Tokamak Energy

Observation of Bifurcated Scrape-off-Layer Power Drop-off Width in the ST40 High Field Spherical Tokamak

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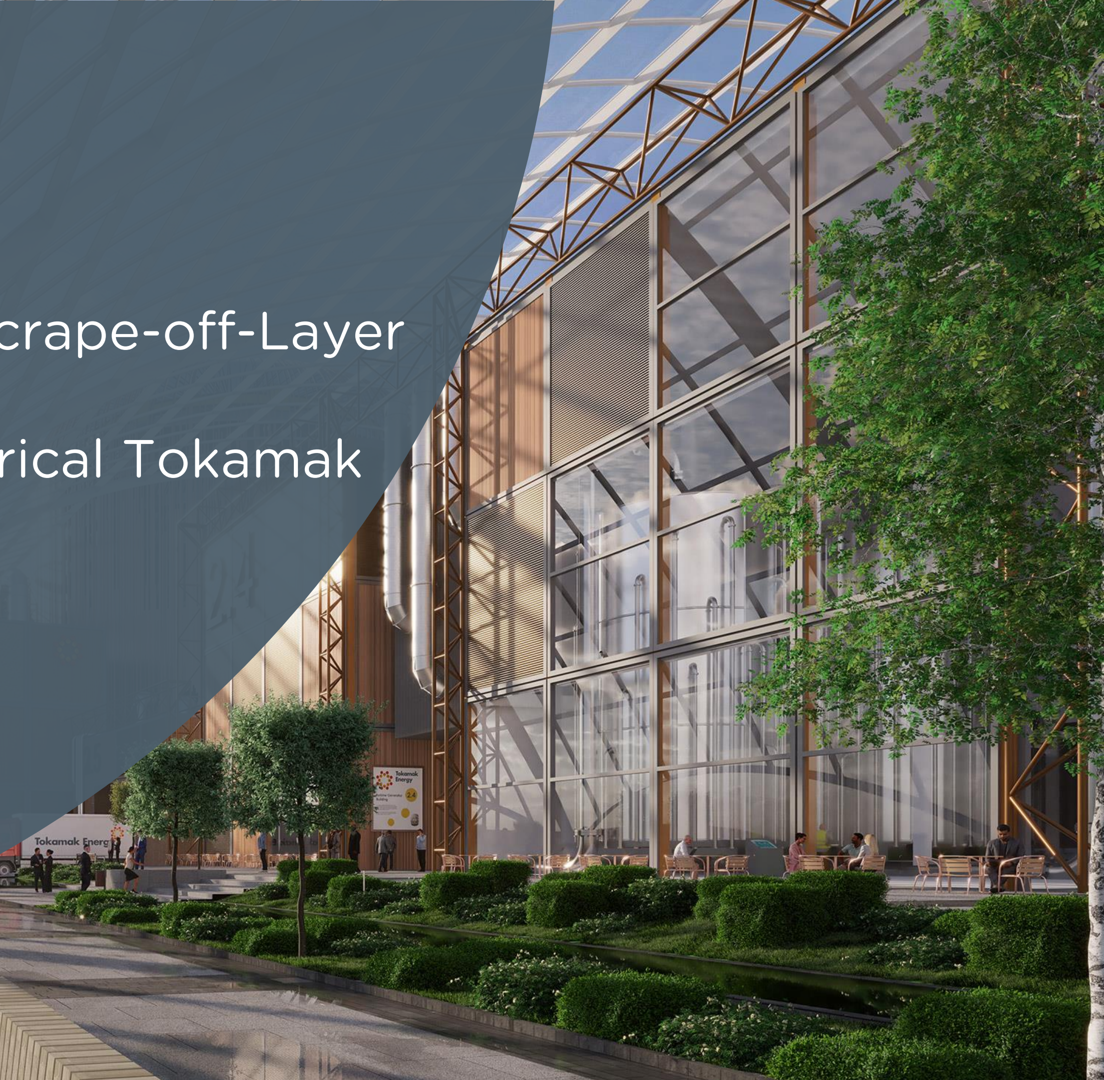
on behalf of the ST40 Team

April 2024



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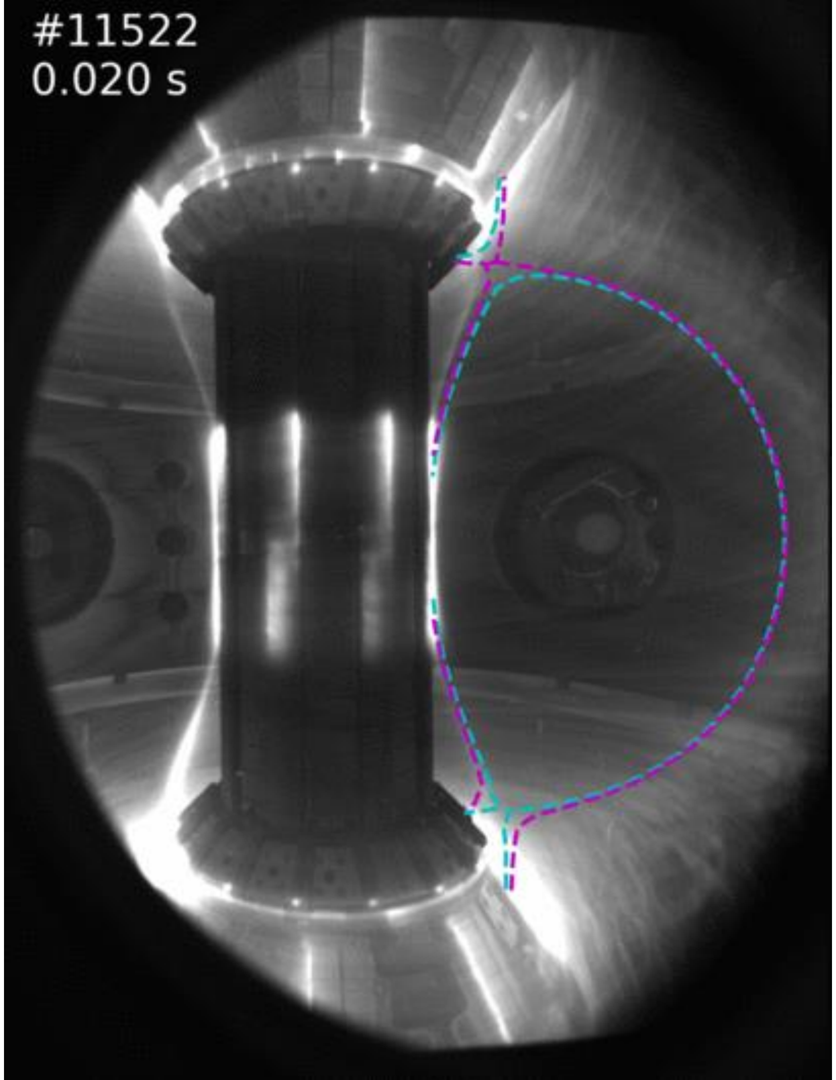
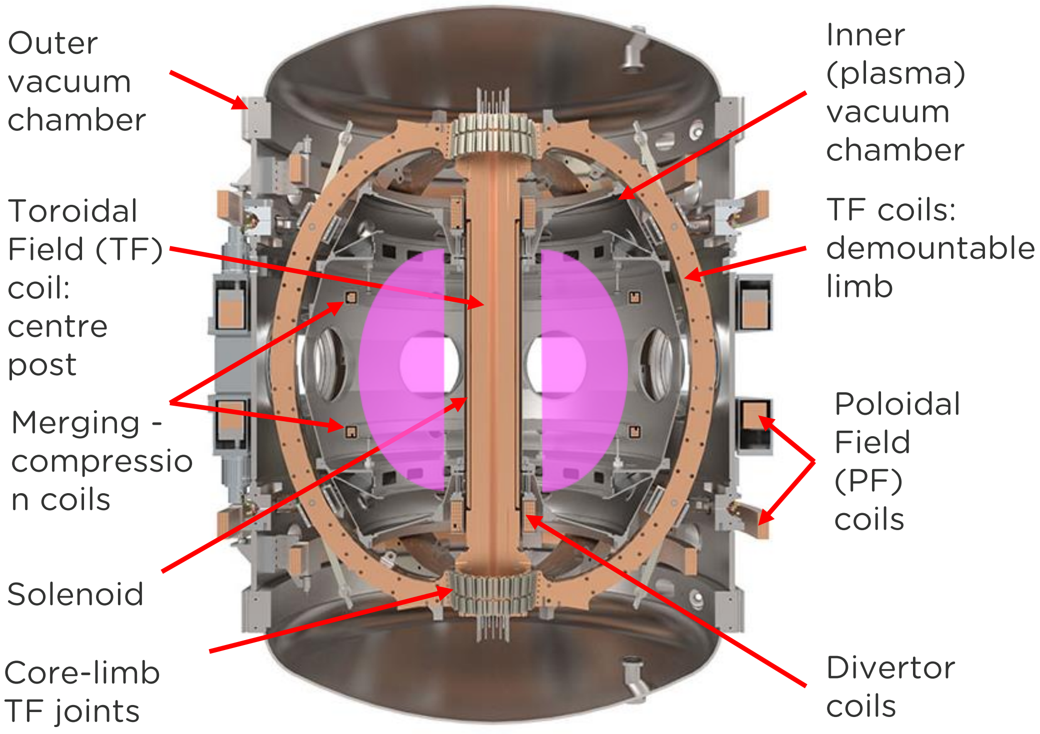
Part 1

ST40 Diverted plasma and divertor diagnostics



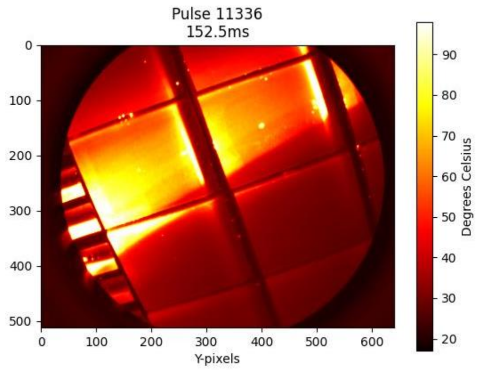
ST40: Expanding the high field ST physics basis

