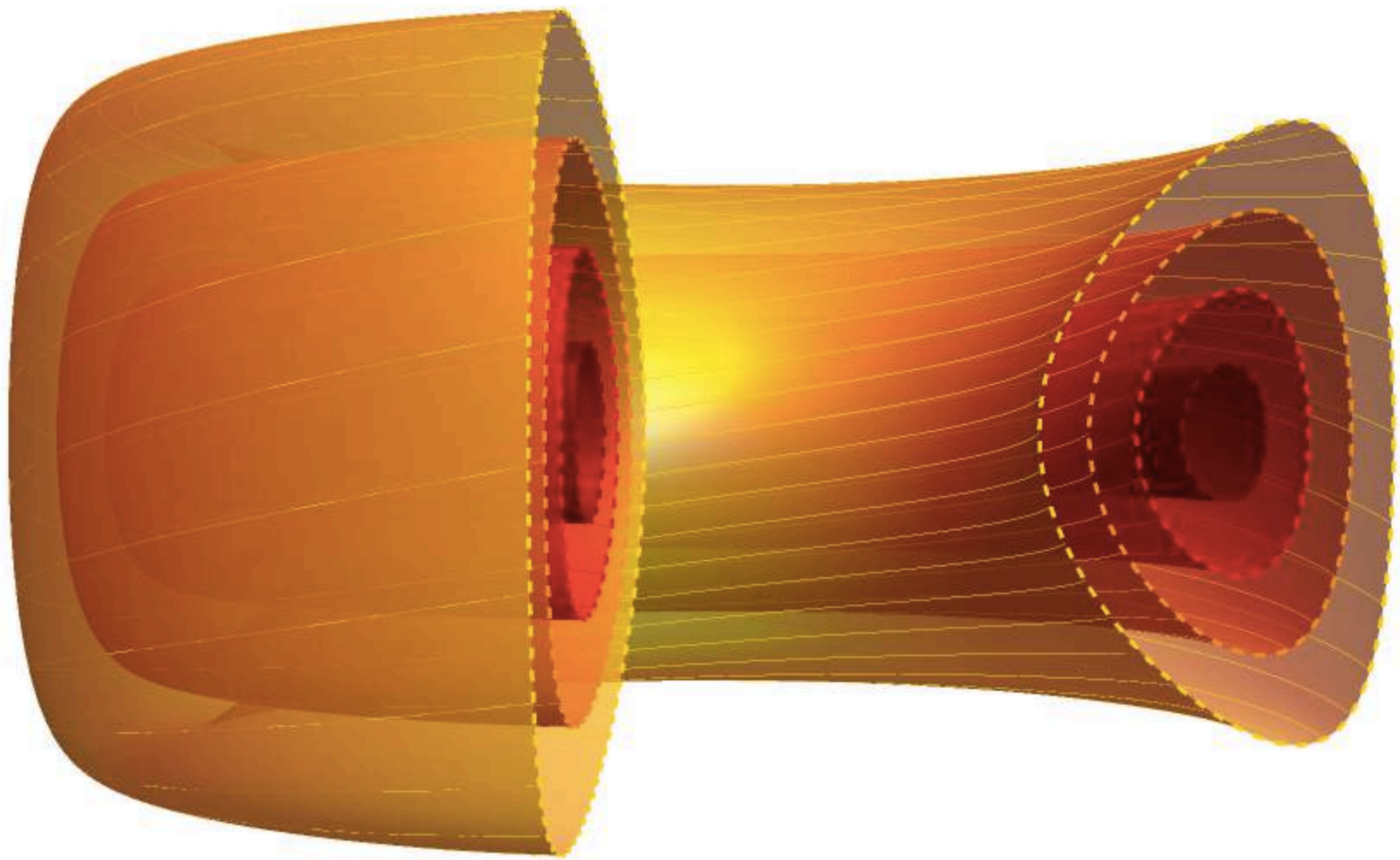
TSVV 2: Negative triangularity and plasma shaping

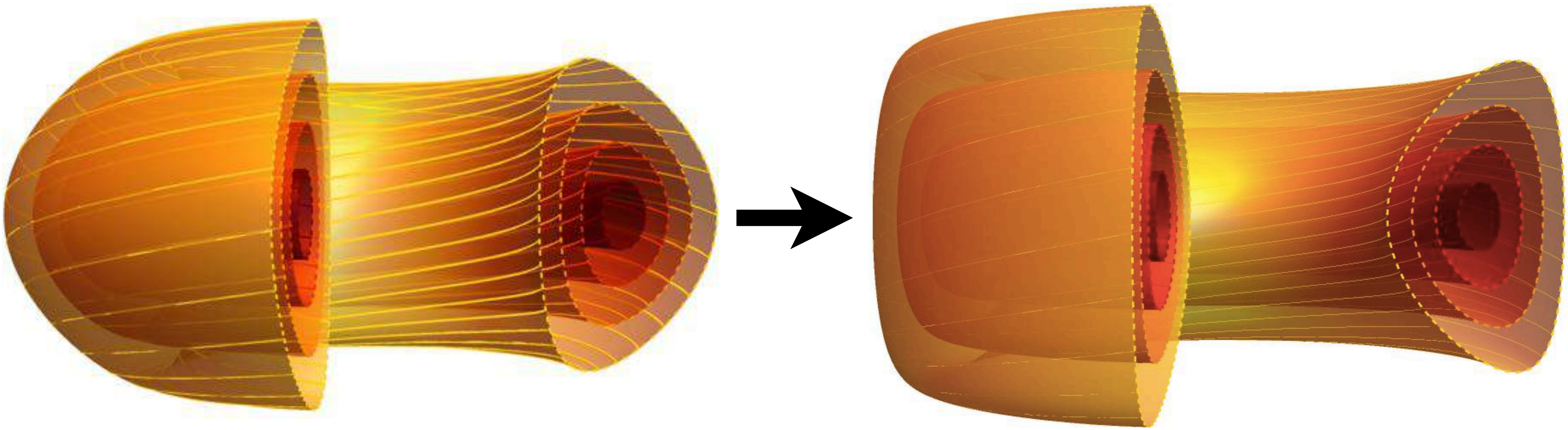


Justin Ball on behalf of the TSVV 2 team

CEA	H. Luetjens, P. Donnel
DIFFER	M. Pueschel, J. Citrin
ENEA	G. Fogaccia, P. Muscente, P. Mantica, A. Mariani, G. Vlad, P. Innocente
EPFL	J. Ball, G. Di Giannatale, K. Lim, A. Merle, O. Sauter, M. Vallar, A. Balestri, P. Ricci

EUROfusion TSVV Midterm Review
11 September 2023

Assess a new operating regime for power plants



Positive Triangularity (PT) in H-mode

1) H-mode performance
2) ELMs
3) Standard H-mode SOL width
4) Everything else is similar

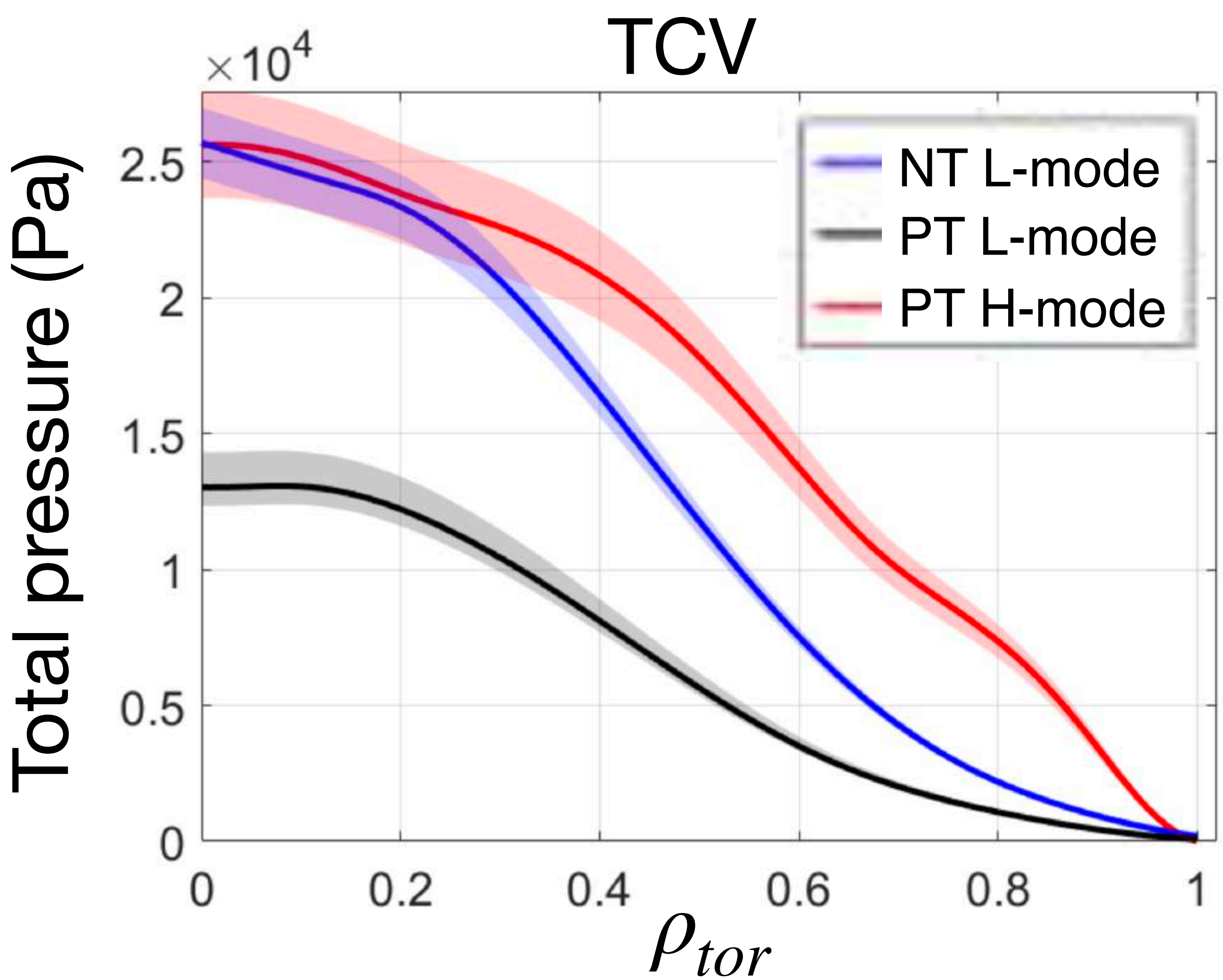
Negative Triangularity (NT) in L-mode

1) H-mode-**like** performance
2) **No** ELMs
3) **L-mode-like** SOL width
4) Everything else is similar

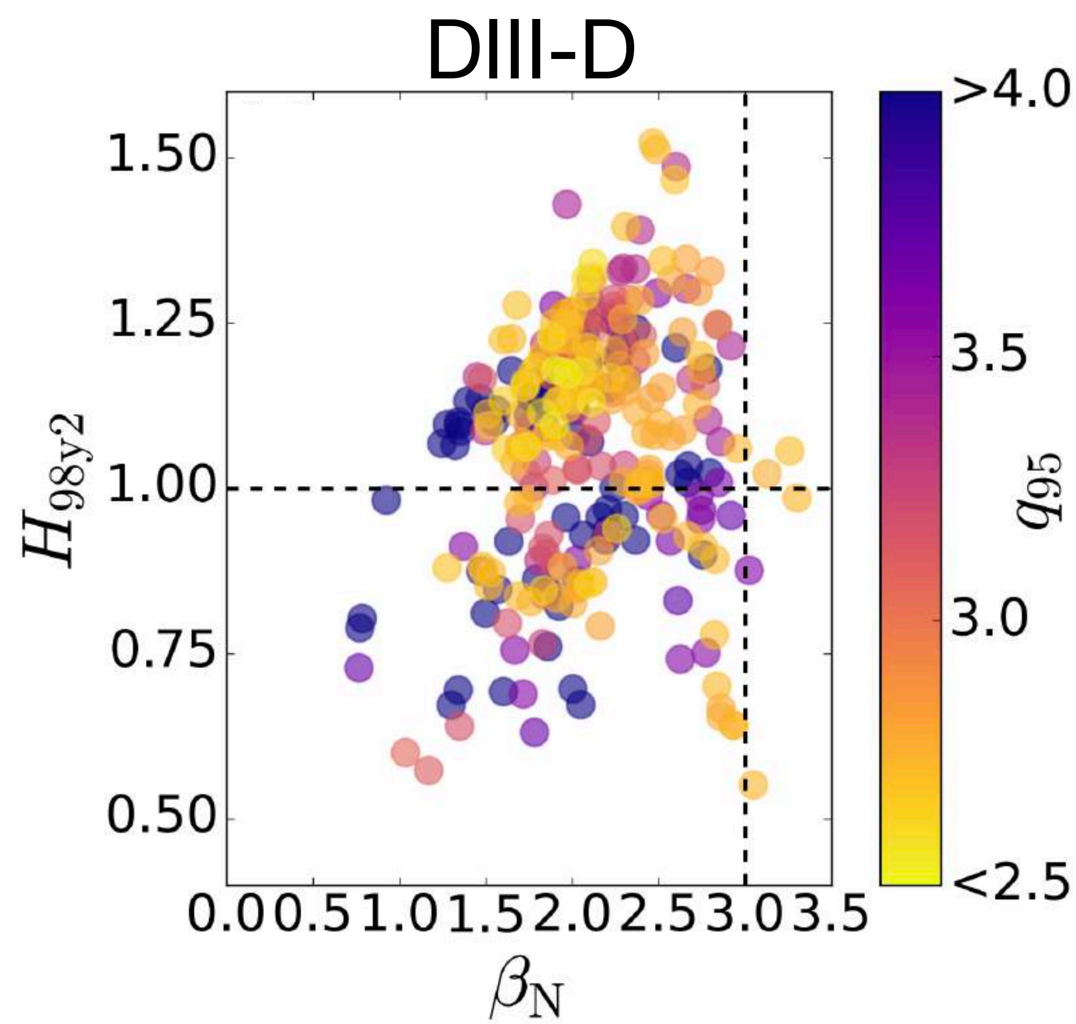
Overall project status

- Overall, project progressing smoothly, albeit with a few minor delays
  - Detailed status of milestones/deliverables can be found in Appendix
  - Publication list is on the TSVV 2 wiki and Nuclear Fusion special issue in Nov.
  - Two team members (M. Vallar, A. Merle) recently left, but have replacements
  - Only planned deviation is to replace D6.3 and M6.2.3 with additional work on electromagnetic turbulence (result of the lack of a DIFFER ACH)
- Little code development directly in TSVV 2, but supporting work on GENE, ORB5, XTOR-K as well as IMAS compatibility
- Strong links with experimental work (especially on TCV)

