

IAEA 2025

The physics of ELM-free regimes in EUROfusion tokamaks

Pedestal tailoring via ballooning modes

Mike Dunne

IPP-Garching



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.





Co-authors

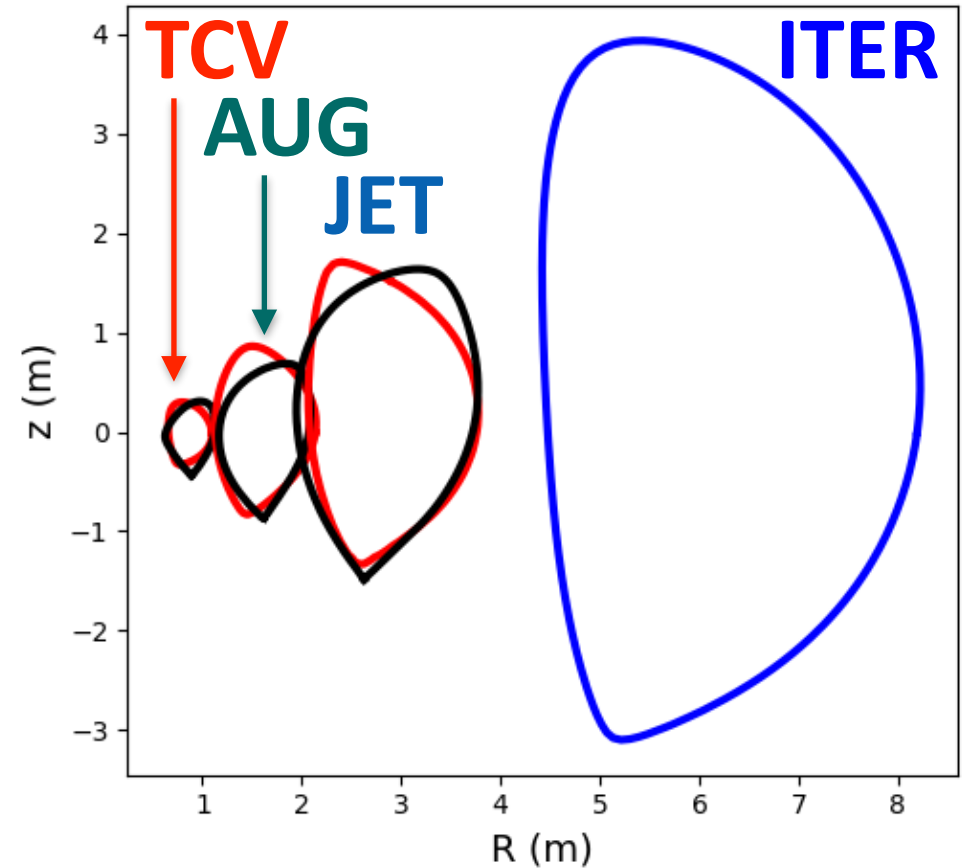
M. Faitsch, O. Sauter, E. Viezzer, B. Labit, A. Kappatou, D. Keeling, B. Vanovac, I. Balboa, P. Bilkova, P. Bohm, D. Kos, J. Hobirk, E. Lerche, P. Lomas, S. Menmuir, A.O. Nelson, T. Pütterich, L. Radovanovic, S. Saarelma, S. Silburn, D. Silvagni, E.R. Solano, H.J. Sun, A. Tookey, E. Wolfrum

EUROfusion WPTE team,
ASDEX Upgrade team,
JET contributors, and
TCV Team



Aims of the research topic

- **Develop understanding of physics of ELM free scenarios**
 - Integration of all regions of plasma (core, pedestal, SOL, divertor) challenging
 - Understand physics of regimes -> extrapolate
- **Utilise smaller, flexible devices to understand physics mechanisms**
 - Demonstrate this understanding on larger machines (notably JET)
 - Extrapolate to JT-60SA, SPARC, ITER..
- **Regimes of interest:**
 - MP ELM-suppression
 - QH-mode
 - EDA/QCE
 - NT
 - I-mode

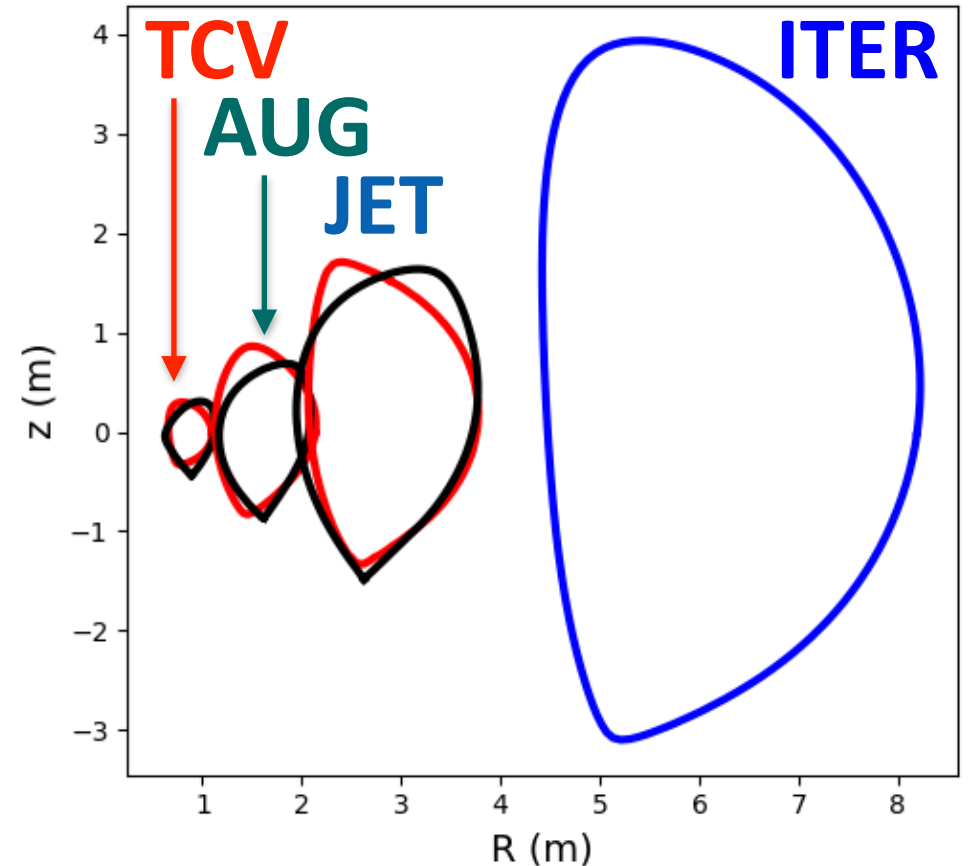




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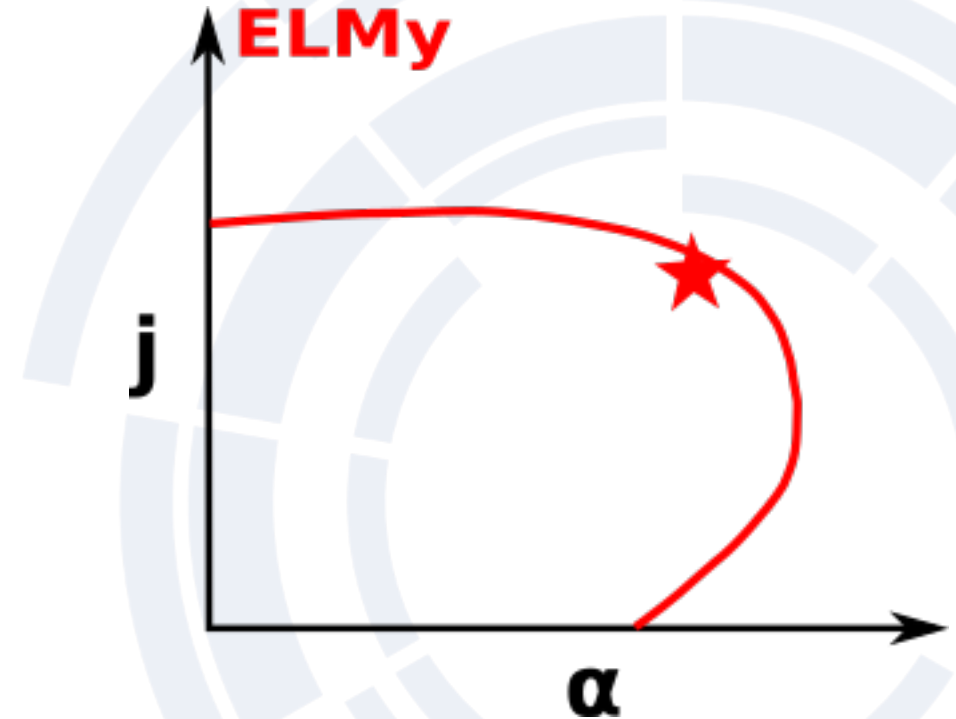
} Focus of this talk





ELM avoidance; a simple picture

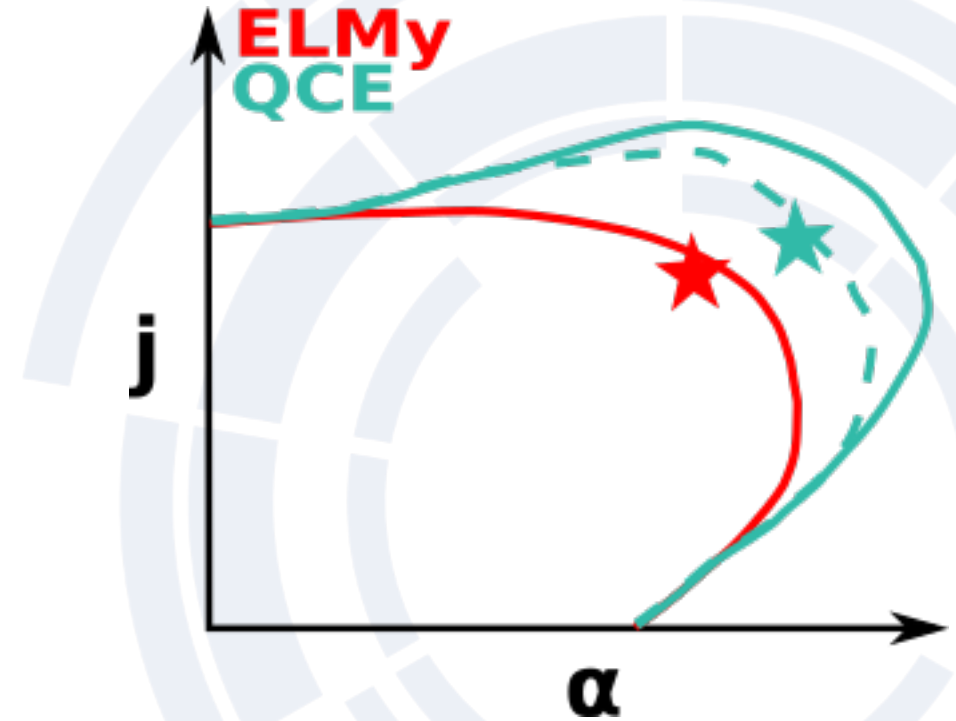
- ELM occurs due to intersection of “average” transport and global MHD
- Can avoid this intersection via:
 - Increasing ELM stability limit via shaping
 - With increased transport: remain below threshold for large-scale MHD
 - **Separatrix localised ballooning:**
 - Hypothesis behind QCE
 - Decreasing both limits until H-mode avoided
 - **Unstable ballooning in the pedestal middle, blocking second stability access:**
 - Negative triangularity





ELM avoidance; a simple picture

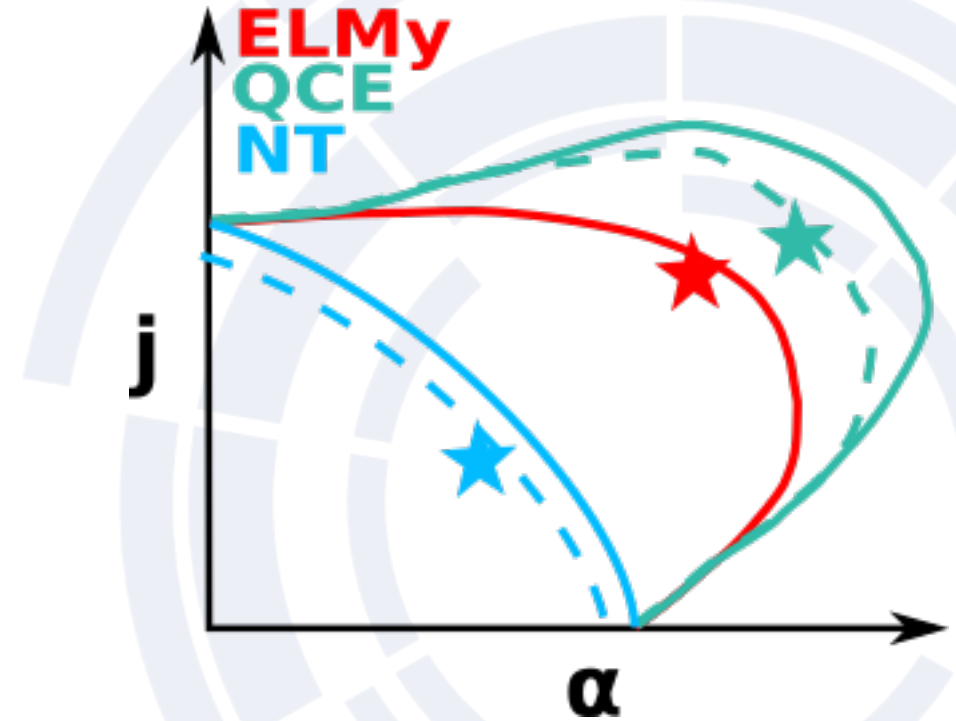
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Ballooning stability in the pedestal middle: negative triangularity