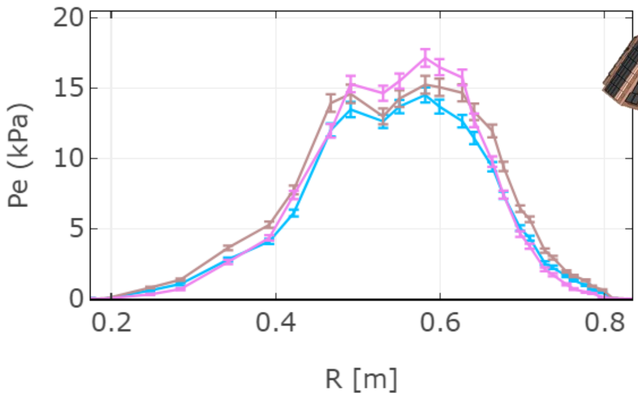


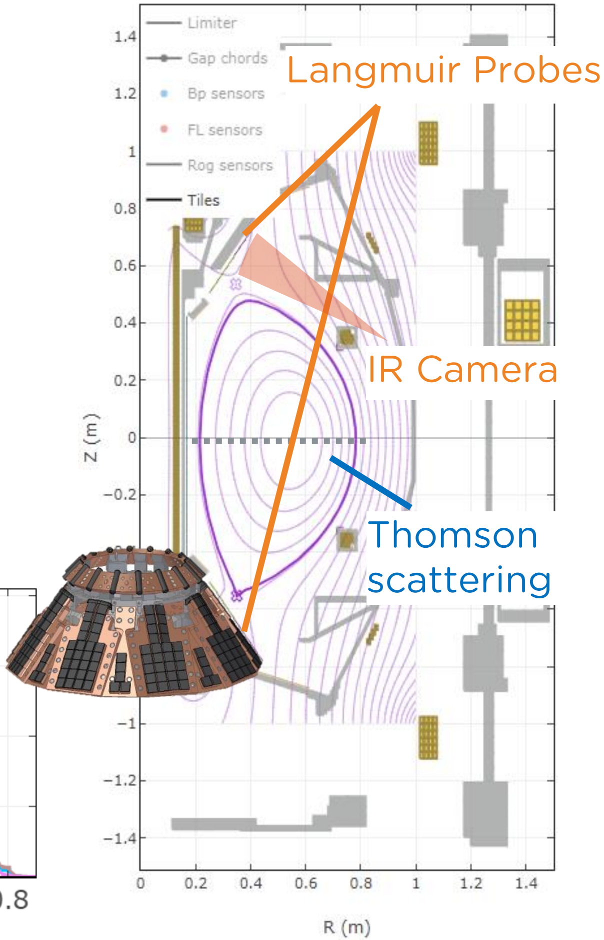
Parameter	Range
Bt [T]	0.9 – 2.1.
Ip [MA]	0.3 – 0.8
R_{Geo} [cm]	40 – 50
A	1.6 – 1.9
P_{NB}/E_{NB} [MW/kV]	0.8/24, 1.0/55
Ip flattop [ms]	~150
Start-up	Merging-compression

ST40 achieved diverted configuration in 2023

- IR camera viewing upper divertor, LP at upper and lower
  - NEW! Divertor T_e and n_e measured!
- IR thermography analysis commissioned
  - NEW! Divertor heat flux footprint measured!
- New! Thomson scattering up and running!



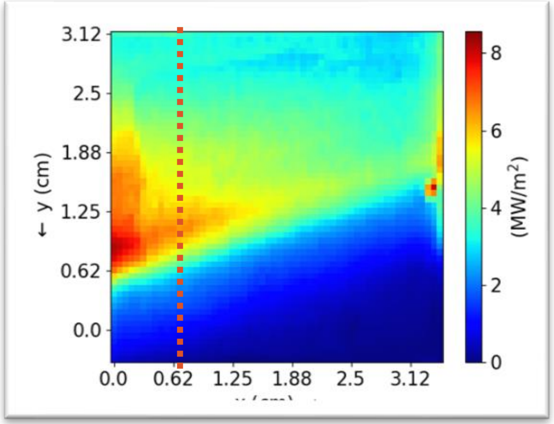




IR thermography computes parallel heat flux from target temperature

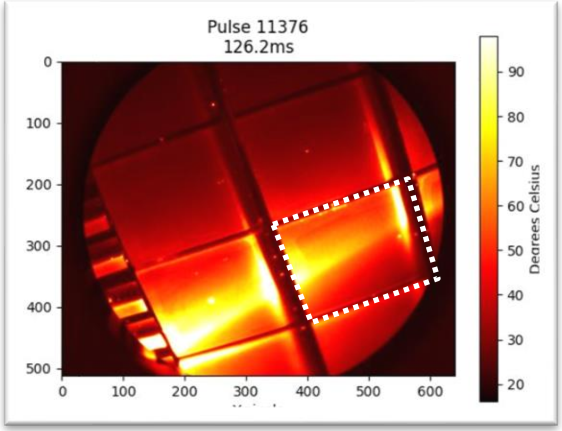
FAHF
Camera angle calibration, 2D/3D thermographic inversion

Surface heat flux

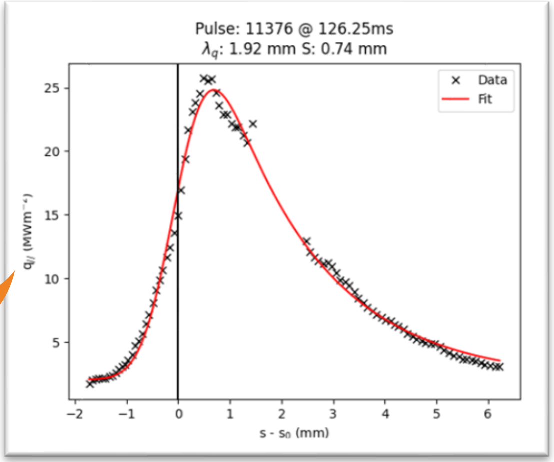


IRRITANT
Fully 3D field-line mapping, non-linear curve fit

Temperature



Parallel heat flux



ST40 λ_q Database

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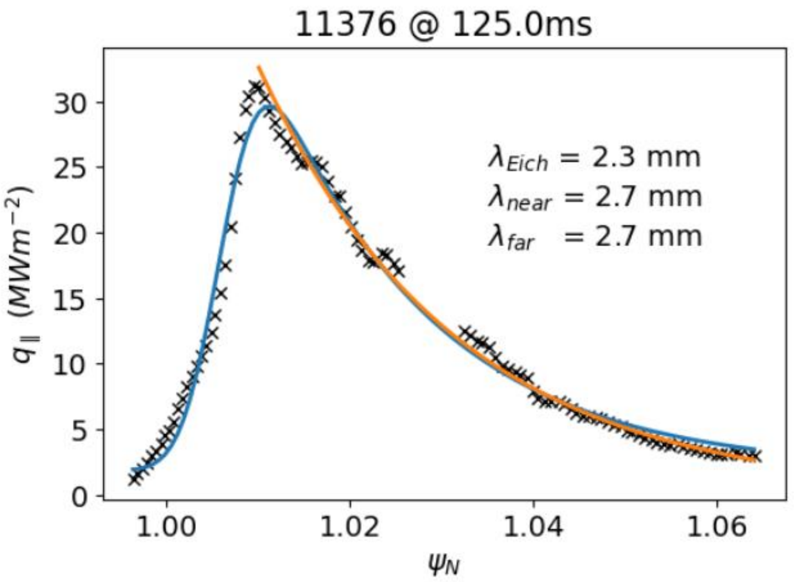
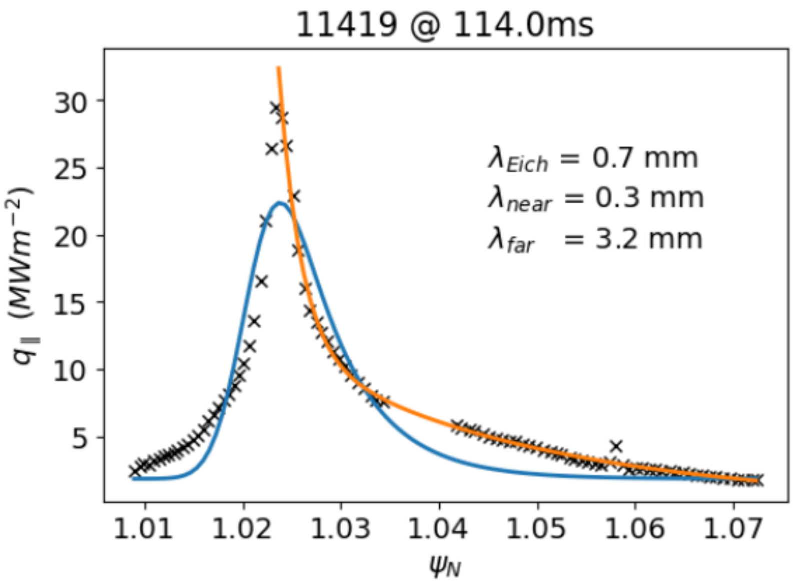
Data analysis and the ST40 scrape-off layer width database

We observe two types of heat flux profiles on the target



'Eich profile'

A single exponential decay from the core into the SOL, convoluted with a Gaussian to account for transport into the PFR

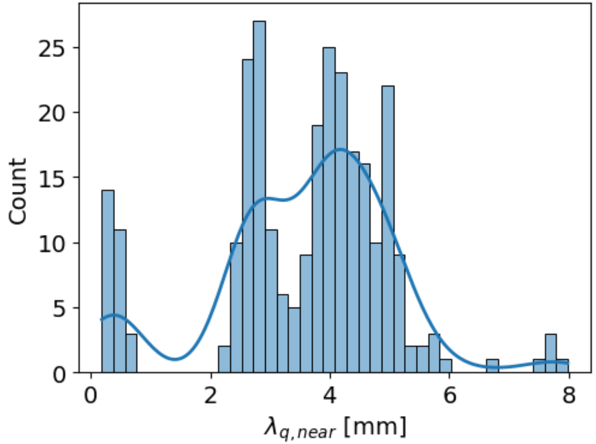


'Brunner profile'