1) Core confinement



[This TSVV]



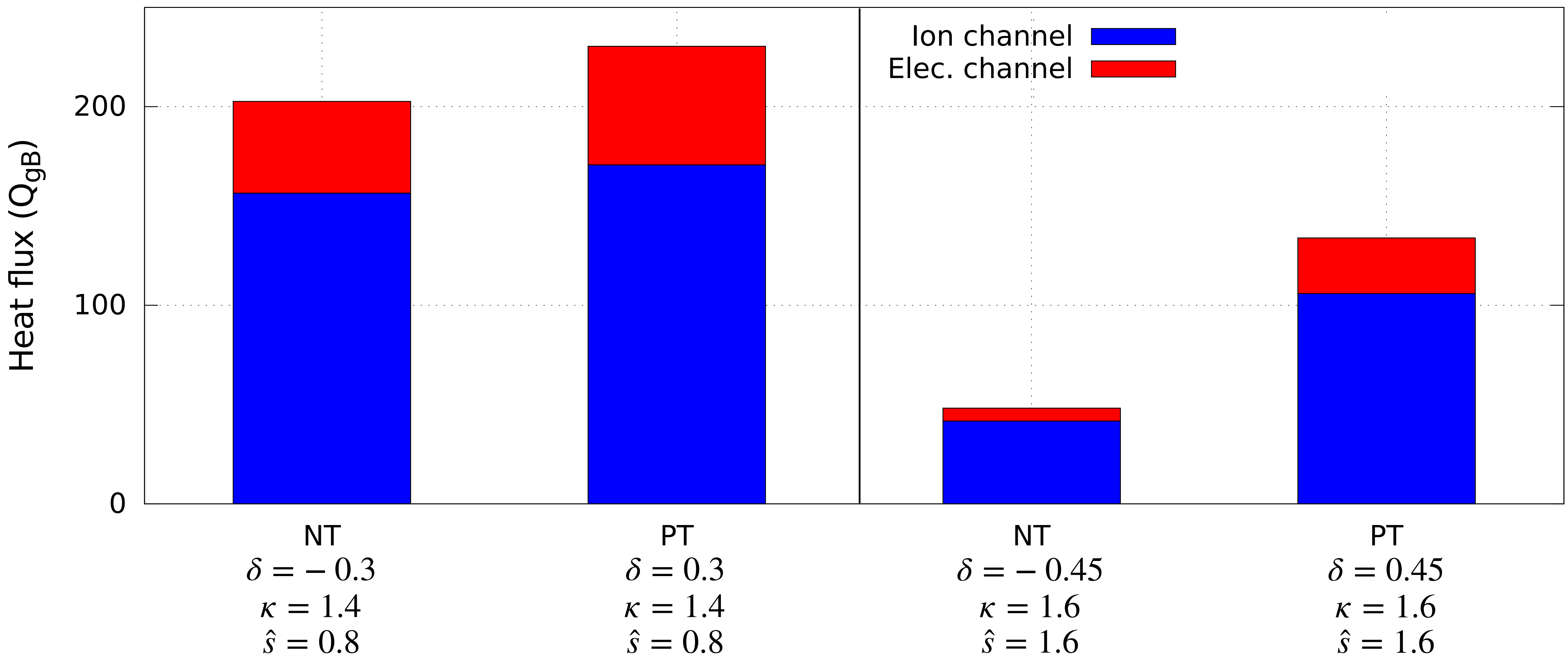
[C. Paz-Soldan. arXiv:2309.03689]

Basic gyrokinetic (GK) studies

[1] G. Merlo. *Phys. Plasmas* (2019).
[2] A. Balestri. EPS (2023).
[3] J. Ball. PPCF (2023).
[4] A. Mariani. Nucl. Fusion (submit.).
[5] J. Duff. Phys. Plasmas (2021)., M.J. Pueschel. Nucl. Fusion (special iss.).
[6] J. Ball. PMI-5.2.1-T050 (2020).
[7] G. Merlo. *PPCF* (2015).

- Regardless of turbulent regime, GK simulations generally display a transport reduction when flipping PT→NT (holding background profiles constant)[1-4]

- Effect larger at high $|\delta|$, large aspect ratio, high $\hat{s}$, and high κ



EUROfusion EPFL

[1] G. Merlo. *Phys. Plasmas* (2019).
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[7] G. Merlo. *PPCF* (2015).

Basic gyrokinetic (GK) studies

- Regardless of turbulent regime, GK simulations generally display a transport reduction when flipping PT→NT (holding background profiles constant)[1-4]

- Effect larger at high $|\delta|$, large aspect ratio, high $\hat{s}$, and high κ

- Usually need kinetic treatment of electrons to observe this[3]

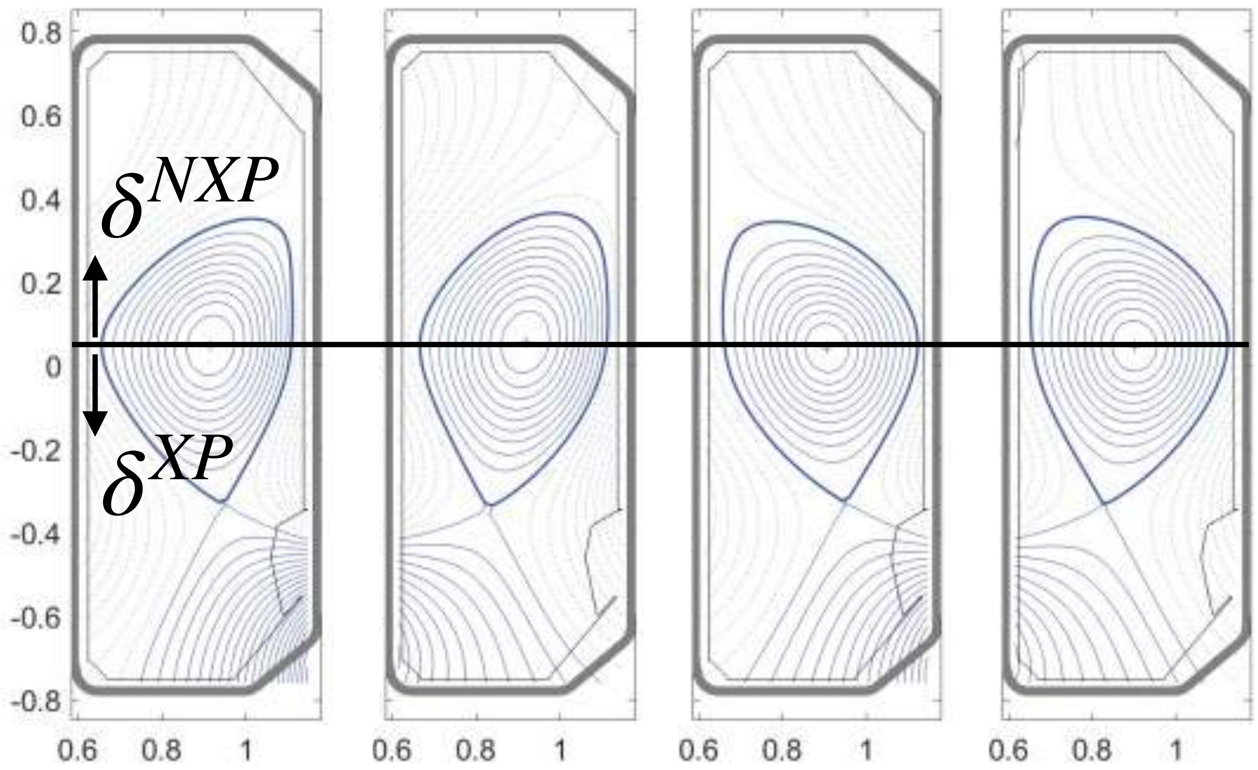
- Nonlinear saturation physics can be considerably different[5]

- Triangularity primarily affects the critical gradient, but not the stiffness[4,6,7]

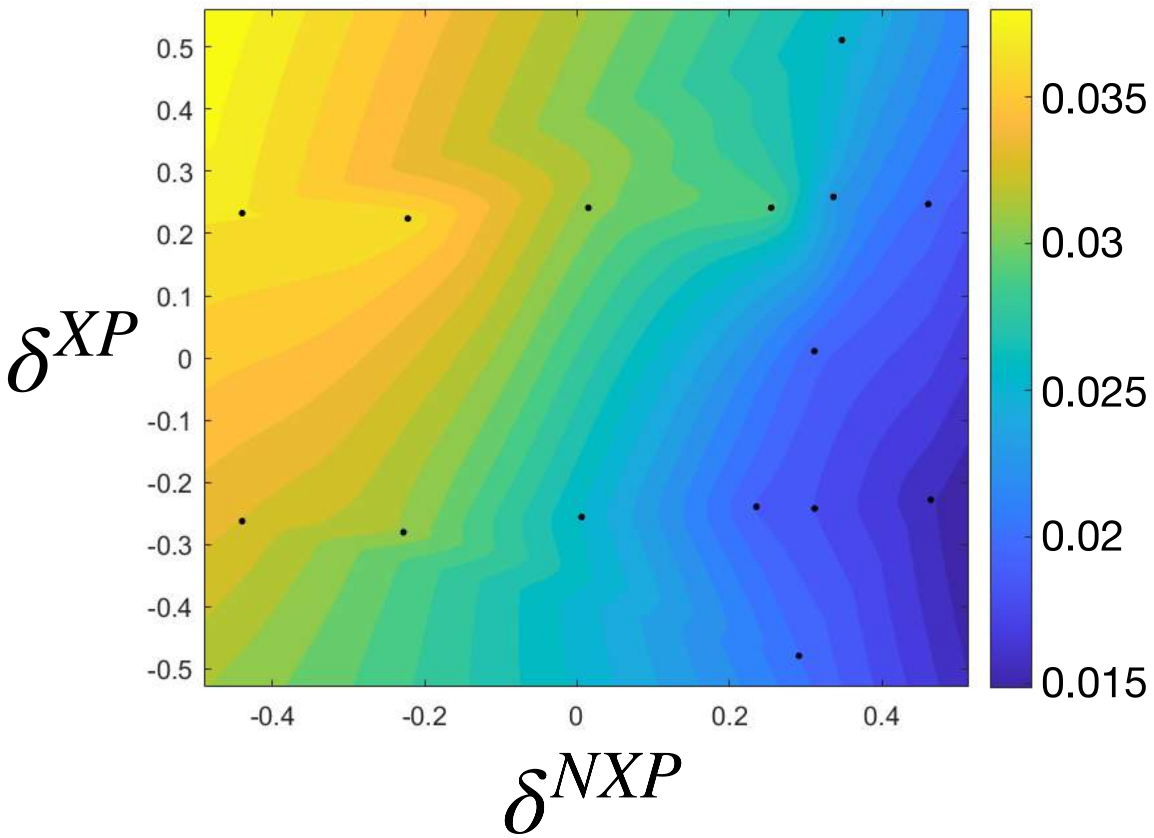
Validation with experiment

[1] A. Marinoni. *PPCF* (2009).
[2] G. Merlo. *JPP* (2023).
[3] A. Balestri. *Nucl. Fusion* (special iss.).
[4] G. Di Giannatale. *Nucl. Fusion* (special iss.).
[5] M.J. Pueschel. Nucl. Fusion (special iss.).

- GK simulations agree, both qualitatively and quantitatively, with TCV[1-5] and DIII-D[3] experiments
- Captures effect of varying δ^{XP} and δ^{NXP} independently in TCV single-null discharges[3]



Energy confinement time (s)



Validation with experiment

[1] A. Marinoni. *PPCF* (2009).
[2] G. Merlo. *JPP* (2023).
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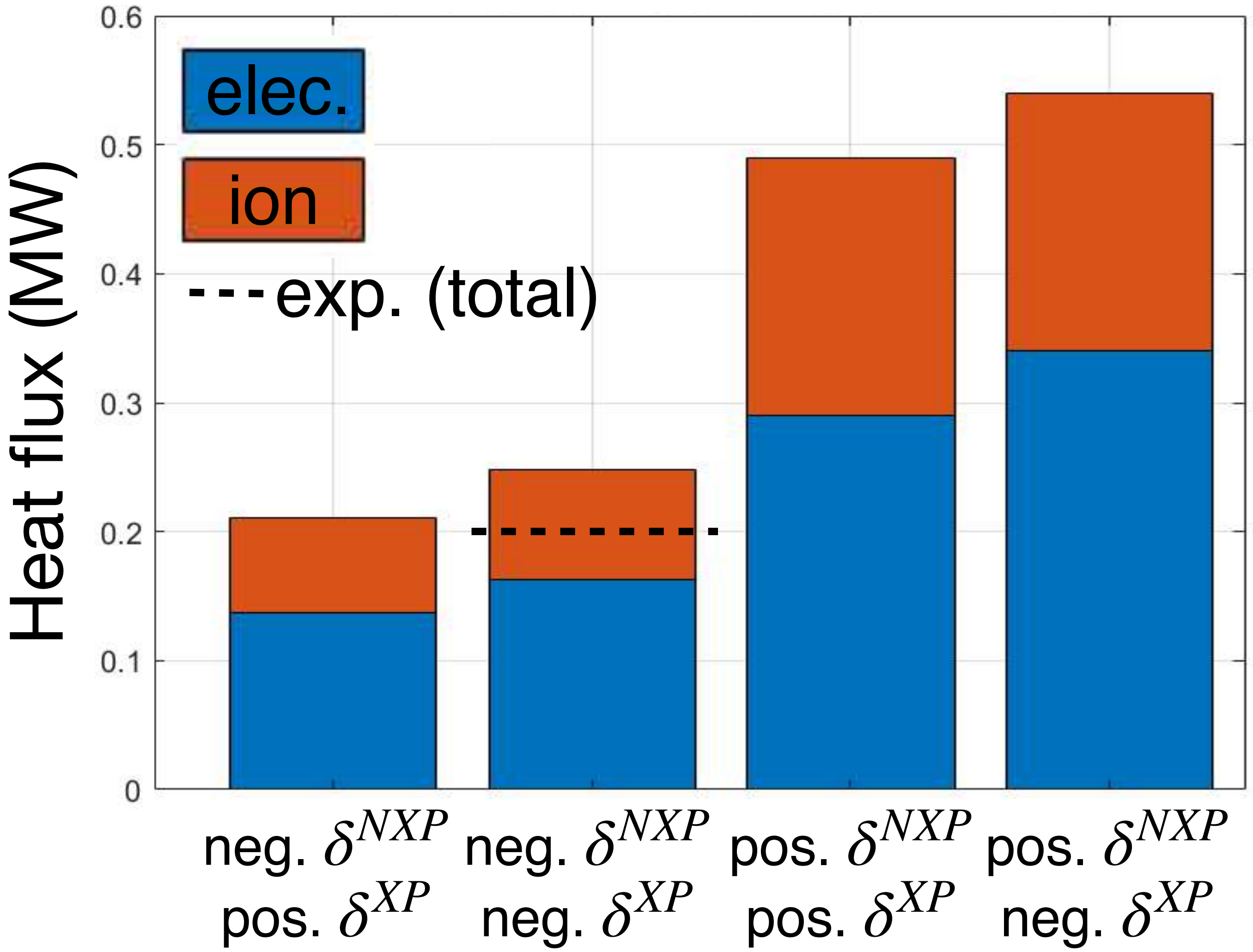

