ASDEX Upgrade experiments for a physics basis of ITER operation and DEMO scenarios

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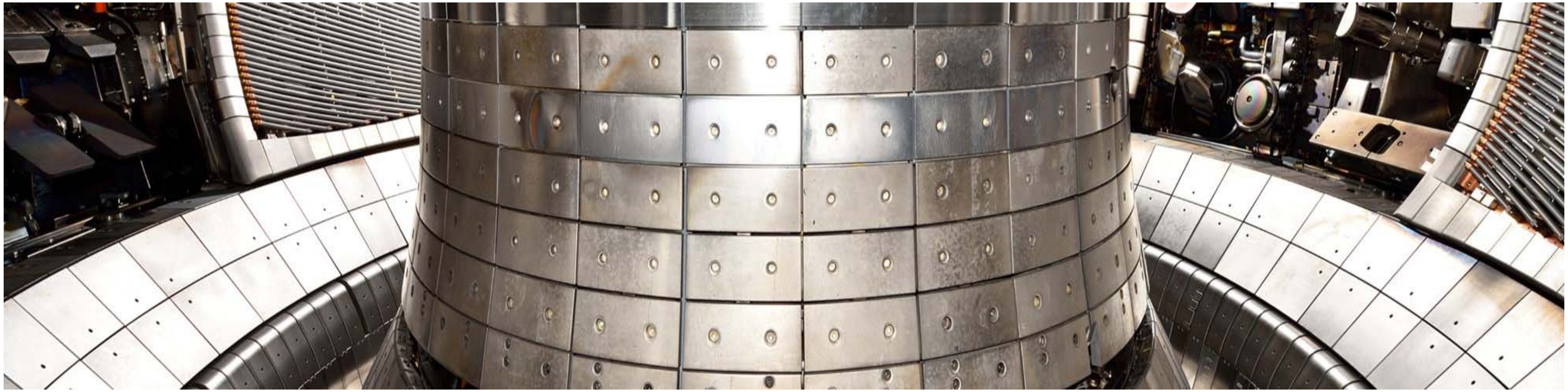


ASDEX Upgrade

Total heating power of 27 MW

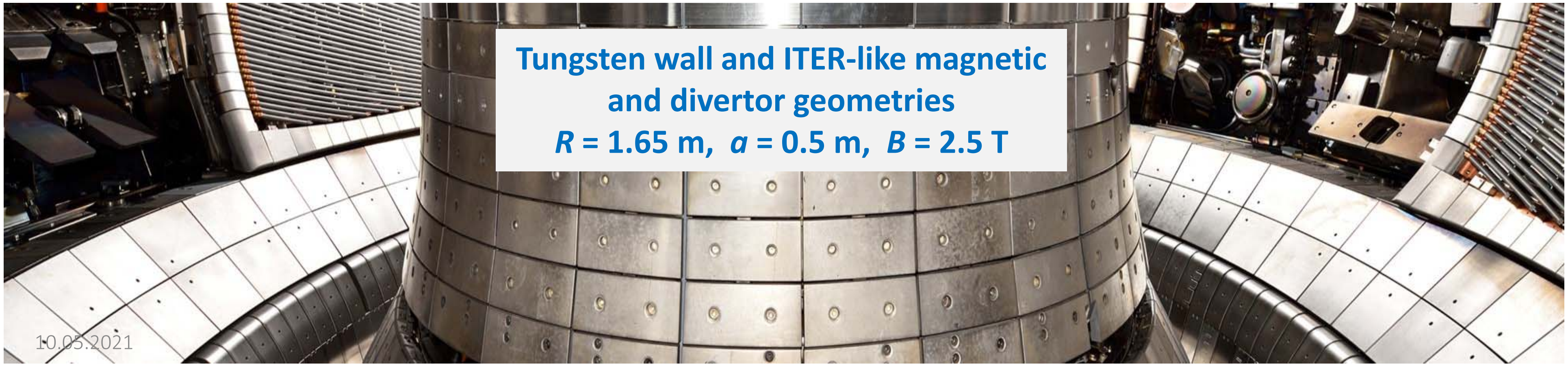
- NBI: 16 MW
- ECRH: 6.0 MW
- ICRH: 5 MW

Versatile discharge control system

- Enhanced real-time capabilities
- Increasing number of real time sensors
- Coupled with discharge ‚flight simulator'

Continuously improved diagnostics

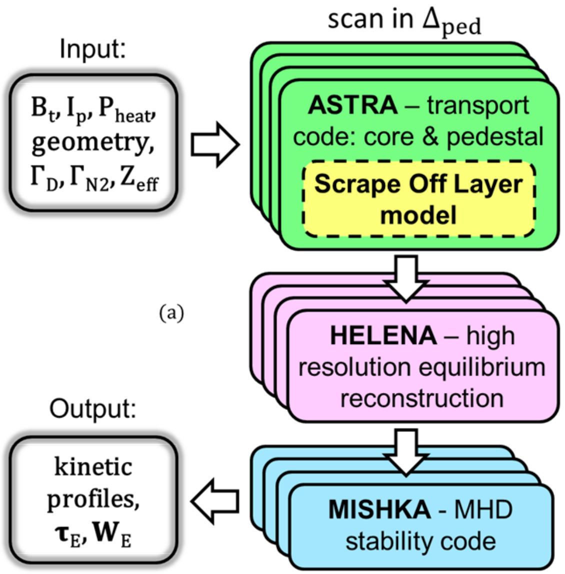
- Imaging Motional Stark Effect (IMSE)
- Microwave fluctuation diag. (DR, CECE)
- He beam for the SOL/edge dynamics
- Divertor Thomson scattering
- Imaging heavy ion beam probe

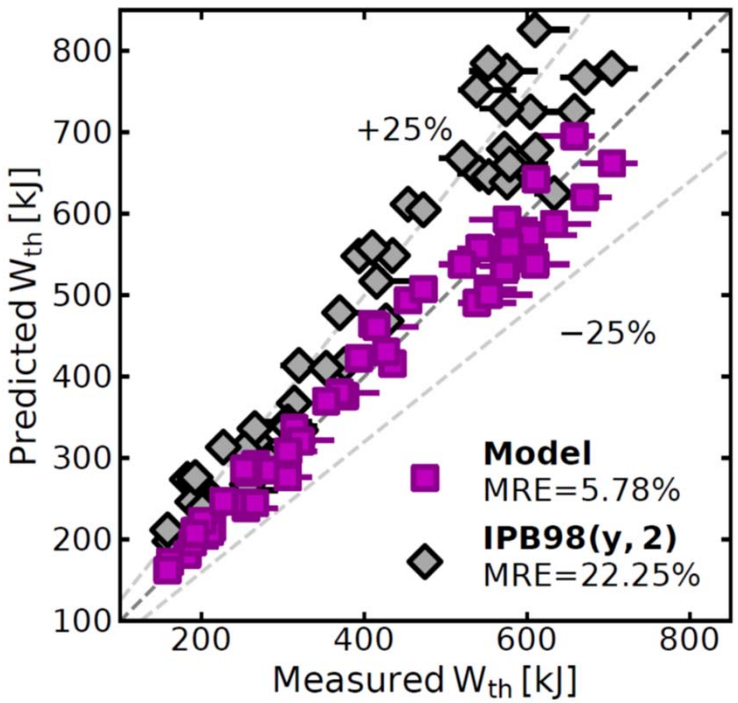


Ultimate goal: physics based predictive modelling

Present status: workflow for predictive profile modelling of AUG discharges

- Separatrix parameters from a empirical model using gas puff and 2-point model
- Pedestal from peeling-ballooning stability with a critical temperature gradient model
- Core plasma from pedestal top inwards is modelled with TGLF





