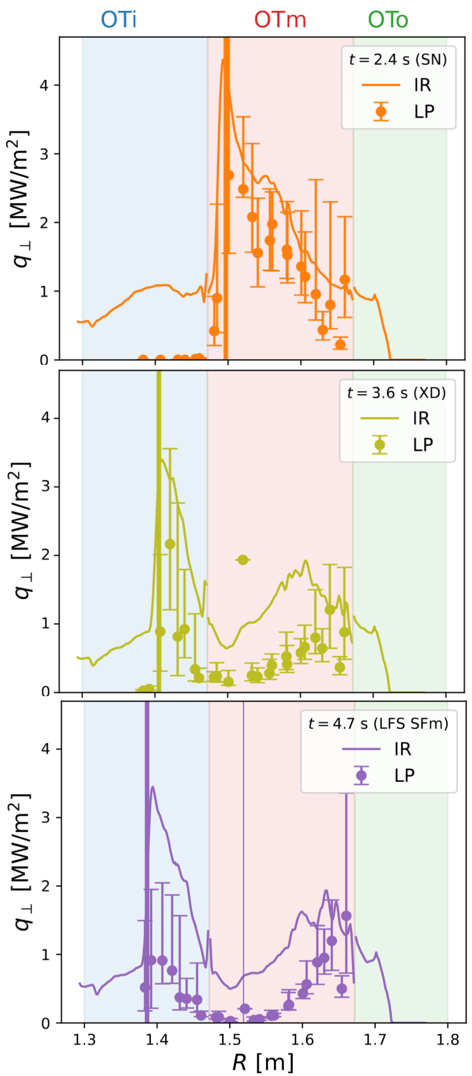


- Discharge going through various divertor configurations
- Power spreading observed

Evolution SN → XD → SF- confirms Power Spreading

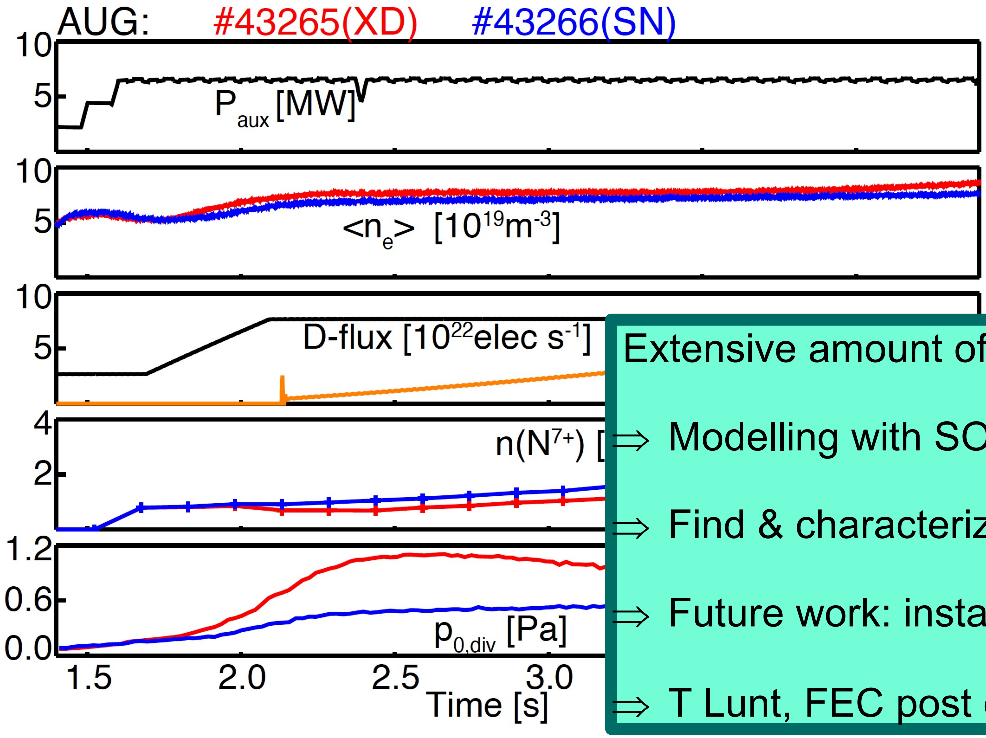


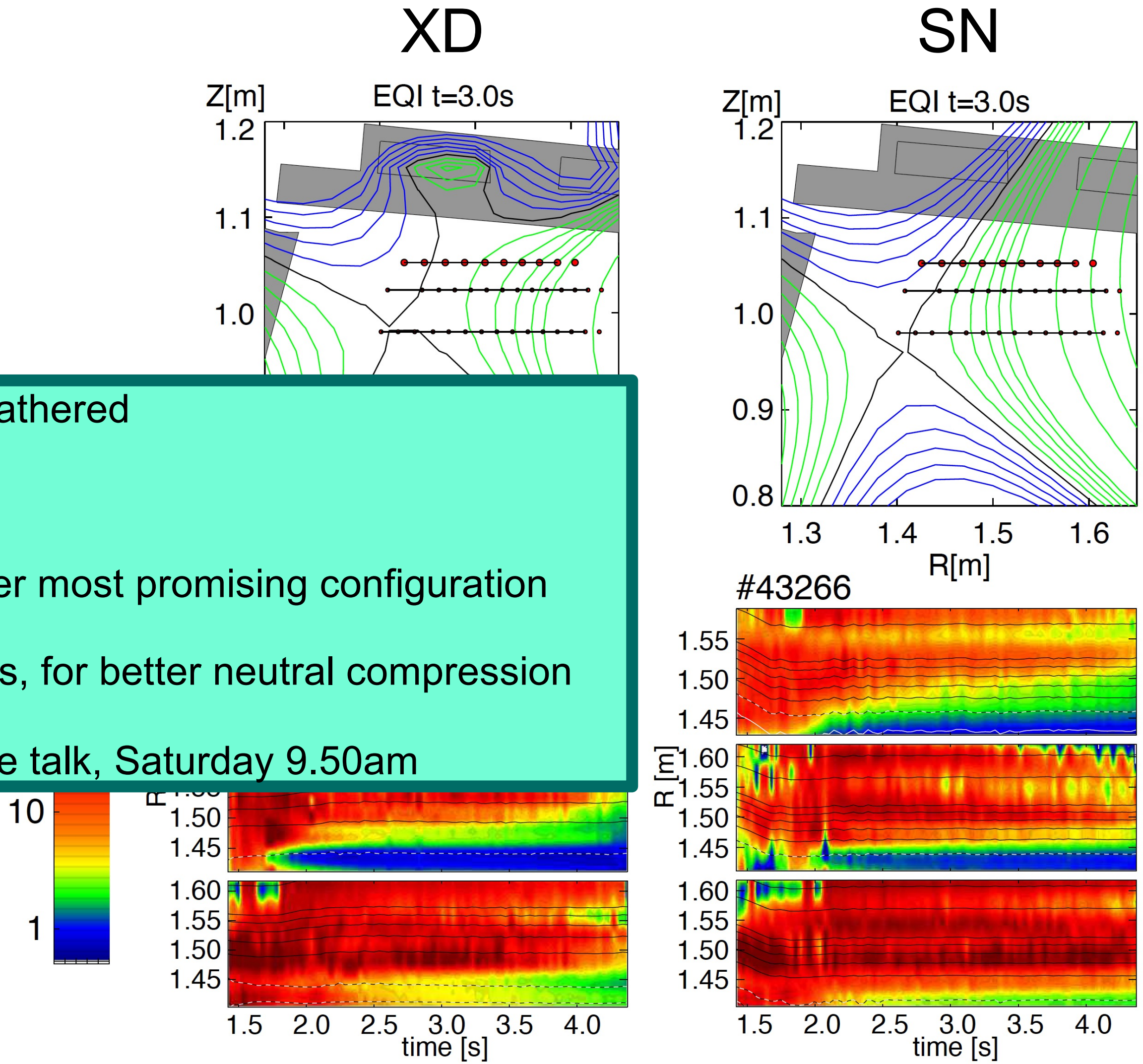




- Discharge going through various divertor configurations
- Power spreading observed
- SF- marginal in this discharge

Unprecedented wealth of profiles in the divertor plasma





Extensive amount of data gathered

⇒ Modelling with SOLPS

⇒ Find & characterize further most promising configuration

⇒ Future work: install baffles, for better neutral compression

⇒ T Lunt, FEC post deadline talk, Saturday 9.50am

- **XD detaches at lower N level than conventional divertor (CD)**

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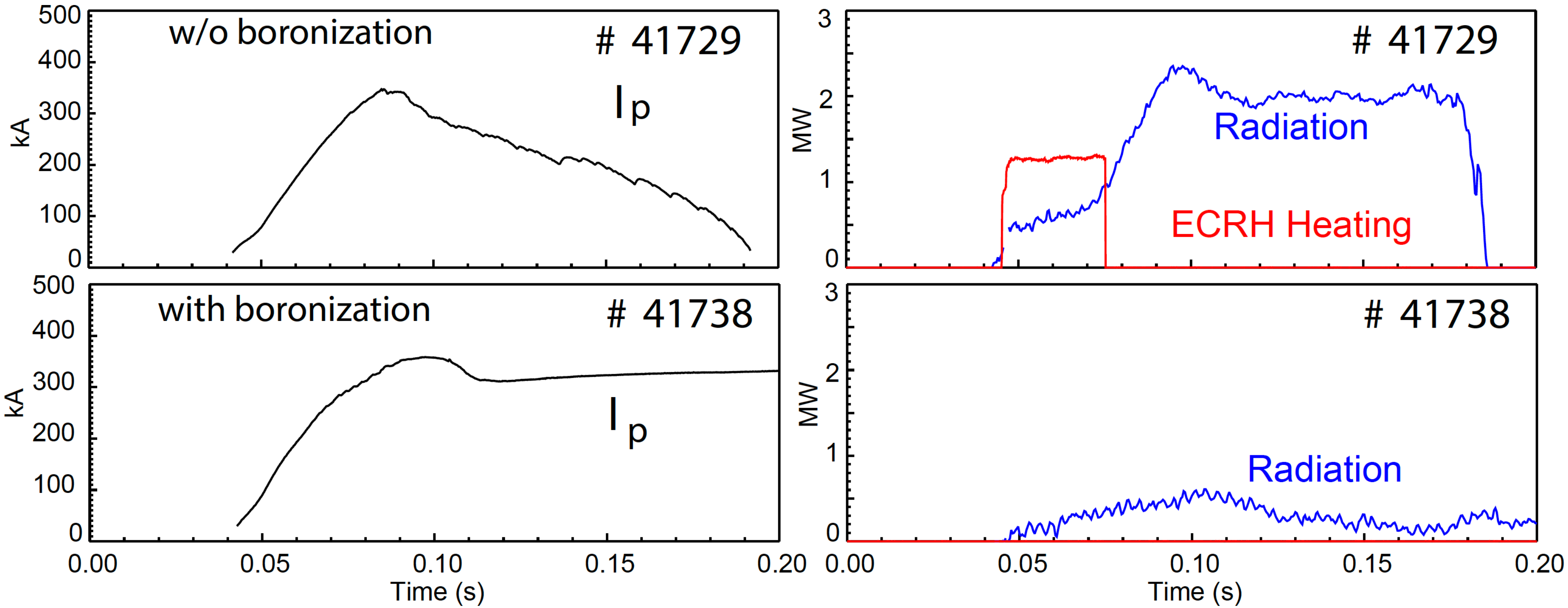
Non-boronized startup with less power challenging