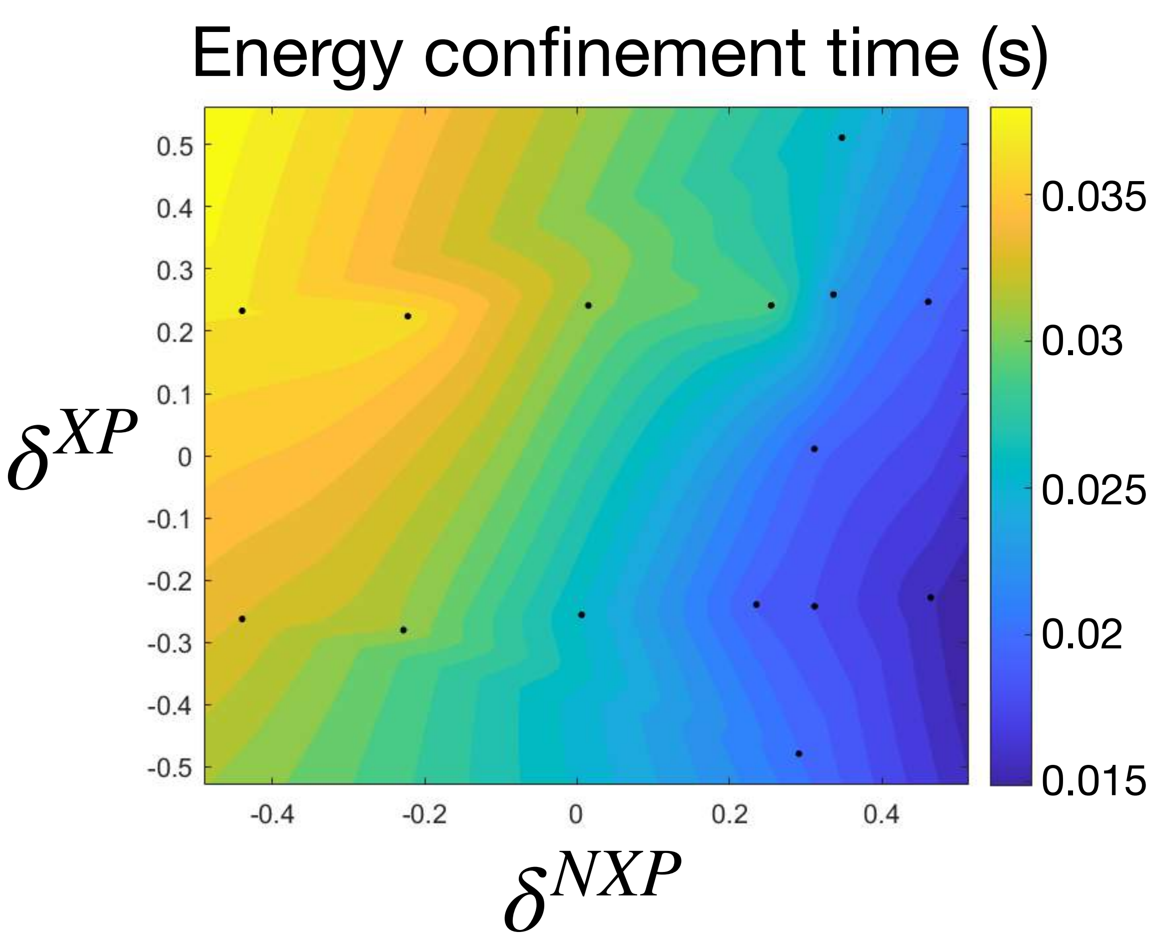

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[4] G. Di Giannatale. *Nucl. Fusion* (special iss.).
[5] M.J. Pueschel. Nucl. Fusion (special iss.).

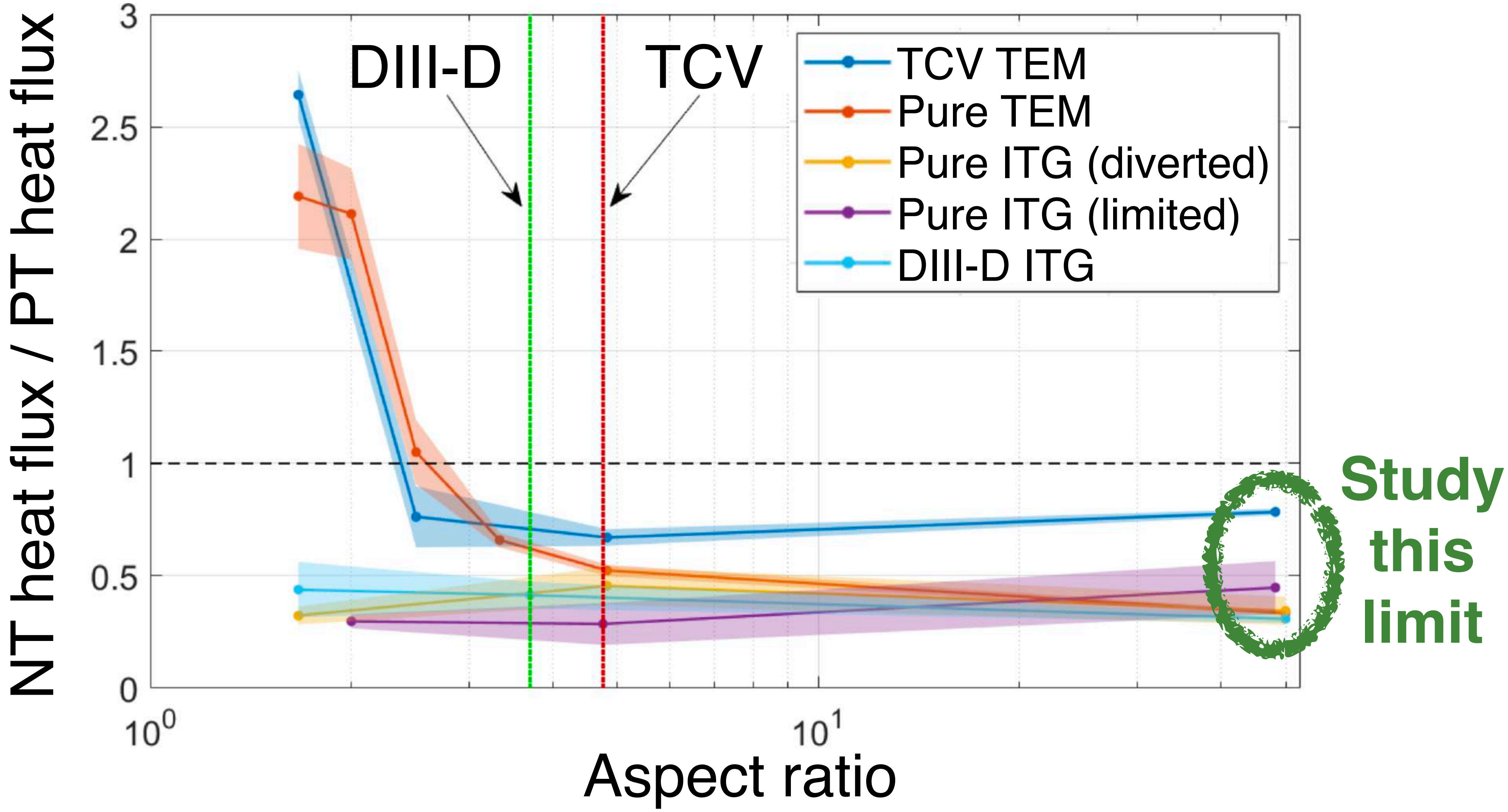
- GK simulations agree, both qualitatively and quantitatively, with TCV[1-5] and DIII-D[3] experiments
- Captures effect of varying δ^{XP} and δ^{NXP} independently in TCV single-null discharges[3]
  - We understand the physical reasons why δ^{NXP} has a bigger effect[3]
  - Does NOT accurately capture effect of toroidal field or plasma current reversal[3]

EUROfusion EPFL

Physical picture of NT confinement

[1] G. Rewoldt. *Phys. Fluids* (1982).
[2] T. Ohkawa. GA-A19184 (1988).
[3] A. Marinoni, *PPCF* (2009).
[4] G. Merlo, *Phys. Plasmas* (2019).
[5] A. Balestri. EPS (2023).
[6] R. Davies. *PPCF* (2022).

- Aspect ratio scan shows traditional theoretical argument[1-4] (based on trapped particle stability) is insufficient[5]

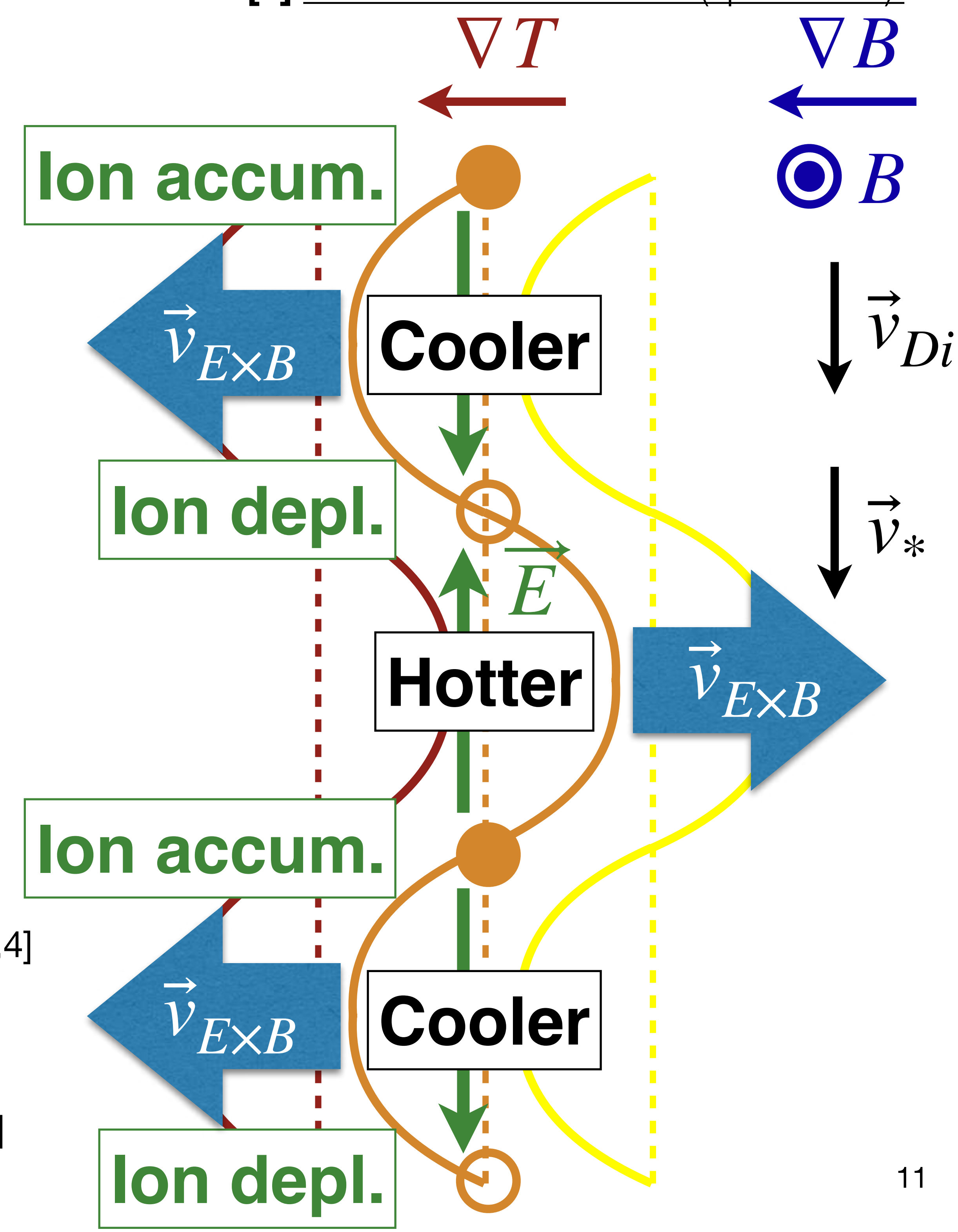


- In spherical tokamaks, NT can harm confinement (when the turbulence is dominated by the Trapped Electron Mode[5] or EM modes[5,6])

Physical picture of NT confinement

[1] M. Beer *PhD Thesis* (1995).
[2] Biglari et al. *Phys. Fluids B* (1989).
[3] A. Balestri, et al. EPS (2023).
[4] A. Balestri. *Nucl. Fusion* (special iss.).