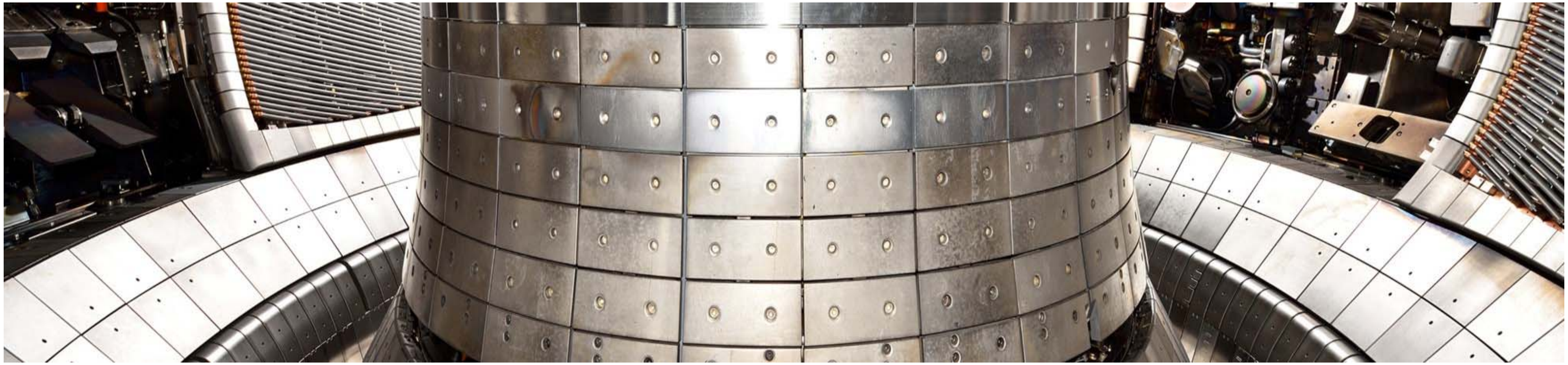
Outperforms scaling laws in predicting AUG energy confinement

[T. Luda et al., NF 2020]

→ poster by G. Tardini

Outline

- Core transport and confinement
- ELM free discharges scenarios
- Importance of the outer plasma edge
- Elements of power exhaust



Plasma current redistribution by dynamo effect

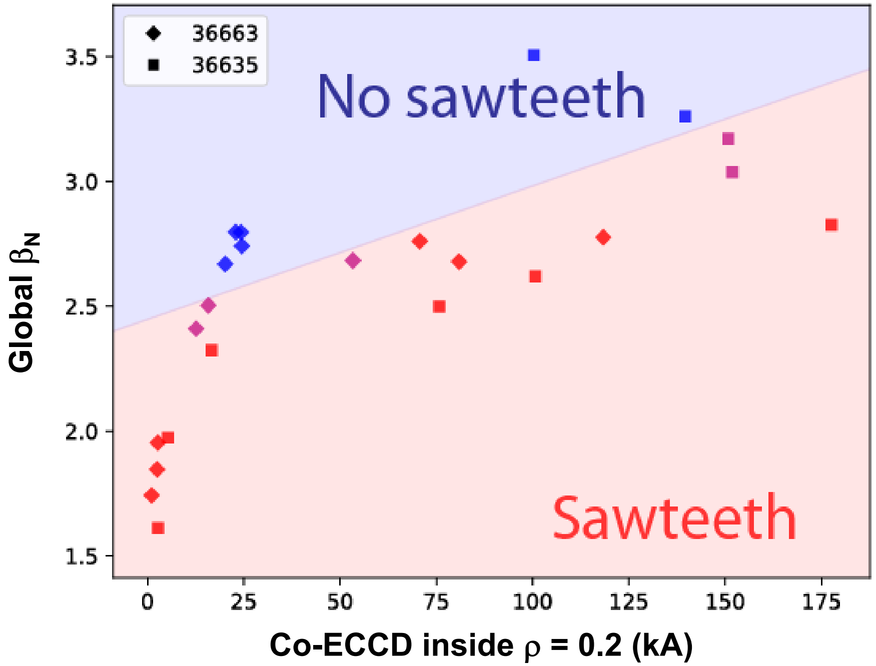
Prediction by nonlinear MHD code (*MD3D-C1*)

- Current redistribution at high β_N related to (1,1) mode can lead to $q(0) > 1$

[I. Krebs et al., PoP 2017]

Experimental confirmation of sawtooth suppression at high β_N

- At high β_N sawteeth vanish
- On-axis co-ECCD makes them reappear
- At high β_N more ECCD power can be tolerated without sawteeth



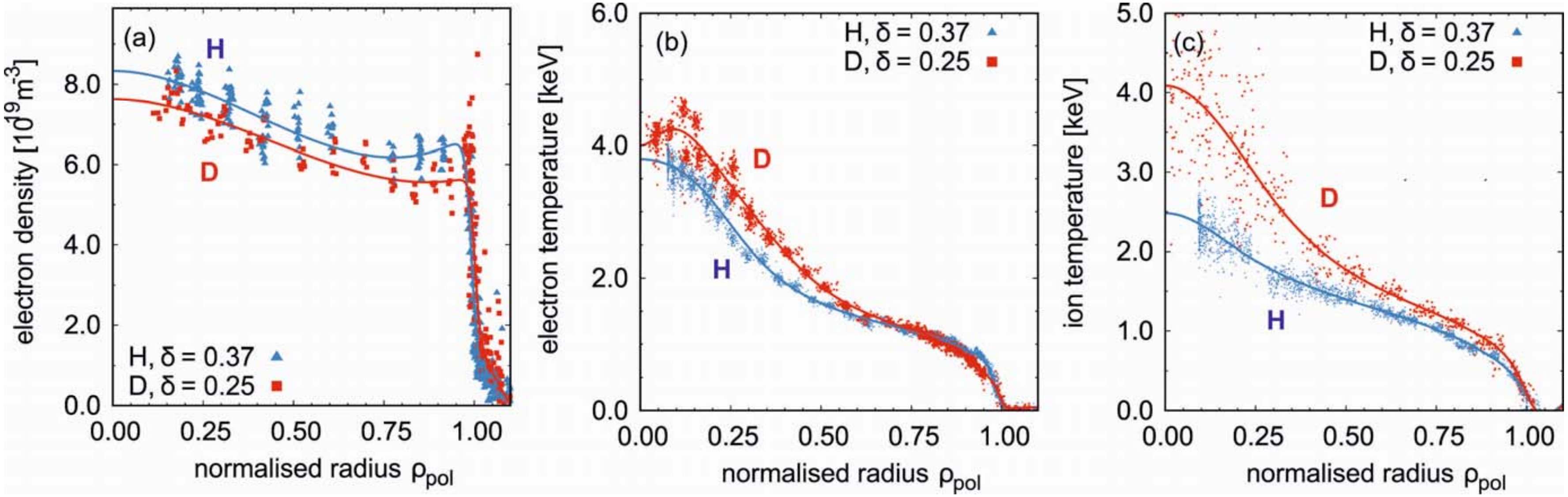
→ talk by A. Burckhart, Thu. 14:00

Enables central ECCD in reactor plasmas at high efficiency and flat *q* profiles

Core transport: isotope effect in H-mode plasmas

Matched edge profiles (by shaping) keeping the source profiles similar

- Low NBI power: core profiles are also similar (no isotope effect)
- High NBI power: reduced ion heat transport in D plasmas