- **Present understanding:**
 - Sufficient negative delta to block access to ballooning second stability^{1,2}
- **Approach of experiments:**
 - Use ideal MHD to predict critical shaping, combined with what a particular device can achieve (limited at AUG and JET)
 - Use flexible shaping at TCV to verify predictions
 - Attempt experiments on larger devices

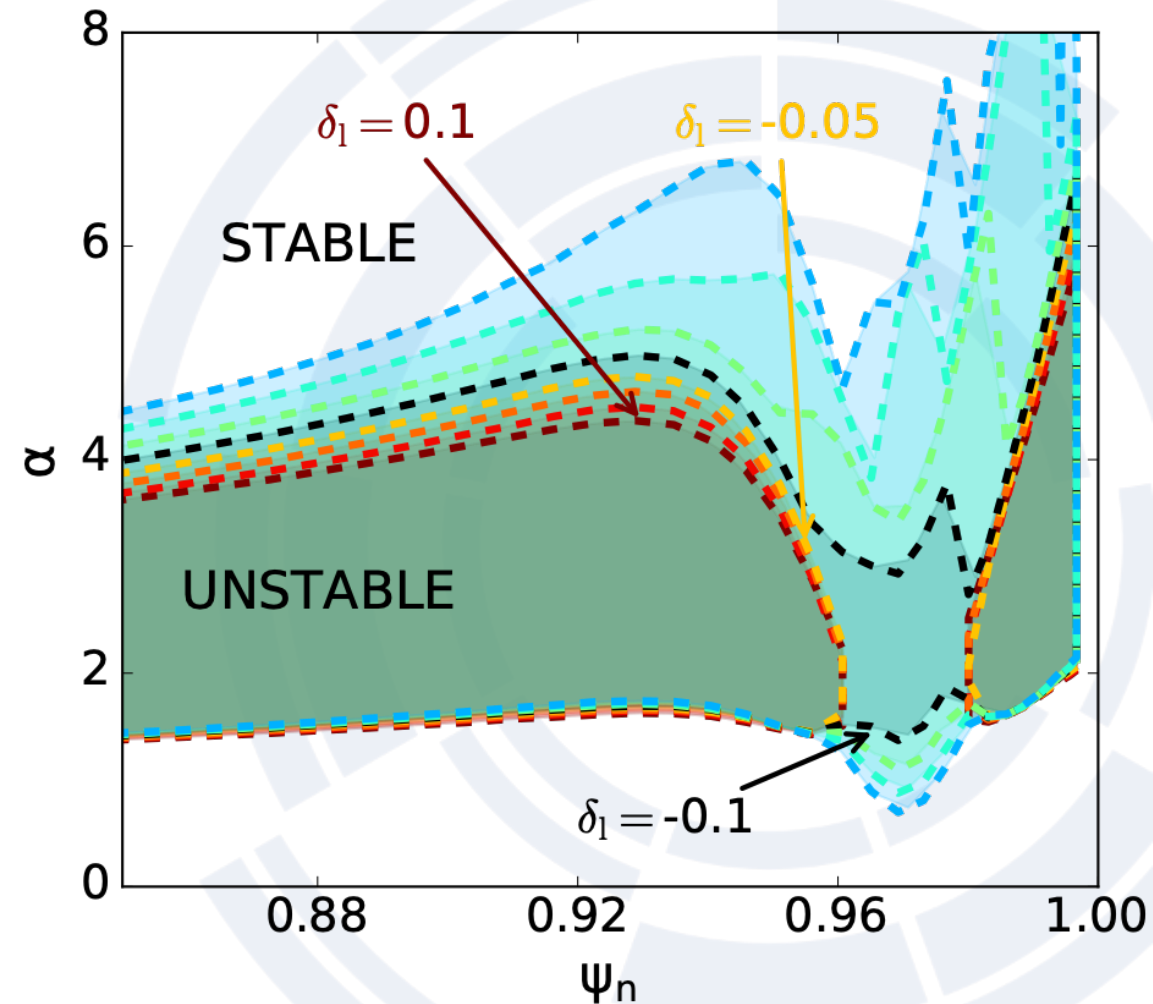


Figure courtesy A.O. Nelson

¹Nelson et al., PRL 2023

²Sauter et al., IAEA 2023



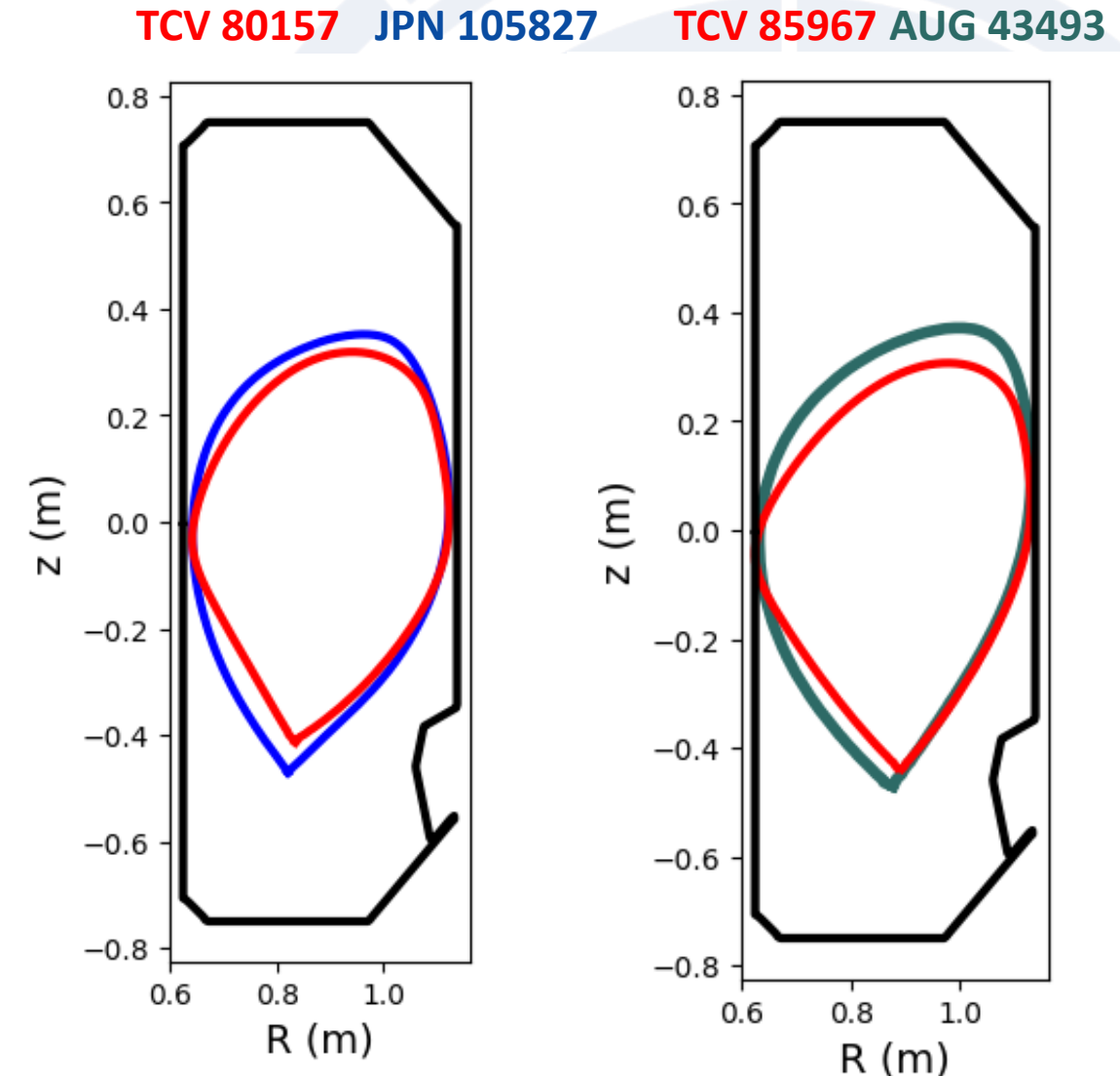
Exploring possible NT shapes for AUG and JET

JET



EPFL

- **Initial attempts on AUG:**
 - No ELM avoidance due to low shaping^{1,2}
- **Modelling predictions for AUG:**
 - Small changes in shape sufficient to avoid H-mode entry
- **Predictions for JET:**
 - Shape is marginal for ELM avoidance
 - No confinement improvement expected
- **Test planned shapes in TCV**
 - Expect ELM-free behaviour in both AUG and JET



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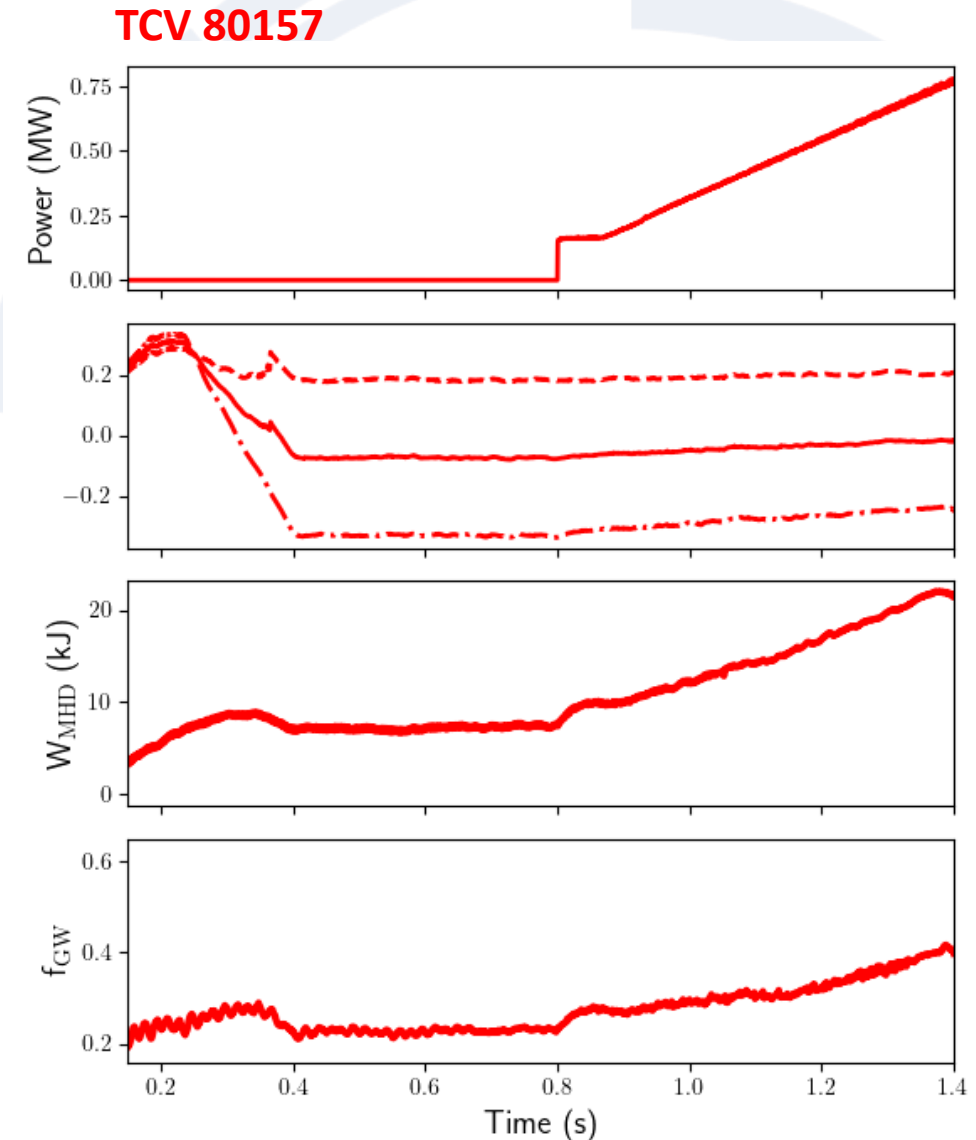
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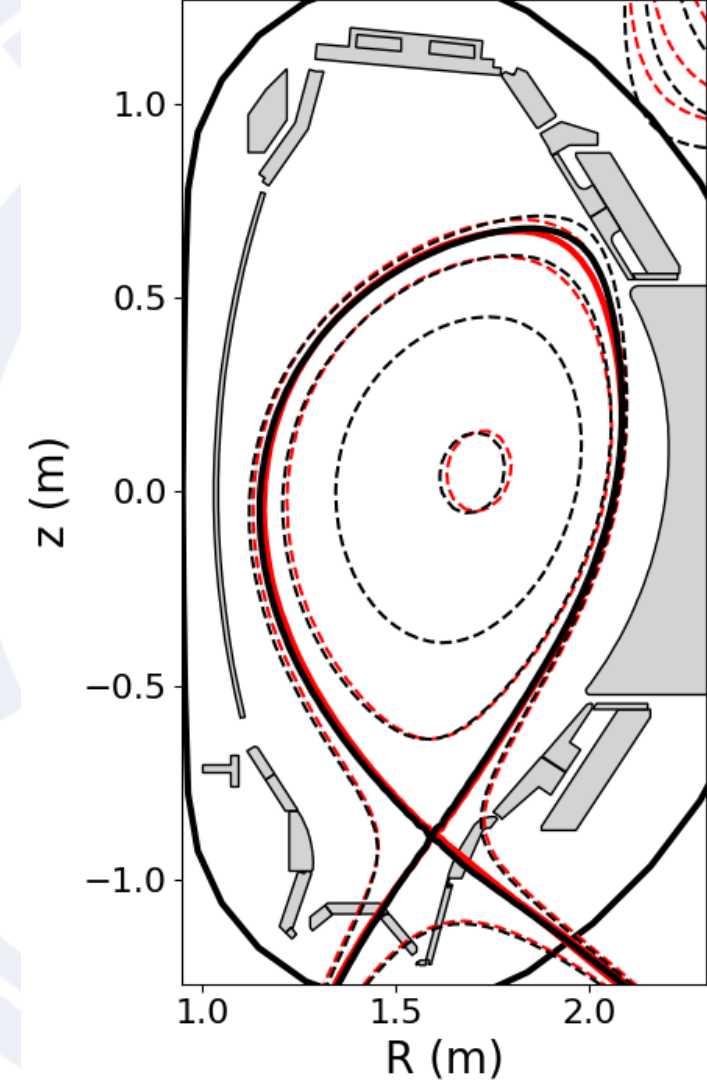