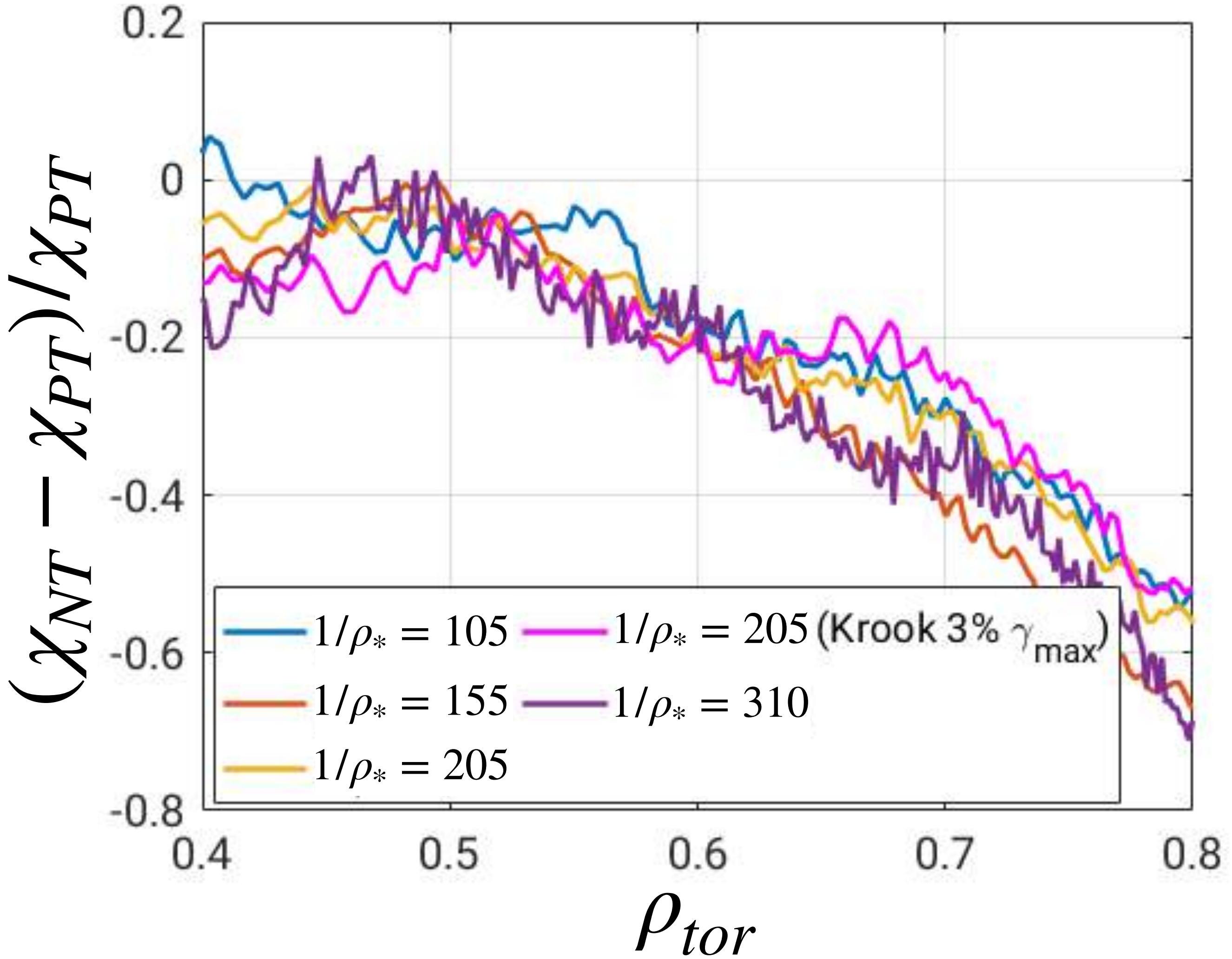
- Turbulence in tokamaks arises from a destabilization of drift waves
- Drift waves travel with a velocity
$$\vec{v}_* \propto \vec{B} \times \nabla T$$
- Destabilized by ion magnetic drift velocity
$$\vec{v}_{Di} \propto T_i \vec{B} \times \nabla B$$
- These velocities must be similar $\vec{v}_{Di} \approx \vec{v}_*$ to enable instability[1,2]
- PT enables this resonance, but not NT[3,4]
- Can explain dependence of NT confinement on $\hat{s}$, κ, and aspect ratio[3,4]



Extrapolating confinement to a power plant

[1] G. Di Giannatale. *Nucl. Fusion* (special iss.).
[2] J. Ball. PPCF (2022).

- Global ORB5 simulations indicate confinement improvement from NT is independent of machine size[1]



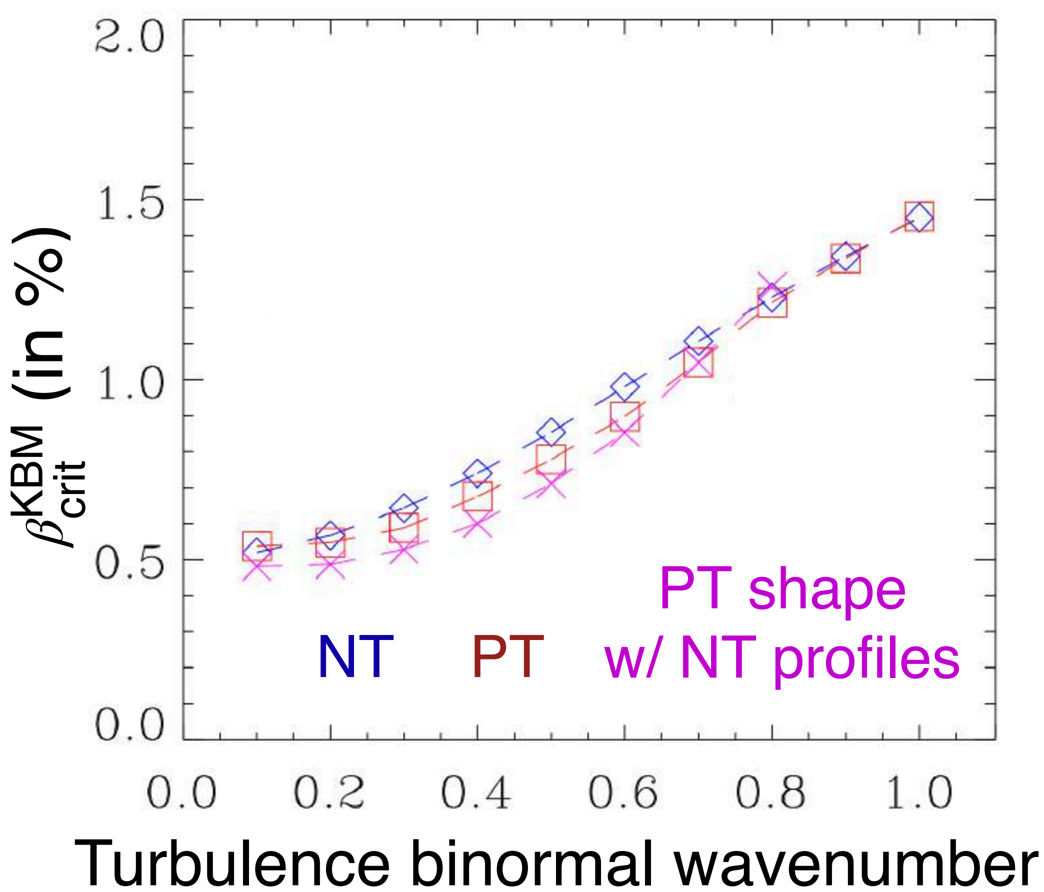
- Novel GENE flux tube simulations with profile shearing show the same[2]

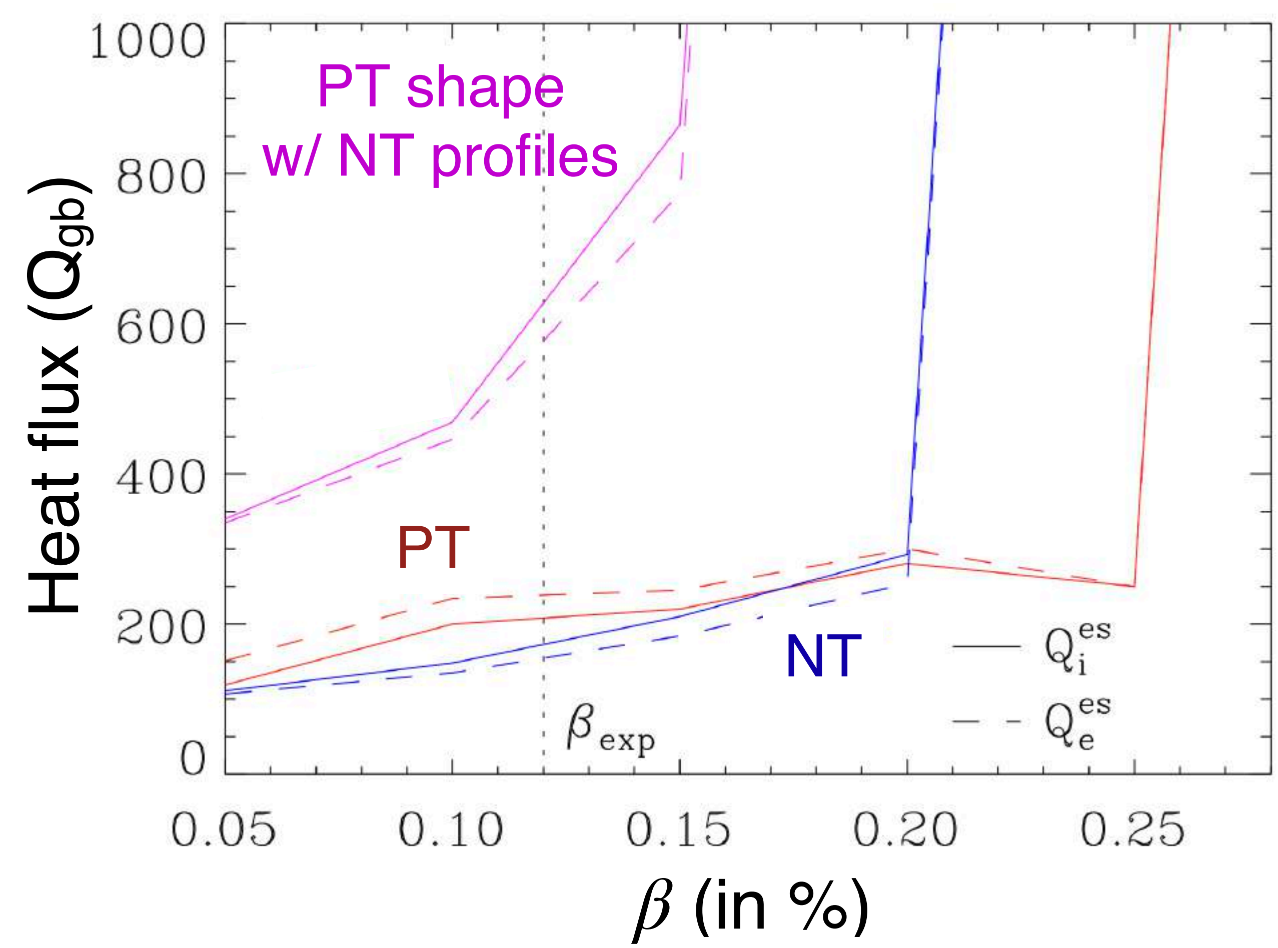
Further work important

Extrapolating confinement to a power plant

[1] M.J. Pueschel. APS (2022).
[2] A. Mariani. Nucl. Fusion (submit.). **[3]** A. Balestri, et al. EPS (2023).
[4] R. Davies. *PPCF* (2022).

- Local GK simulations of TCV indicate that β-driven turbulence scales similarly in NT and PT[1,2]





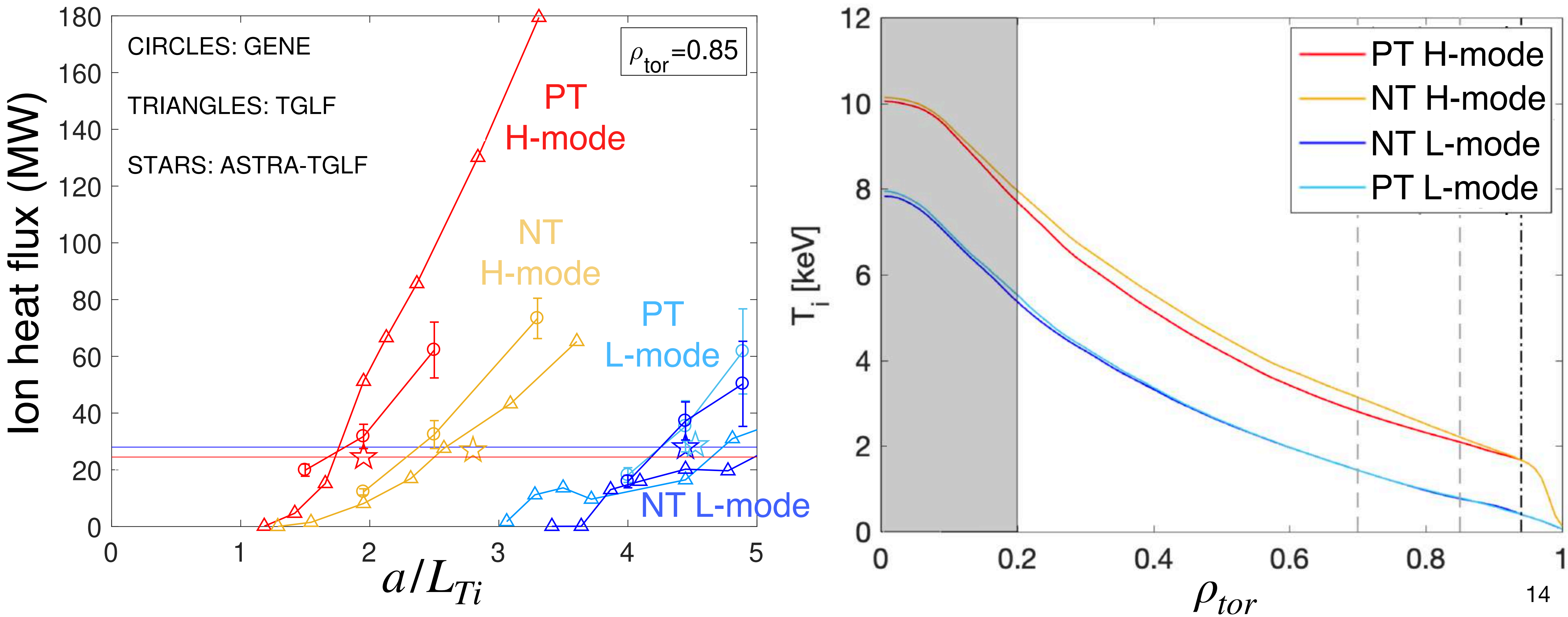
- In spherical tokamaks, KBMs and MTMs seem stronger for NT[2,3]

Integrated modeling of NT

[1] A. Mariani. Nucl. Fusion (submit.).
[2] A. Balestri. Nucl. Fusion (special iss.).