[P. A. Schneider et al., NF 2021]

- Interpretation by nonlinear GENE simulations: stabilizing effect of fast ions on turbulence transport and higher fast-ion content in D plasmas (slowing-down time)
- Fast ion effects are also important to explain low-*Z* impurity transport (B, He)

[A. Kappatou et al., NF 2018; R. McDermott et al., NF 2020; Manas et al., NF 2020]

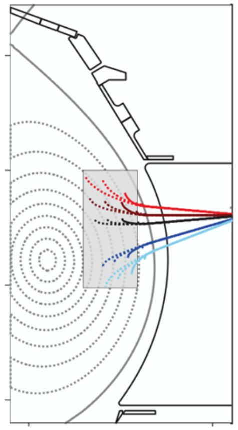
Edge isotope effect → poster by P.A. Schneider (P4.1084)

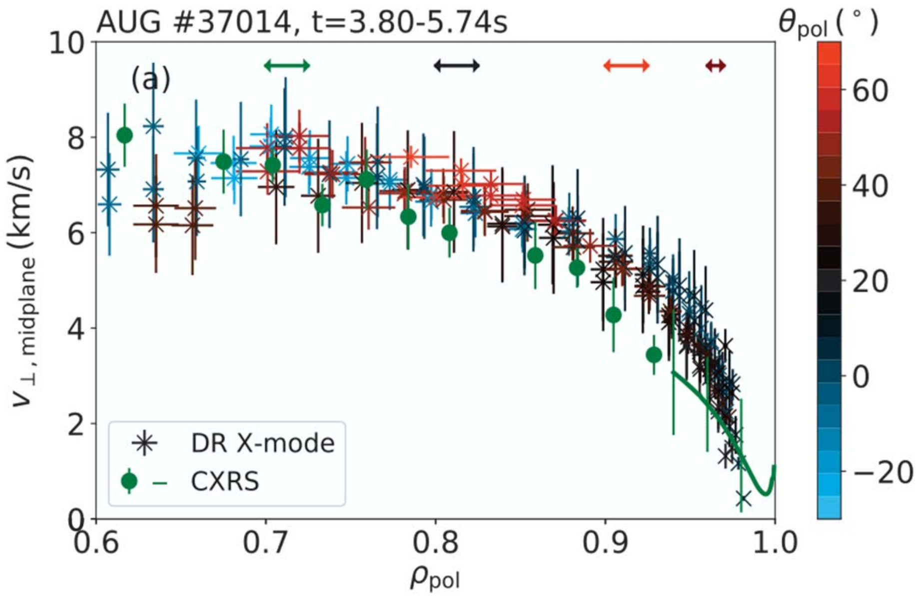
Comprehensive study of core turbulence characteristics

Experimental data to compare with global gyro-kinetic simulations (GENE)

- Density fluctuation *k* spectra
- Electron temperature fluctuation ω spectra
- Radial correlation lengths
- *n*-*T* cross phases
- Turbulent phase velocity
- Zonal flow structure …

Example: poloidal flow symmetry



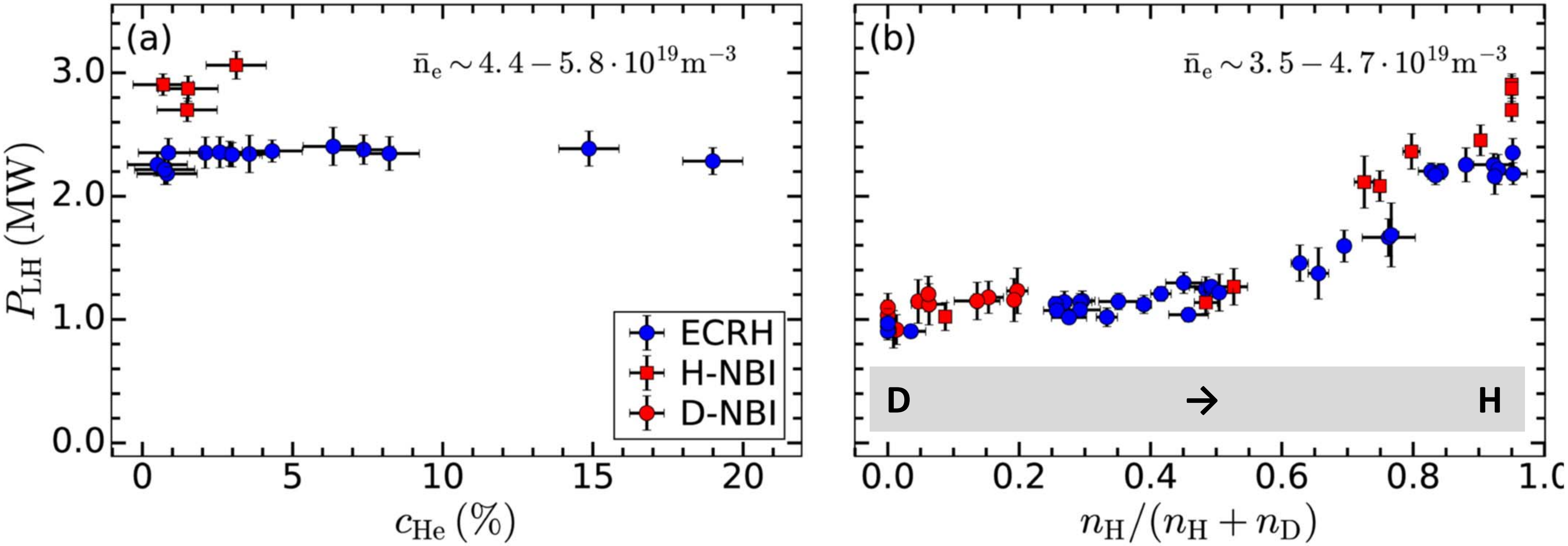


- Doppler reflectometer measures poloidally symmetric *ExB* flows
- Flows agree with CXRS measurements

[K. Höfler et al., NF 2021]

Isotope effect in the L-H power threshold

Important for ITER operation in H, He and D-T



- Small helium content in D plasmas doesn’t change H-mode power threshold
- Continuous increase of the power threshold with H concentration in D plasmas
- Different from JET results and consistent with the critical *ExB* shear criterion

[U. Plank et al., NF 2020 & Ph.D.]