NT on ASDEX Upgrade



AUG 43114, 43493

- **New campaign¹:**
 - Experiments with small changes in triangularity
- **Weaker shaping:**
 - Clear high frequency ELMs, as in previous experiments
- **Stronger shaping:**
 - Dithering behaviour, no clear ELMs observed



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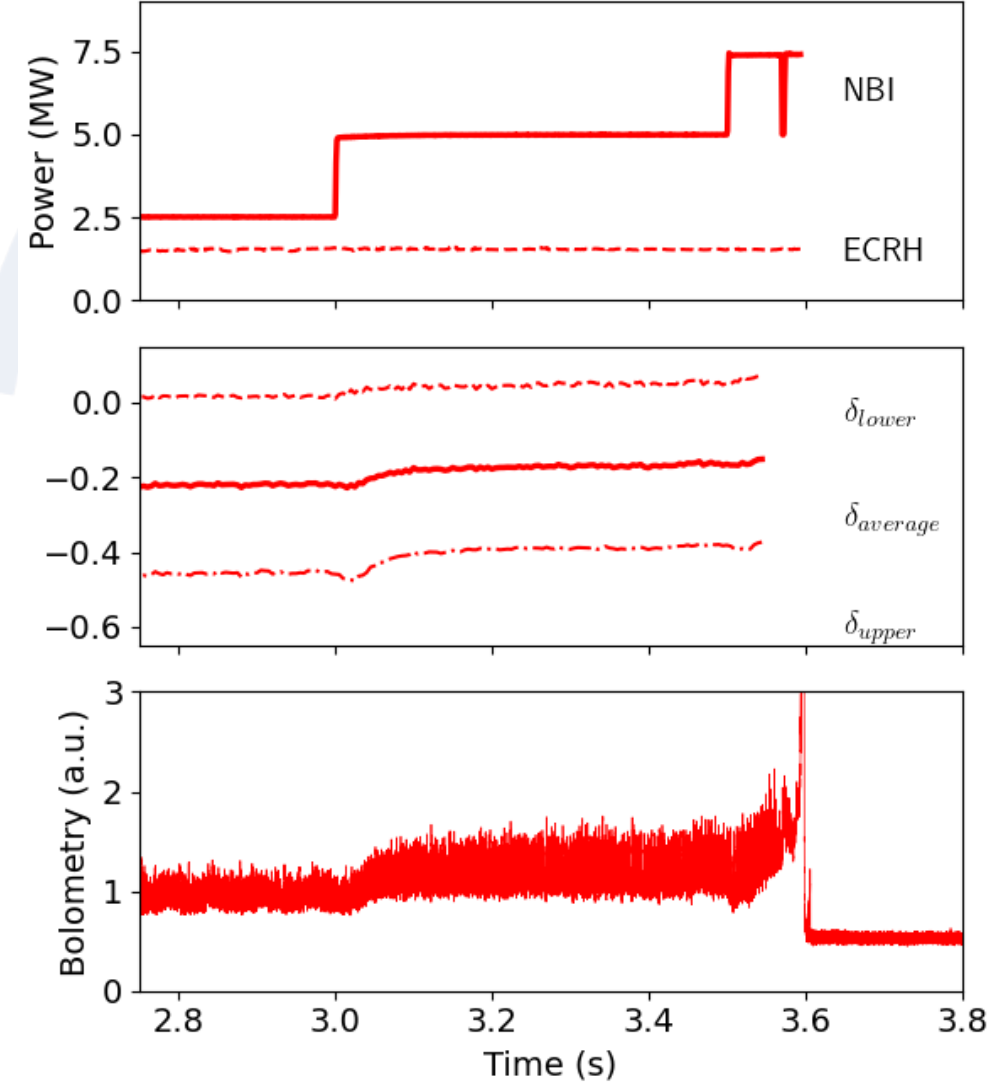


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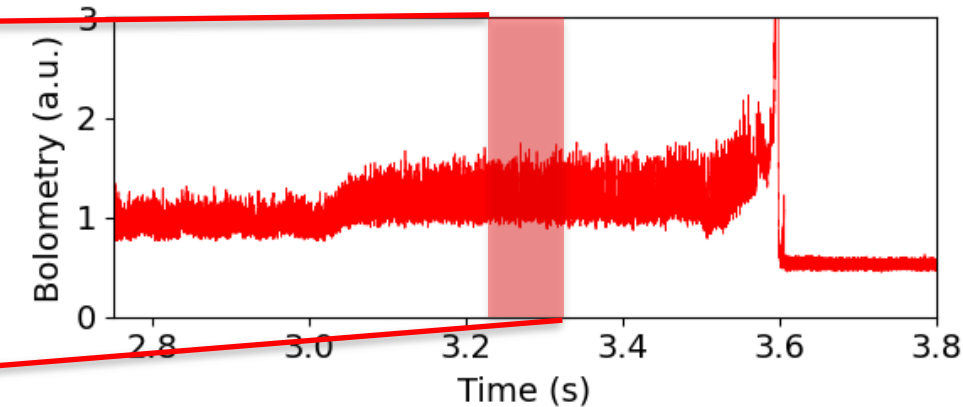
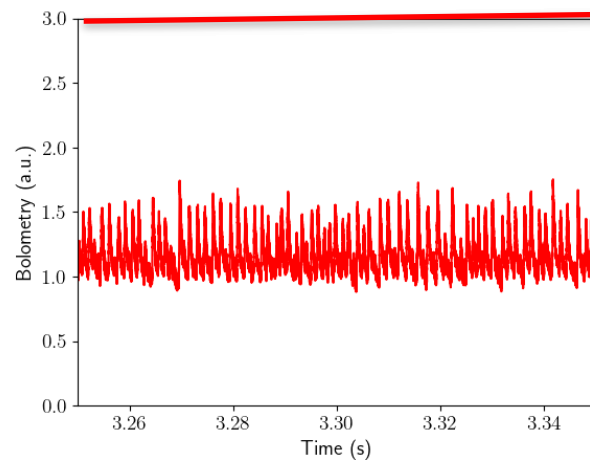
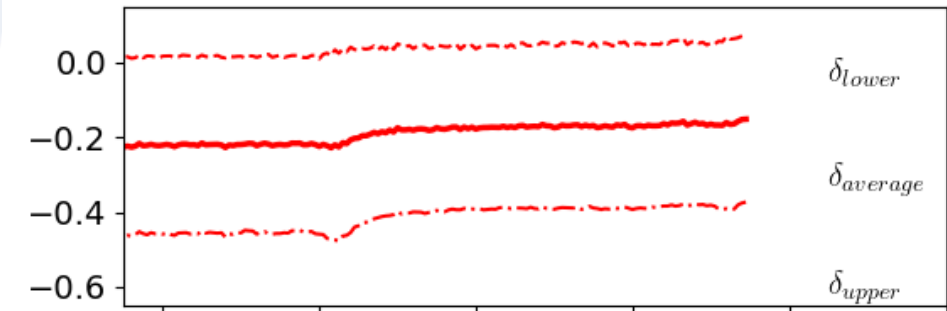
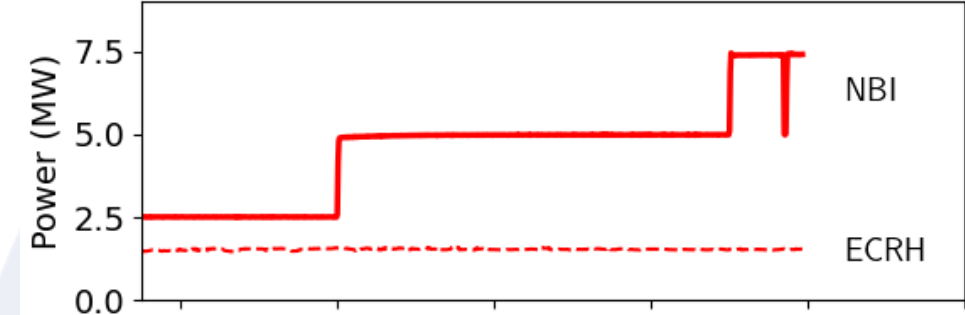


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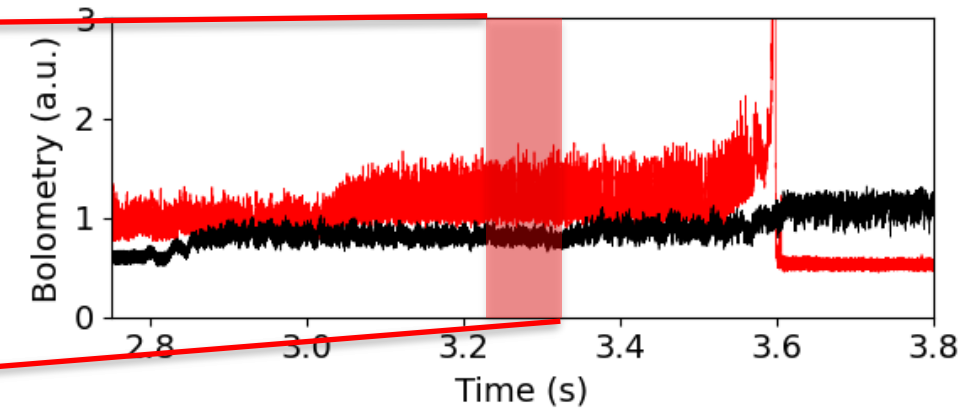
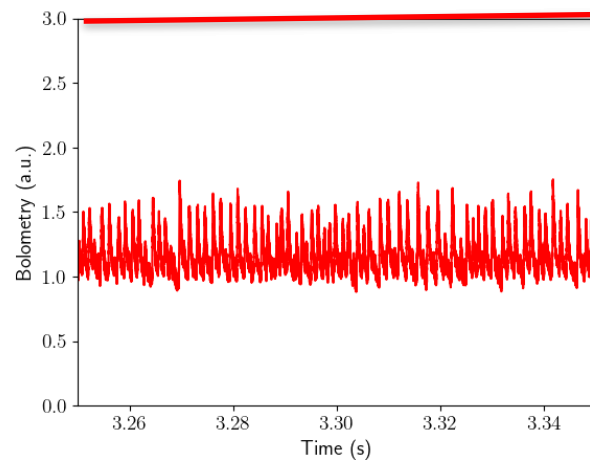
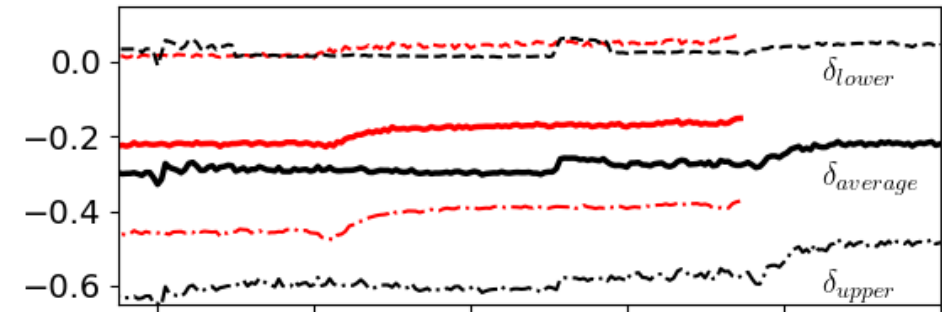
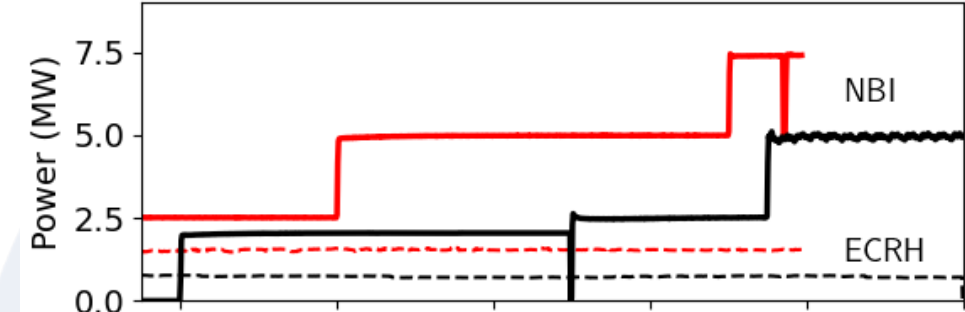