- ASTRA-TGLF (SAT2) modeling verified against local GENE and finds a flux reduction from NT[1]

- Local increases to the logarithmic gradients are insufficient to recover the pedestal[1]



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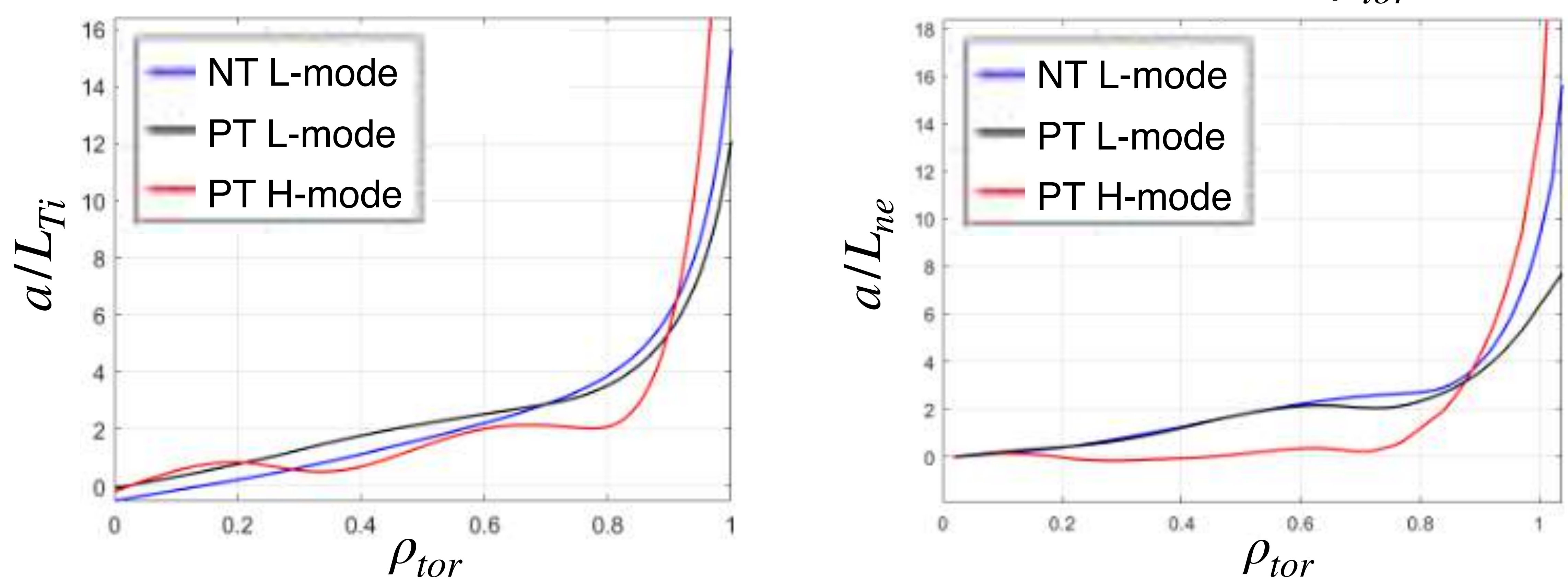
- <u>At least in this case, the quantitative improvement arises from</u> $\rho_{tor} > 0.9$[1,2]



EUROfusion EPFL

Further work important

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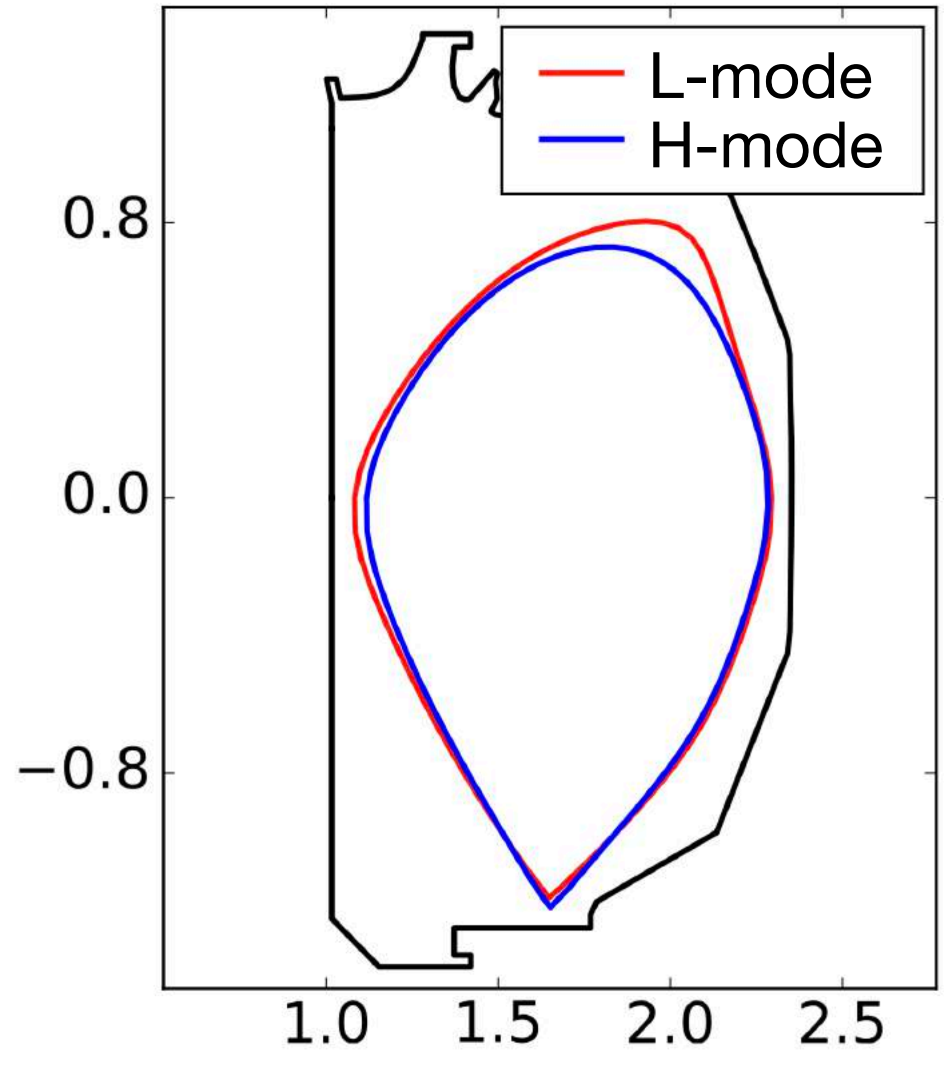
- ASTRA-TGLF (SAT2) modeling verified against local GENE and finds a flux reduction from NT[1]
- Local increases to the logarithmic gradients are insufficient to recover the pedestal[1]
- At least in this case, the quantitative improvement arises from $\rho_{tor} > 0.9$[1,2]
- Topic for collaboration with TSVVs 1, 3, and/or 4

2) Pedestal stability

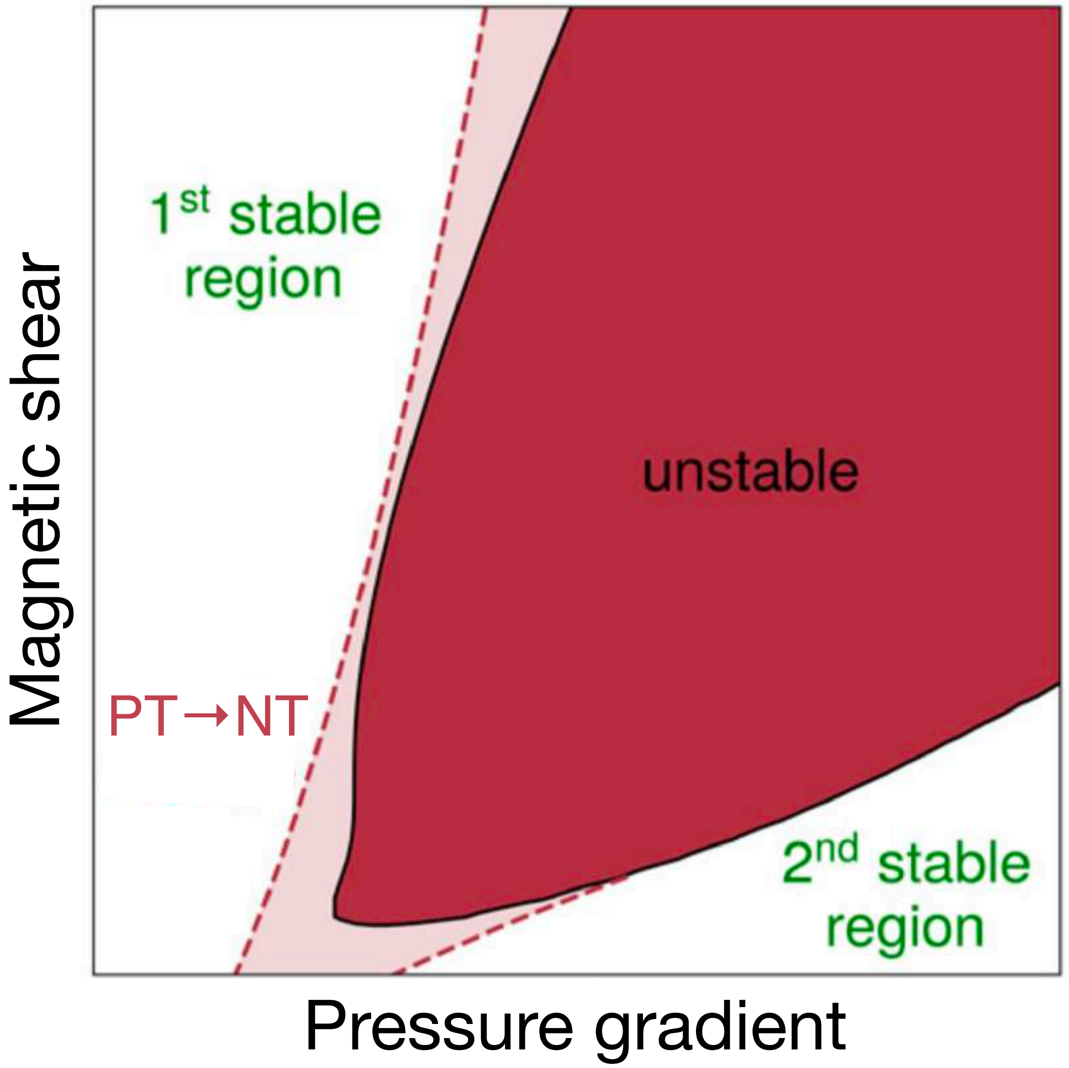


[S. Saarelma. PPCF (2021).]

Transition to H-mode

[1] A. Merle. PPCF (2017).
[2] A. Marinoni. Rev. Mod. Phys. (2021).
[3] S. Saarelma. PPCF (2021).
[4] O. Nelson. Nucl. Fusion (2022).
[5] T. Happel. Nucl. Fusion (2023).

- Sufficiently negative δ closes access to the 2nd stability region for infinite-n ballooning modes, which is associated with the transition to H-mode[1-4]



Transition to H-mode

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[2] A. Marinoni. Rev. Mod. Phys. (2021).
[3] S. Saarelma. PPCF (2021).
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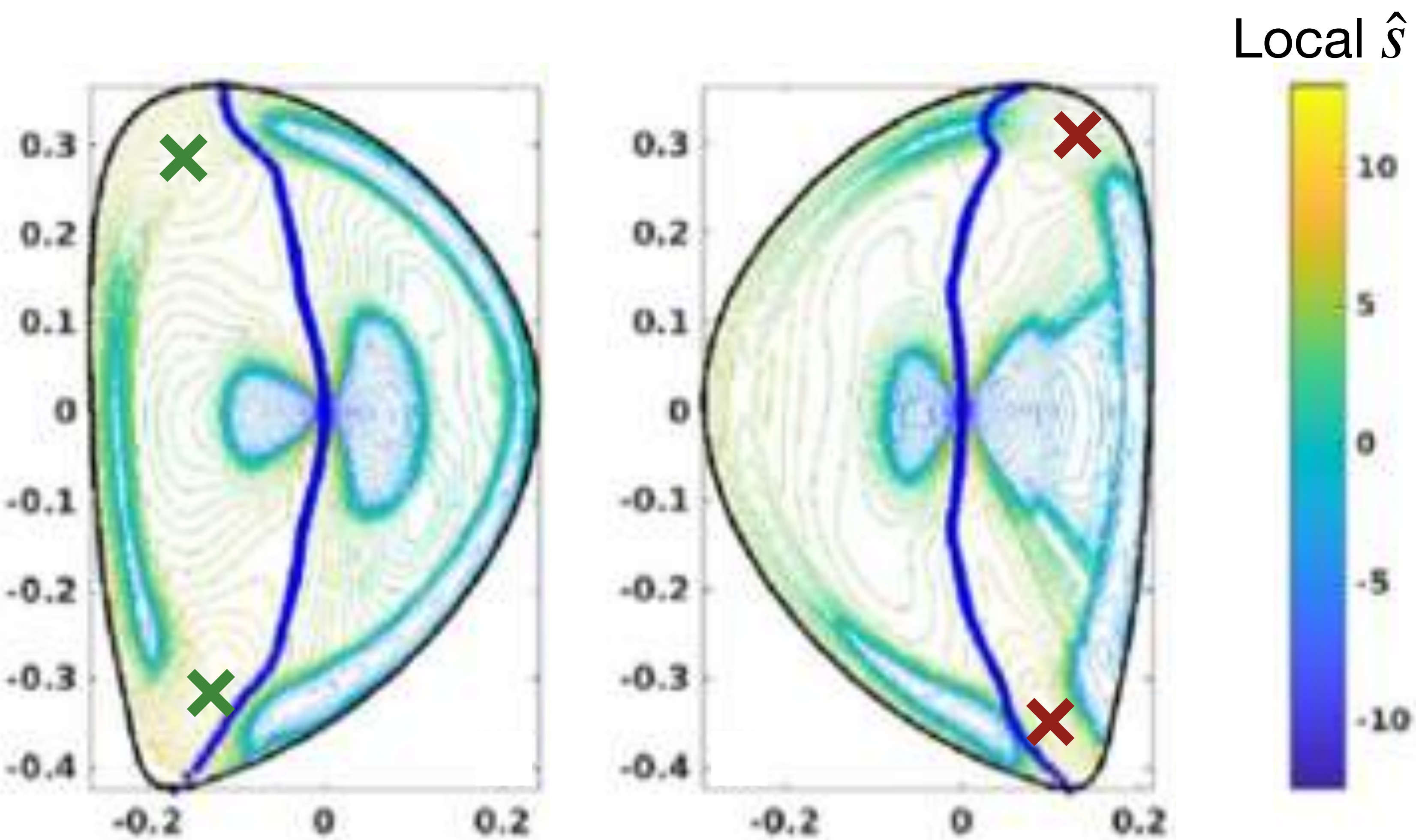
[5] T. Happel. Nucl. Fusion (2023).