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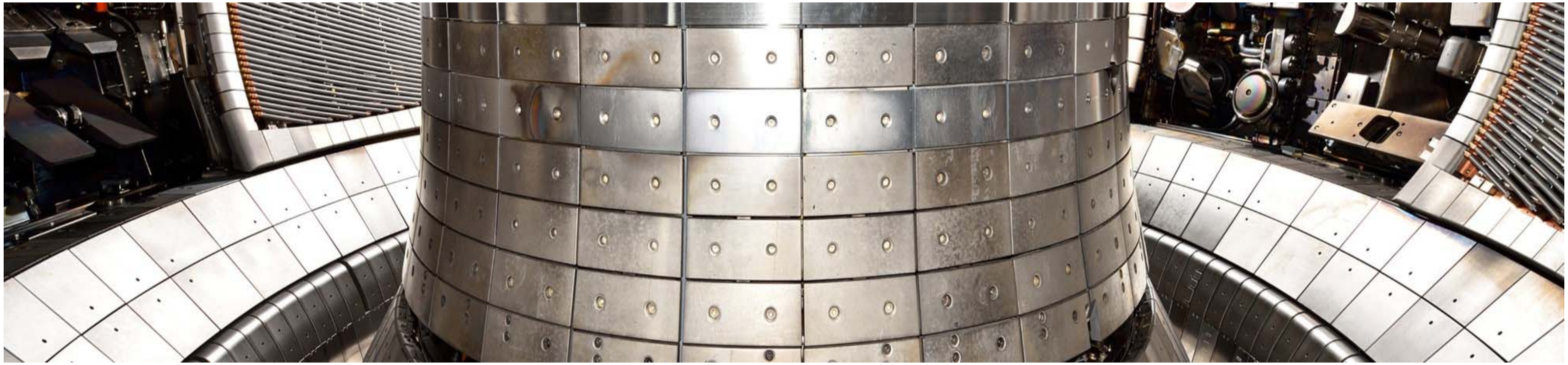
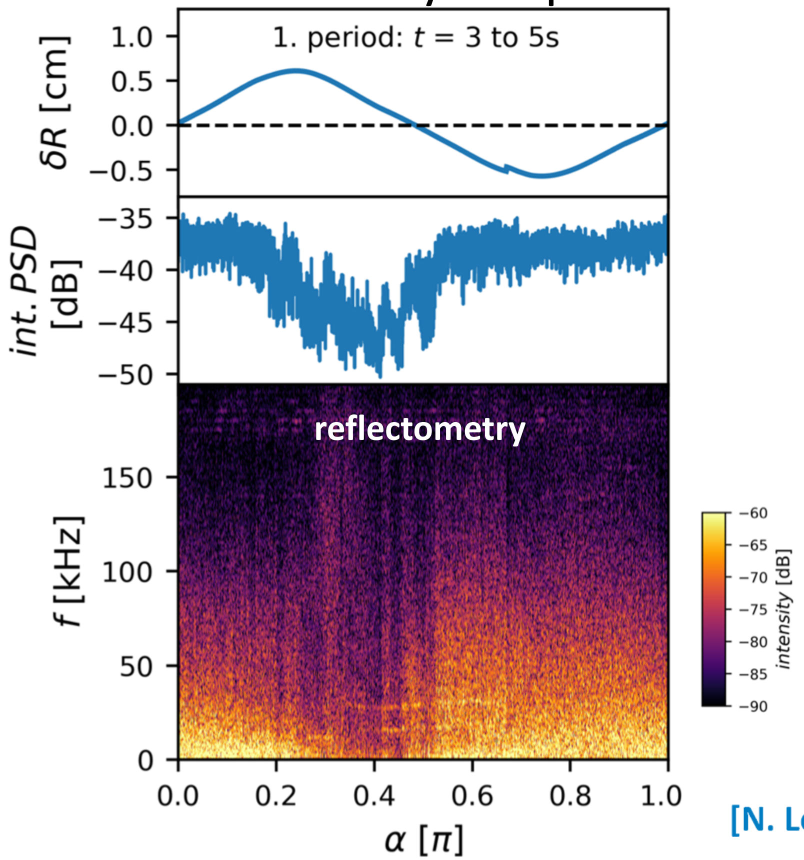


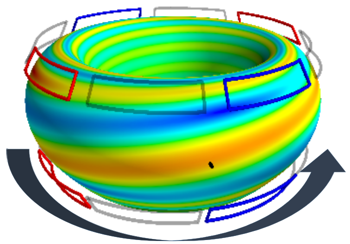
ELM suppression by RMP fields

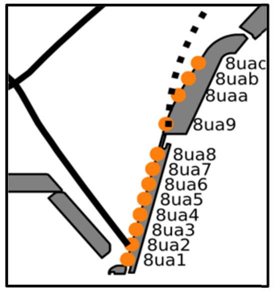
RMP field correlates with 3D pattern in turbulence and transport to the divertor

Reflectometry at midplane

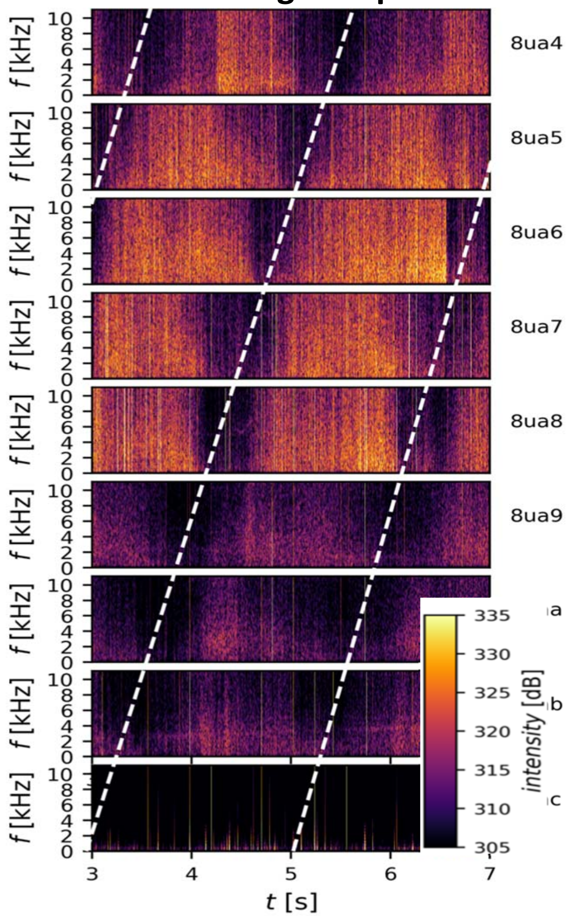


***n* = 2 perturbation**





Divertor Langmuir probes

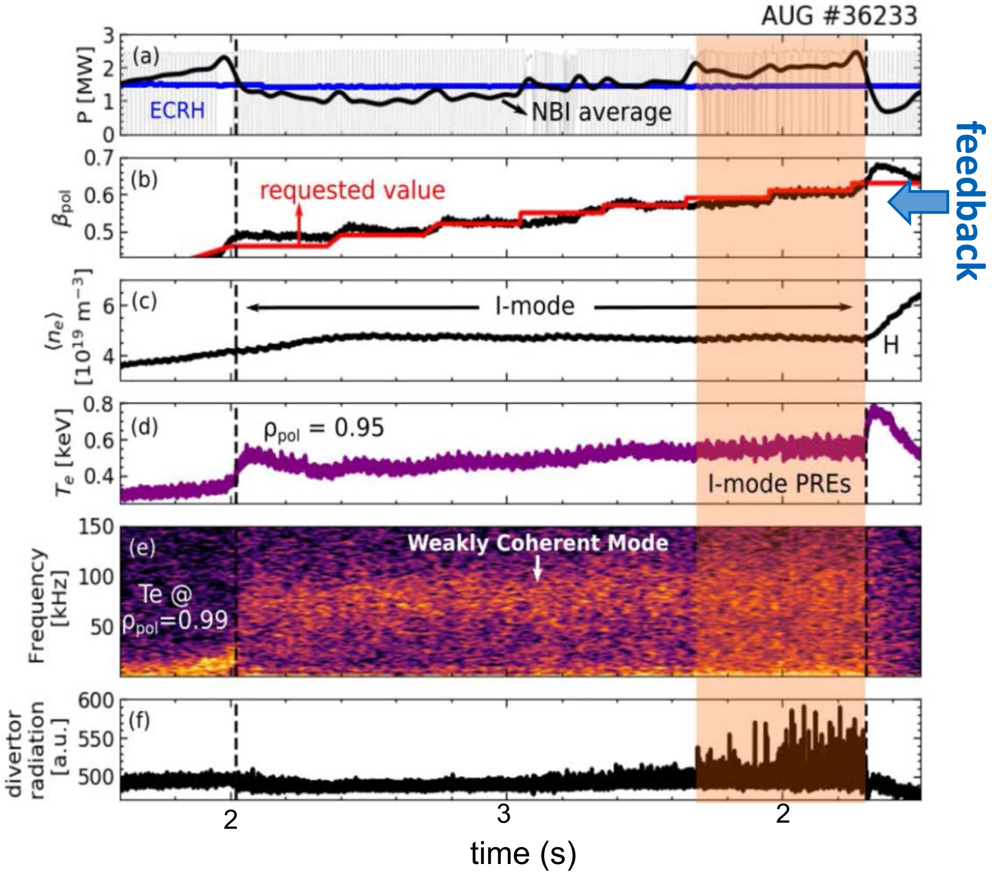


[N. Leuthold, Ph.D. thesis 2020]