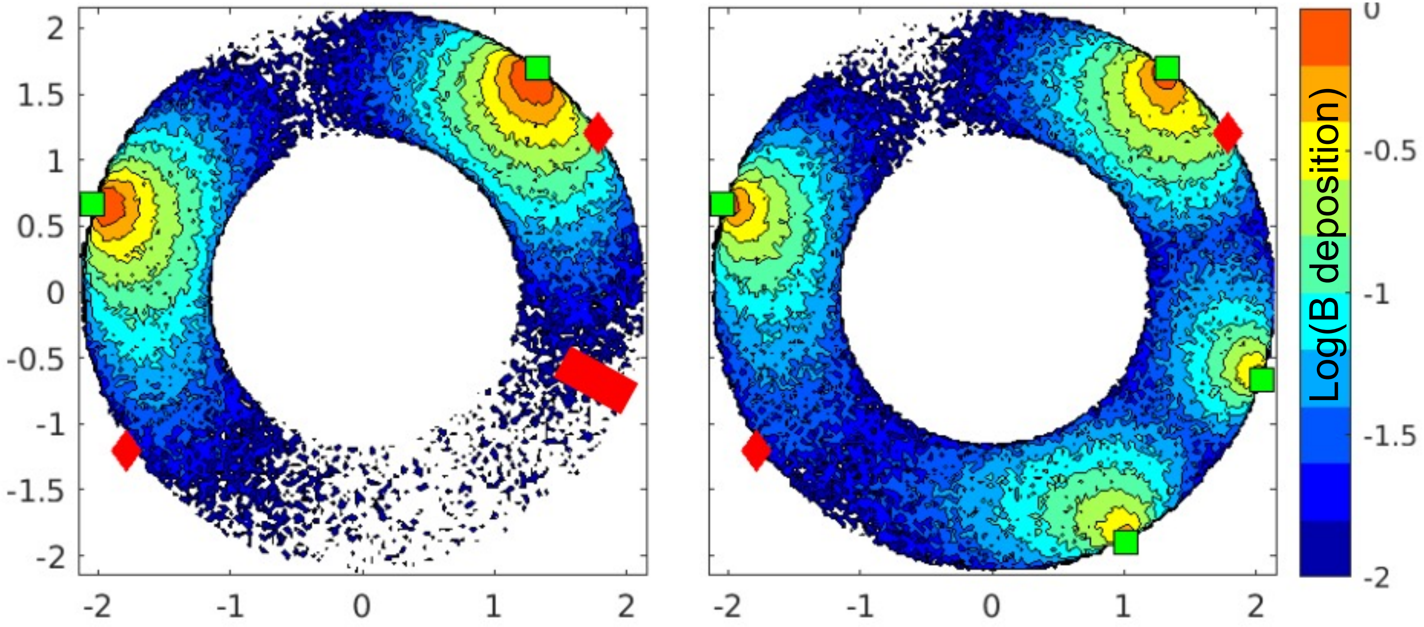
V. Rohde, PFMC 2025

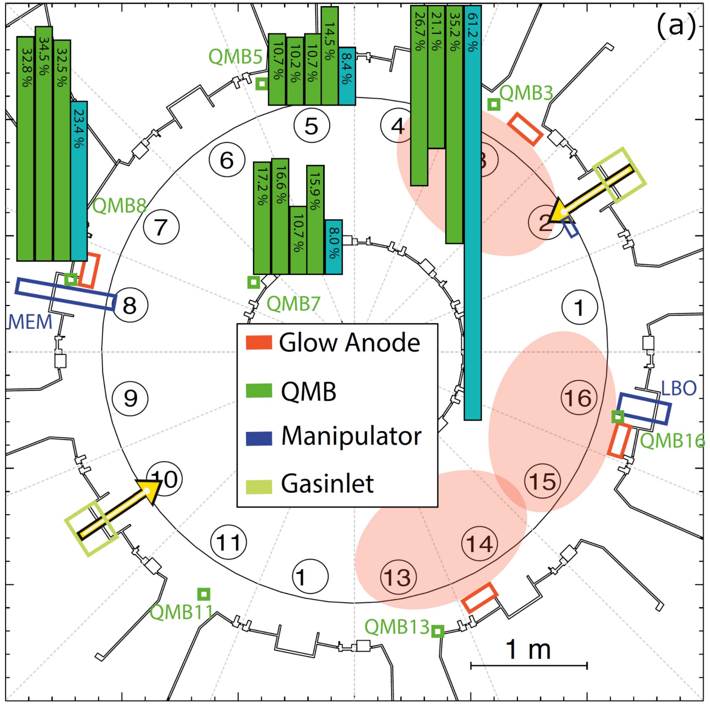
Restart after long vent was done with cleaned W-surfaces but w/o boronisation

- difficult to establish stable plasma discharge, but relevant number of runaways observed
- boronisation immediately led to stable plasma discharges

Strong recommendation towards an ITER boronisation system for start-up

Boronizations are more homogenious than expected



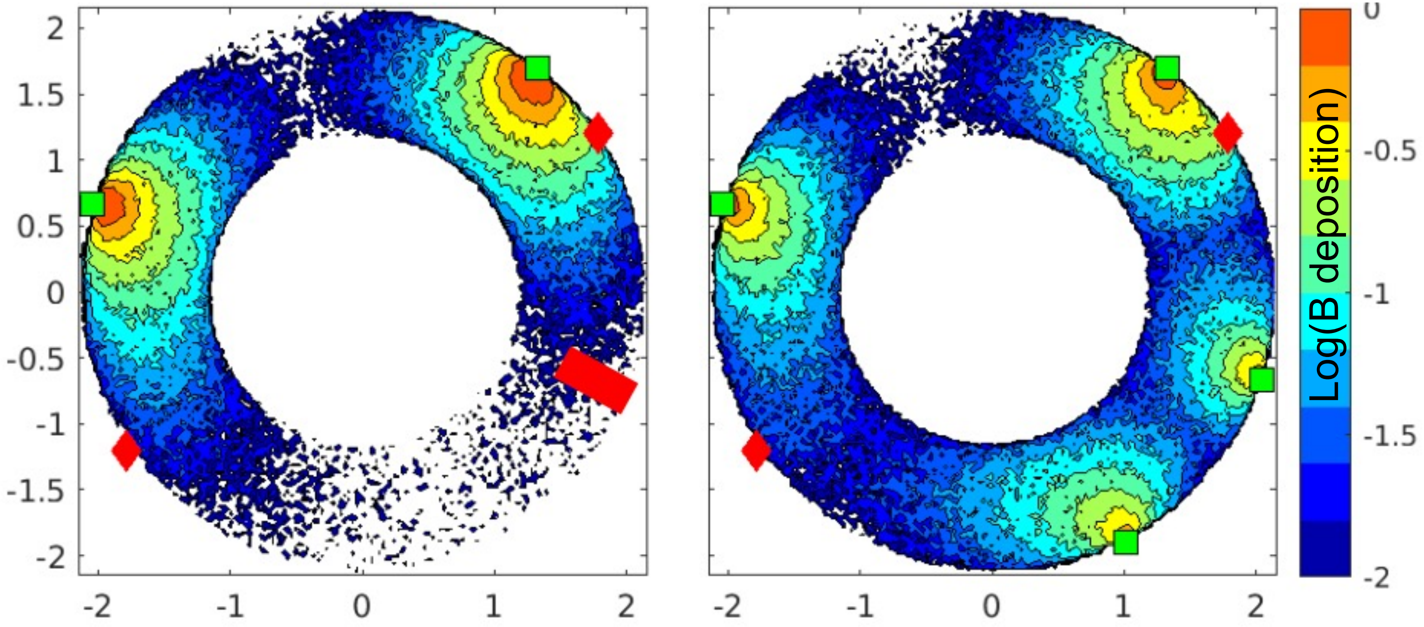


T Wauters NME 2025, T Wauters ITPA-SOL 2025

Important question: required number of anodes to achieve homogeneous coatings

- ITER prediction tool applied to ‚half boronisation‘ in ASDEX Upgrade predicts inhomogeneity by large factor ~100 (!)
- measurements using quartz micro balance show reduction in S8 by only 35%
- Possibly linked to a lower B-sticking coefficient (measured ~0.3) than in model (1.0)

Boronizations are more homogenious than expected



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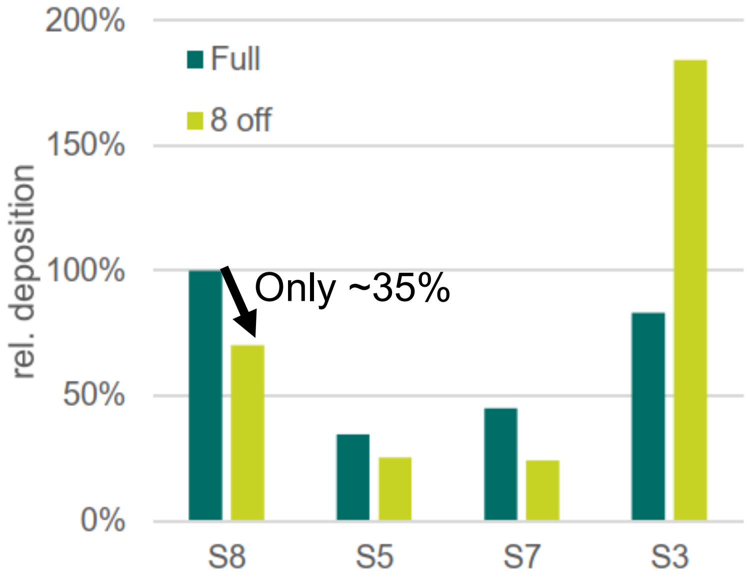

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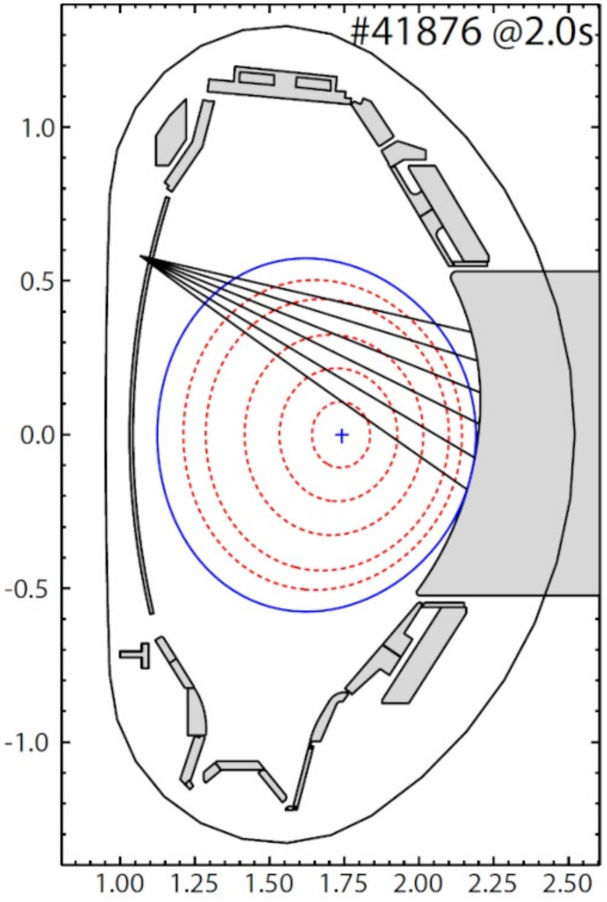
Erosion data for boron and tungsten taken during limiter phase