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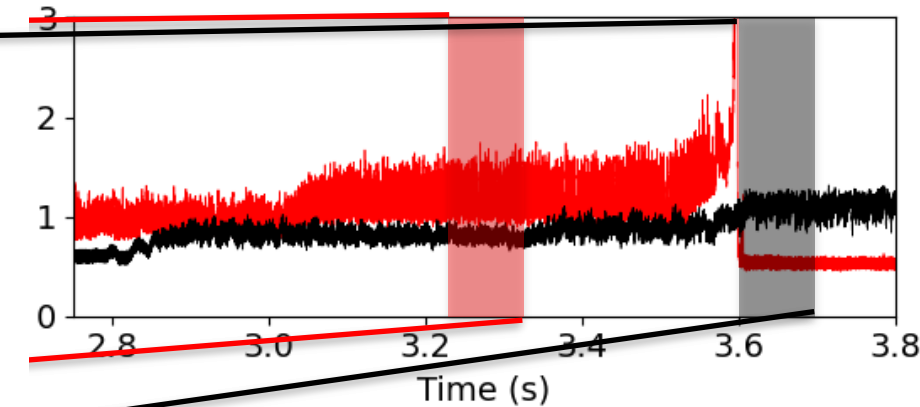
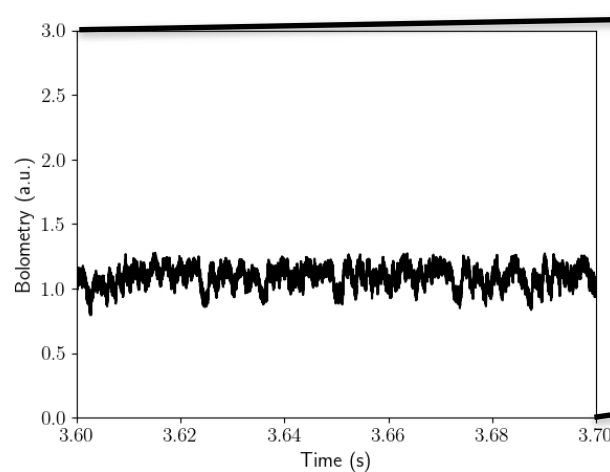
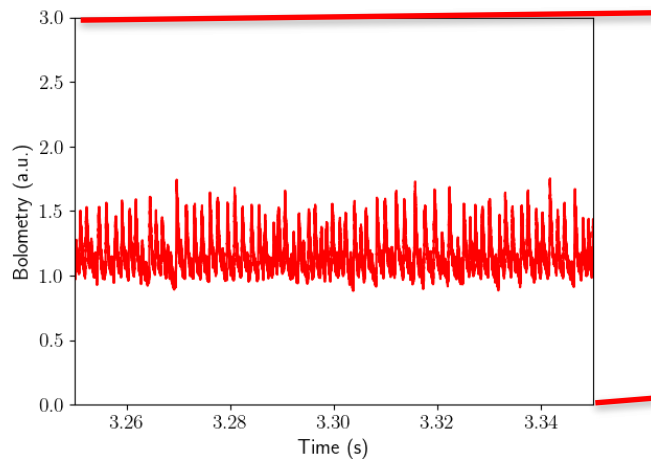
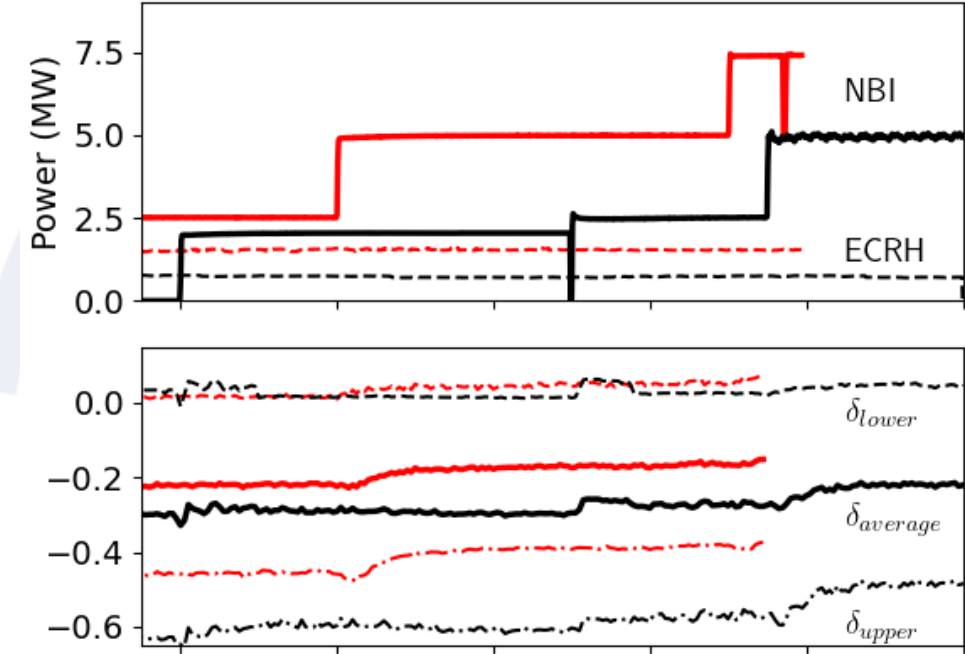


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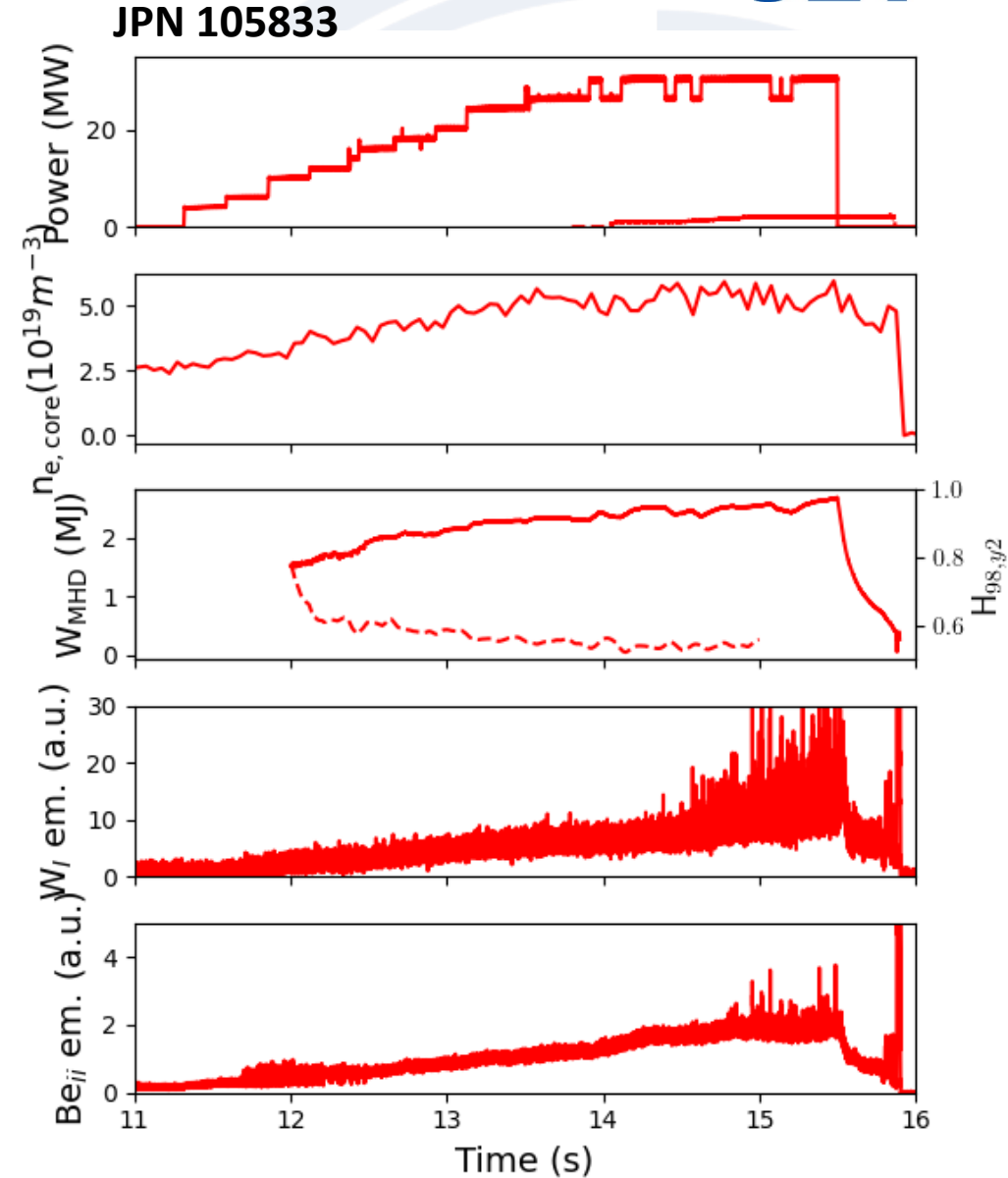
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NT development on JET

JET

- **Experiments:**
 - Up to 32 MW heating power
 - No clear H-mode or ELMs
 - First signs of filaments at highest heating power
- **T_e , n_e profiles show no clear pedestal**
 - Excellent confirmation of H-mode avoidance model
 - Can use to extrapolate to potential future NT devices