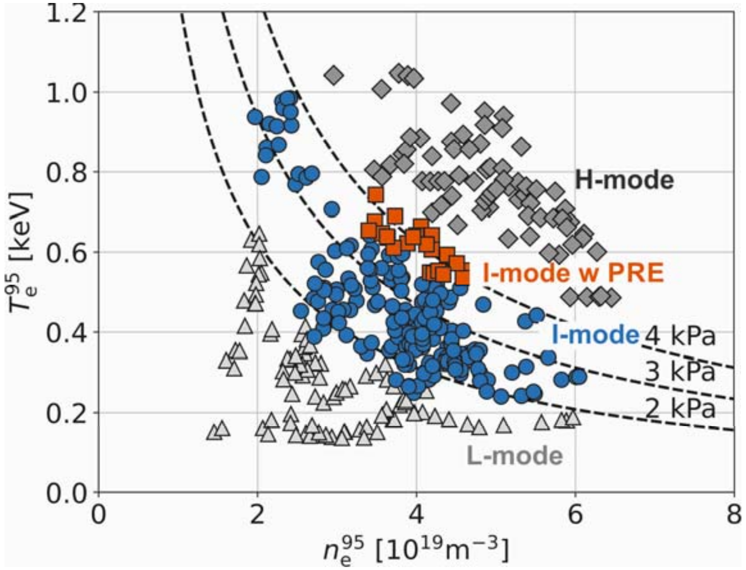
- Edge turbulence causes „density pump out“ which reduces edge density leading to peeling-ballooning stability
- RMP field induced island at pedestal top is not observed

I-mode: power window and detachment

β-feedback controlled NBI power ramp



- I-mode operational window is determined by edge pressure

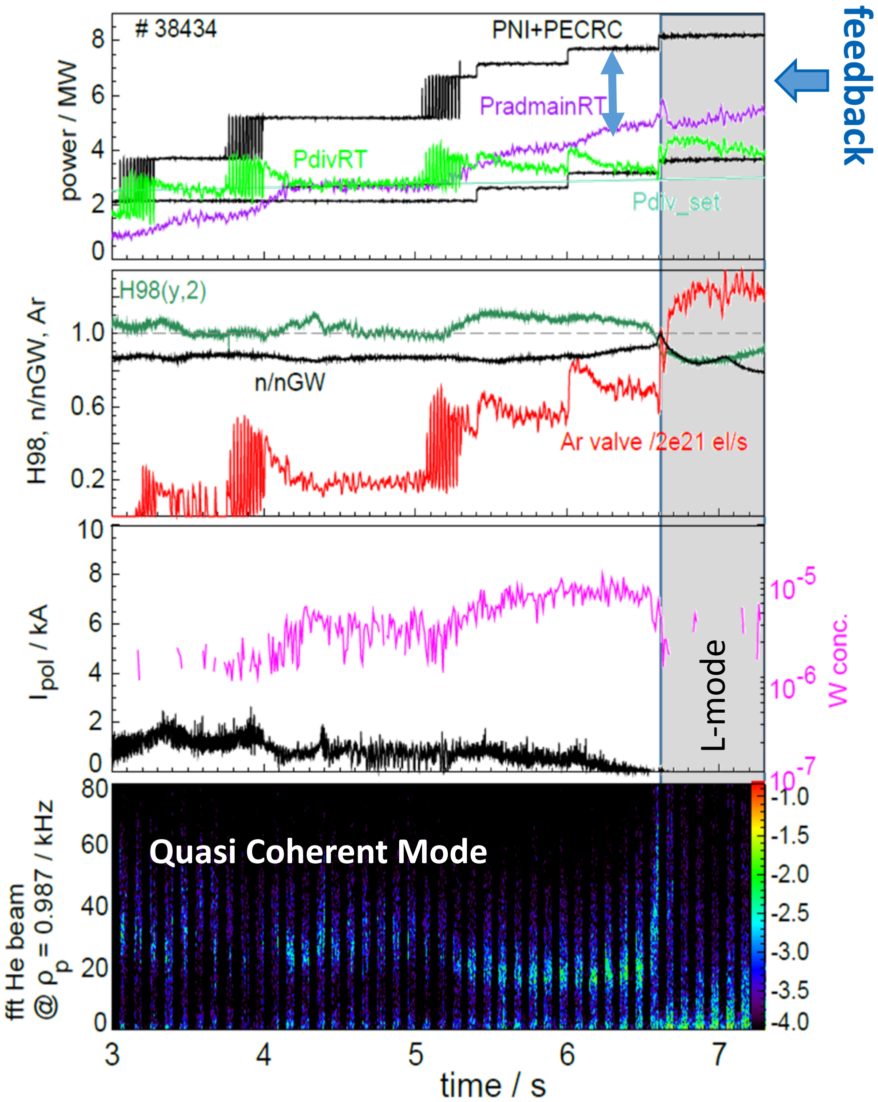


- Pedestal relaxations close to H-mode are harmful for the divertor
- N seeding detaches inner divertor
- Theoretical description **[P. Manz et al., NF 2020]**

Power window and detachment remain challenges

[D. Silvagni et al., NF 2020 & Ph.D., T. Happel et al., FEC 2018 & NF 2021]

EDA H-mode: extend power window by argon seeding



Discharge with full ELM suppression

- Stationary $H_{98} > 1$, $n/n_{GW} = 0.9$, $\beta_N = 2$
- Low tungsten concentration $< 10^{-5}$
- Edge transport by QCM
- N seeding effective for detachment

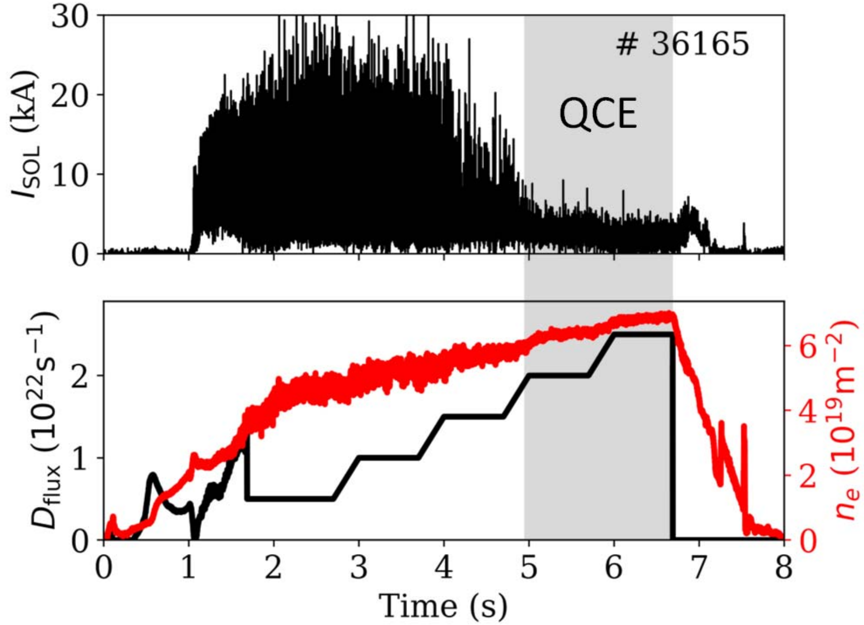
Power window and low q_s remain challenges