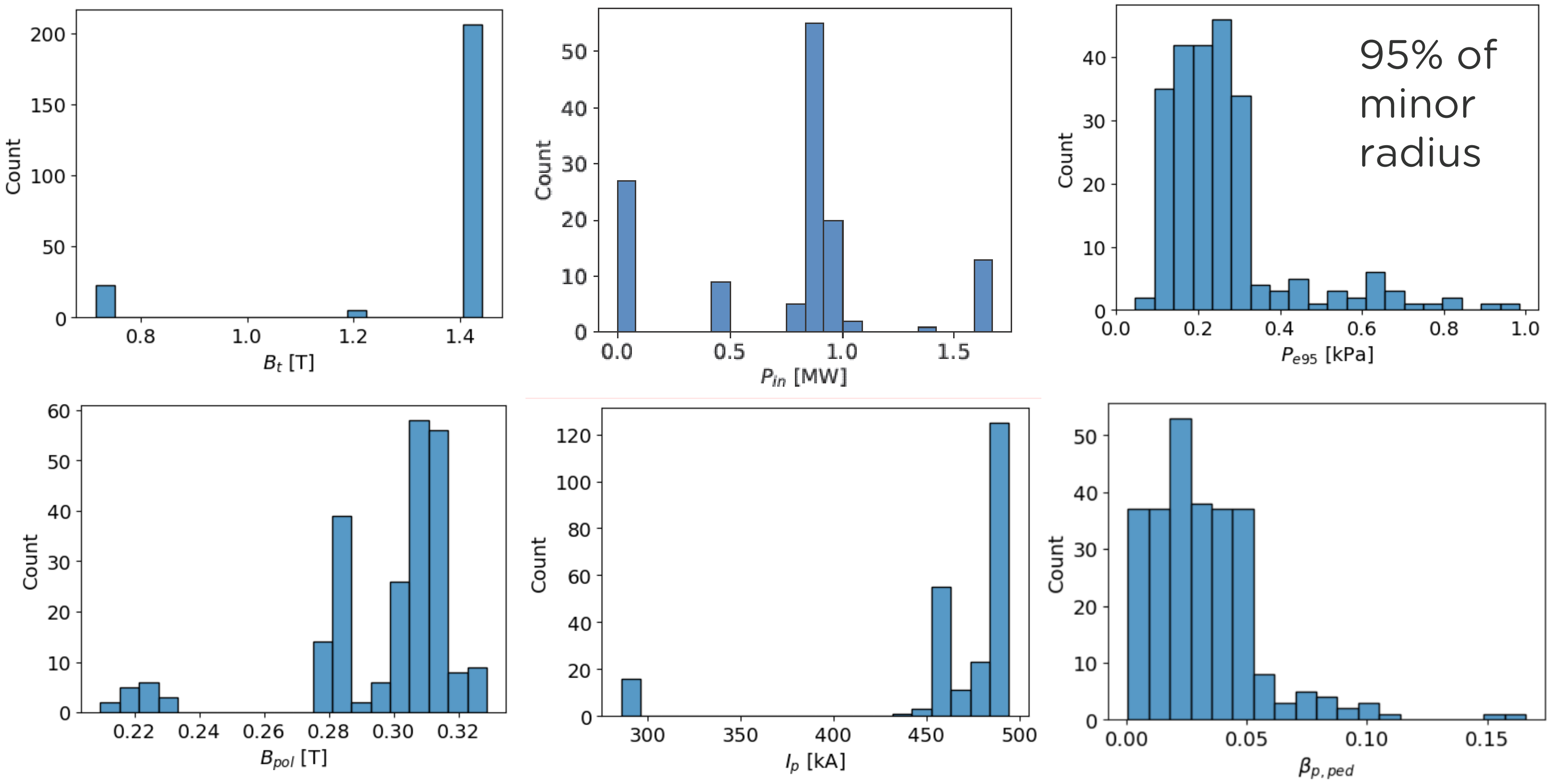
Two exponential decays in the CFR, describing different transport properties in the near and far SOL

The ST40 scrape-off-width database – Selection Criterion

- All diverted plasmas with IR images available processed (284 shots)
- Analysis performed only when EFIT strike point is in view of the IR camera (90 shots)
- Individual frames selected for data quality and plasma condition
  - No saturation occurs on the 'observation chord'
  - Steady plasma - current is within 10% of flat top, time padding after beam turn on
  - At least 3 consecutive frames is available for the shot
  - Thomson Scattering measurements available at nearby times
  - Goodness of fit - $R^2 > 0.95$
- 42 shots, 375 profiles remain (descriptions follow).
  - 28 Brunner profiles (8%), 347 Eich profiles (92%)

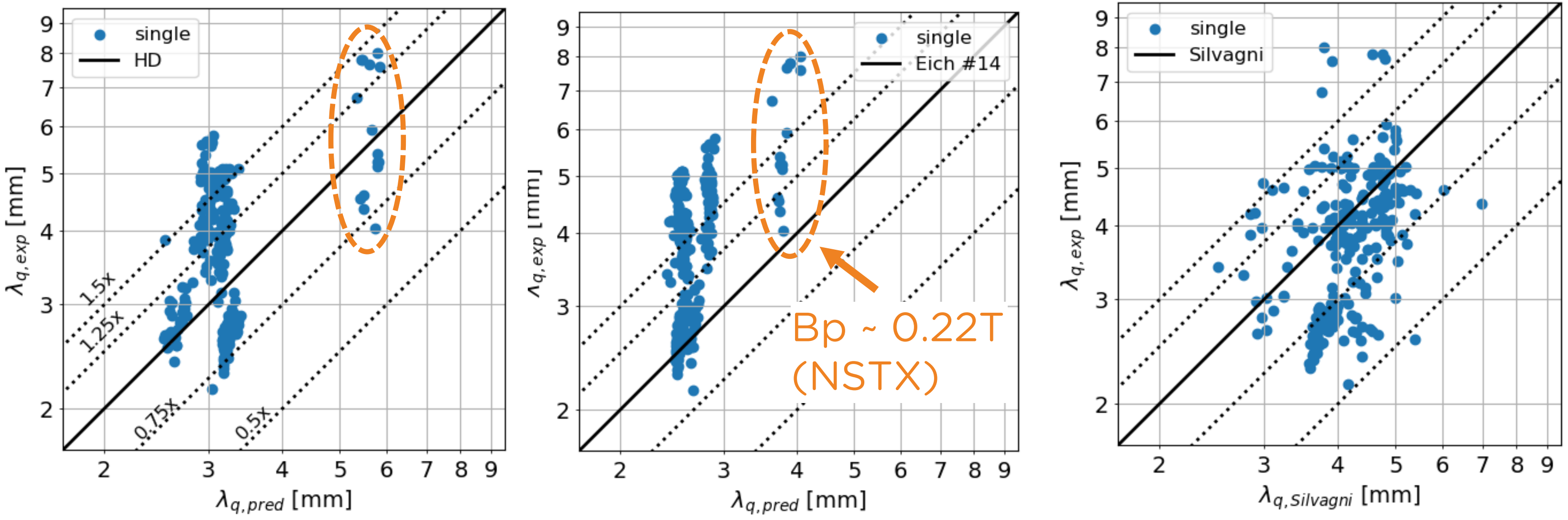


Database covers a wide range of plasmas and engineering parameters



Single exponential (Eich profiles) group loosely follow existing scalings

- ST40 L-mode plasmas, *good* confinement (h~1), no type-I ELMS
- Scaling with Bp is strong, as predicted by Eich #14 / HD model
- Scaling with edge pressure p_e appears weaker



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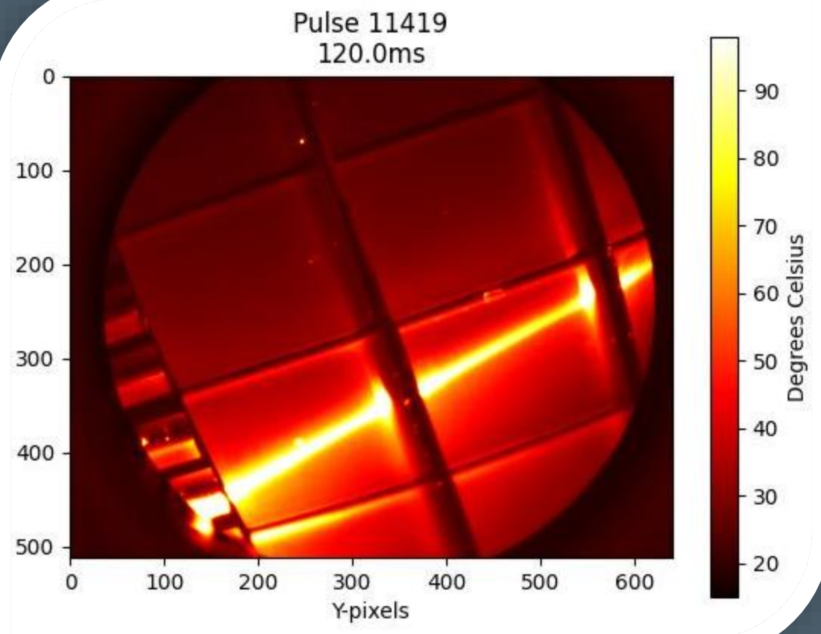
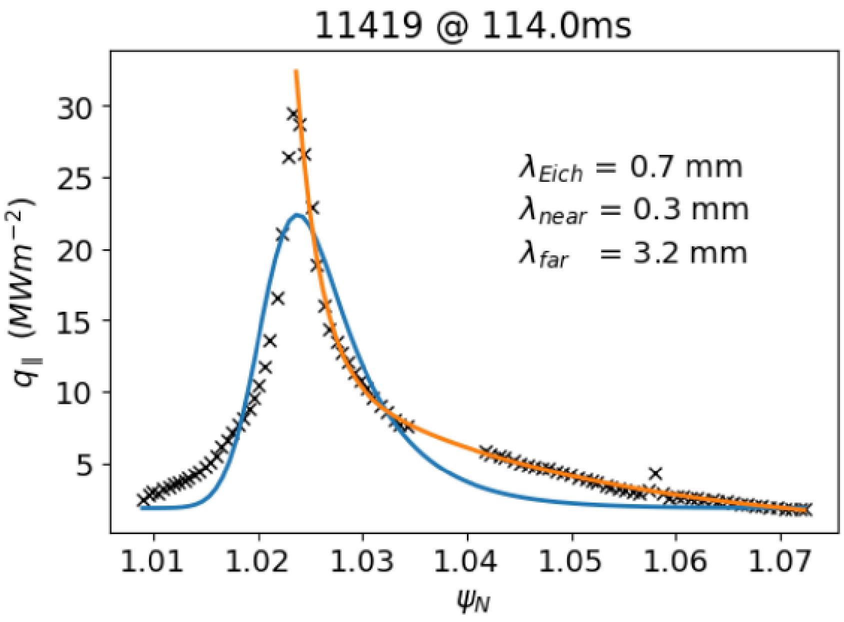
Onset of very narrow power drop-off width at the near SOL