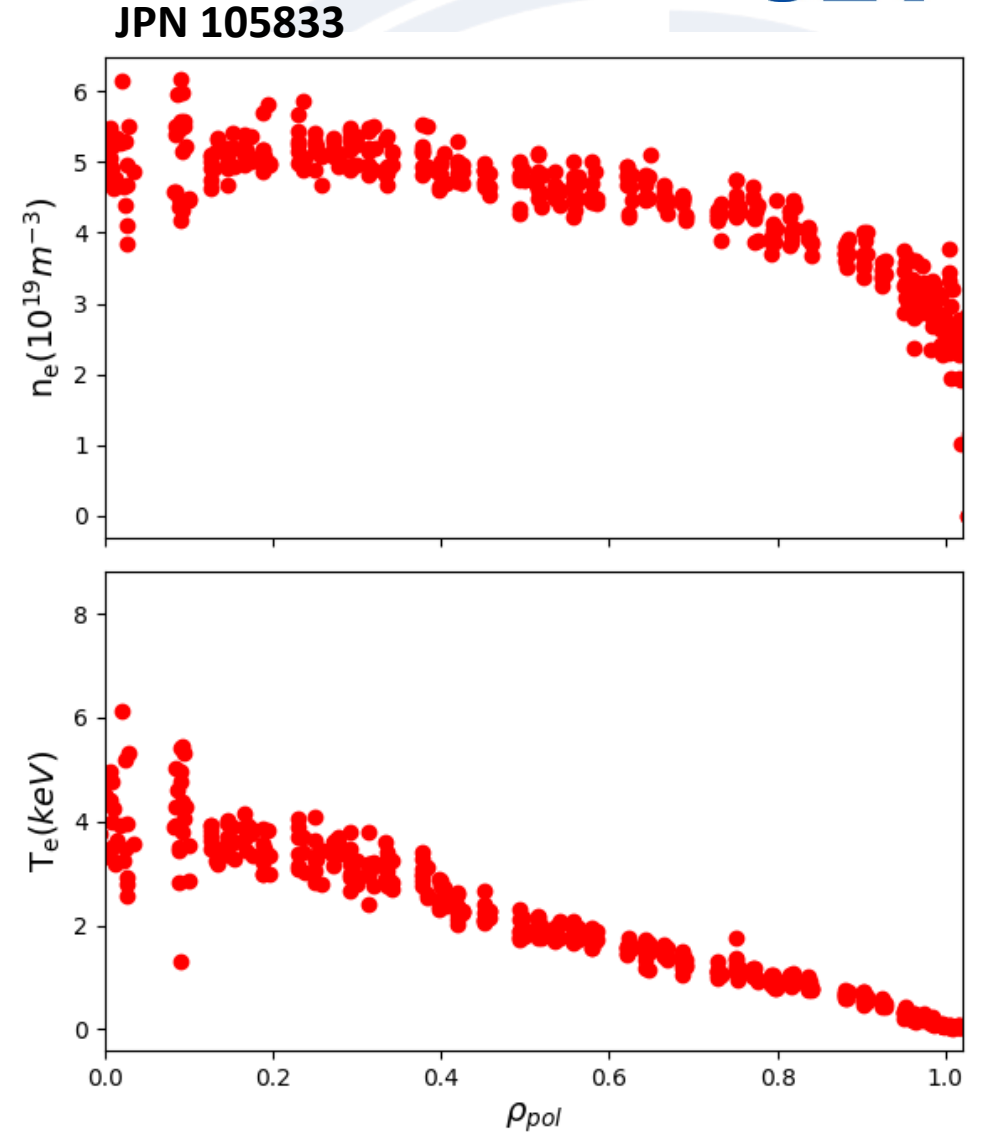




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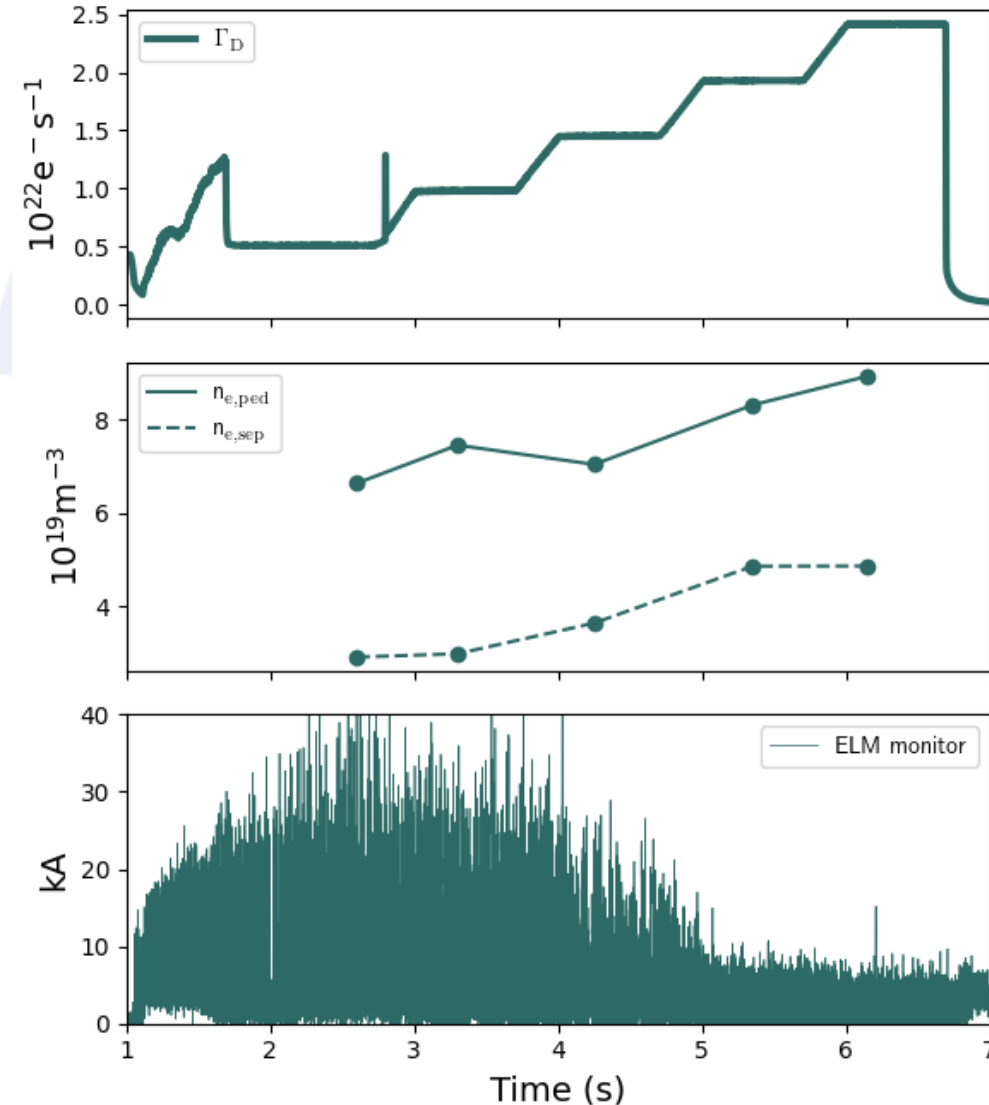


The quasi-continuous exhaust regime



- **Study access at high plasma shaping and (separatrix) density^{1,2,3}**
 - On present-day devices, this usually means high pedestal top collisionality
- **Exhibits H-mode-like pedestal, without large ELMs**
- **Transport enhanced by filaments**
 - Large-scale peeling-ballooning instability not triggered
- **Broadened power fall-off length in SOL region⁴**

AUG #36165



¹Harrer et al., NF 2018

²Labit et al., NF 2019

³Dunne et al., NF 2024

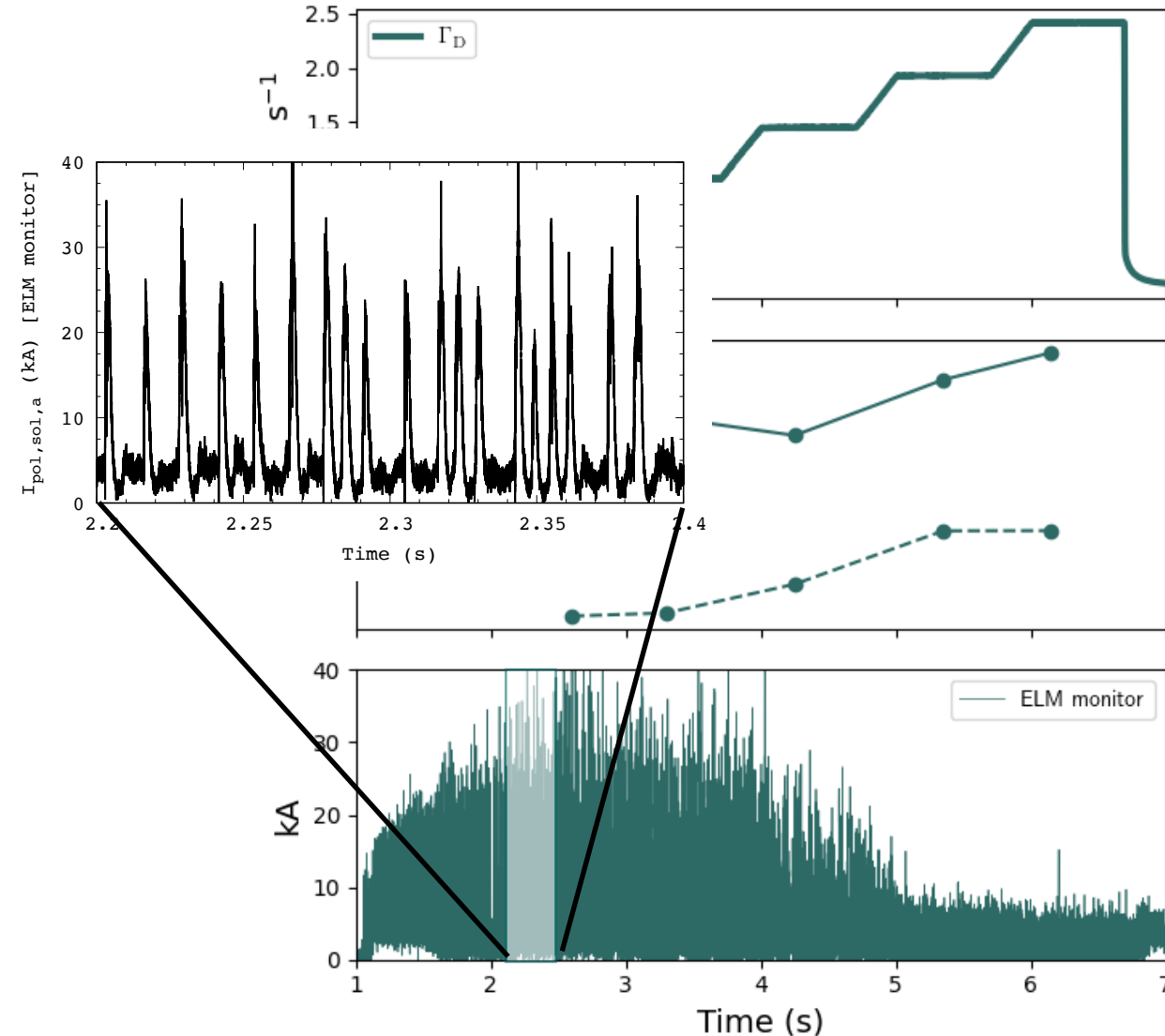
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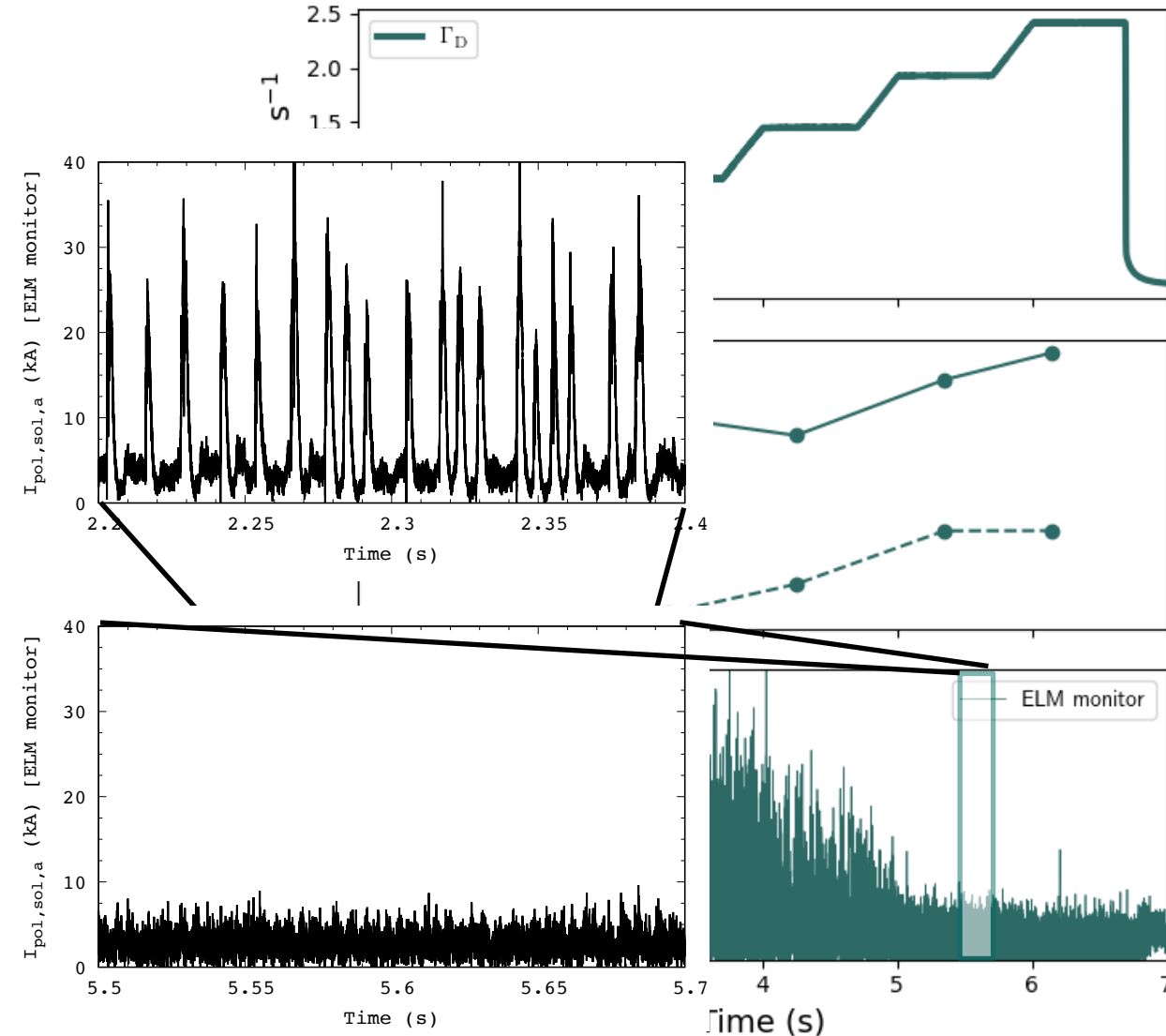
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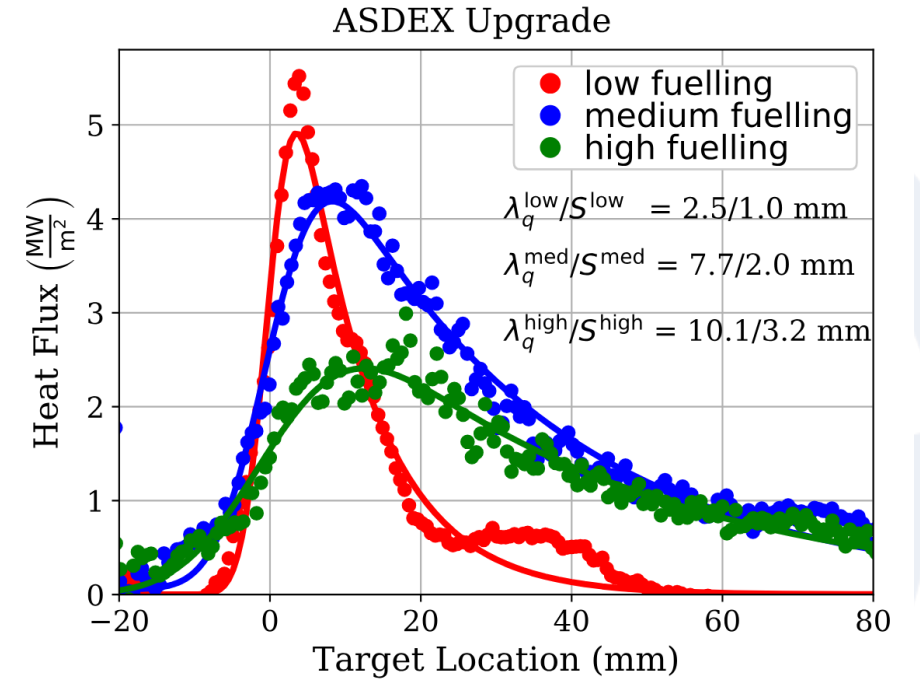