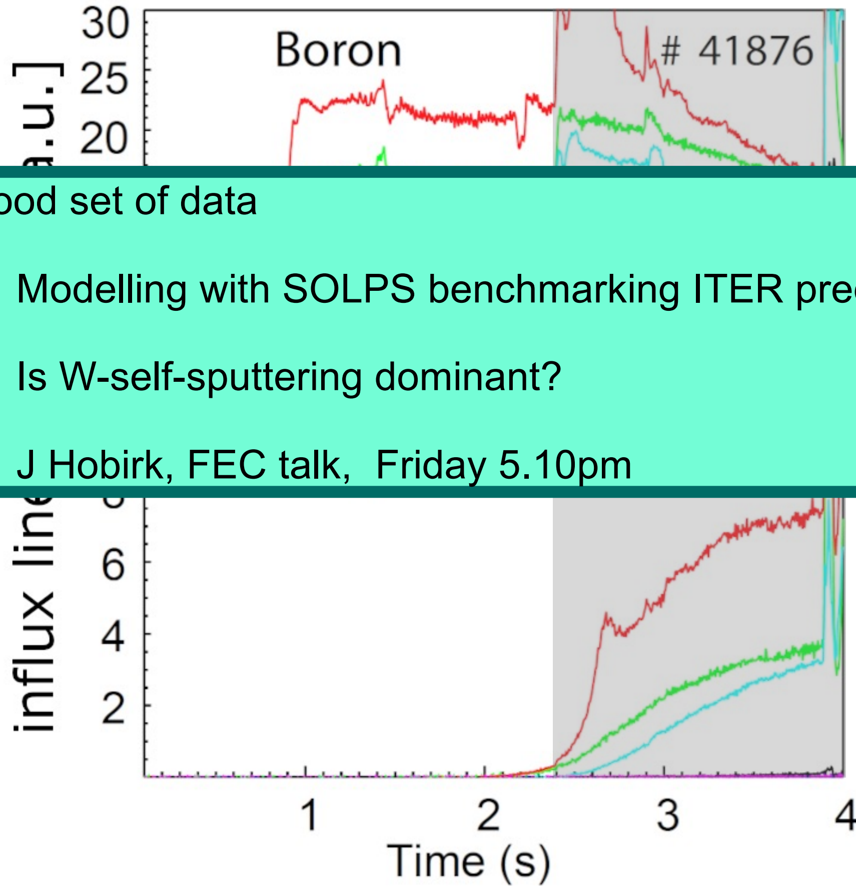
Limited at outboard limiters:

Good diagnostics + small active surface



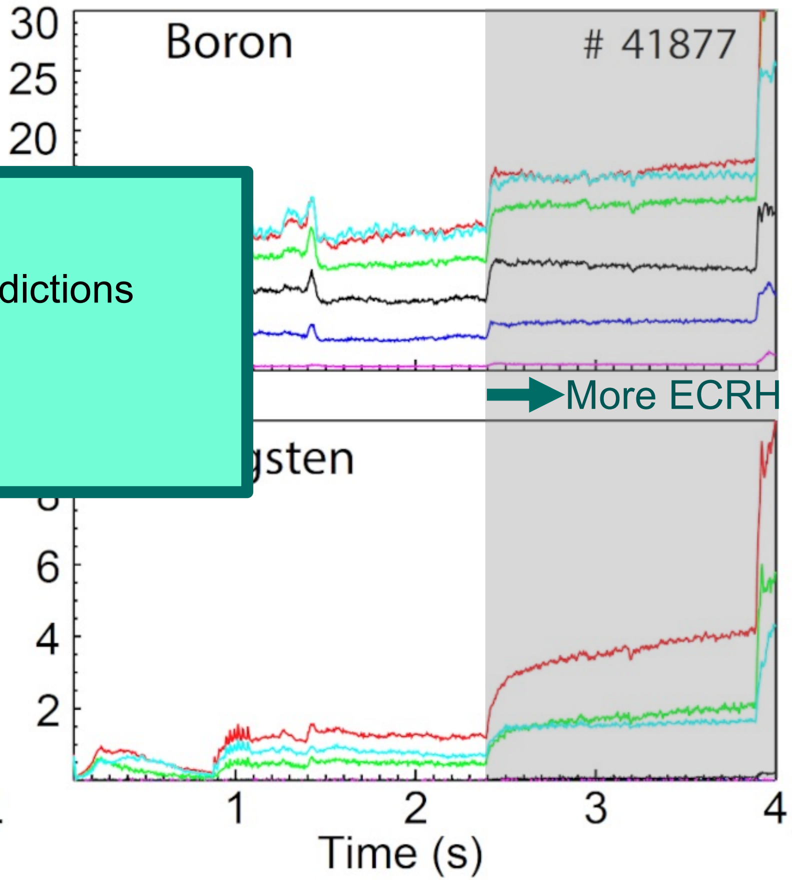
1st discharge after boronization

W-erosion visible at 2.4s



2nd discharge after boronization

W-erosion almost steady



Good set of data

⇒ Modelling with SOLPS benchmarking ITER predictions

⇒ Is W-self-sputtering dominant?

⇒ J Hobirk, FEC talk, Friday 5.10pm

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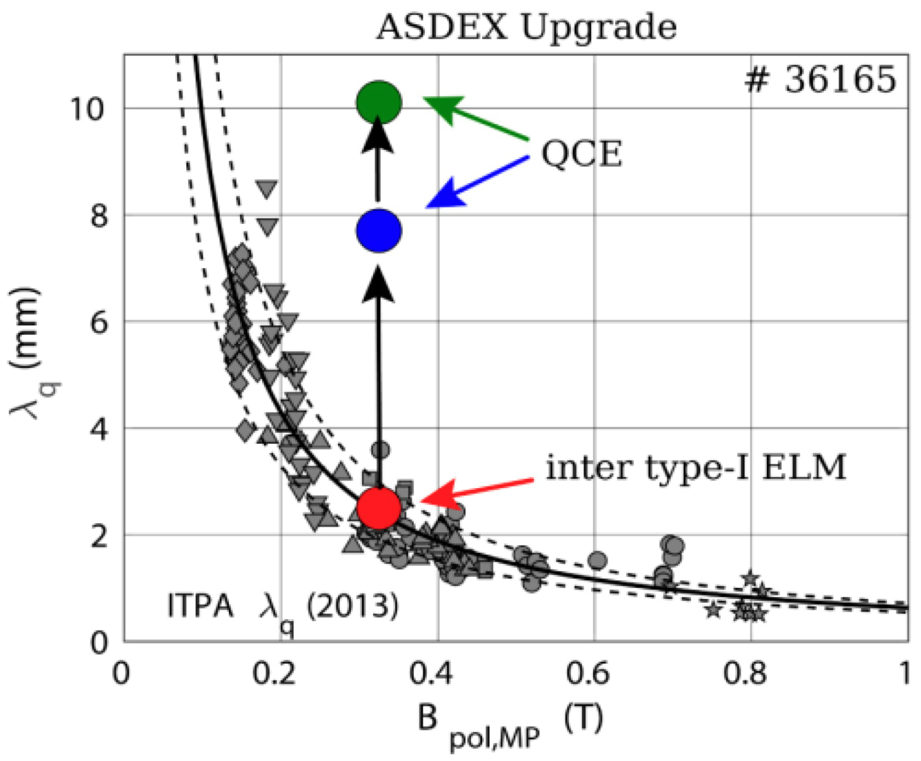
Quasi-continuous exhaust regime (QCE)

- **Small ELMs at high gas puff**
- **Good Confinement, H98~1**
- **Large (λ_q), i.e. power spread in divertor**
- **New: Understanding of access (next slide)**
- **New: GRILLIX modelling of QCE**

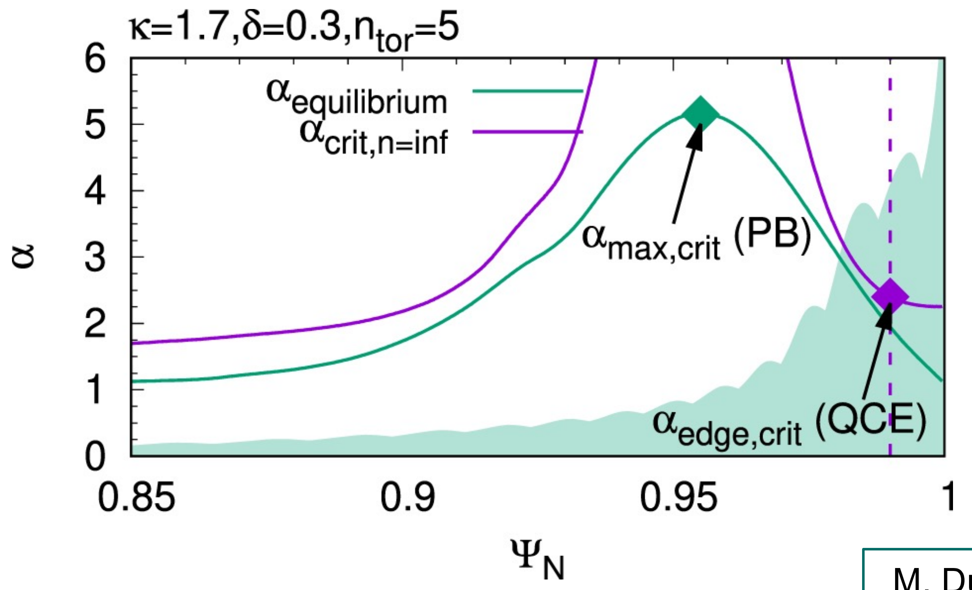
Zholobenko NF 2024

W. Zholobenko FEC Talk, Wednesday 3.00pm

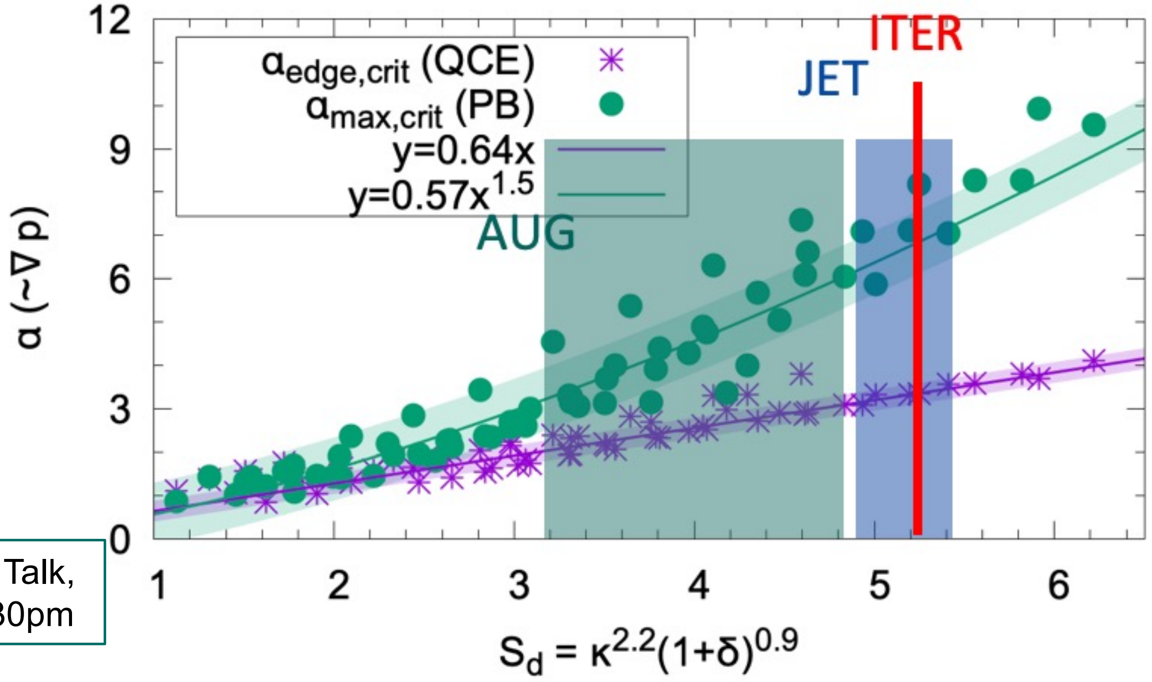


M Faitsch NME 2021

New: QCE as a consequence of ballooning vs. peeling-ballooning stability



M. Dunne FEC Talk, Wednesday 4.30pm



- Infinite-n ballooning stability (local calculation)
- Finite-n peeling-ballooning (PB) stability applies for full pedestal ($\alpha_{max,crit}$ used as proxy for PB limit)
- Experimental α-curve increases with more sh