Brunner-like double exponential profiles are seen clearly

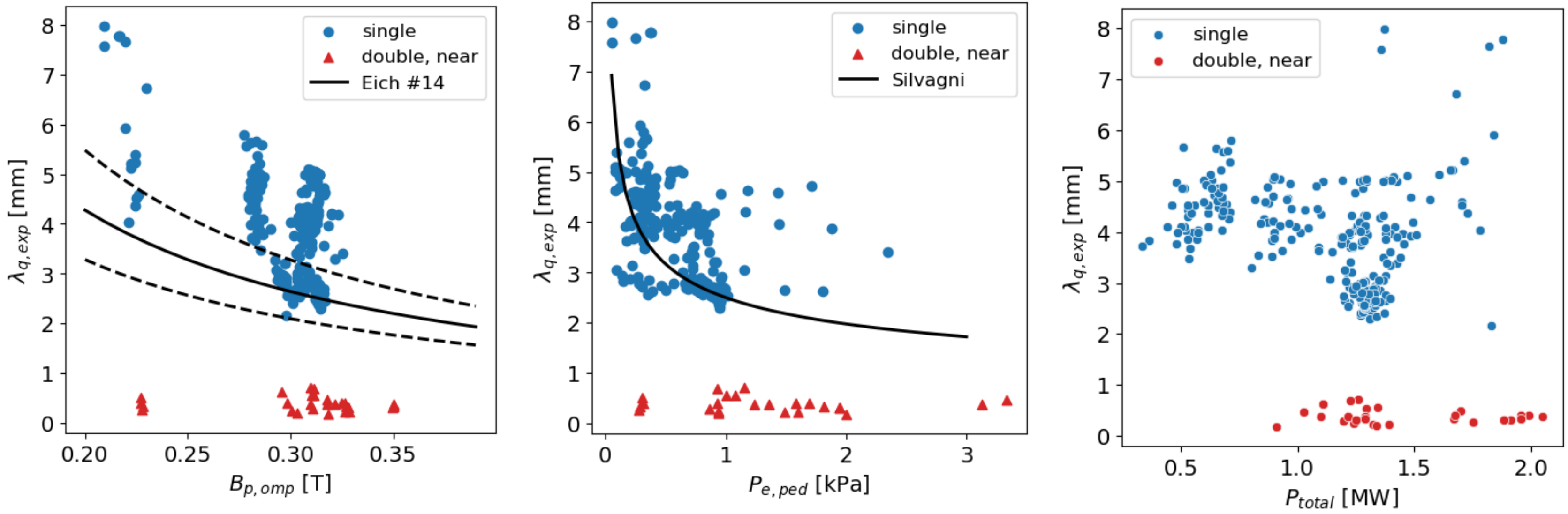
- In a minority of the dataset, Eich fits fail to find satisfactory results (9 shots, 28 profiles)
  - Clear distinctions between near and far SOL
- Double exponential fit was introduced* for near and far SOL with different transport
  - The near SOL widths were then used to compare with other devices
  - Similar profiles subsequently published for JET, COMPASS, …
- Brunner fits converge well for our dataset when Eich fails



* D. Brunner, B. LaBombard, A. Kuang, and J. Terry, High-resolution heat flux width measurements at reactor-level magnetic fields and observation of a unified width scaling across confinement regimes in the alcator c-mod tokamak, Nuclear Fusion **58**, 094002 (2018).

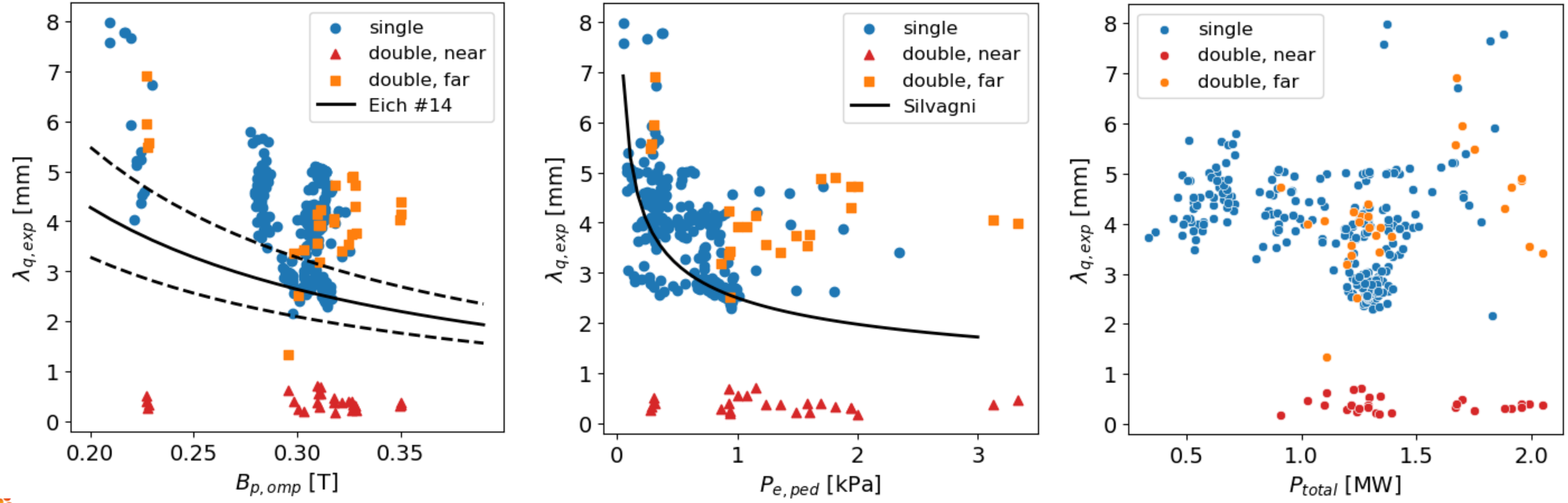
Very narrow near SOL widths are observed, up to 10x below scaling

- Onset of narrow width has no clear correlation with Bp, Pe, Bt, etc.
- Only observed for beam heated plasmas
  - Available data is limited for plasmas with 2 beams (IR camera saturation)
  - More likely to occur at high beam power? (NSTX saw steep step down at threshold input power)



Far SOL width of Brunner profiles close to scaling predictions

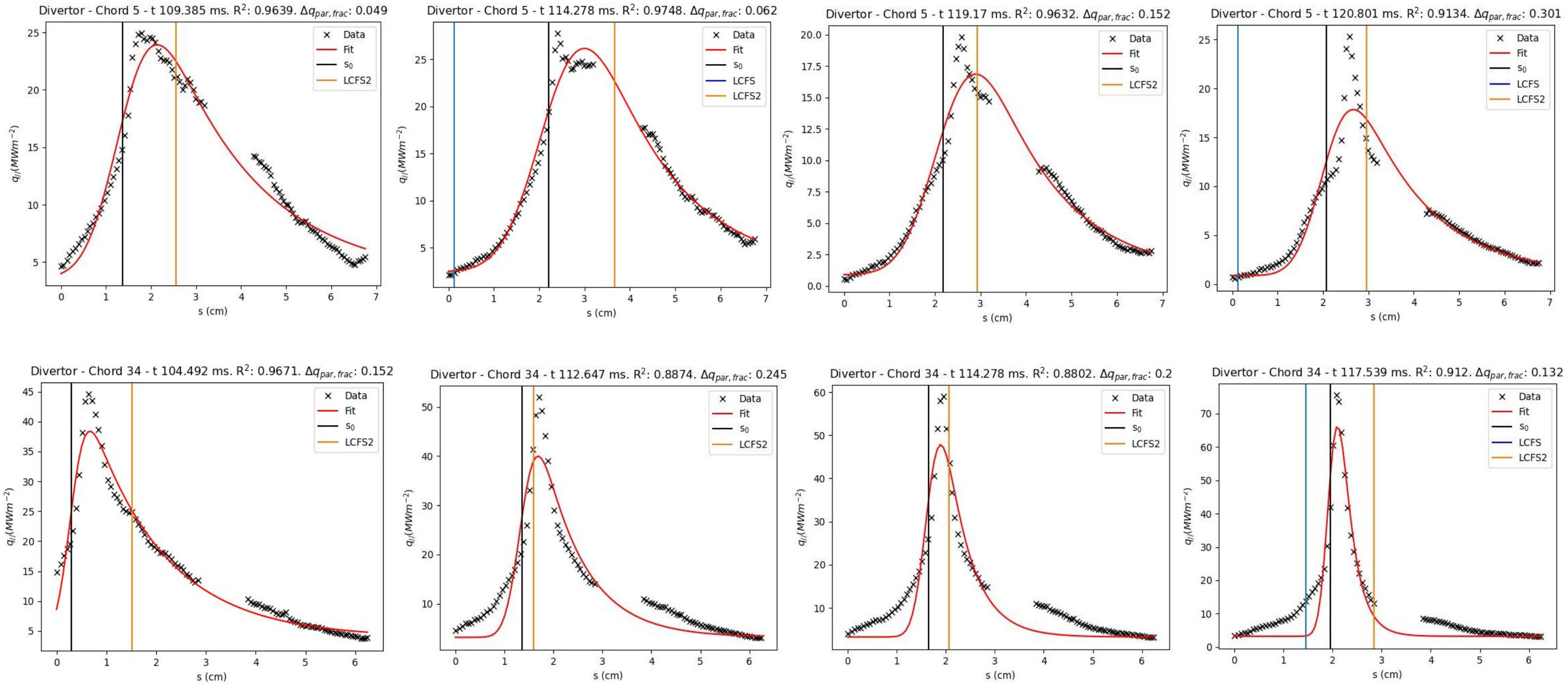
- When near SOL width is narrow (< 1 mm), far SOL width is found to be close to poloidal Larmor radius / ion drift orbit (banana) size
- Far SOL widths smoothly connect with the wide branch, with a *slight* upwards trend.
- Suggests the onset of a distinct transport region very close to the separatrix, while the ion drift orbit driven transport remained constant