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Inter Type-I ELM

QCE

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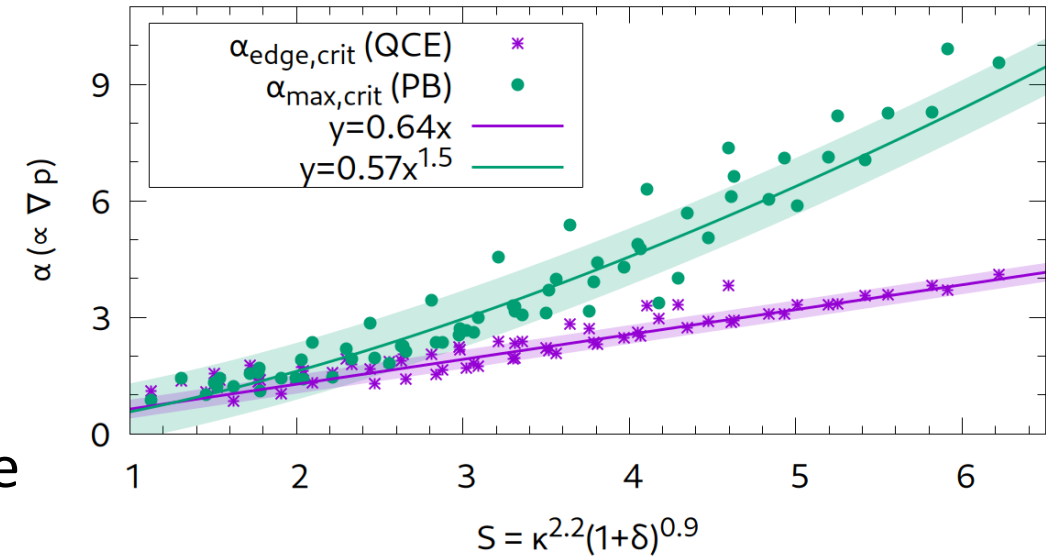
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Separatrix ballooning modes: quasi-continuous exhaust

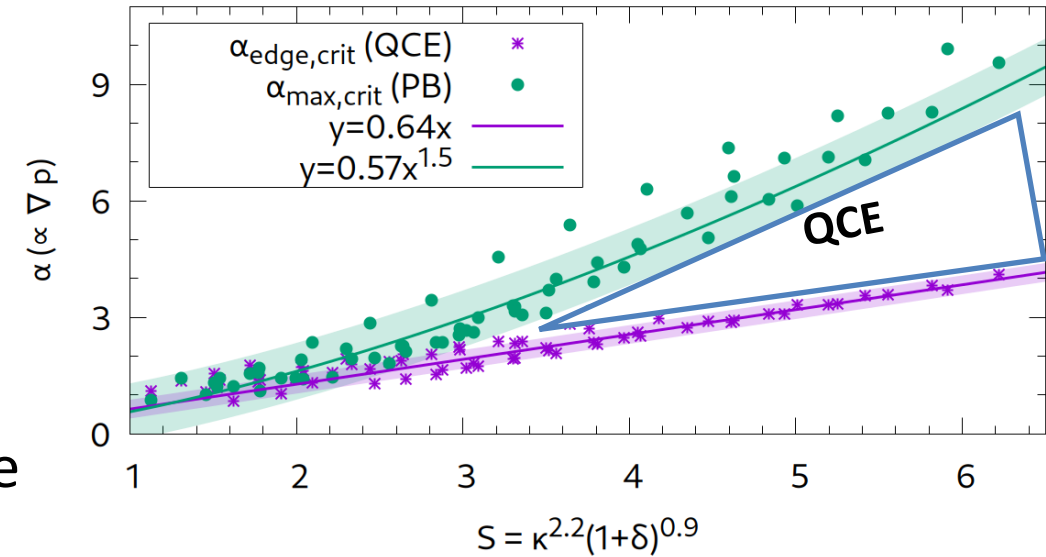
- **Predictive scan of plasma shape:**
 - More shaping ($\sim \kappa^2(1+\delta)$): stabilises local ballooning and large-scale peeling-ballooning modes
- Higher shaping opens possibility to destabilise ballooning modes for transport **before** large-scale PB modes
- **Can express critical α as critical $n_{e,sep}$:**
 - $\alpha_{edge,scale} = Rq^2\beta/\lambda_{p,scale}$, $\beta \propto n_{e,sep}T_{e,sep}$
 - $\lambda_{p,scale} = 1.55(1+0.61(0.001q_{cyl}V_{sep}^*)^{2.35})\rho_s$
- **Can (in principle) make predictions for any scenario on any device**





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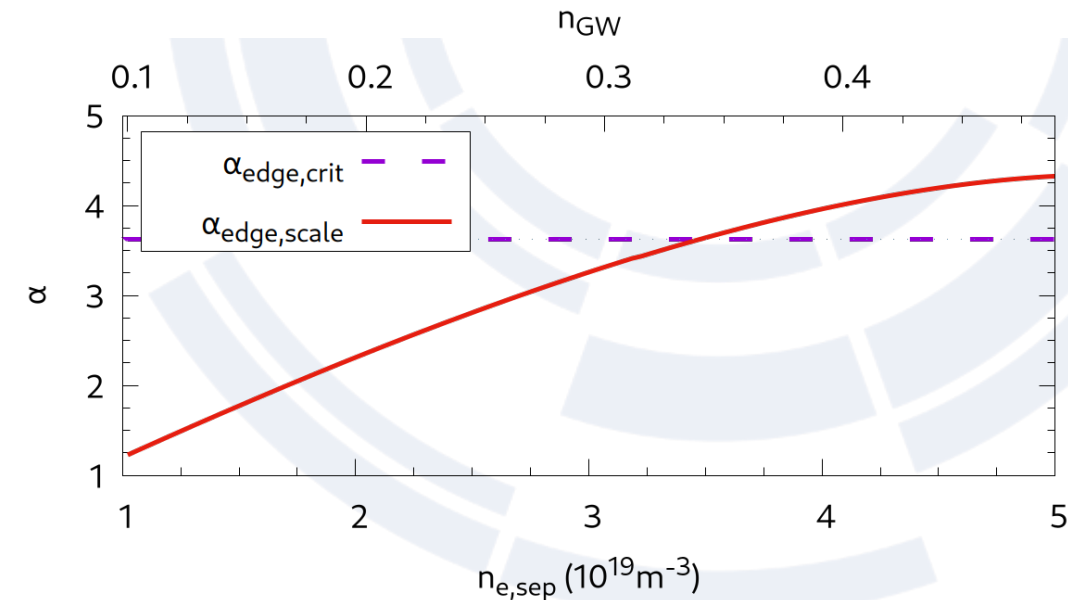
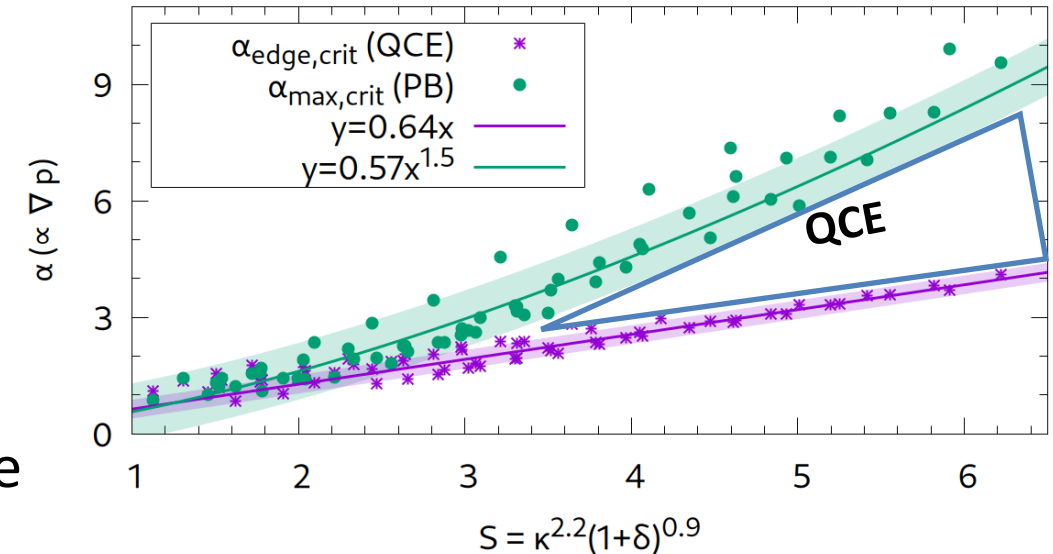
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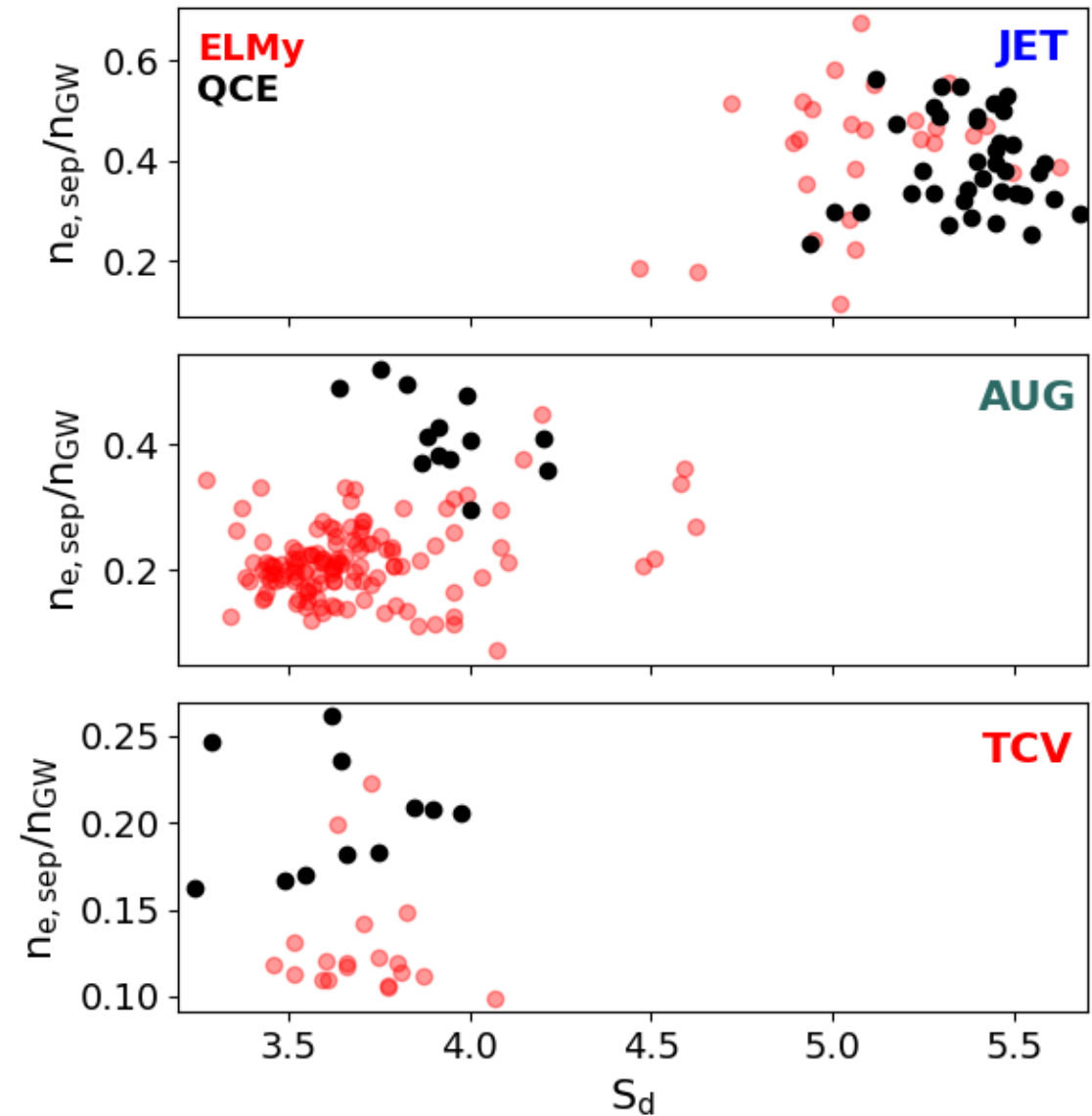
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QCE: Critical separatrix density