L. Radovanovic NF 2022
L. Radovanovic NF 2025
M. Dunne NF 2024

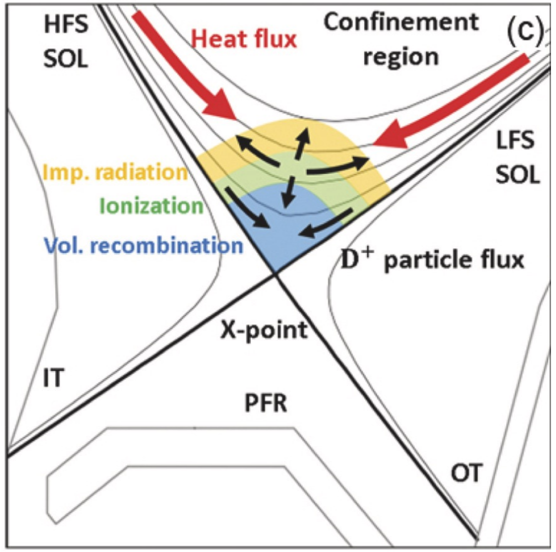
Related:
EDA H-mode
G. Grenfell FEC Poster, Friday 2.00pm
Machine Scaling of $n_{e,sep}$
D. Silvagni FEC Poster, Wednesday 2.00pm

- Finite-n PB stability improves with shaping more than Infinite-n ballooning stability
- More shaping gives access to QCE
- JET and ITER have access to QCE
- Sufficient pressure (density) at the edge neccessary

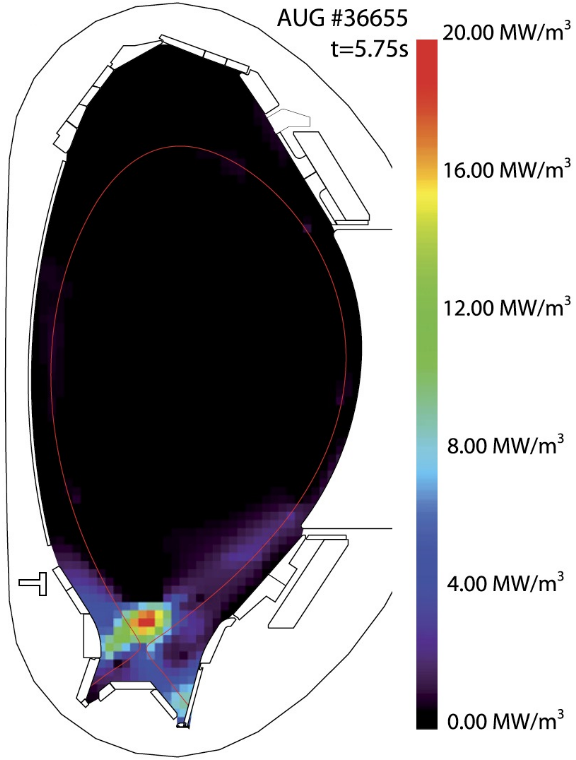
M. Faitsch NME 2025
M. Faitsch NF 2023

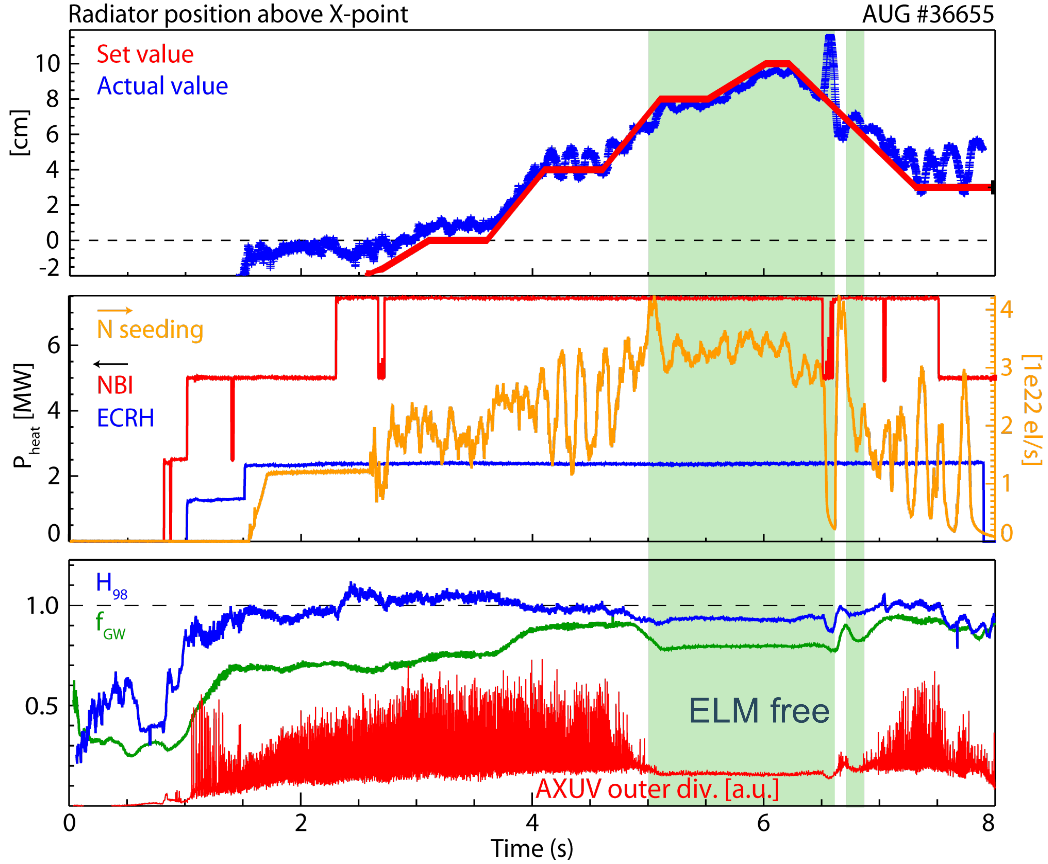
X-point radiator regime (XPR)

- no ELMs
- High density
- Good Confinement, H98~0.95
- Fully detached, well controlled



Bernert NME 2025

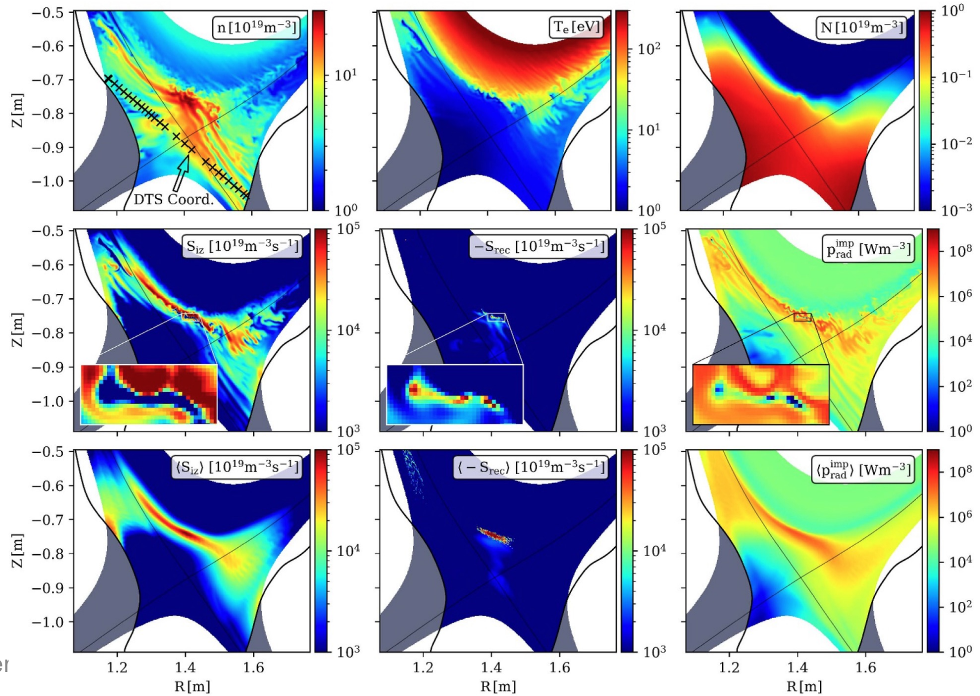


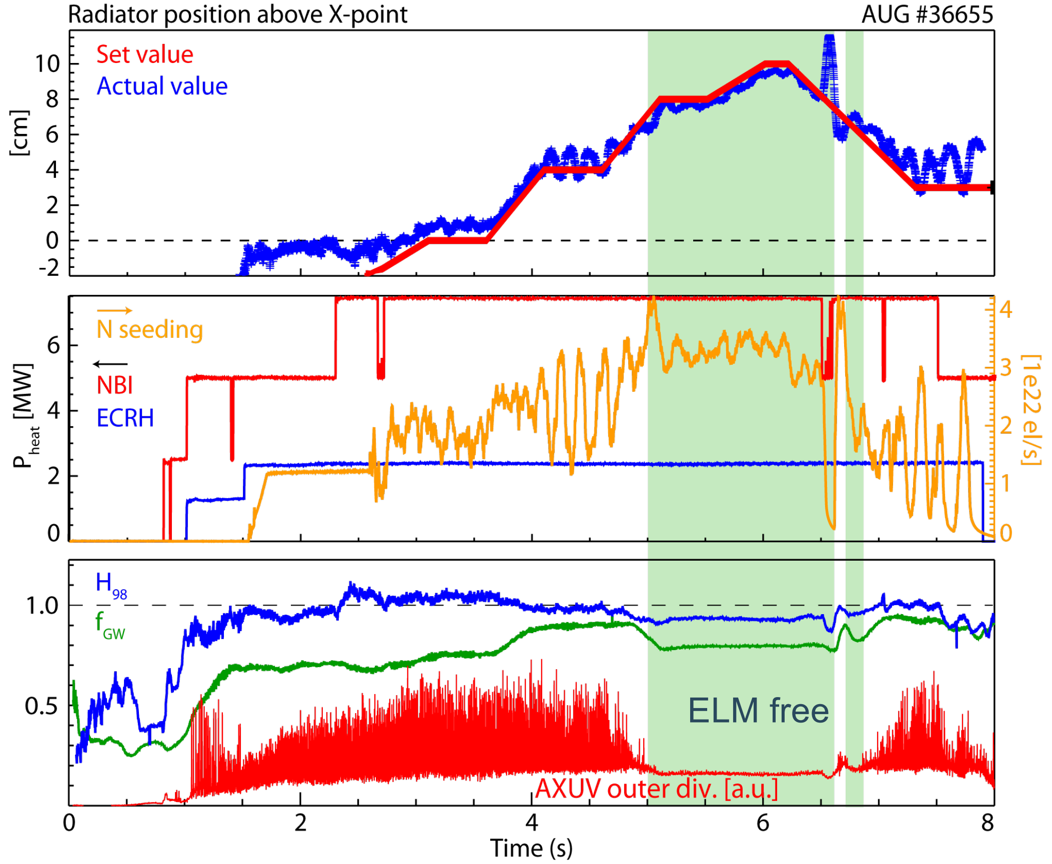


Bernert NF 2021

X-point radiator regime (XPR)