[L. Gil et al., NF 2020 & Ph.D, A. Kallenbach et al., NF 2020]

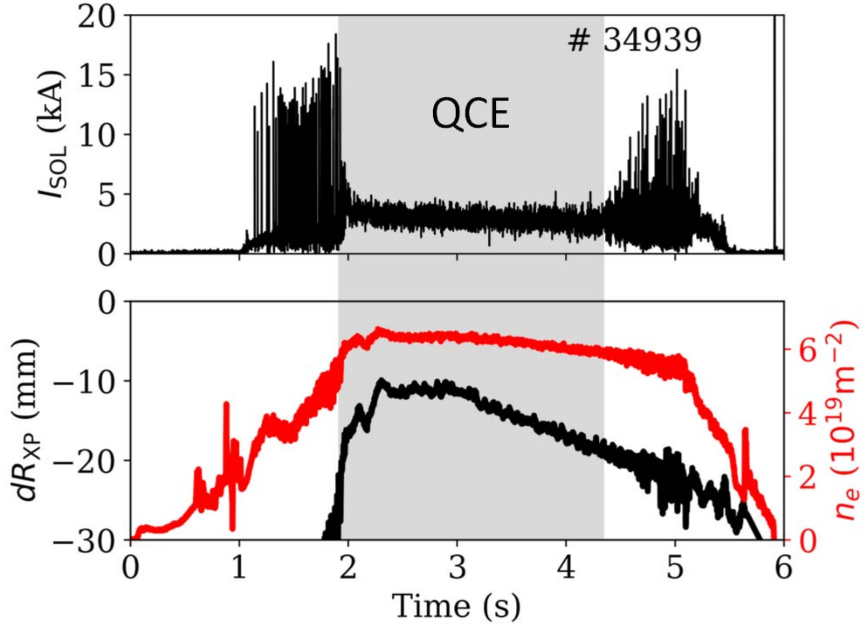
→ talk by A. Kallenbach

The QCE regime: key elements

Strong gas puff



Closeness to double null configuration

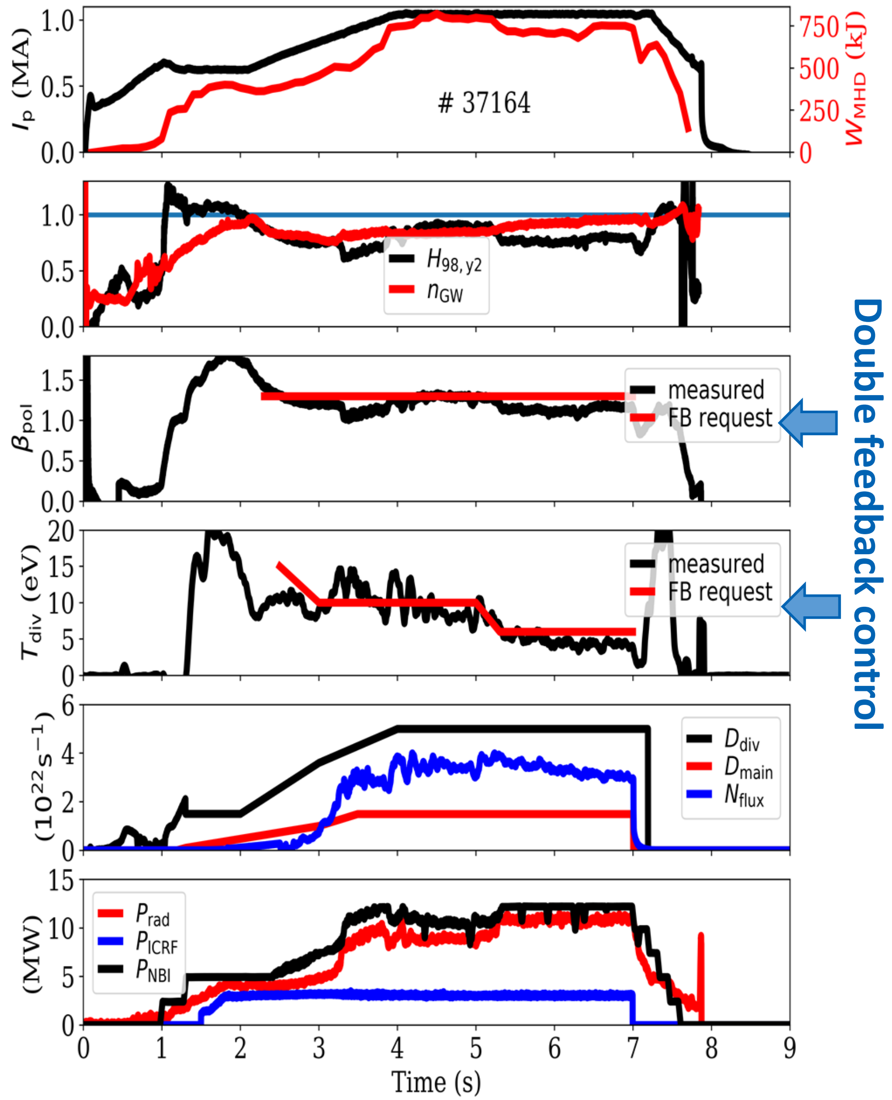


Stability calculations indicate

- Reduced high-*n* ballooning stability at $\rho \approx 0.99$
- Related transport changes pedestal and stabilizes peeling-ballooning mode

[G. Harrer et al., NF 2018, B. Labit et al., NF 2019]

QCE: high-power discharge without any large ELM



An integrated scenario at DEMO relevant separatrix parameters

- High power (15 MW), partially detached divertor, close to H-mode confinement
- Quasi continuous transport by small (type II) ELMs
- Power fall-off length 4 times larger than between ELMs in H-Mode

→ poster by M. Faitsch et al.

[M. Faitsch et al. NME 2020]