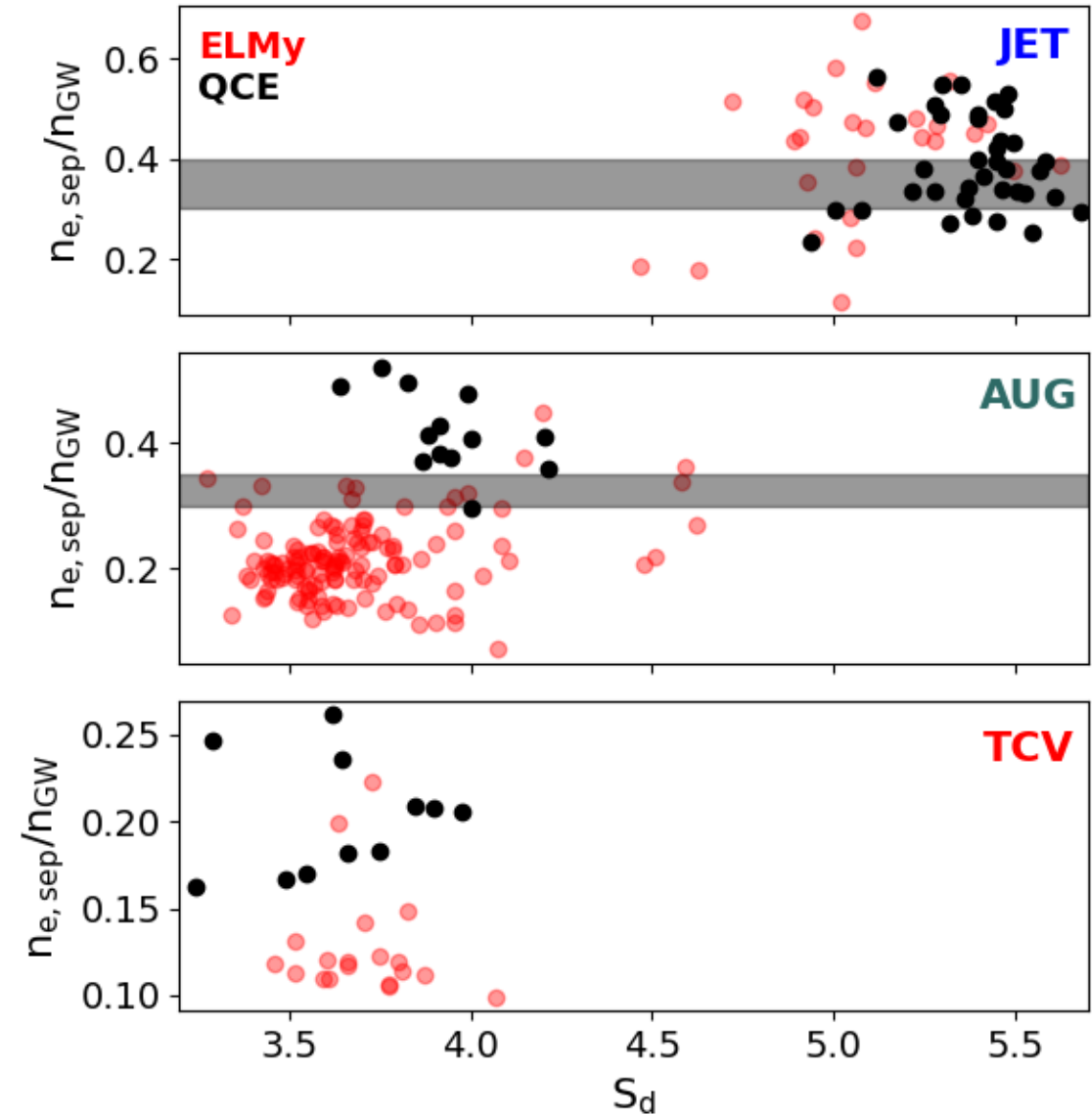
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 - TCV data only from baffled divertor
- Observed separatrix density consistent with predicted critical density in AUG and JET
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- ITER prediction for critical separatrix (15 MA BL) falls within range of:
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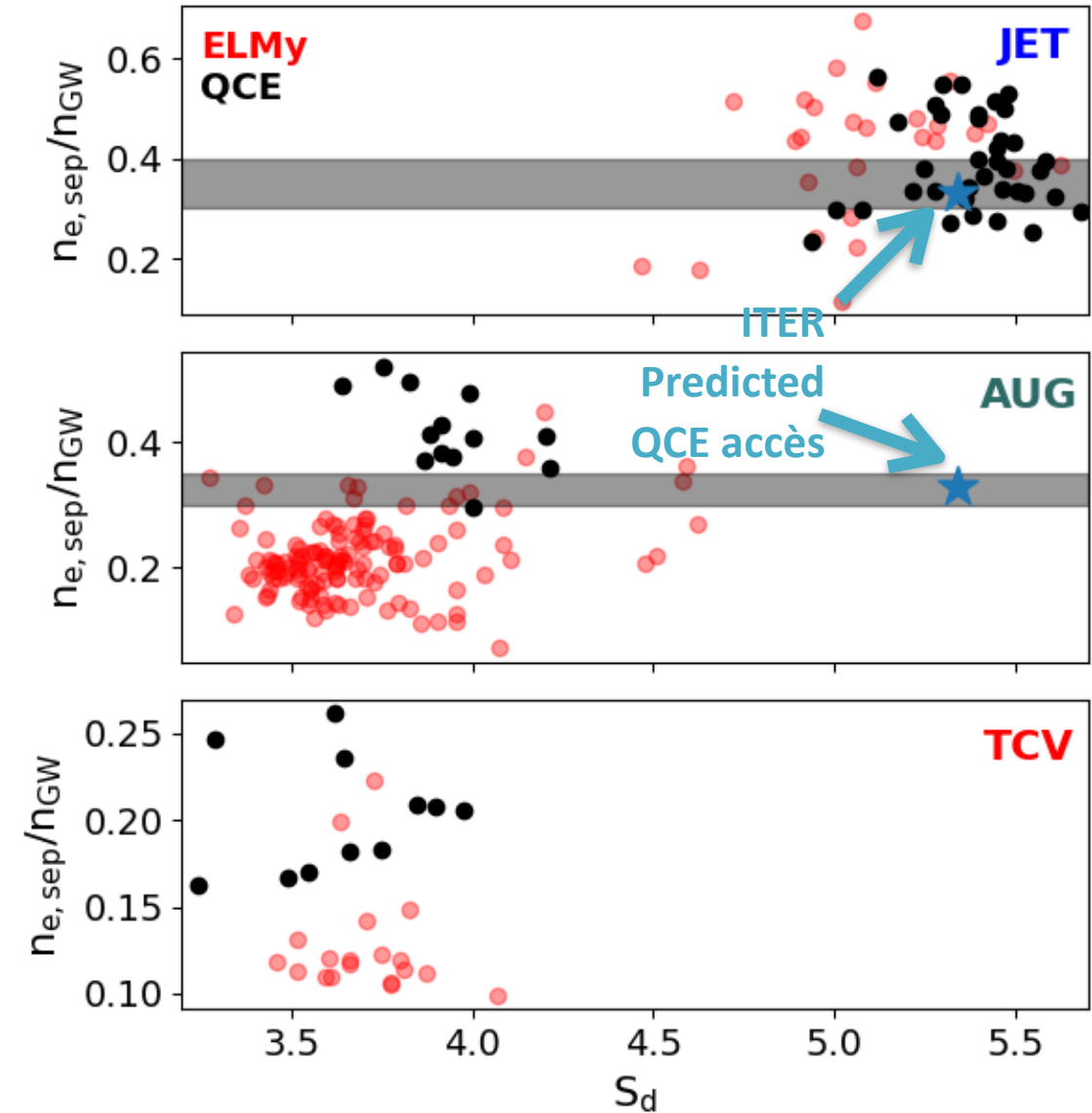
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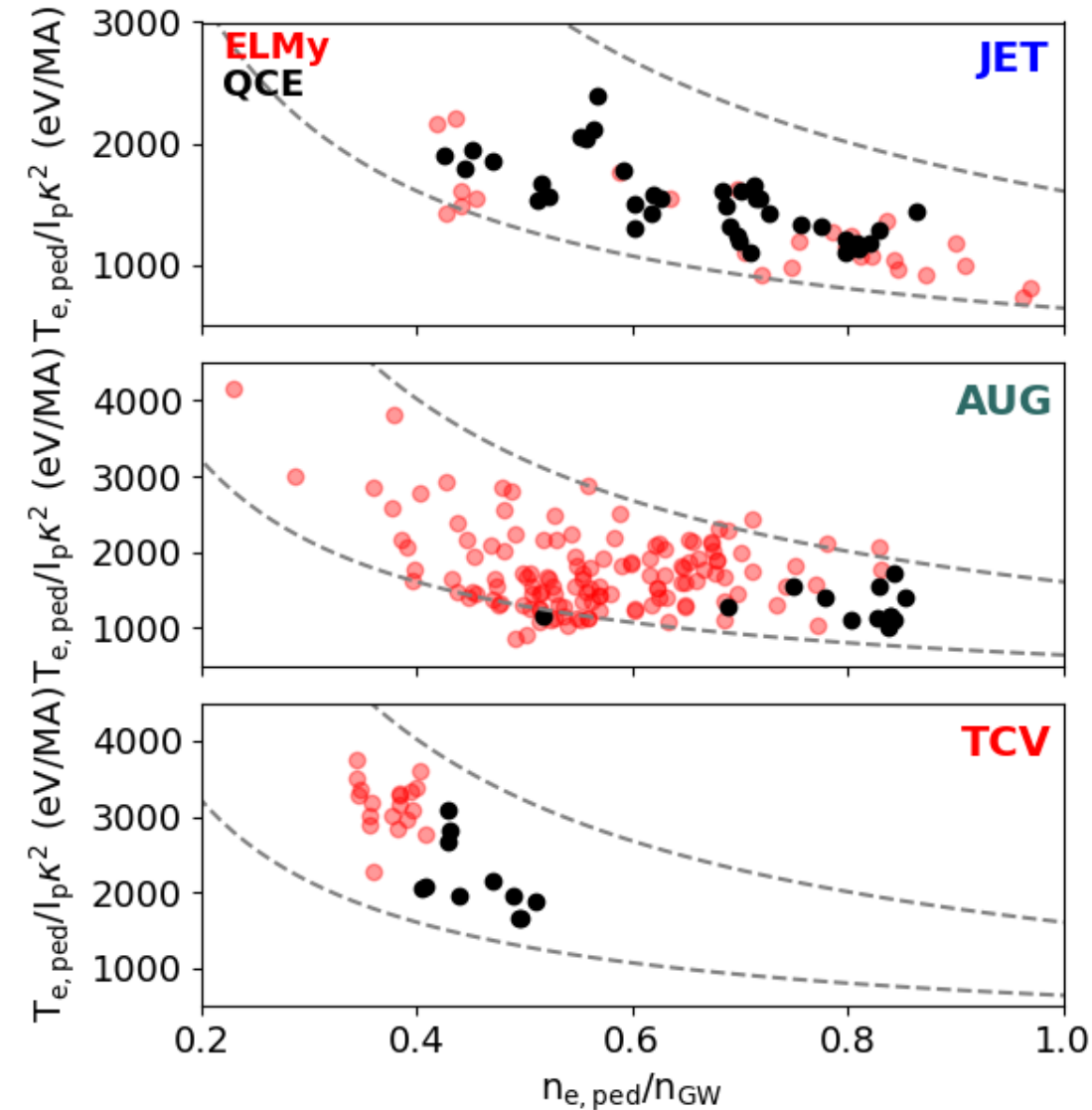
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QCE: Pedestal top performance

- Compare different scenarios:
 - Normalise density to n_{GW}
 - Normalise temperature to I_p/κ^2
 - Dashed lines are then lines of constant β_{pol}
 - Range = 0.08-0.2, same in all devices
- Pedestal top pressure in QCE comparable to similar ELMing H-mode pedestal
 - JET data overlaps in temperature and density
 - AUG & TCV at higher density than ELM cases
- IPED predictions correspond to experimental pedestal top pressure in AUG, JET, TCV
 - Predictions for ITER with standard ITER shaping compatible with edge ballooning modes^{1,2,3,4}