- no ELMs
- High density
- Good Confinement, H98~0.95
- Fully detached, well controlled Bernert NME 2025
- New: Model for Radiator position Stroth PPCF 2025
- New: GRILLIX modelling of XPR Eder NF 2025,





Bernert NF 2021

W. Zholobenko FEC Talk, Wednesday 3.00pm

Negative triangularity (not ITER)

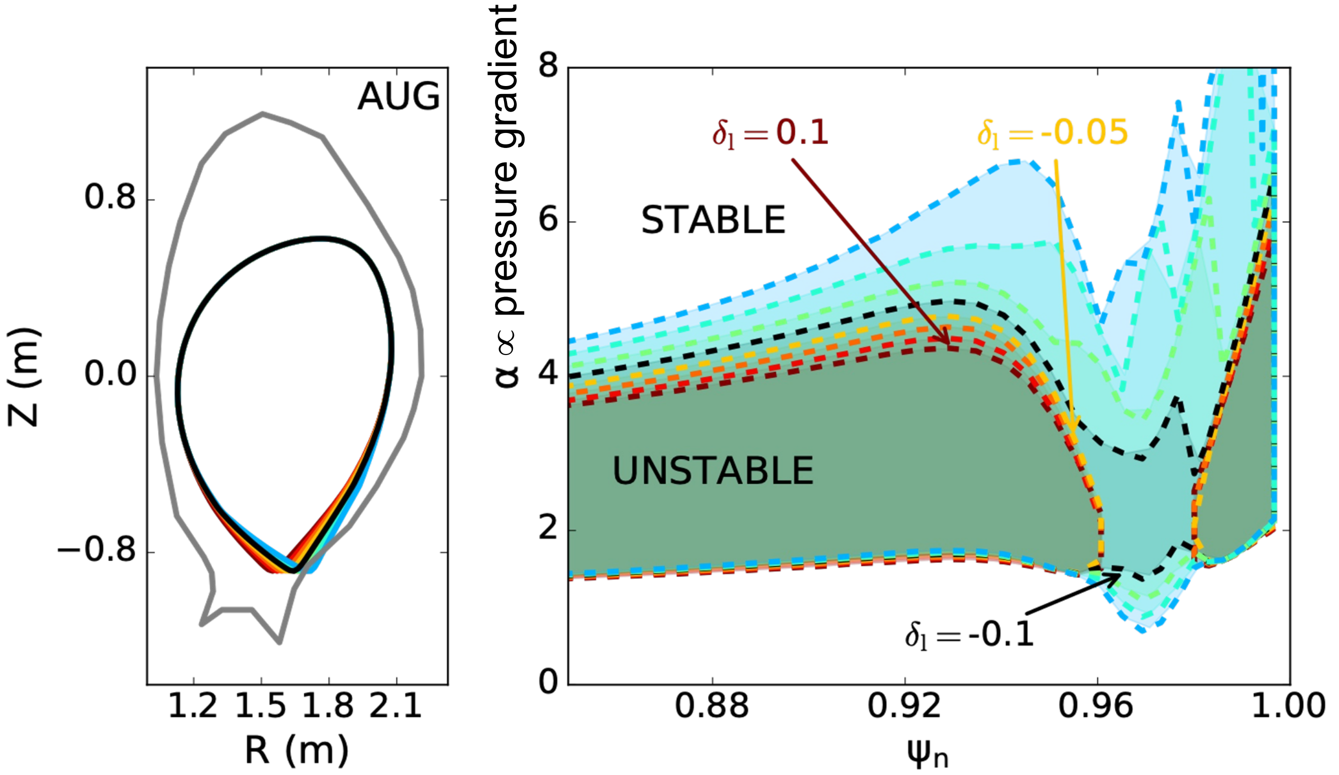
- **no ELMs (L-mode): was not yet reliable at AUG** [Happel NF 2023, Vanovac PPCF 2024]
- **Good Confinement** [Pochelon NF 1999, Camenen NF 2007, Austin PRL 2019, Marinoni RMP 2021, Happel NF 2023]
- **AUG at high heating power: confinement not yet impressive; possibly seeding is key**

[Vanovac APS conf. 2025]

New: Avoid H-mode / ELMs:

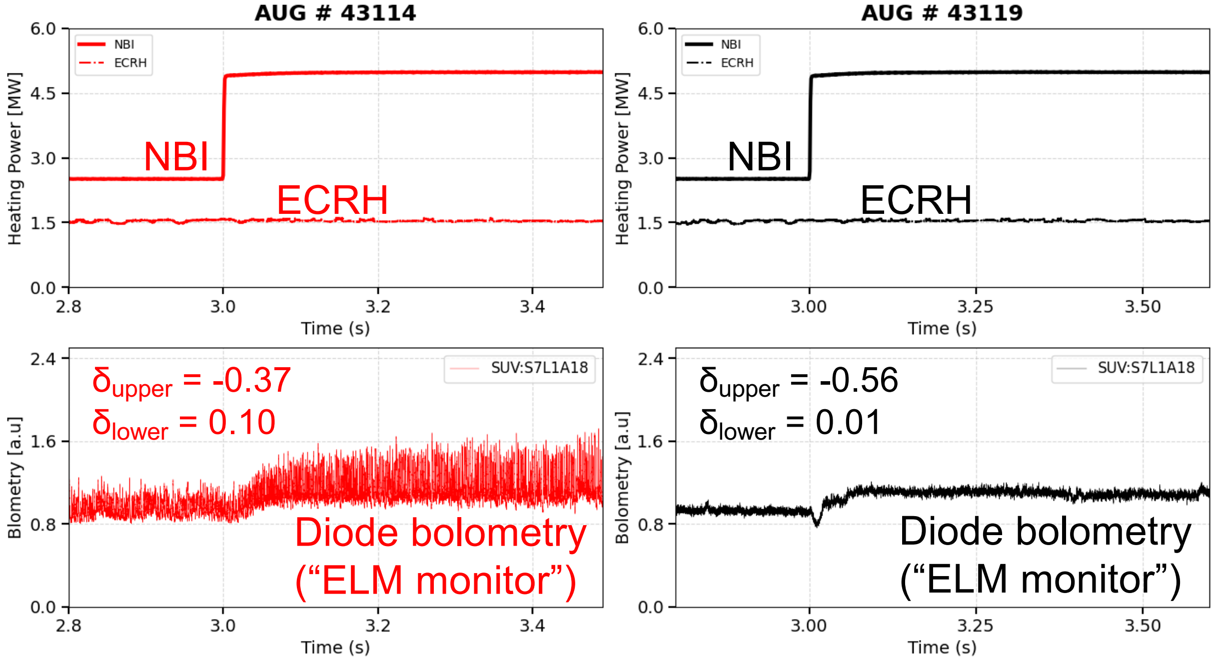
- **MHD code BALLOO shows closure of the 2nd stability with stronger shaping**

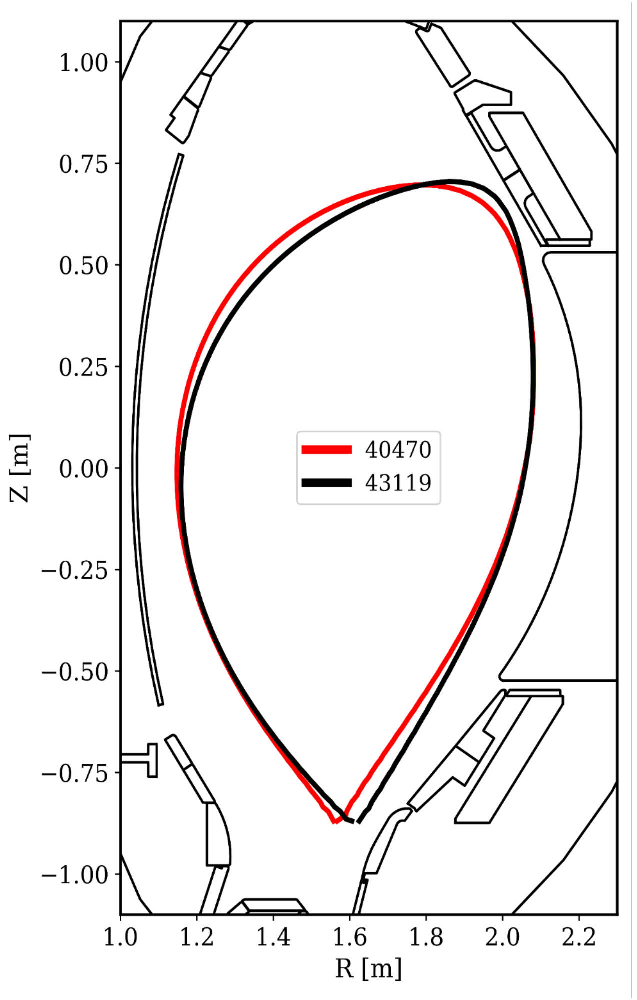
[Nelson NF 2022]



ELM avoidance finally achieved in NT, and well predicted

- This campaign, δ_{bot} and δ_{top} more negative than reference
- ELMs avoided throughout the discharge
- Prior to AUG experiment, target shape at TCV
  => did not show ELMs