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- Naturally type-I ELM free discharges
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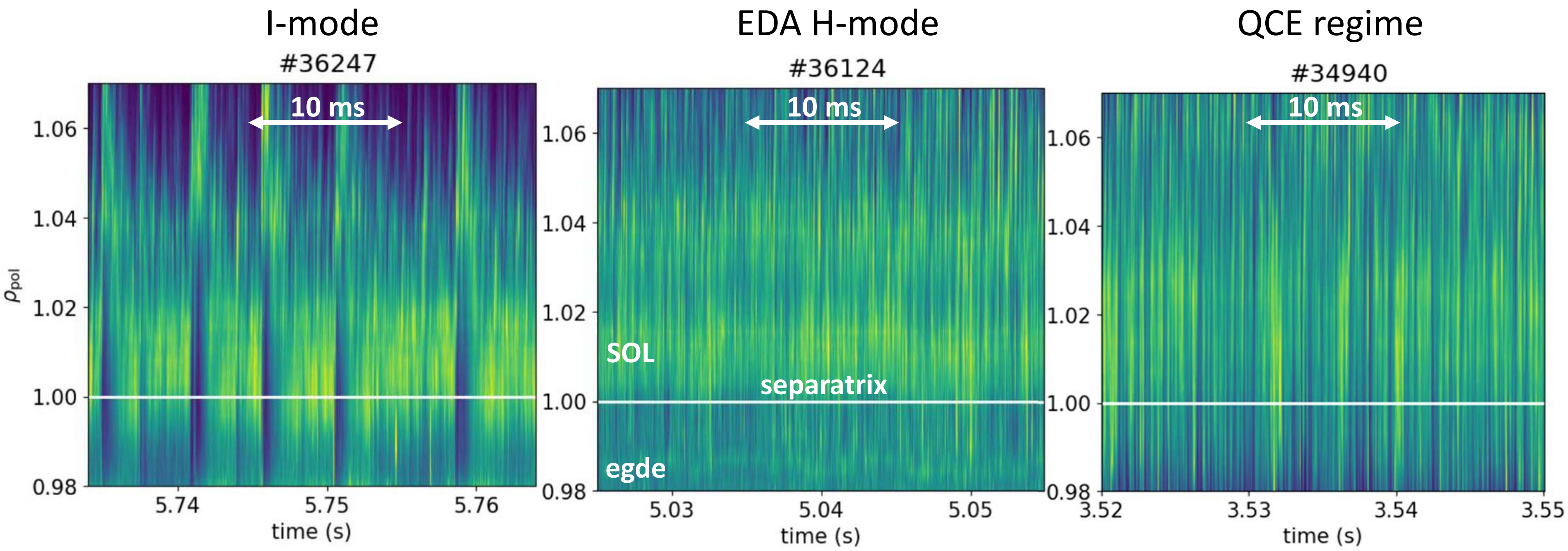
Modes close to the separatrix cause filamentary transport

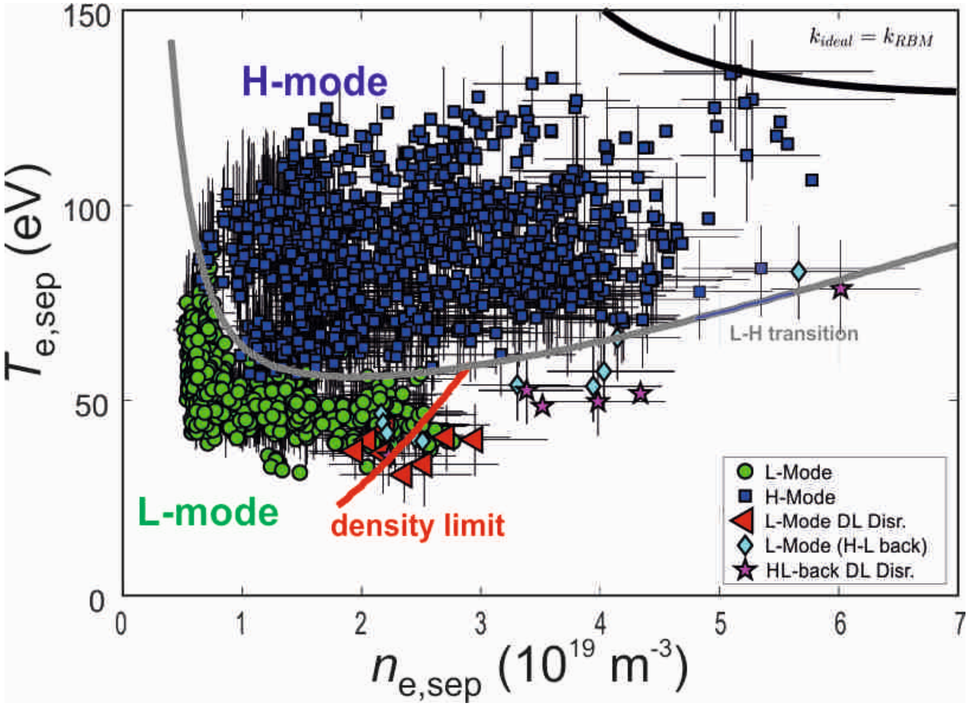
Edge density fluctuations from a new helium beam diagnostics



[M. Griener et al., PSI 2021, NME 2020]

Separatrix parameters set operational boundaries

Boundaries from interchange-drift-Alfvén turbulence without any free parameter



Boundaries for one specific configuration

- Density limit at transition from electrostatic to em resistive ballooning turbulence
- L-H transition: turbulence suppression by neoclassical ExB flow shear

[T. Eich & P. Manz, NF subm.]

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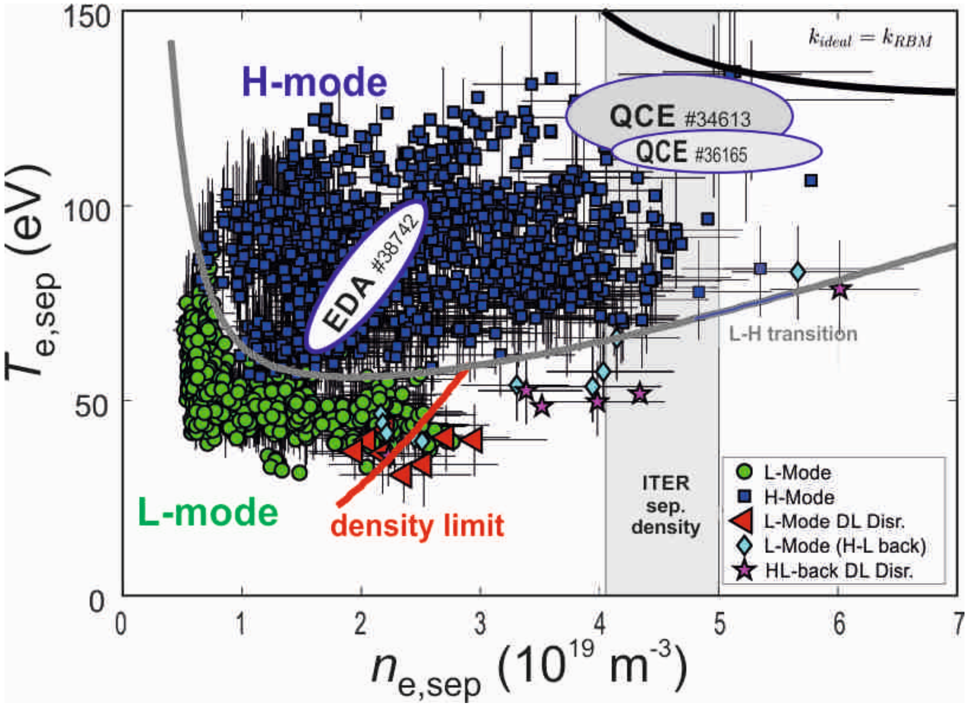