- Sufficiently negative δ closes access to the 2nd stability region for infinite-n ballooning modes, which is associated with the transition to H-mode[1-4]

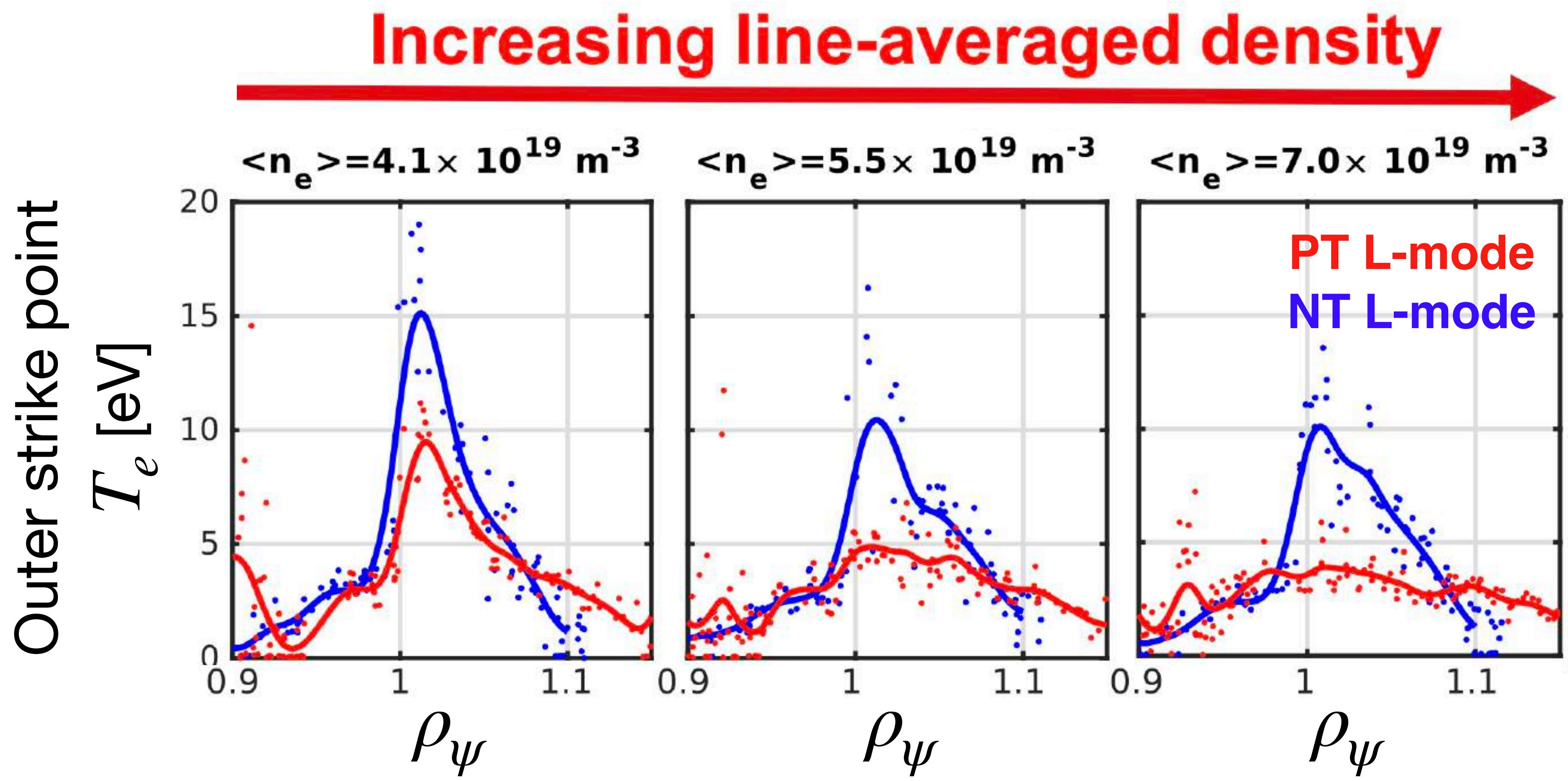
- Developed proxy for blocking the H-mode transition: when the maxima in the edge local magnetic shear crosses into the bad curvature region[2]

- Can be used to explain ASDEX Upgrade results[5]

- Argument appears independent of machine size



3) SOL width

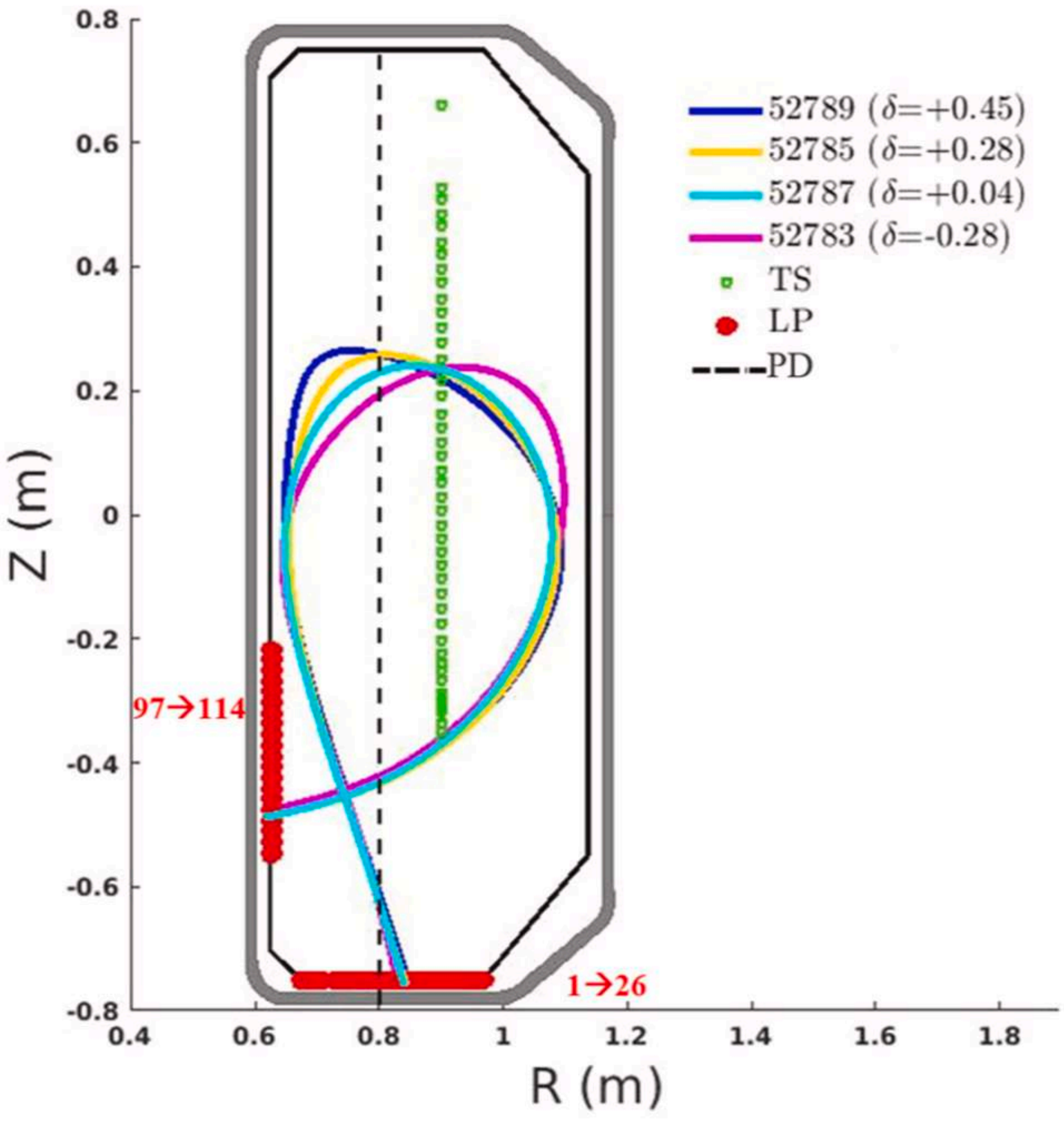


[O. Fevrier. EPS (2023).]

Interpretative study of single null TCV discharges

[1] M. Faitsch. PPCF (2018).
[2] P. Muscente. J. Nucl. Mater. (2023).

- SOLEDGE-EIRENE simulations of a scan in top triangularity δ^{top}[1]
- Radial profiles of diffusivities were tuned within SOLEDGE to match experimental observables



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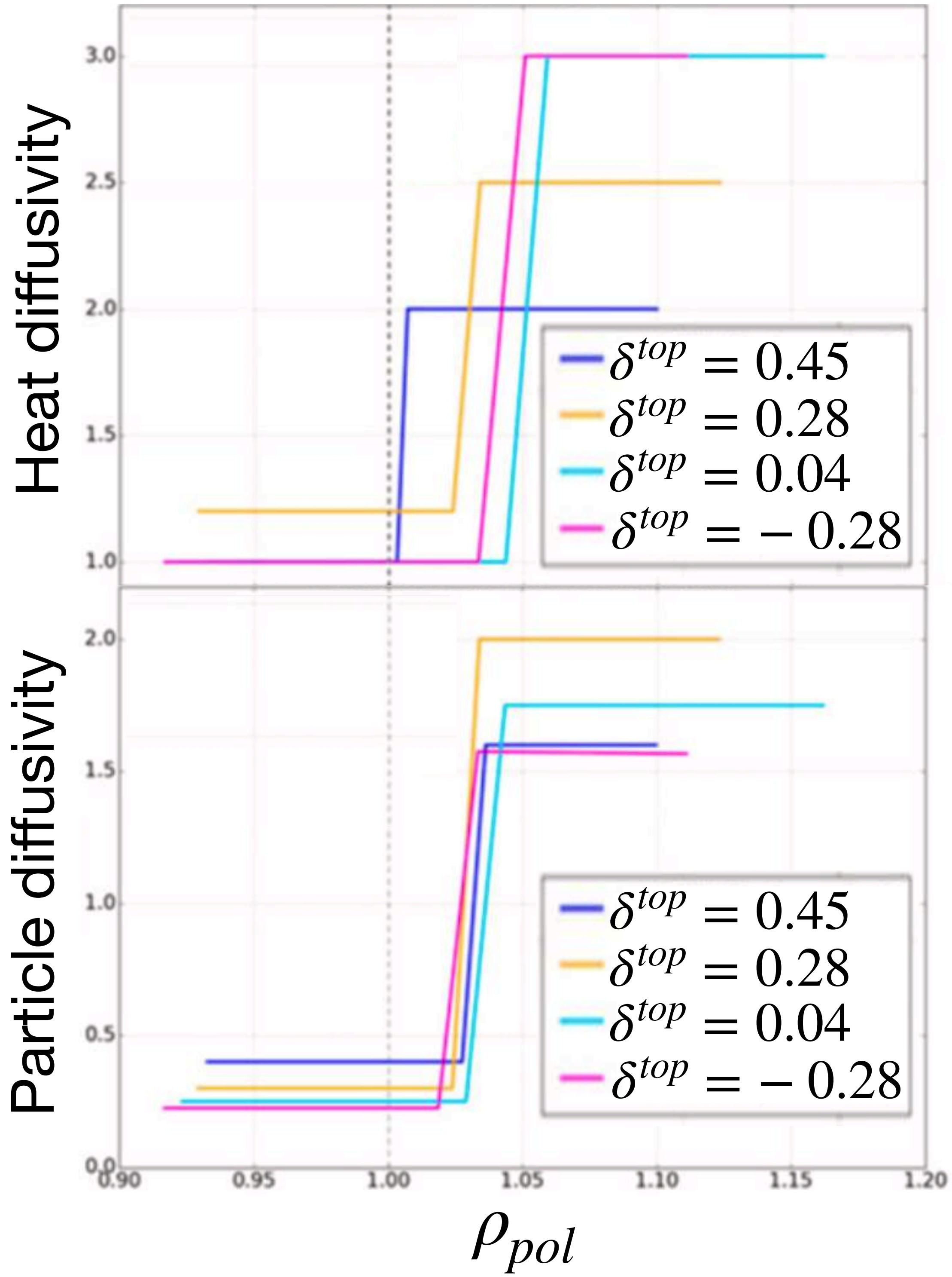