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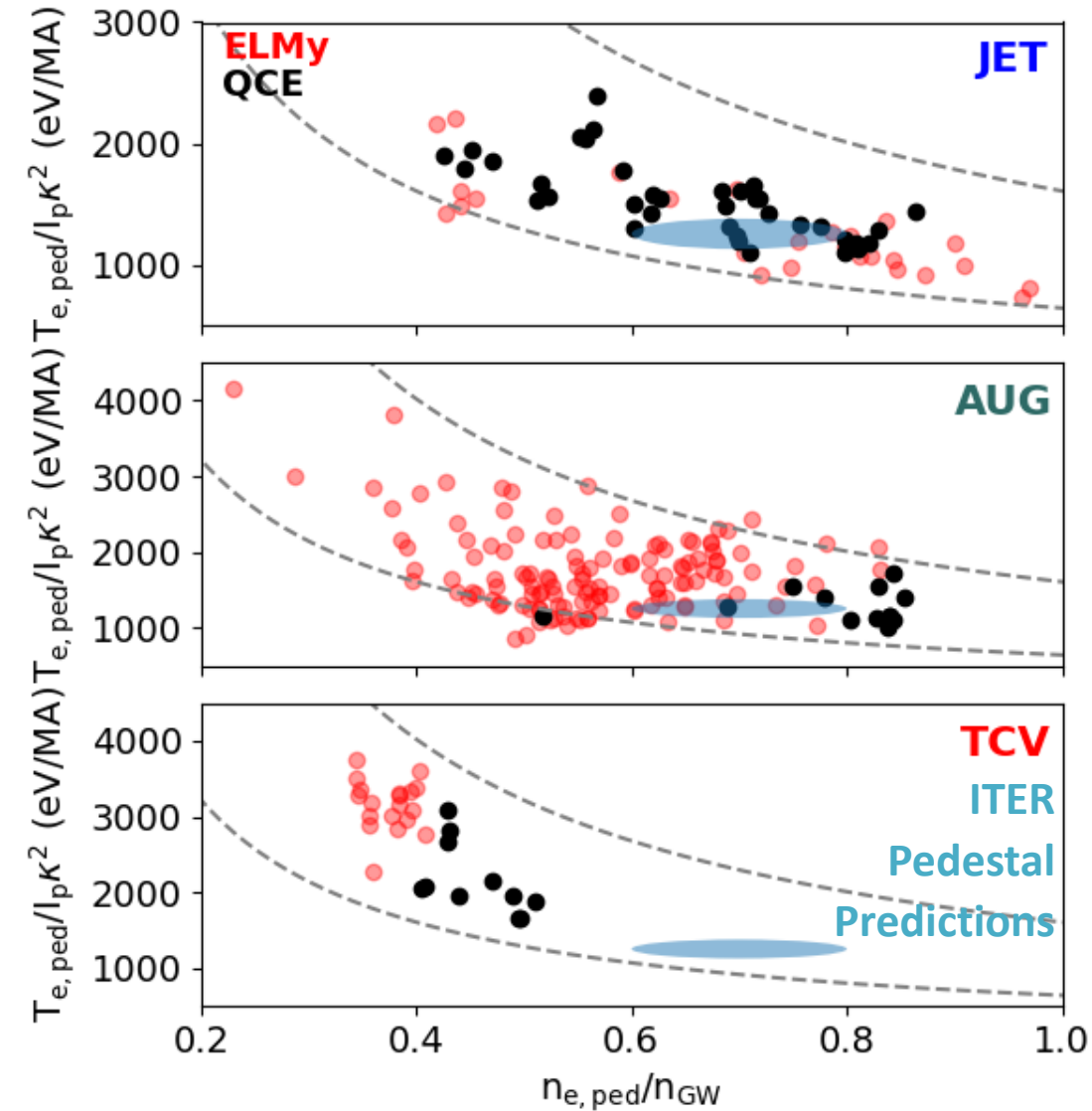
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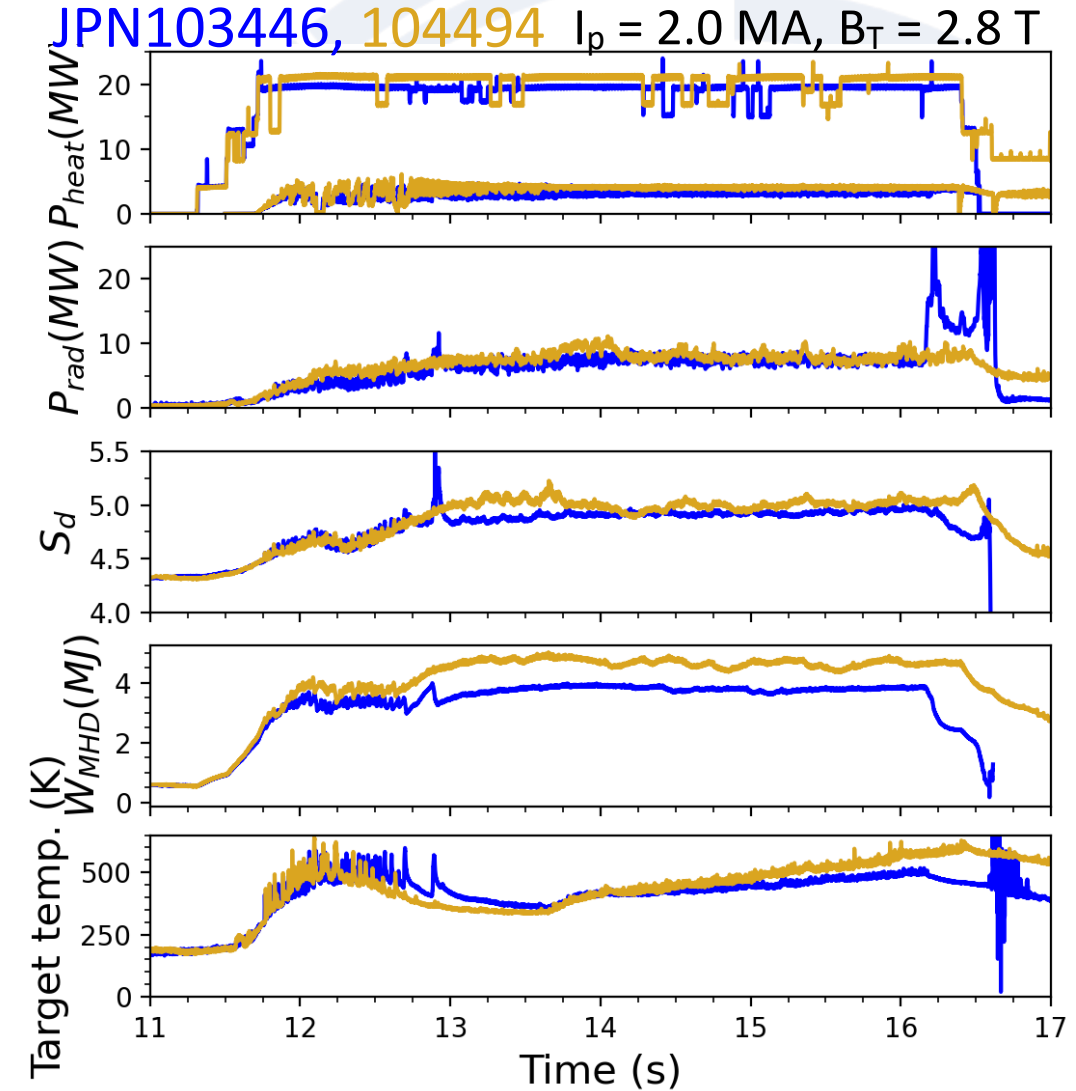
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QCE regime in DT at JET

- **QCE demonstrated in DT plasmas at JET^{1,2}**
 - Access QCE at same engineering parameters as in D pulse
- **Features best combination of ELMy H-mode and QCE from D plasmas:**
 - No large ELMs observed at similar engineering parameters
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 - IPED predictions in line with measured pedestal heights

JET



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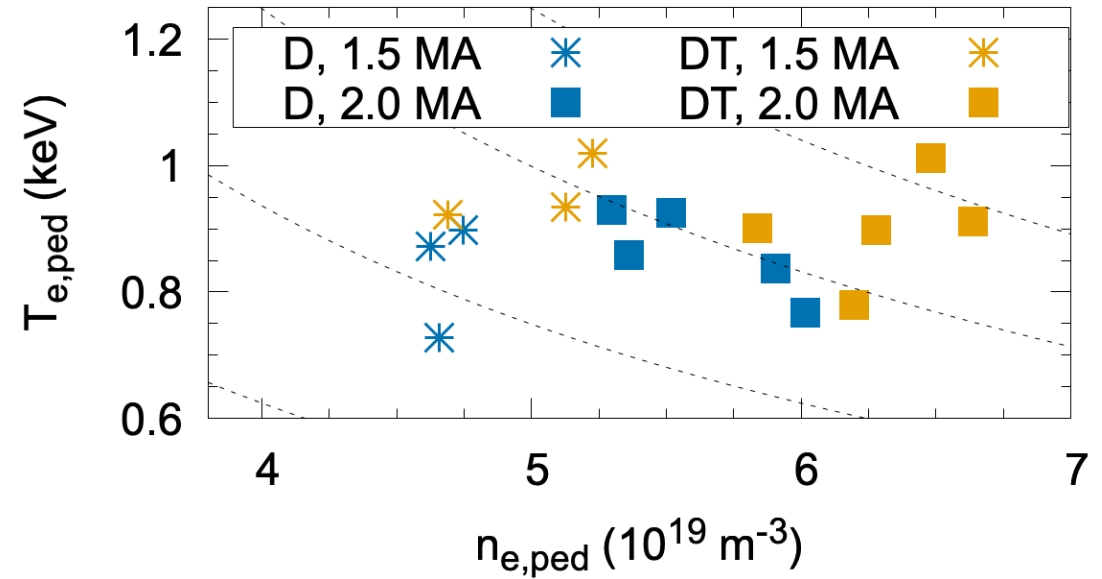
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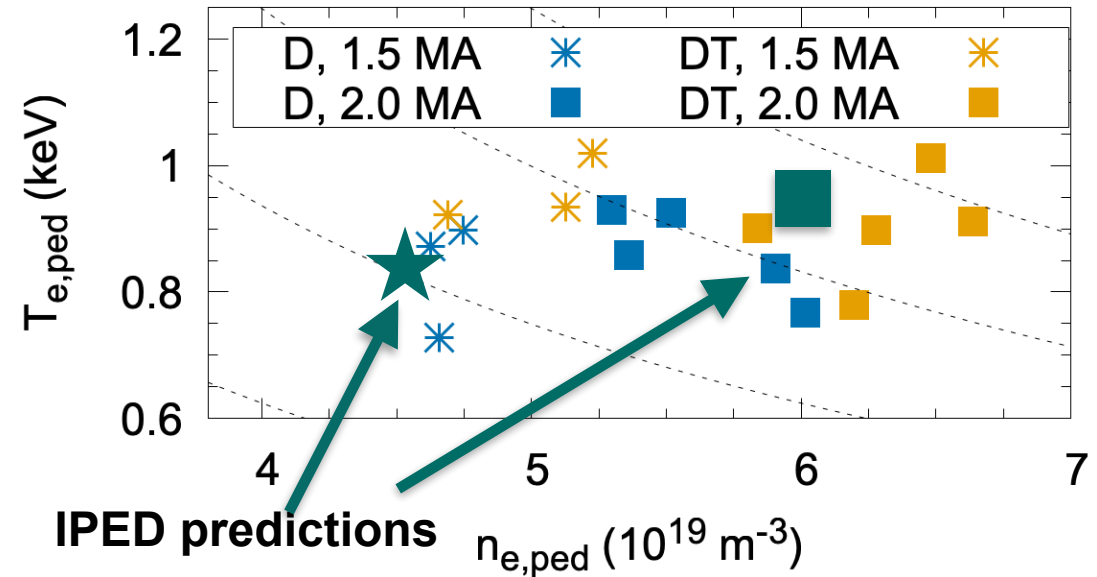
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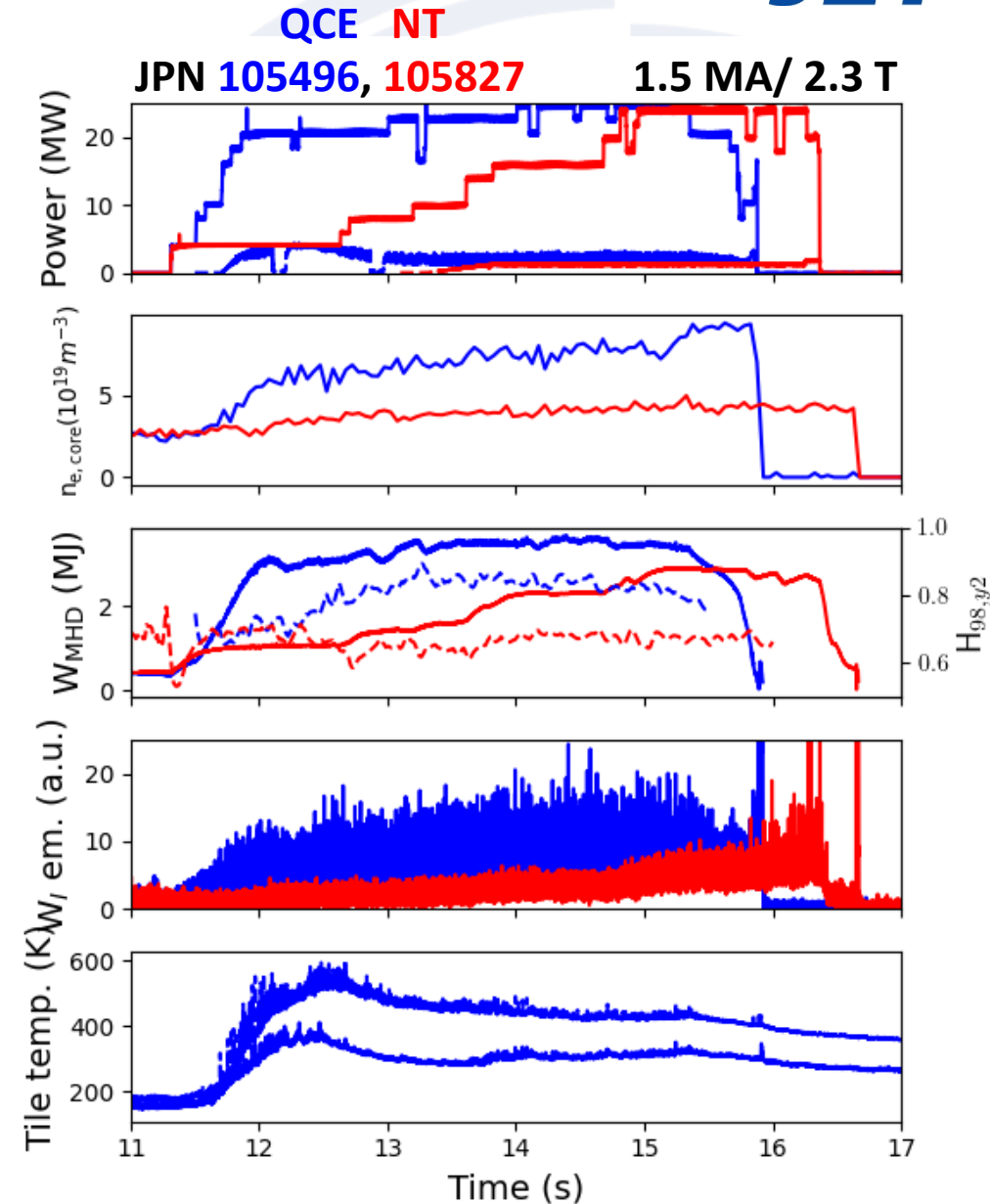
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Comparison of QCE and NT at JET

JET

- Compared scenarios at 1.5 MA/2.3 T
 - Same heating power
- Comparable stored energy at same heating power
- Significantly higher density in QCE pulse
 - Core temperature similar in QCE and NT
- Normalised confinement higher in QCE
 - NT recovers stored energy with much larger plasma volume
- Filaments visible in QCE
 - Very little activity visible in camera diagnostics in NT





Summary and conclusions

- Understand QCE and NT ELM avoidance in EF tokamaks
- Demonstrated both regimes in final JET campaign
 - Stepladder approach made this possible
 - QCE demonstrated in DT
- Predictions show QCE access in ITER/SPARC/DEMO
- NT ELM avoidance based on ideal MHD
 - Can predict an NT-DEMO
- Ongoing work:
 - Extending NT, QCE to WEST, MAST-U
 - Expanding QCE operational range to higher current and (even) lower q_{95} in operational devices
 - Demonstrate robust ELM avoidance also in ramp-up
 - Further exploration and development of MP ELM suppression and QH-mode
- Prospective:
 - QCE at lower ν_{ped}^* in JT-60SA