Dynamical behaviour – emergence of the narrow peak

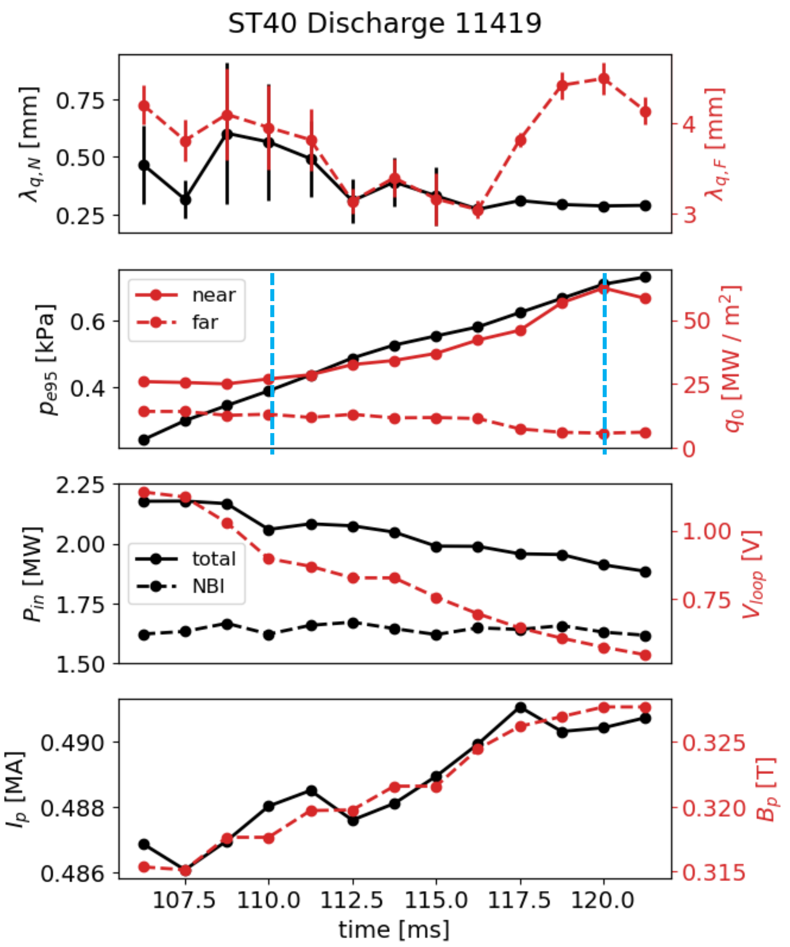
ST40 11336

ST40 11419



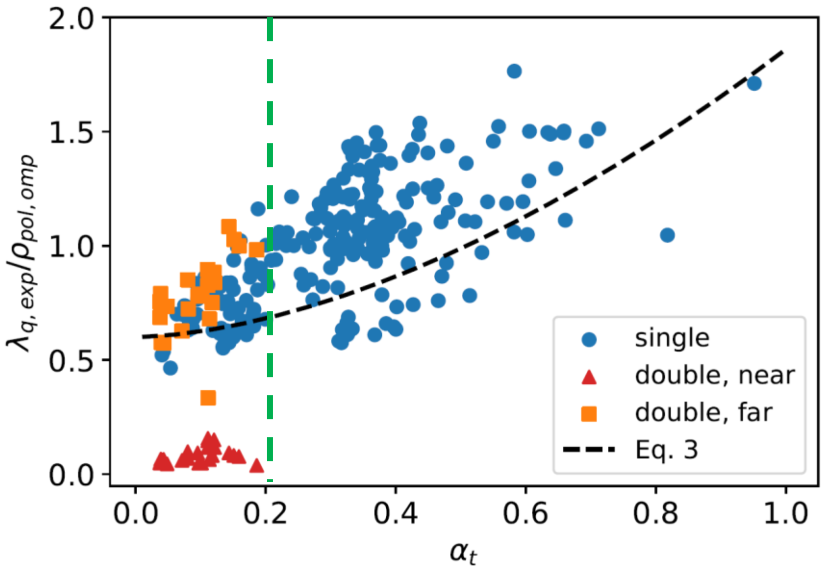
Dynamical behaviour - 11419

- 16 ms, 13 continuous IR profiles with good quality data and Brunner fit
- TS pressure measurement at 110 ms and 120 ms; interpolated linearly in between.
- NBI power constant (RFX turns on at 100 ms)
- Total power *decreasing* because of V_{loop}
- Dual channels observed during the entire time window, with $\lambda_{q,N} \approx 0.4\ mm, \lambda_{q,F} \approx 3.5\ mm.$
- Both widths trend down with increasing pressure and B_p until 116 ms, consistent with scaling (1% change in I_p, 4% change in B_p)
- Spike in peak heat flux correlated with the widening of $\lambda_{q,F}$ and reduced power into the far channel



Wide branch follows scaling, with bifurcation occuring at low α_t

- The wide branch folloes ASDEX λ_T regression, with assumed Spitzer-Harm conductivity
- Wide branch asymptotes to ion drift orbit width at turbulence control parameter α_t
- Narrow branch onset at low α_t -> hinting at correlation with reduced turbulence levels



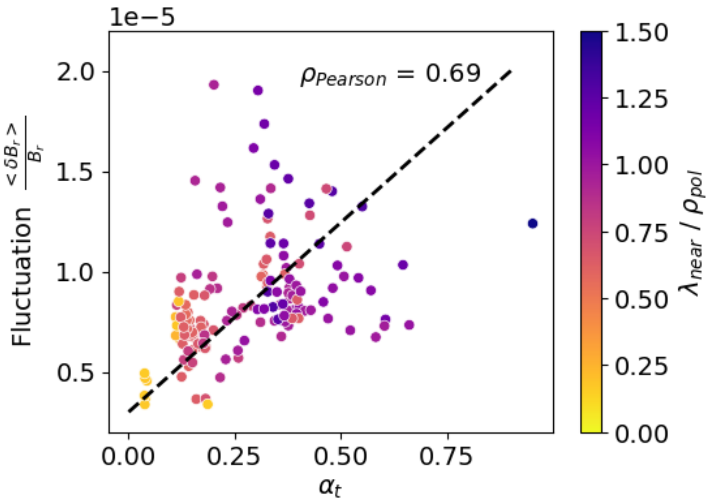
$$\alpha_t \equiv C\omega_B = 1.02 \frac{\nu_{ei}}{c_s} \frac{m_e}{M_i} \hat{q}_{cyl}^2 R \cdot \left(1 + \frac{1}{\bar{Z}}\right)$$

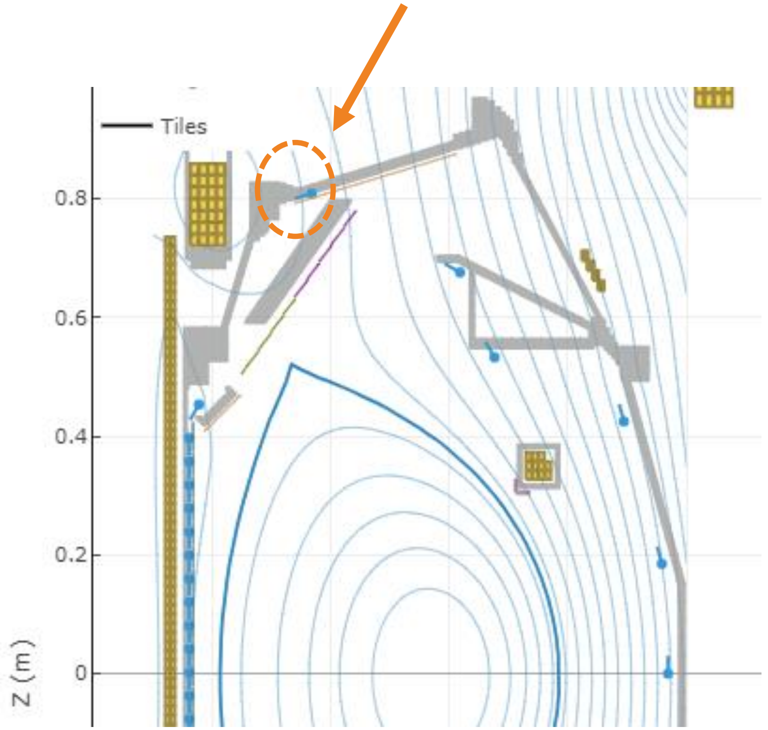
$$\frac{\lambda_q}{\rho_{pol}} = \frac{2}{7} \frac{\lambda_{T_e}}{\rho_{pol}} = 0.6(1 + 2.1\alpha_t^{1.7}). \qquad (3)$$

T. Eich, P. Manz, R. Goldston, P. Hennequin, P. David, M. Faitsch, B. Kurzan, B. Sieglin, E. Wolfrum, A. U. Team, *et al.*, Turbulence driven widening of the near-sol power width in asdex upgrade h-mode discharges, Nuclear Fusion **60**, 056016 (2020).

Fluctuation characterization with fast Bp probes

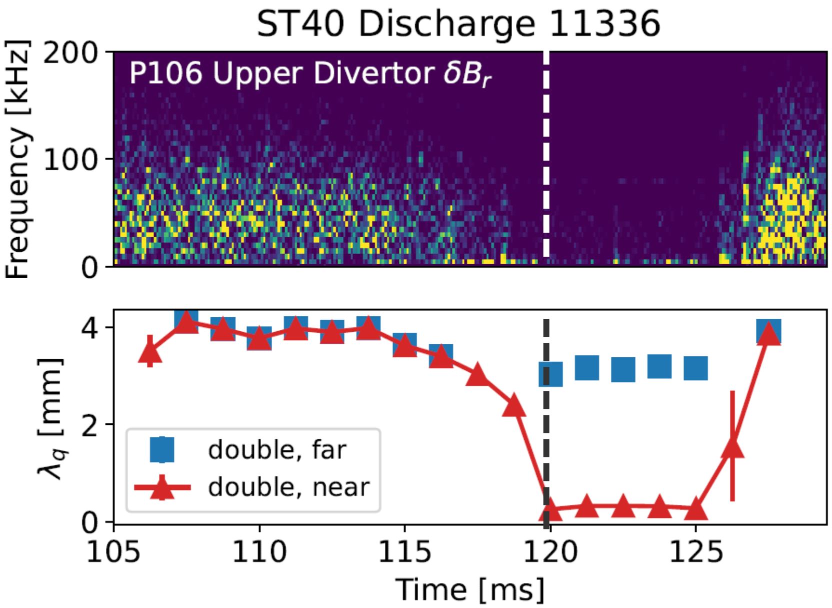
- Probe #106 located behind the upper target measures Br, perpendicular to flux surfaces
  - 2 MHz acquisition rate
- Fluctuation level correlate strongly with α_t

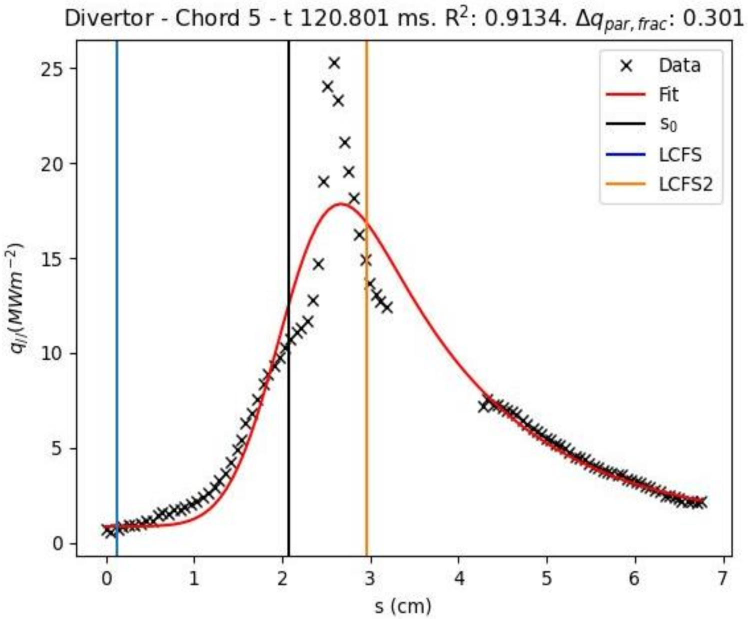




Onset of narrow branch coincides with suppressed magnetic fluctuations

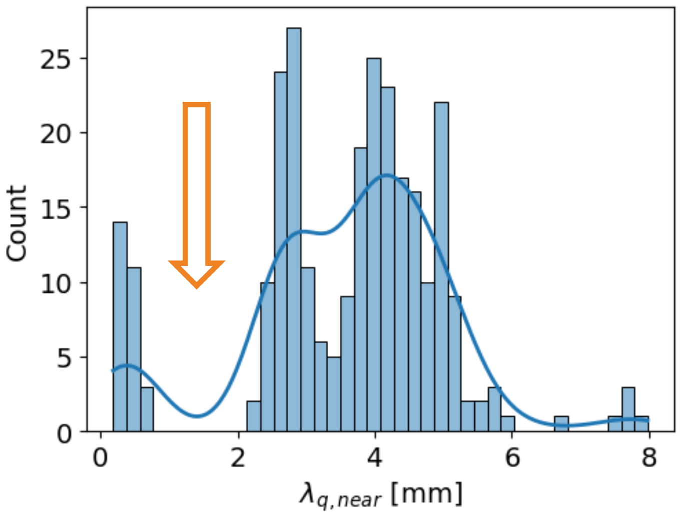
- Strong suppression of Br fluctuations, from 1e-5 to 1e-6, in the 100 kHz range.
- In this case, the heat flux into the far SOL was suppressed, revealing the narrow near SOL