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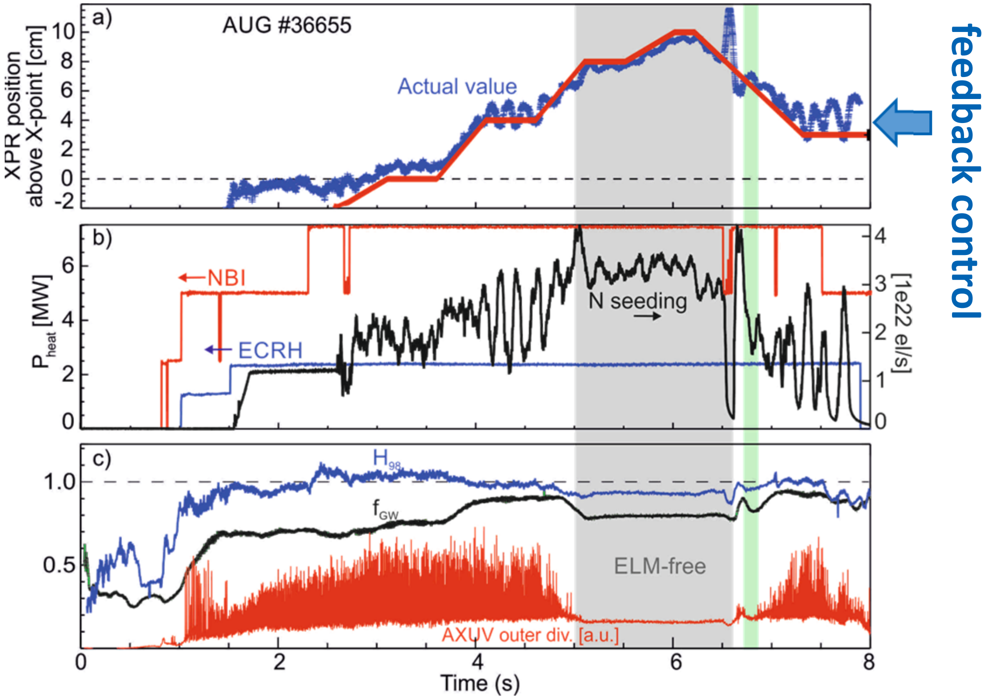
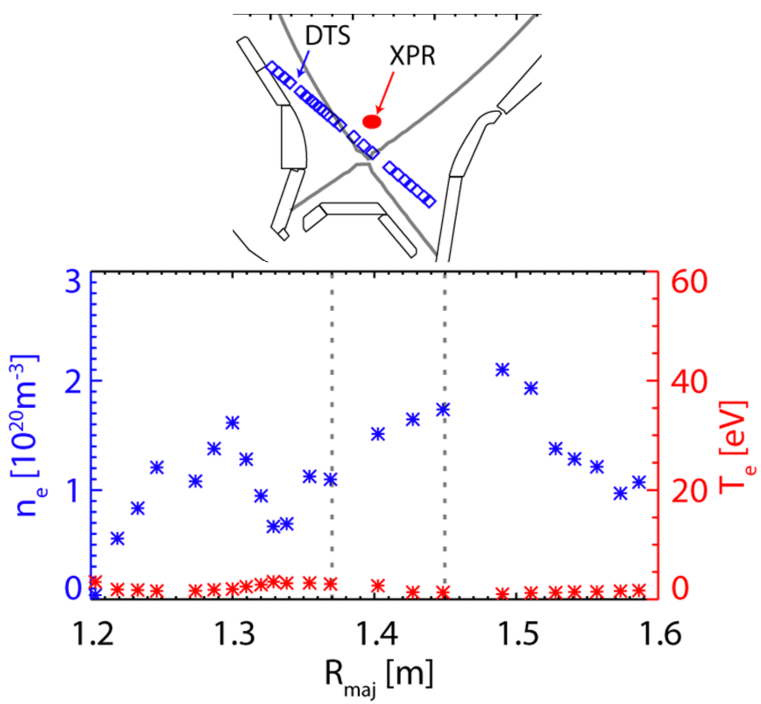
Stable and controlled X-point radiator (XPR)

Dense, cold, and strongly radiating plasma above the X-point on AUG and JET





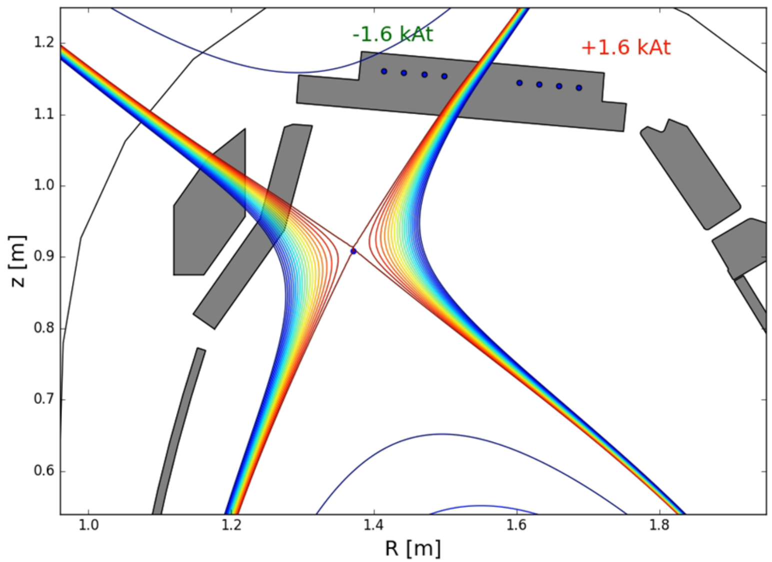
- ELM-free phase: 90 % radiative fraction; f_{GW} = 0.8; H_{98} = 0.95
- Potential for detachment control and marfe avoidance

→ talk by M. Bernert

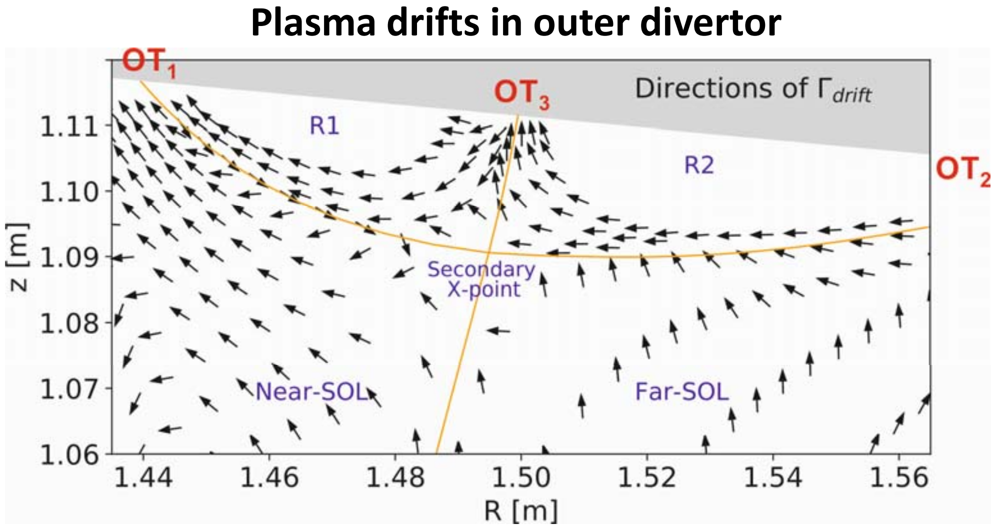
[M. Bernert, NME 2017, S. Glöggler, NF 2020]

New upper divertor will be installed in 2022/23

Allows for continuum of configurations between single null and snow-flake



Plasma drifts in outer divertor



First SOLPS-ITER simulations including drifts of a snowflake divertor plasma

- Increased flux expansion facilitates detachment with nitrogen seeding
- Drifts bring power to additional strike point and increase power on primary strike point

[T. Lunt et al., NME 2019]

[Ou Pan et al., PPCF 2018 & 2020]

Summary

- Progress in physics understanding core and edge transport for improved modelling of future tokamak plasmas
- Importance of fast particles for turbulent core transport
- Integrated scenarios for naturally ELM-free plasmas. The QCE regime is a promising candidate, combining high power, high confinement, high density with detachment
- Plasma parameters close to the separatrix play key role for the operational space and the access to small-ELM regimes
- Studies on AUG will be extended to alternative divertor configurations in 2023

Thanks to the AUG and MST1 teams and all external collaborators