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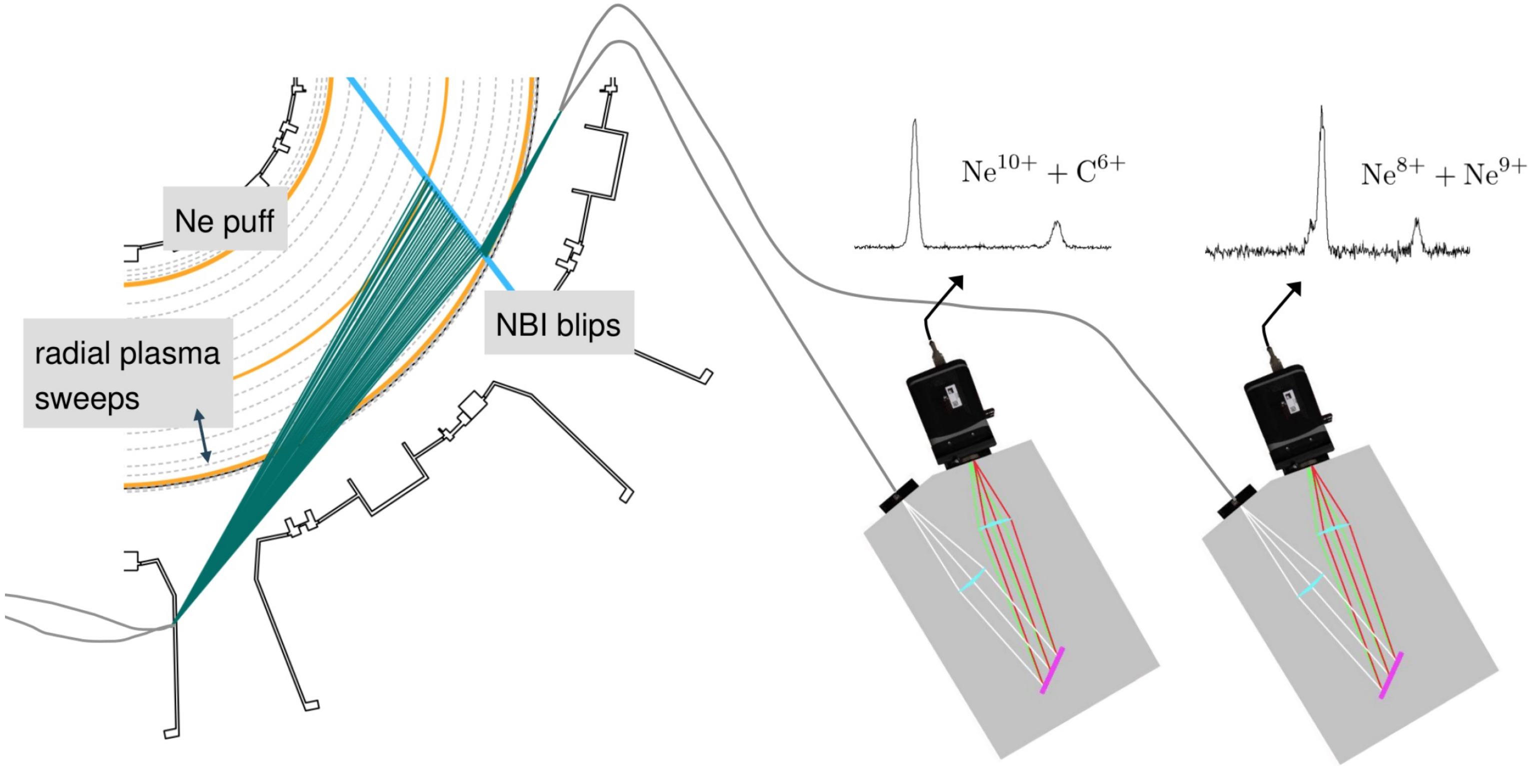
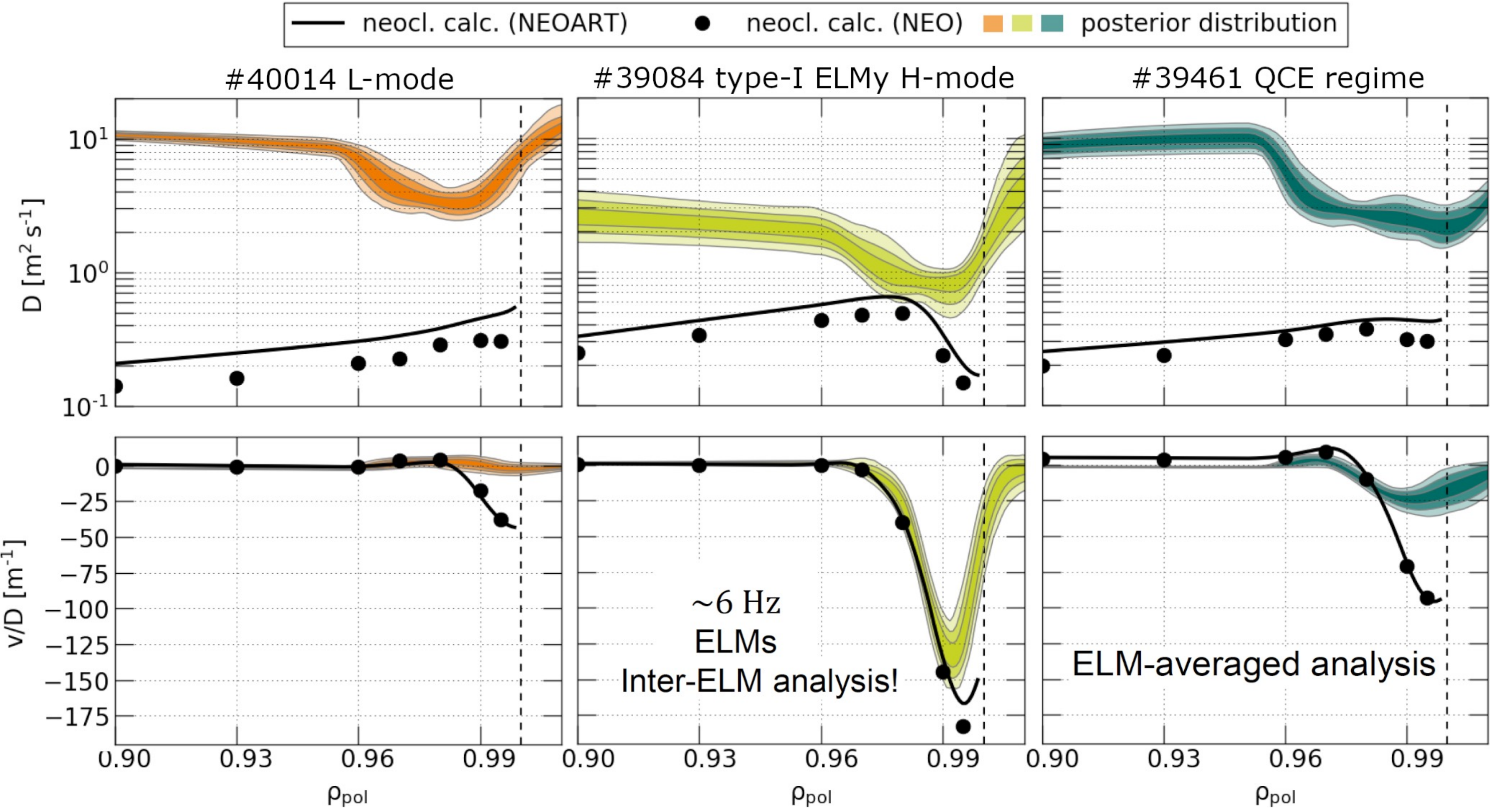
Impurity (neon) transport in the pedestal using superior method

- **New improved method:**
  - **Bayesian inference using edge and core CXRS**
  - **Ne^{8+} to Ne^{10+} at edge**



T. Gleiter NF 2025

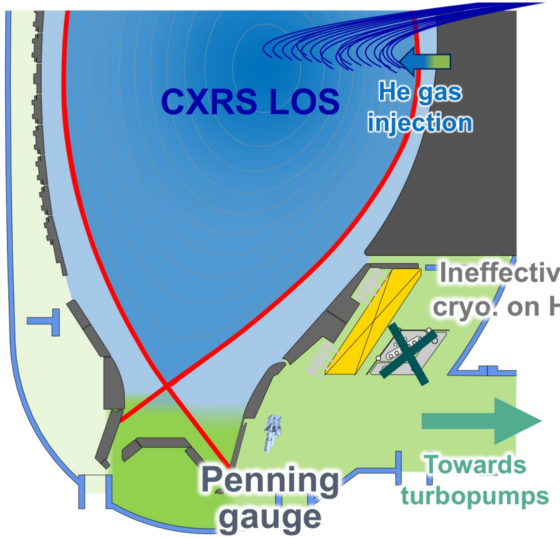
Ne transport exhibits strong non-neoclassical diffusion for L-mode & QCE



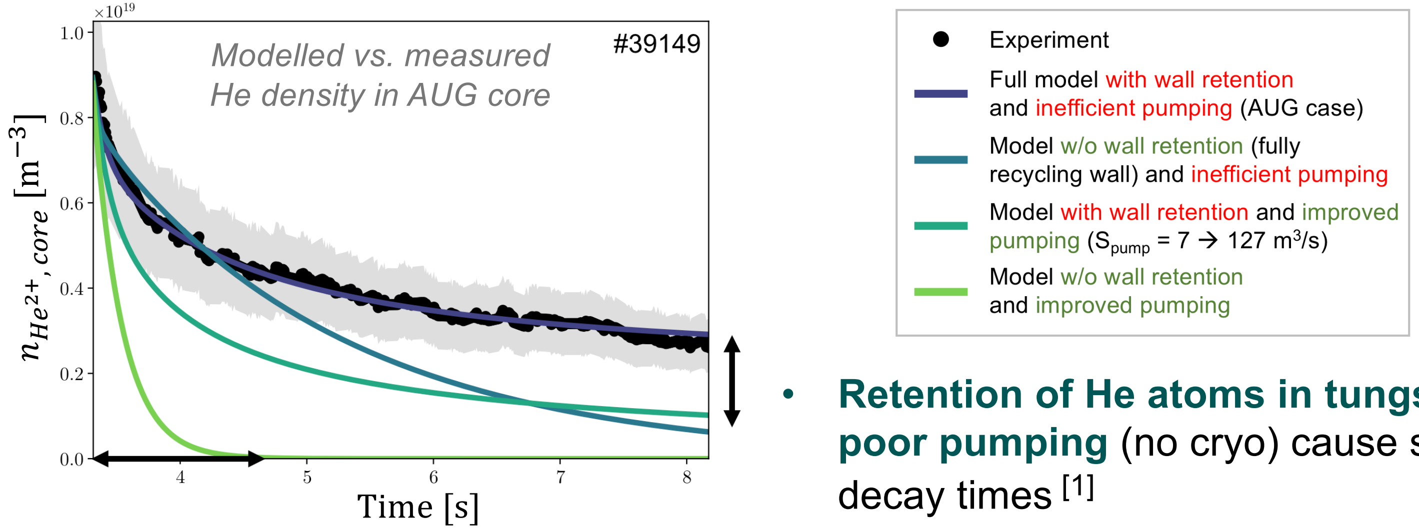
T. Gleiter NF 2025

- **L-mode: Clear additional transport (w.r.t. neocl.)**
- **Type-I ELM H-mode inbetween ELMs: Consistent with neocl. transport**
- **QCE exhibits strong additional transport, weakening neocl. transport at pedestal**

He exhaust including all details: ELMs crucial for div. compression

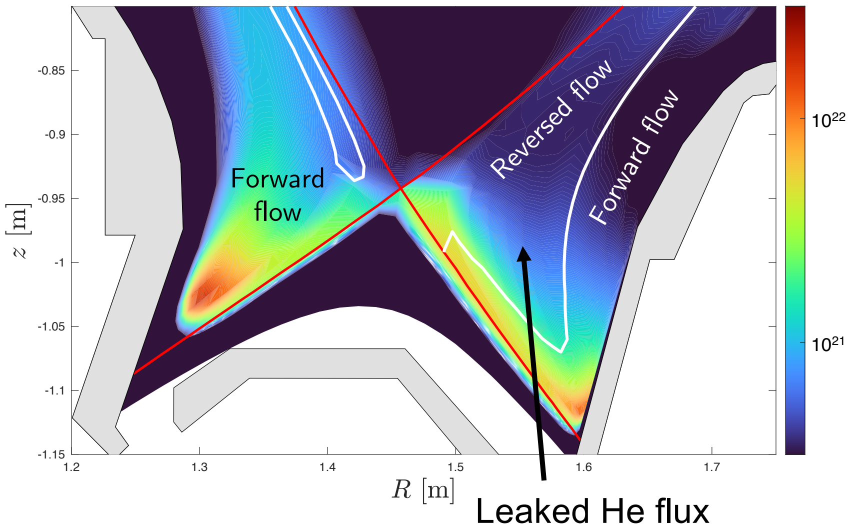


- **Reduced model to self-consistently simulate He transport & wall retention** [1]



- **Retention of He atoms in tungsten-wall & poor pumping** (no cryo) cause slow He decay times [1]

Ionization source from recycled He atoms [$m^{-3}s^{-1}$]