So what? Part 1 – Theoretical implications

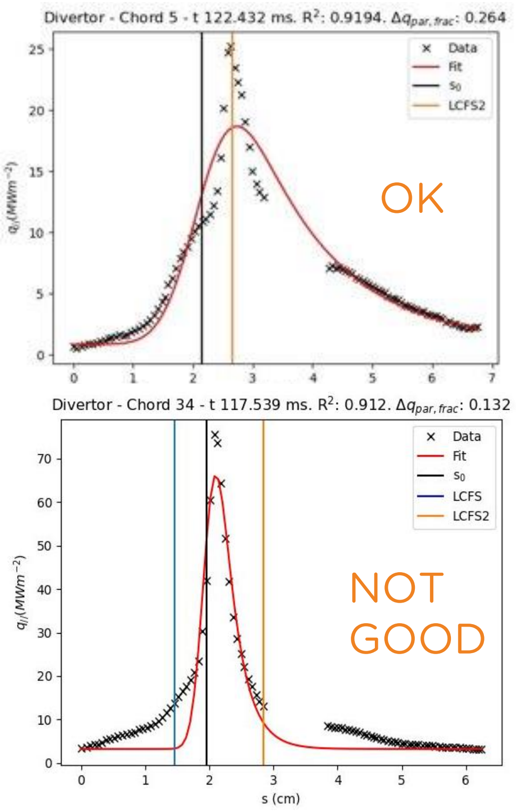
- Narrow near SOL measured to be between 0.3 – 0.8 mm at OMP
- Wide SOL / far SOL around 2 – 4 mm



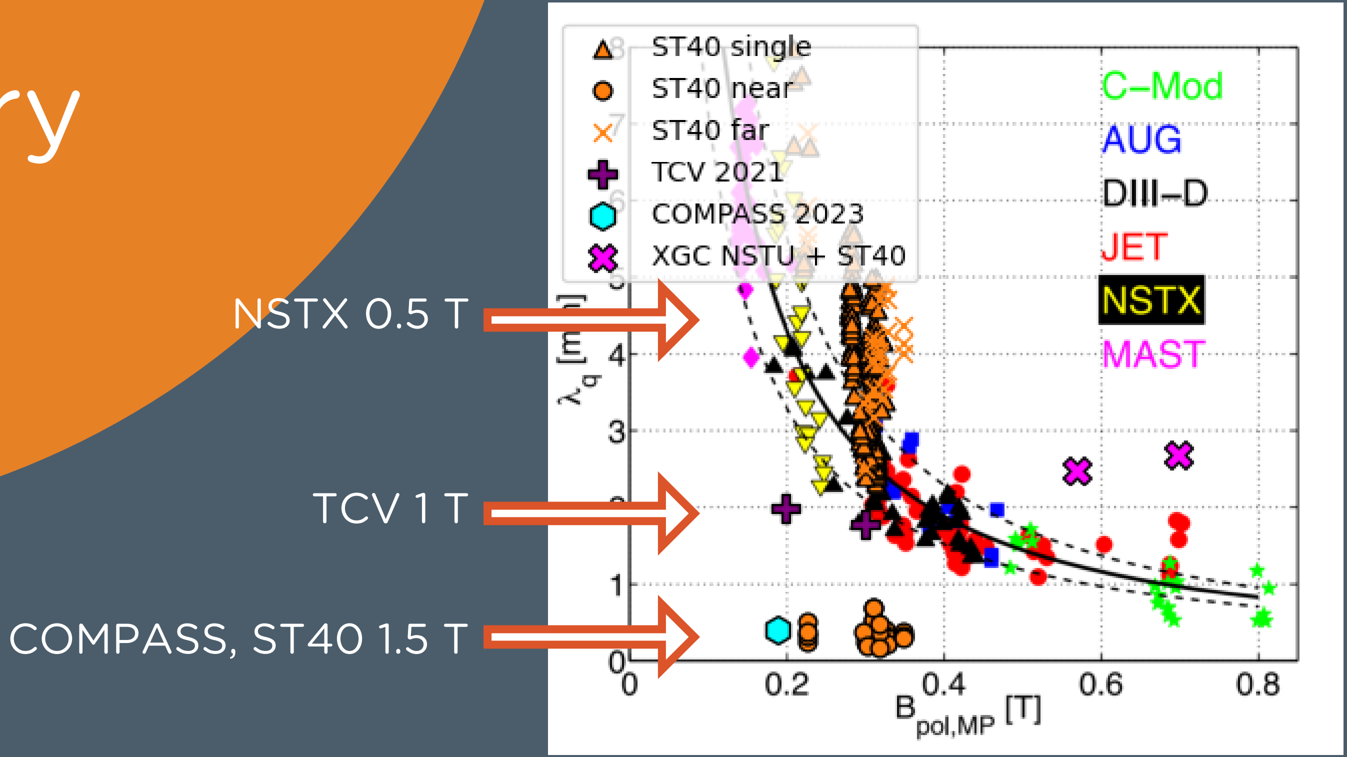
- Assuming $T_i = T_e \approx 50{\sim}100$ eV (all width at OMP):
  - Ion neoclassical drift orbit width $\rho_{pol,i}$ = 2.5 – 4 mm
  - Ion total gyro orbit width ρ_i = 0.4 – 0.7 mm
  - Electron neoclassical drift orbit width $\rho_{pol,e}$ = 0.04 – 0.07 mm
- In the narrow near SOL, for cross-field gradient scale length L, $3\rho_{pol,e} \leq L \leq \rho_i$
  - Weakly magnetized ions?!
  - Strong orbit pinch

So what? Part 2 – Divertor survivability implications

- Because of the bifurcation of the profile shape, the single parameter $\lambda_{q,N}$ is no longer sufficient for predicting the heat flux profile, or the peak heat flux
- The width AND power sharing between the two channels is needed to protect the divertors:
  - IF Narrow near SOL, but low power in the narrow channel - OK
    - Increases peak heat flux mildly
    - Overall small impact on heat flux foot print
  - IF high power in the narrow channel, far SOL width broadens
    - Dramatically increases peak heat flux – target damage
    - Significant power in far SOL – first wall / PFC damage



Summary



NSTX 0.5 T
TCV 1 T
COMPASS, ST40 1.5 T
ST40 single
ST40 near
ST40 far
TCV 2021
COMPASS 2023
XGC NSTU + ST40
C–Mod
AUG
DIII–D
JET
NSTX
MAST
λq [mm]
B pol,MP [T]
0
1
2
3
4
0.2
0.4
0.6
0.8

Summary

- A SOL power drop off width (scrape-off-width) database has been constructed for campaign 2.3 data, consisting of 18 plasma discharges, 131 profiles
- Two branches of near SOL scrape-off-width have been observed
- Wide branch (> 2 mm):
  - Follows Silvagni ASDEX / Ballinger CMOD scaling on edge electron pressure well
  - On the correct order of Eich [14] B_p scaling, with large vertical spread similar to other STs
  - Follows Eich 2020 turbulence parameter α_t scaling well
- Narrow branch (< 1 mm):
  - Bifurcation observed at low edge collisionality / low turbulence
  - When near SOL width is narrow, far SOL width follow conventional H-mode scalings.

Next steps

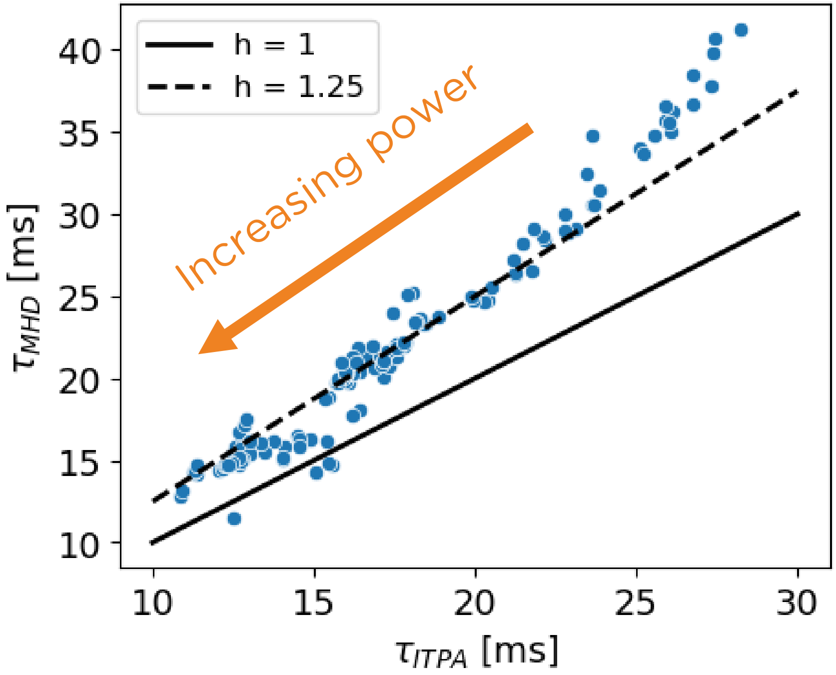
- In-depth theory / modelling work needed to understand:
  - What causes the bifurcation? Is it related to the two branches of pedestal stability?
  - What are the two components of heat flux channels?
  - What sets the width of the two components, and what determines the power sharing?
- More experimental work to test hypothesis:
  - More high power shots for the database
  - Confirm the dependency on collisionality - Ip, Bt, Pe, gas, and P_sol scan
  - Improved SOL characterization – Langmuir Probe array
  - …