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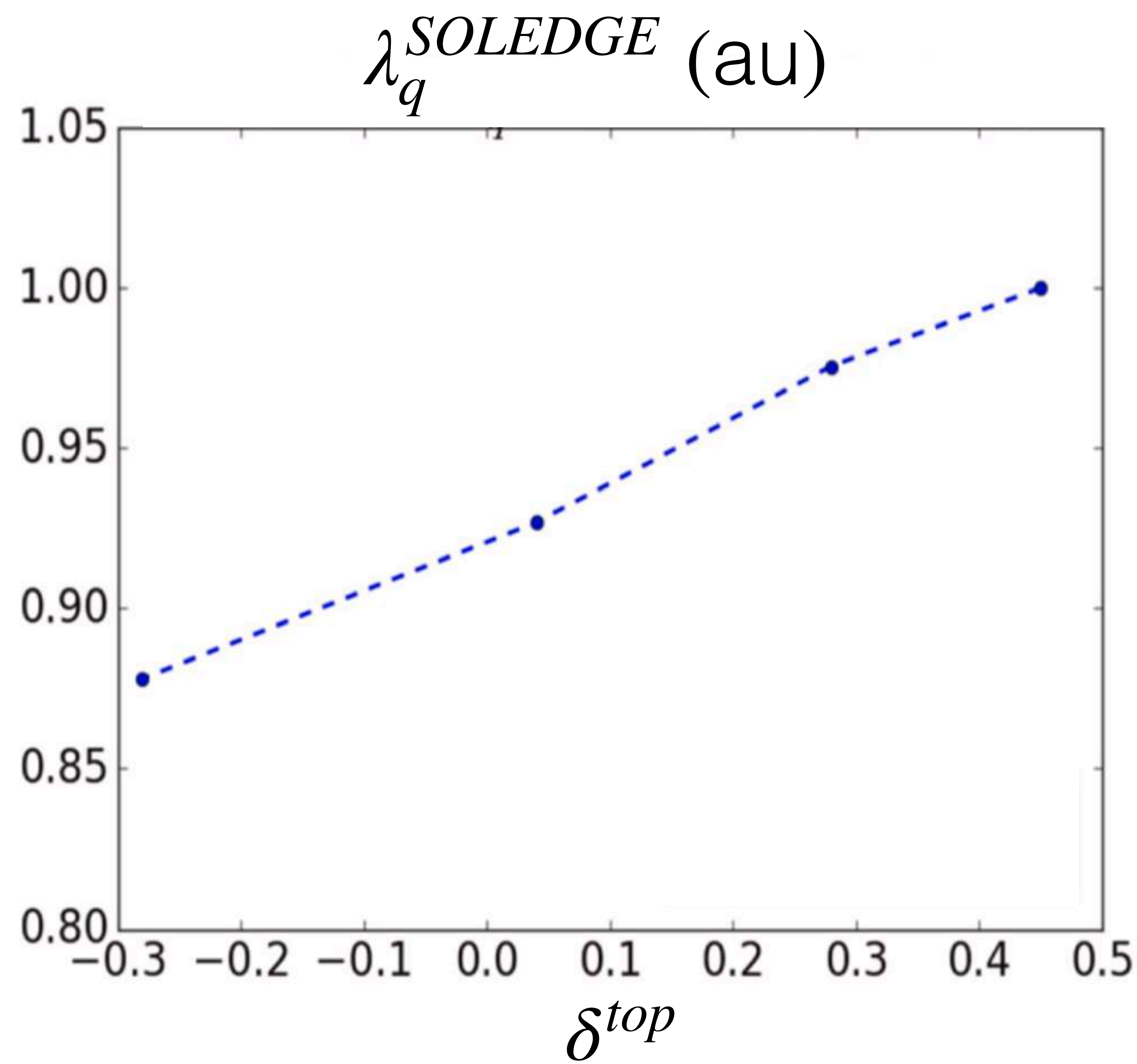
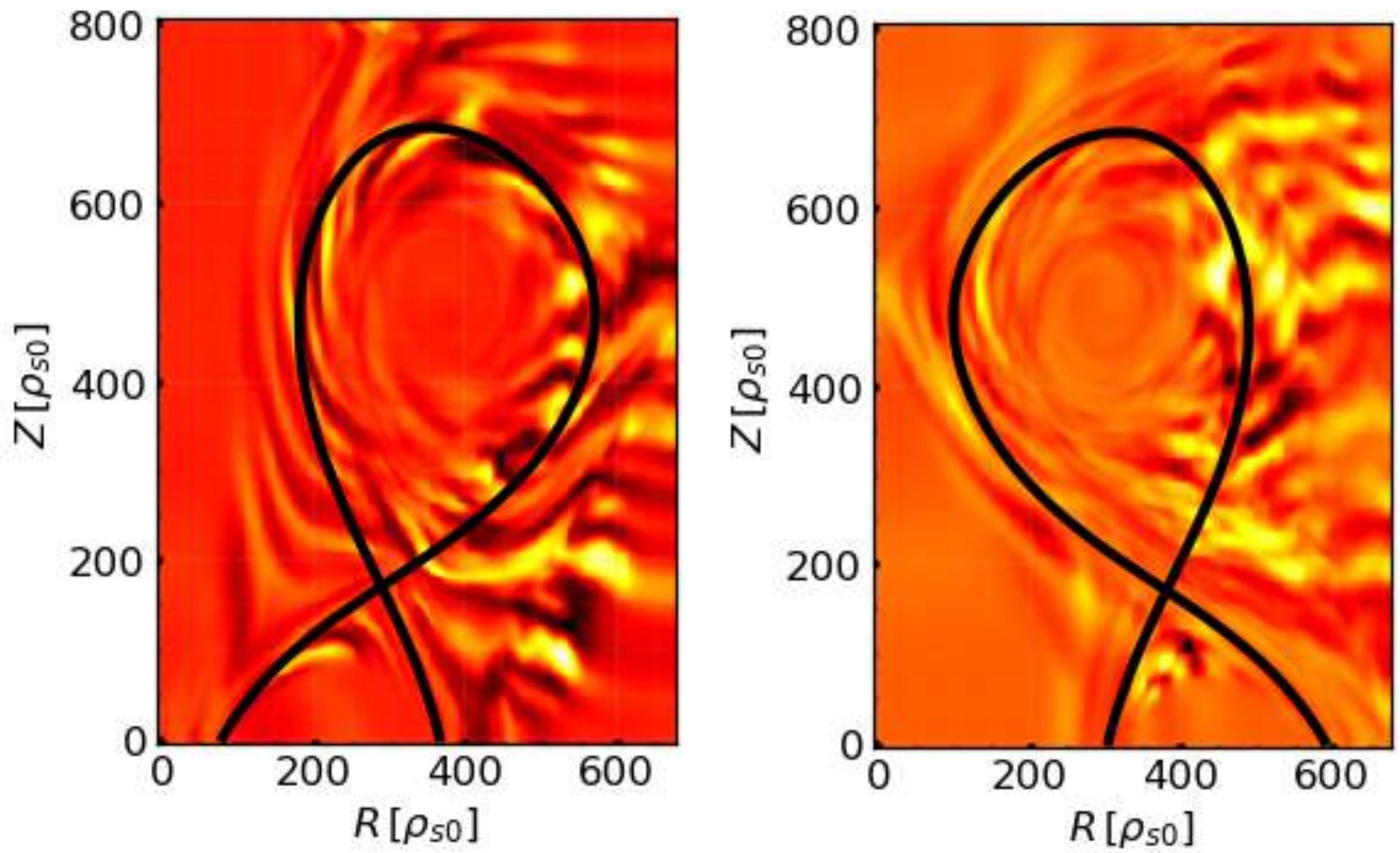
- Radial profiles of diffusivities were tuned within SOLEDGE to match experimental observables
- Matching experiment required a reduced separatrix particle diffusivity for NT (though heat diffusivity was less clear)
- <u>Heat flux decay length at outer midplane measured in these simulations was lowered by NT</u>[2]



Predictive study of single null equilibria

[1] K. Lim. PPCF. (2023).
[2] F. Riva. *PPCF* (2017).
[3] E. Laribi. *Nucl. Mater. Energy* (2021).

- GBS modeled two single null equilibria with varying triangularity $\delta = \pm 0.3$



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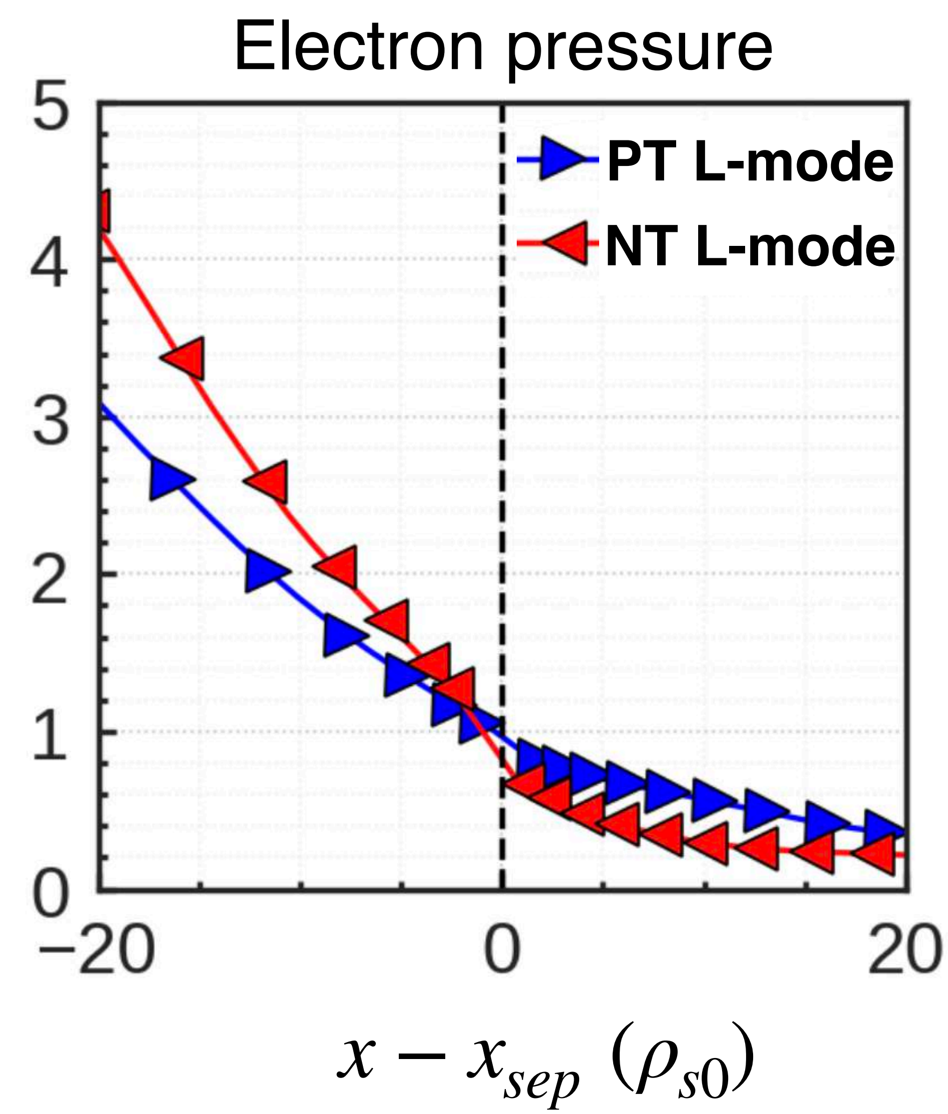
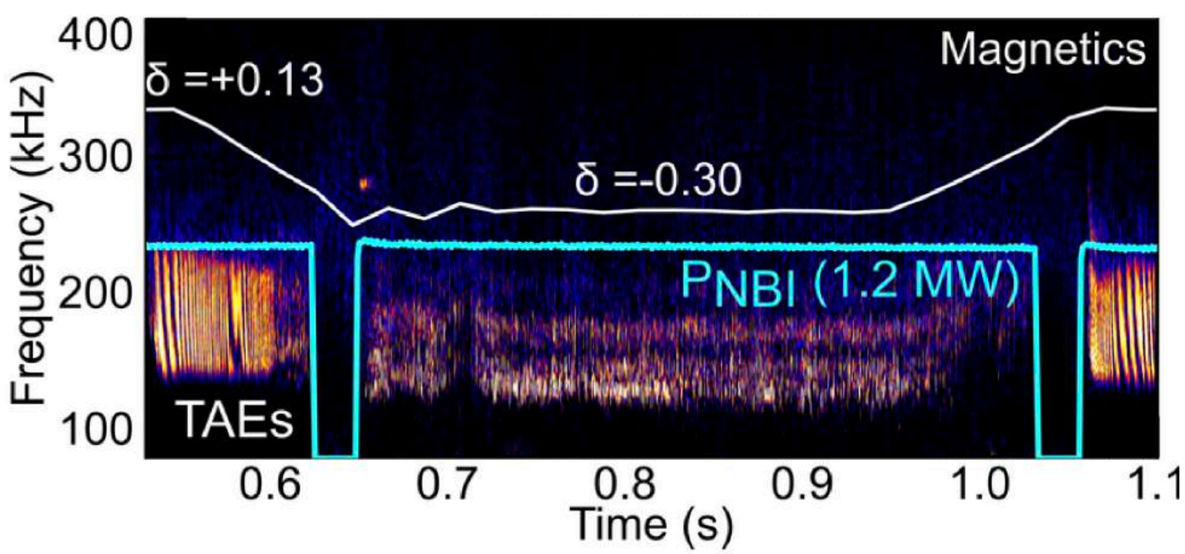
[1] K. Lim. PPCF. (2023).
[2] F. Riva. *PPCF* (2017).
[3] E. Laribi. *Nucl. Mater. Energy* (2021).