SOLPS-ITER: **strong He leakage from divertor** (high ionization energy of He atoms) (24.6 eV) reduces compression [2]

- **He divertor compression:** In experiment larger than in SOLPS modelling (w/o ELMs)
- **=> ELMs (or equivalent) important!**

[1] Zito NF 2023
[2] Zito NF 2025
[3] Zito PET-20 2025

Outline

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- **Supporting the full-W ITER**
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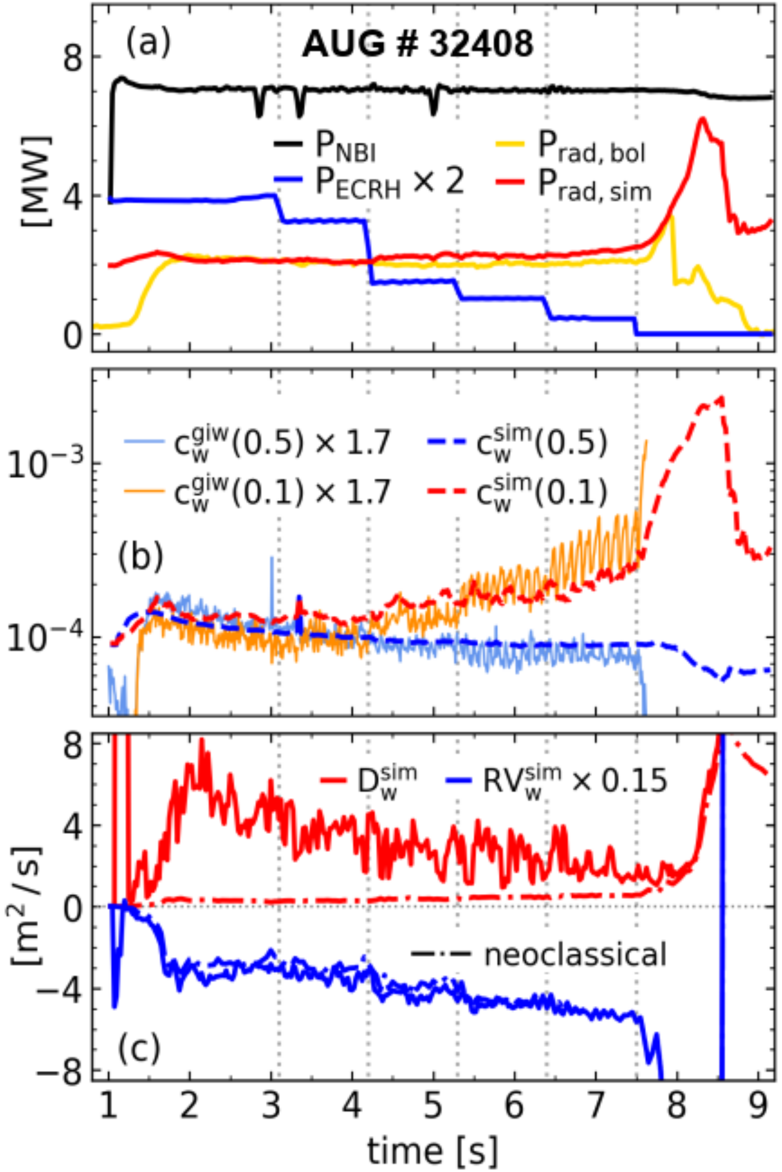
- Summary

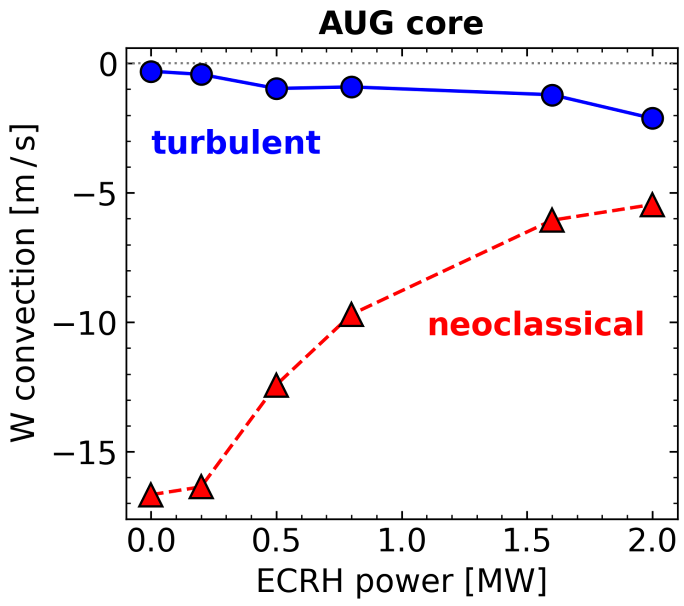
Integrated modeling on ASDEX Upgrade matches W-transport closely

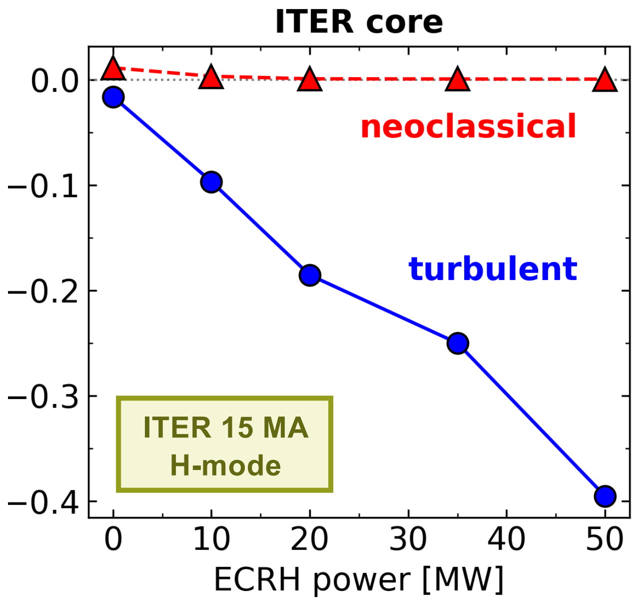
- Simultaneous modelling of core plasma and impurity profiles (FACIT+NCLASS+TGLF-SAT2)
- Quantitative agreement in L-mode and H-mode plasmas in ASDEX Upgrade
- W-accumulation in ECRH power scan well reproduced

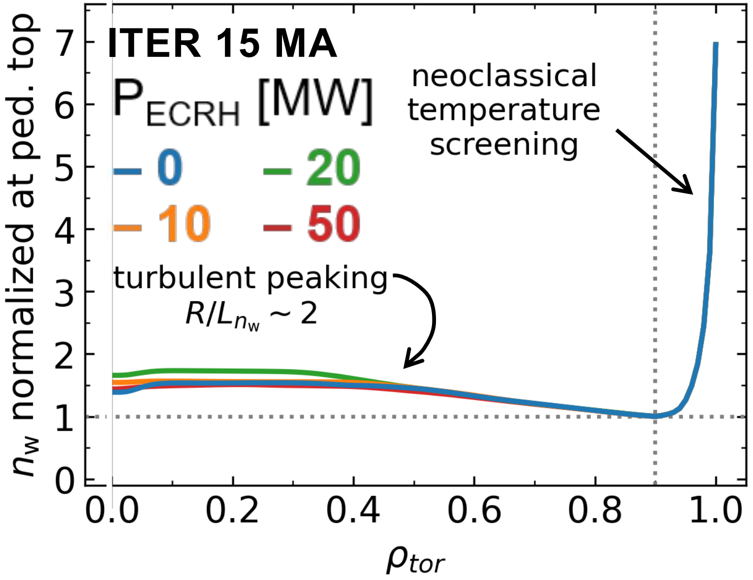


Fajardo, NF 2024

Same Framework for ITER: Core W-transport in ITER is benign







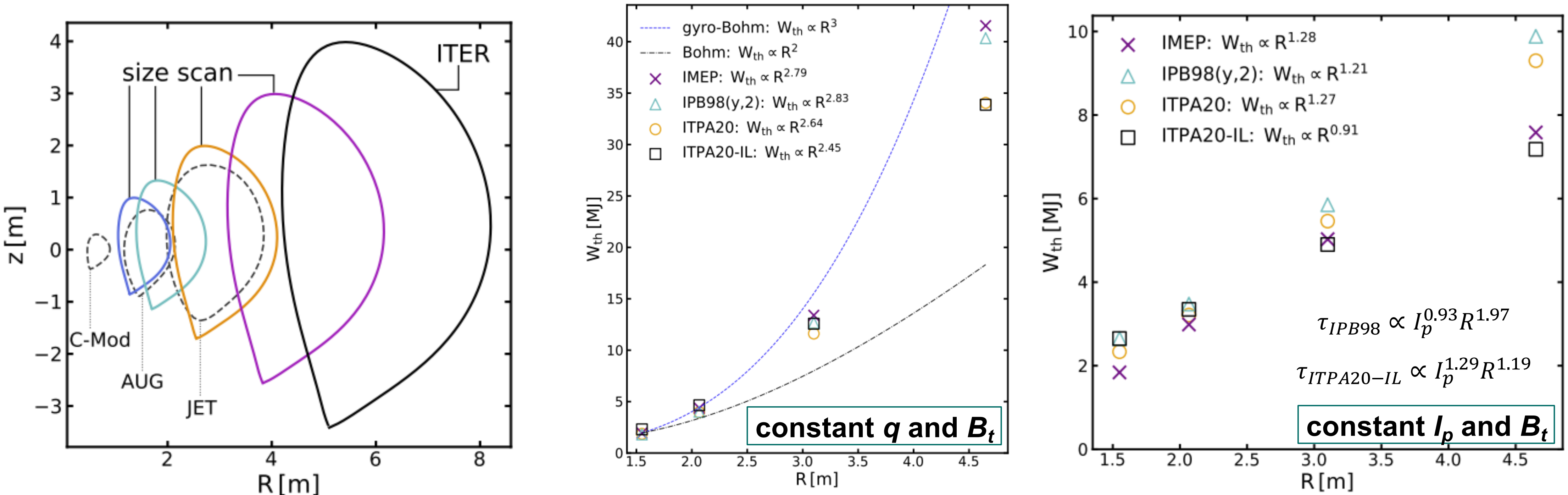
Different from AUG, the inward pinch in ITER is not expected to lead to W accumulation

- turbulent outward transport strong enough to overcome inward pinch even w/o ECRH

D. Fajardo FEC talk, Friday 4.10pm

Fajardo, NF 2025

Integrated (pedestal+core) modelling of H-modes: size scaling optimistic



Luda, NF 2025

The IMEP framework, validated on C-Mod, AUG and JET, was applied towards ITER

- combines TGLF core and peeling-ballooning / critical gradient pedestal to be fully predictive
- scans are compared to predictions by IPB98 and ITPA20-IL empirical scalings
- Prediction to ITER Q=12, dependent on toroidal rotation