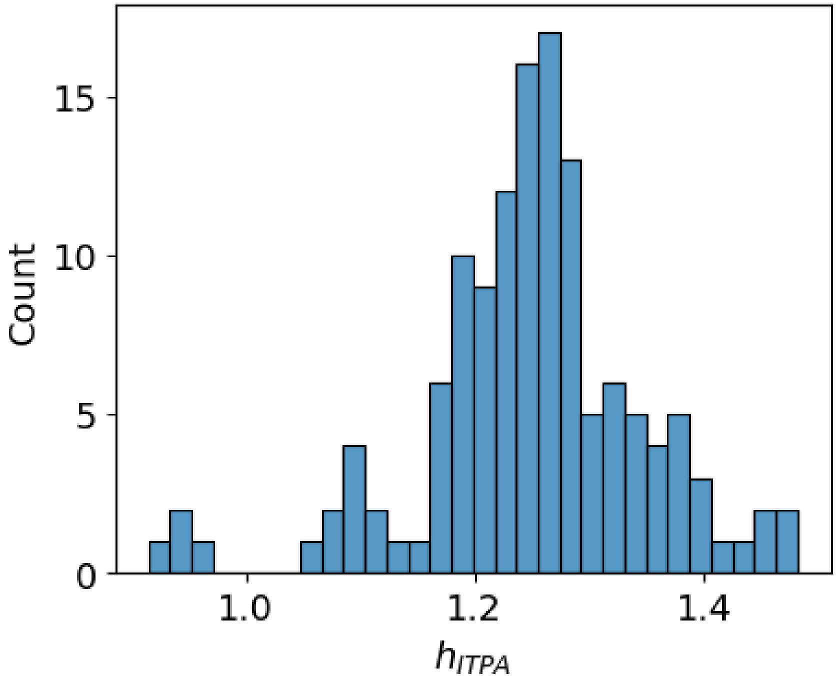
Backup slides

Energy confinement similar to ITPA Type-1 ELMy Hmode

Confinement time = MHD stored energy / P_in – dW/dt (includes <30% fast pressure)

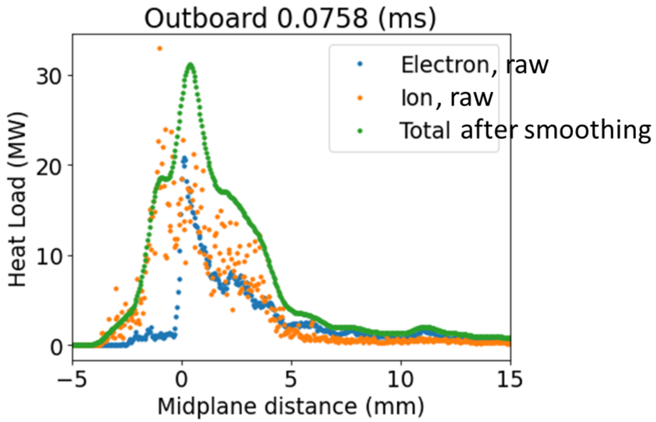
$P_{total} = P_{NBI} + V_{loop} * I_p$

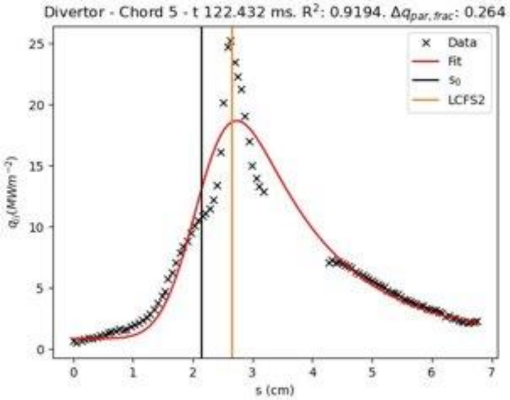




Hypothesis: collisionless electron transport near the separatrix?

- XGC simulation of ST40 10014 at 1MA found similar profile shape to 11336
  - Narrow near SOL attributed to electron heat flux
  - ‘Average’ heat flux width broader than scaling
- Possible explanation: low ν^* at the edge preserves banana orbits in the very near SOL
  - Width set by electron excursion (drift orbit width)?
  - Passing population collisionlessly stream to targets?
  - Strongly distorts electron distribution downstream?
  - Non-Maxwellian distribution increases sheath transmission?



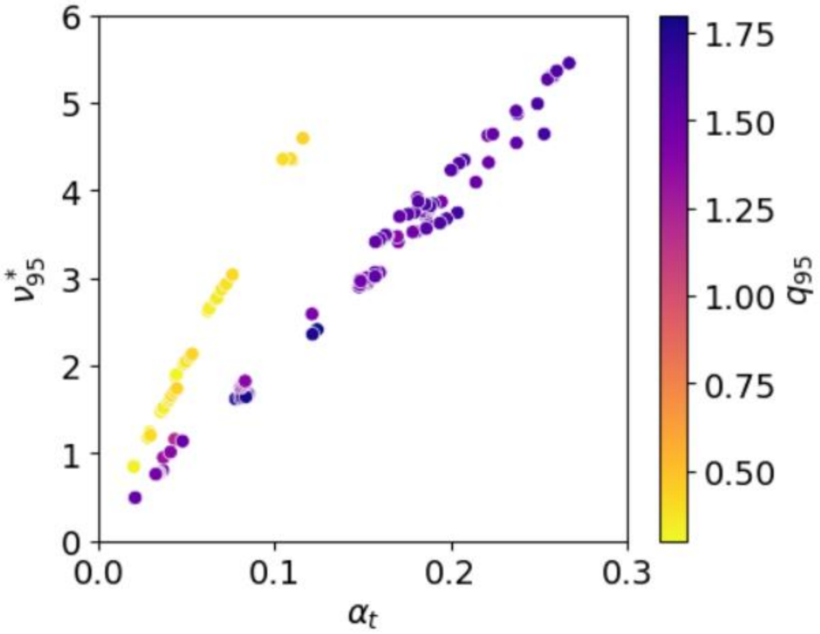


Edge collisionality and turbulence parameter α_t

- Eich 2020 proposes edge turbulence parameter independent of gradient scale length

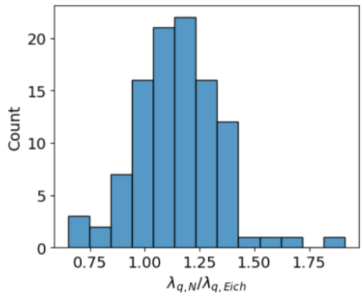
$$\alpha_t \equiv C\omega_B = 1.02 \frac{\nu_{ei}}{c_s} \frac{m_e}{M_i} \hat{q}_{cyl}^2 R \cdot \left(1 + \frac{1}{\overline{Z}}\right)$$

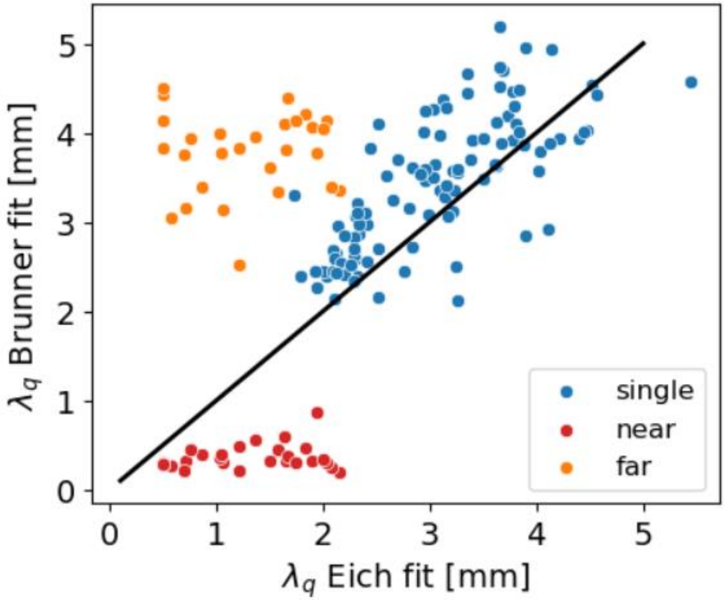
- Found through simulations to control the relative strength of interchange and drift wave turbulence [Scott 2005, 2007]
- Simply related to edge neoclassical collisionality via q_{cyl}
  - This shows up as 2 distinct branches in our database because of the 1 toroidal fields
- Regression on ASDEX found quadratic broadening of near SOL λ_p with α_t



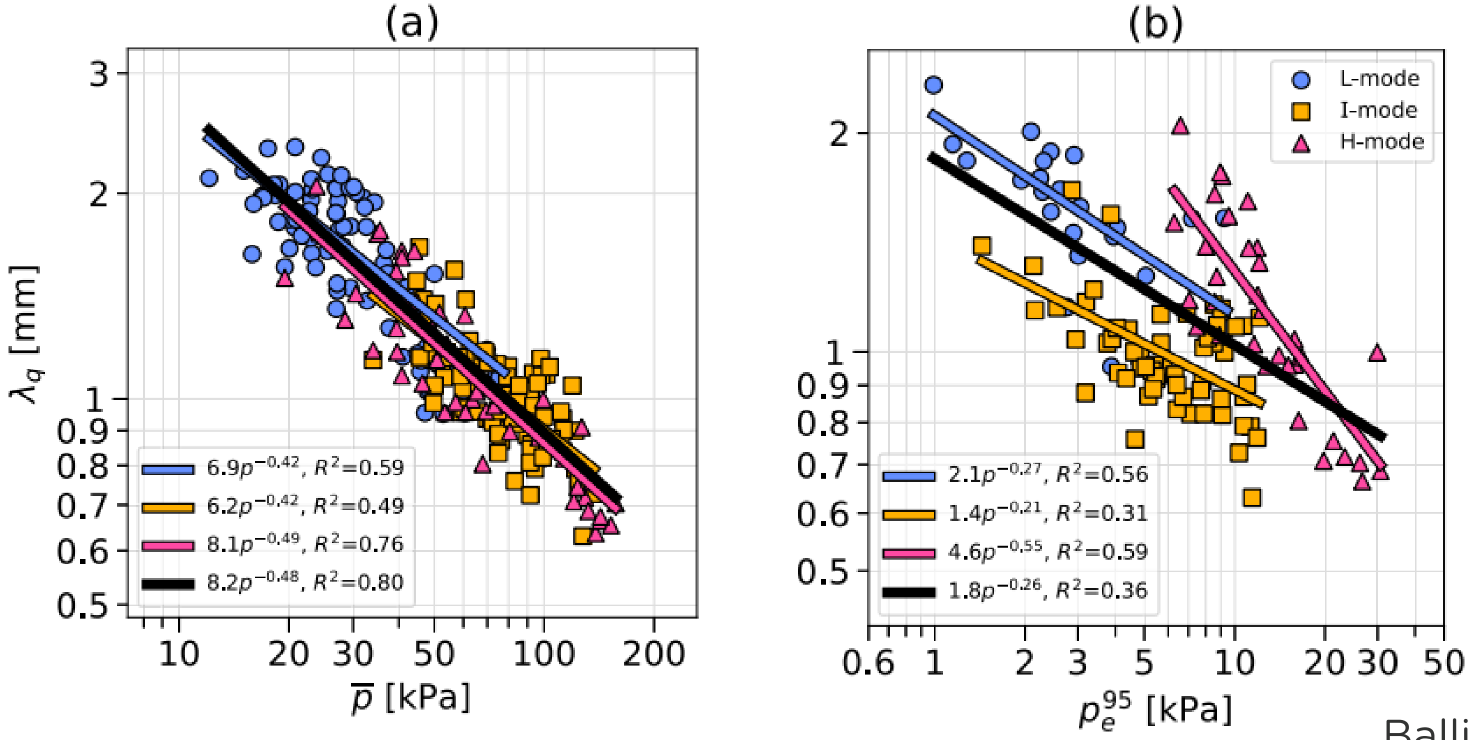
Distinct bifurcation of profile shape at 2mm

- At $\lambda_q > 2mm$, Eich and Brunner fits find similar result for near SOL width
  - Brunner fit 20% wider on average
- At $\lambda_q < 2mm$, Eich fit fails, Brunner finds two distinct SOL widths
  - Near SOL narrows dramatically (x4)
  - far SOL close to the wide branch



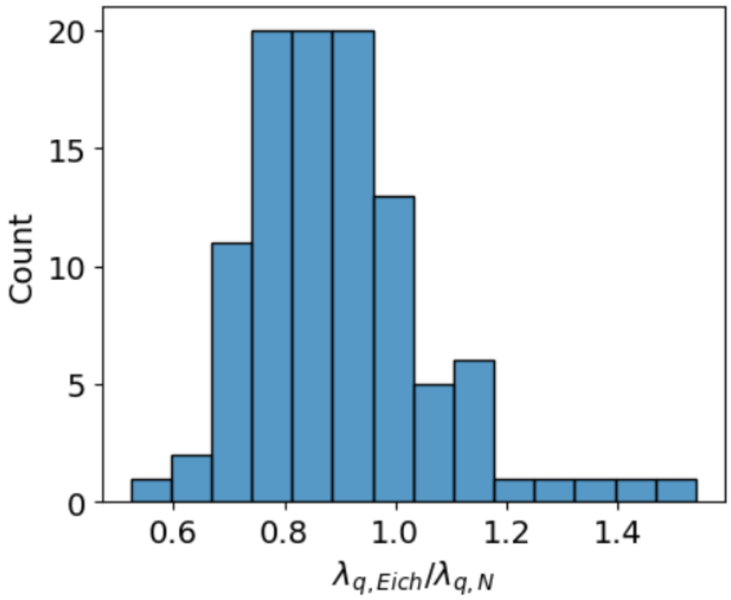


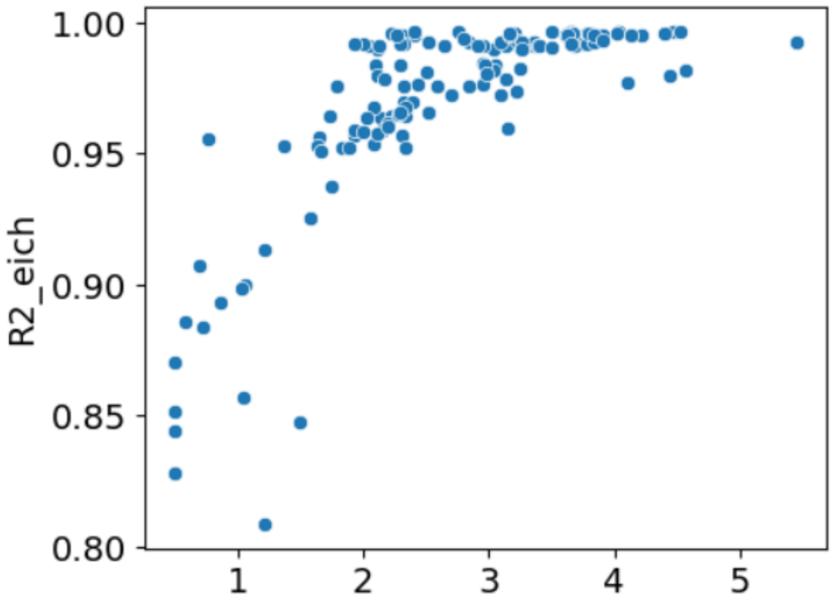
Alcator-CMOD pressure scaling



Ballinger 2022

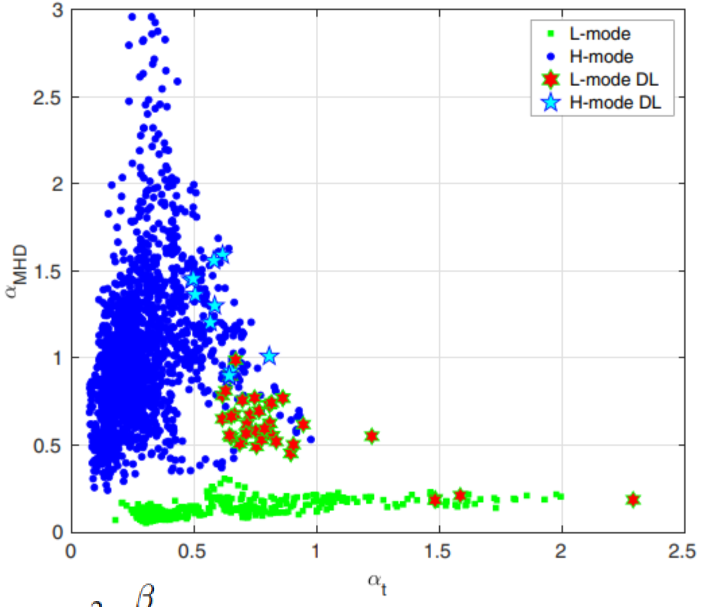
Eich R2 falls off a cliff at <2mm



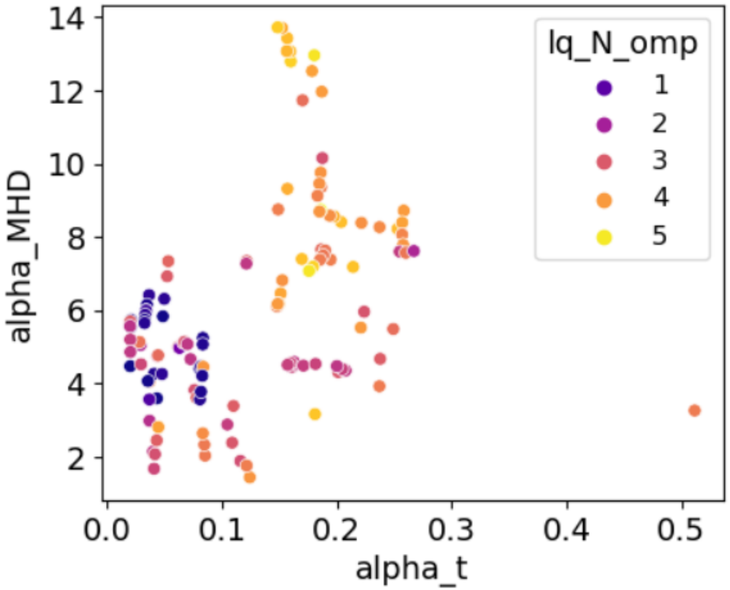


The ST40 edge operating space (NOT for publication)

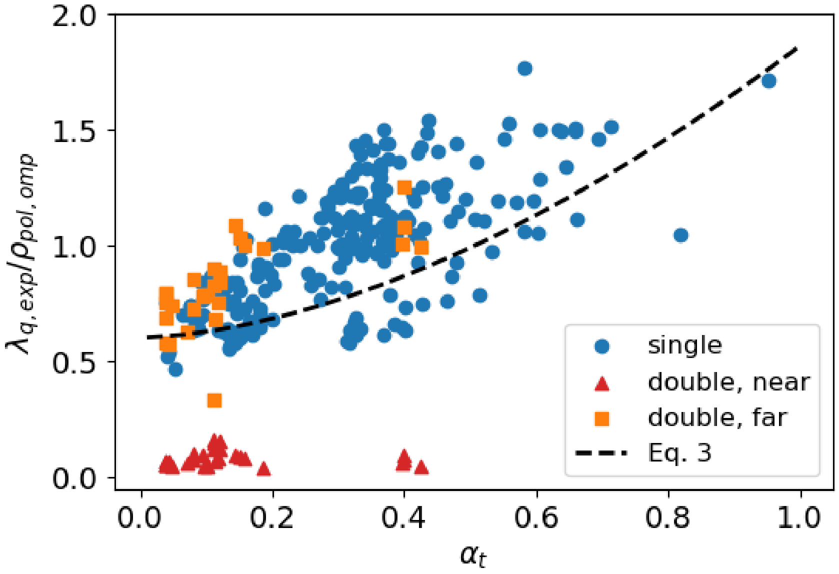
ASDEX [Eich 2020]

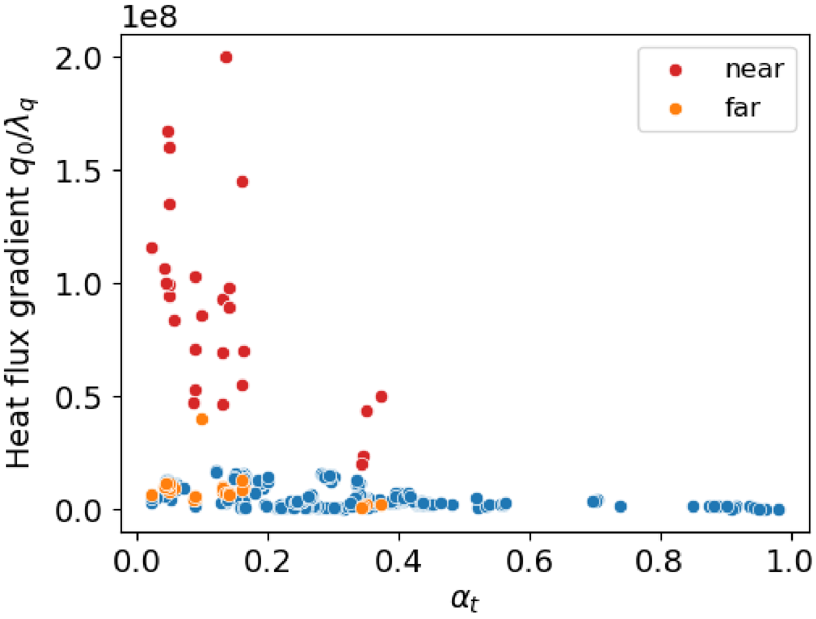


$$\alpha_{\rm MHD} = R\,\hat{q}_{cyl}^2 \frac{\beta}{\lambda_p},$$



Similar to the 2 pedestal stability branches?





P_in dependency in HD model is important – makes it a little better than Eich14

Colored by input power. Purple – Ohmic, Yellow – 2 beams full power