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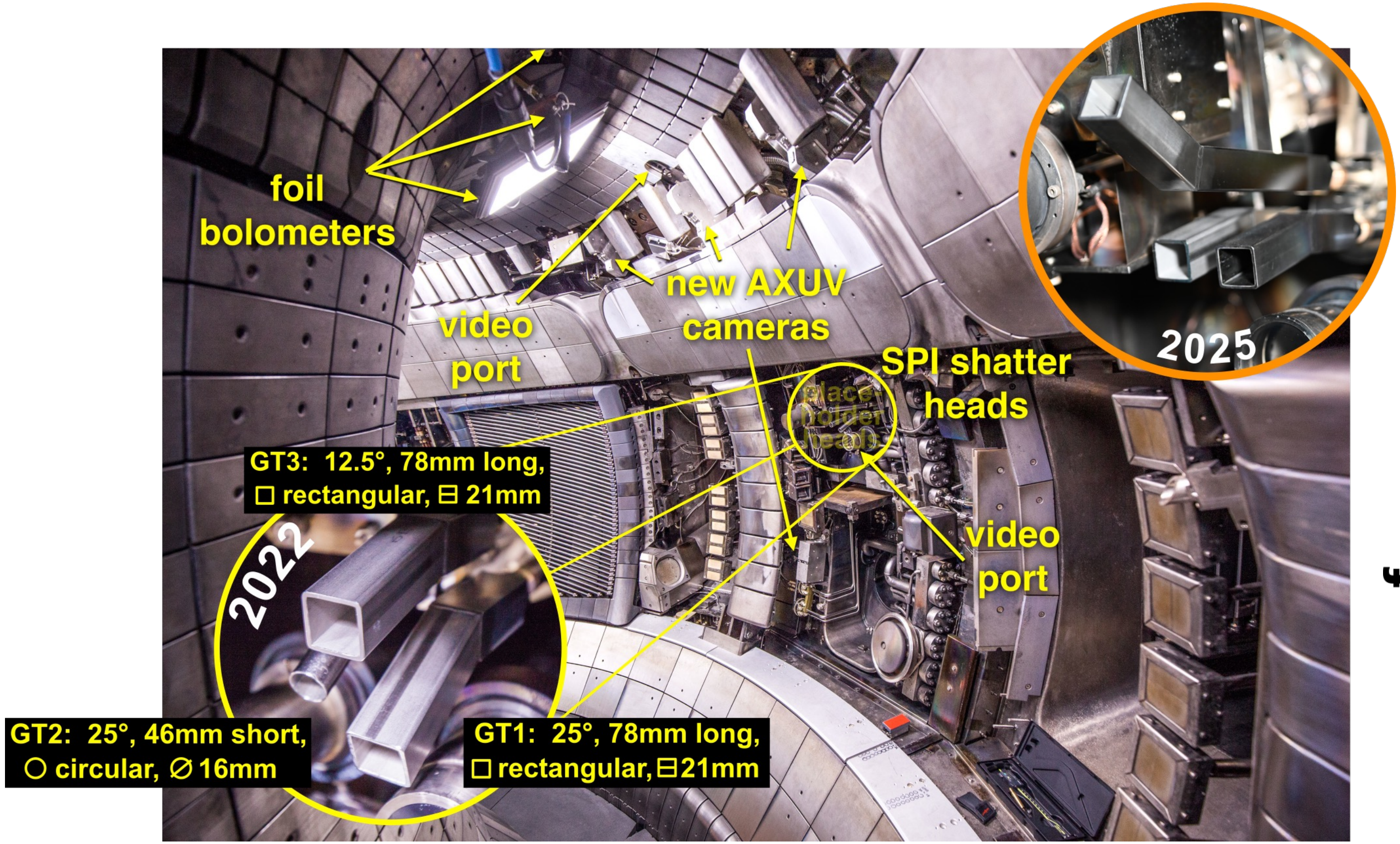
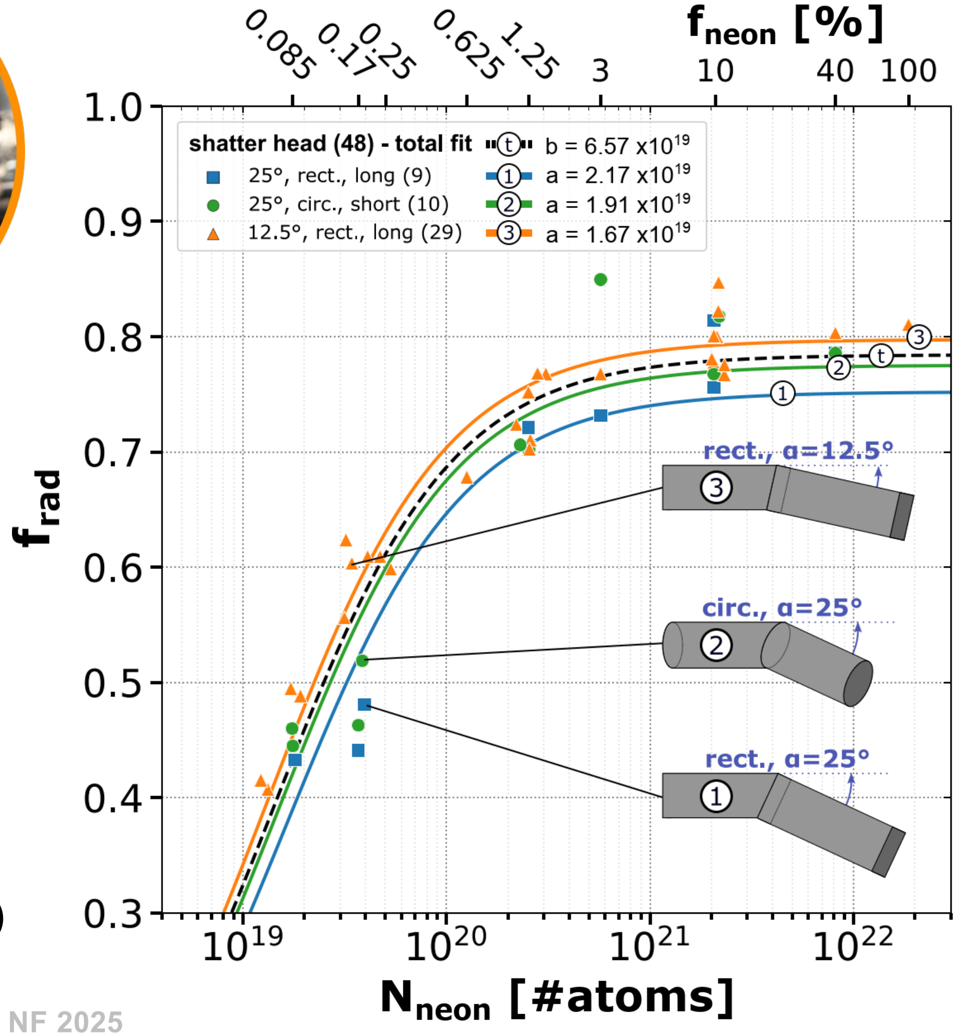
Disruption mitigation by shattered pellet injection: Optimum shatter geometry



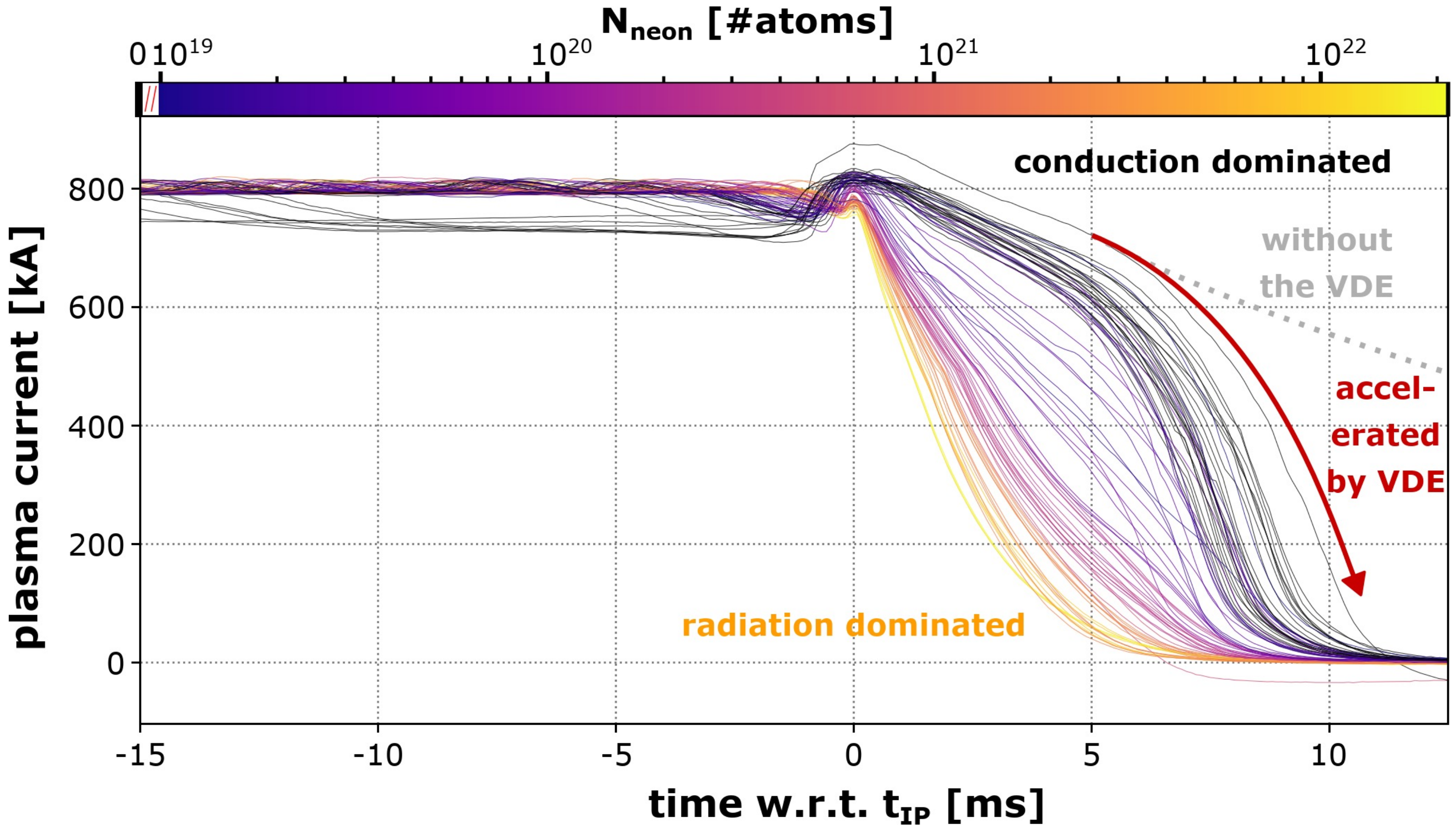


Highest priority by ITER: optimum shatter geometry

- rectangular shatter head with lowest inclination (12.5 degree) showed highest f_{rad} per N_{neon}
- attributed to highest assimilation of material

Heinrich, NF 2025

Disruption mitigation by SPI: pellet doping by Ne allows tailoring of CQ



Ne doping of D-pellets allows to ‚tailor‘ the current quench (CQ) time via the radiative fraction

- fastest current quench avoids significant VDE, but creates highest E-field (runaways!)

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Summary

- **AUG is back in operation with new upper divertor capable of ADCs**
    - In-vessel coils, charcoal cryp-pump and flat SP tile geometry
    - Comprehensive diagnostics suite
- **All accessible ADCs have been accessed and a wealth of data was taken**
- **Full-W ITER is supported with vartious experiments**
    - Good boronization symmetry with fewer anodes possible
    - Limiter phases in AUG for benchmarking ITER-SOLPS
    - Small/no ELM regimes (QCE,XPR, NT), modelling & understanding improves
    - Pedestal impurity transport in QCE: additional diffusive component weakens neoclassical effects
    - Predictions from benchmarked integrated models suggest low W-peaking and good performance (Q=12) in ITER
    - Ne content in the shattered pellet injector allows for tailoring the current quench
- **…….there is more for which I did not have time to report on.**