- GBS modeled two single null equilibria with varying triangularity $\delta = \pm 0.3$
- NT steepens profile gradients at the separatrix, reducing λ_q by ~30%[1]
- Consistent with past GBS and TOKAM3X work[2,3]
- Appears that λ_q in NT will be intermediate between PT L-mode and PT H-mode
- Intuitive based on the confinement just inside the separatrix

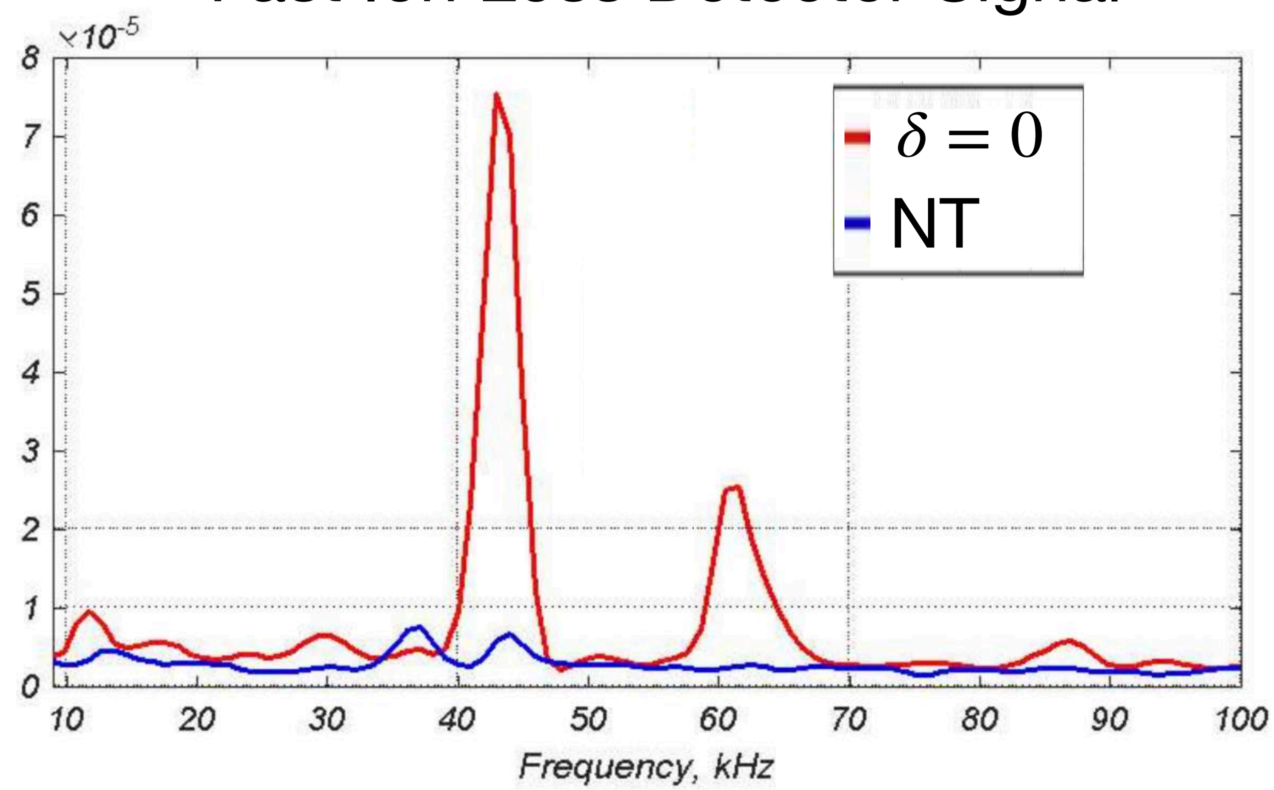


4) Other considerations

TAE Amplitude



Fast Ion Loss Detector Signal



[A.N. Karpushov. EPS (2023).]

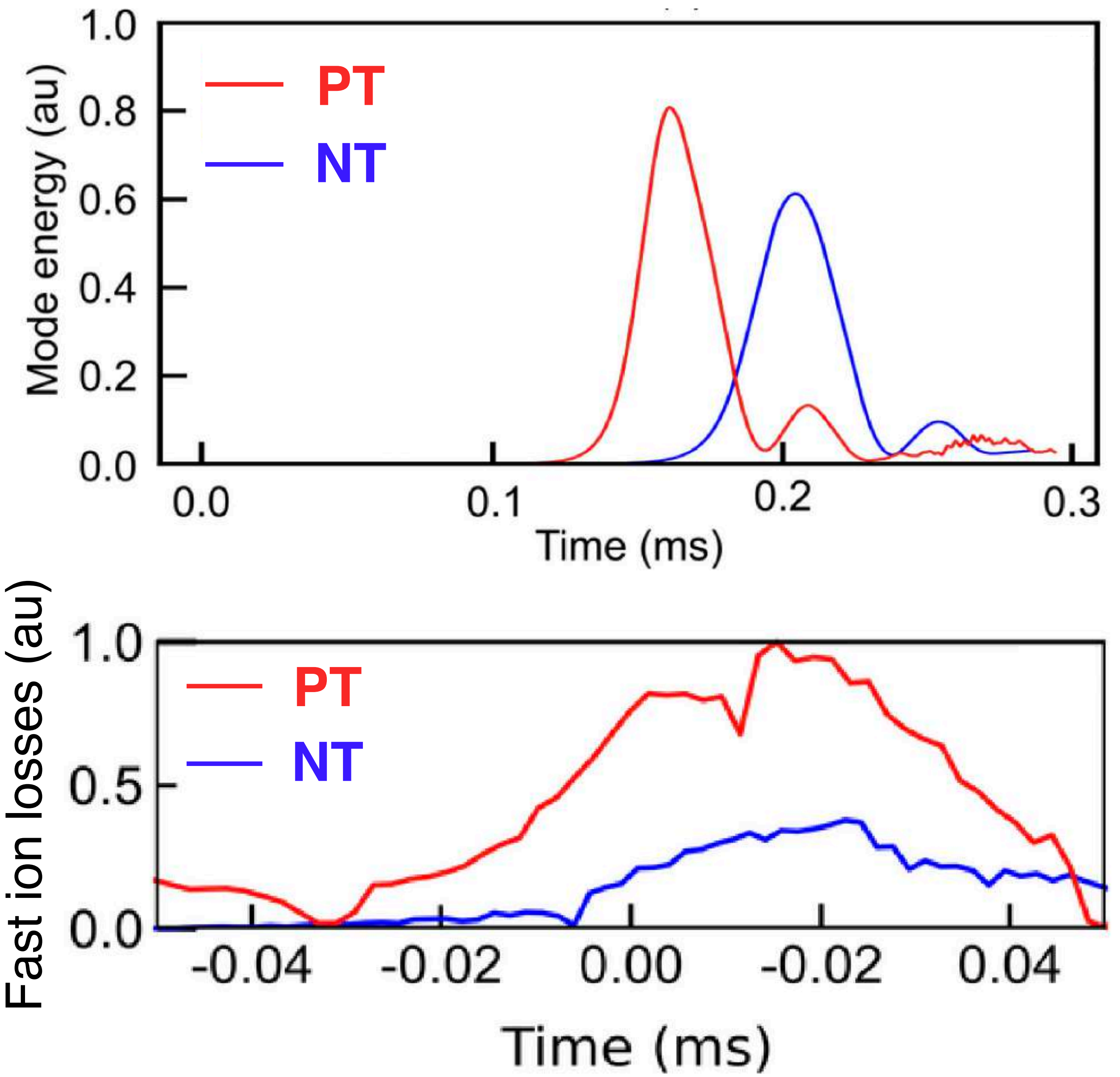
Fast ion driven modes and transport

[1] P. Oyola. IAEA (2023).
[2] A. Karpushov. EPS (2023).

- MEGA analysis of a pair of TCV equilibria show reduction in Toroidal Alfven Eigenmode (TAE) amplitude by 30%[1]

- Resulting TAE-induced fast ion losses to the wall are 3 times smaller in NT[1]

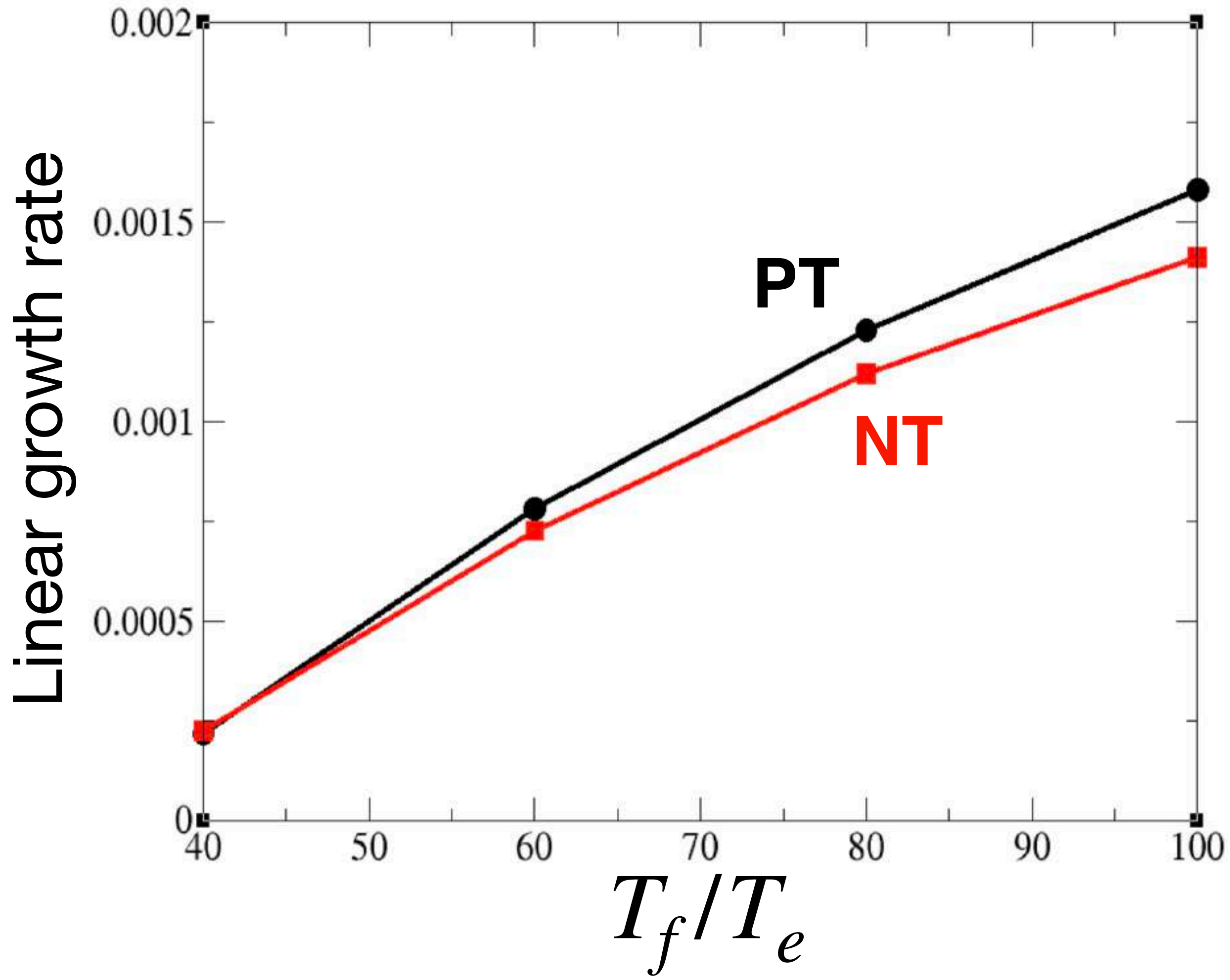
- Both observations are good news for NT and consistent with experimental measurements[2]

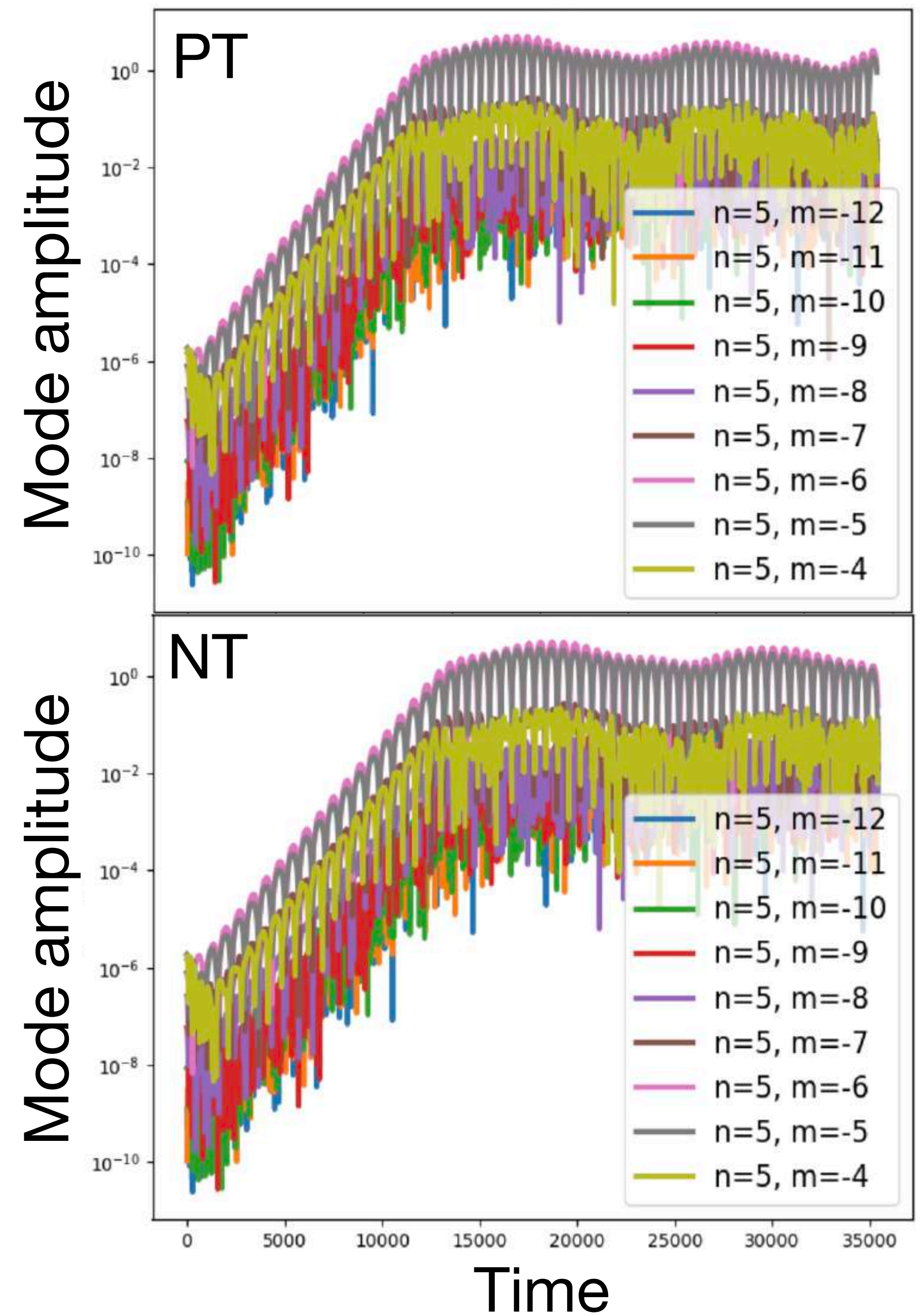


Also consistent with work from TSVV 10

Courtesy of A. Mishchenko

- ORB5 simulations of AEs reveals little direct impact of shape on linear growth rates, nor saturated mode amplitude





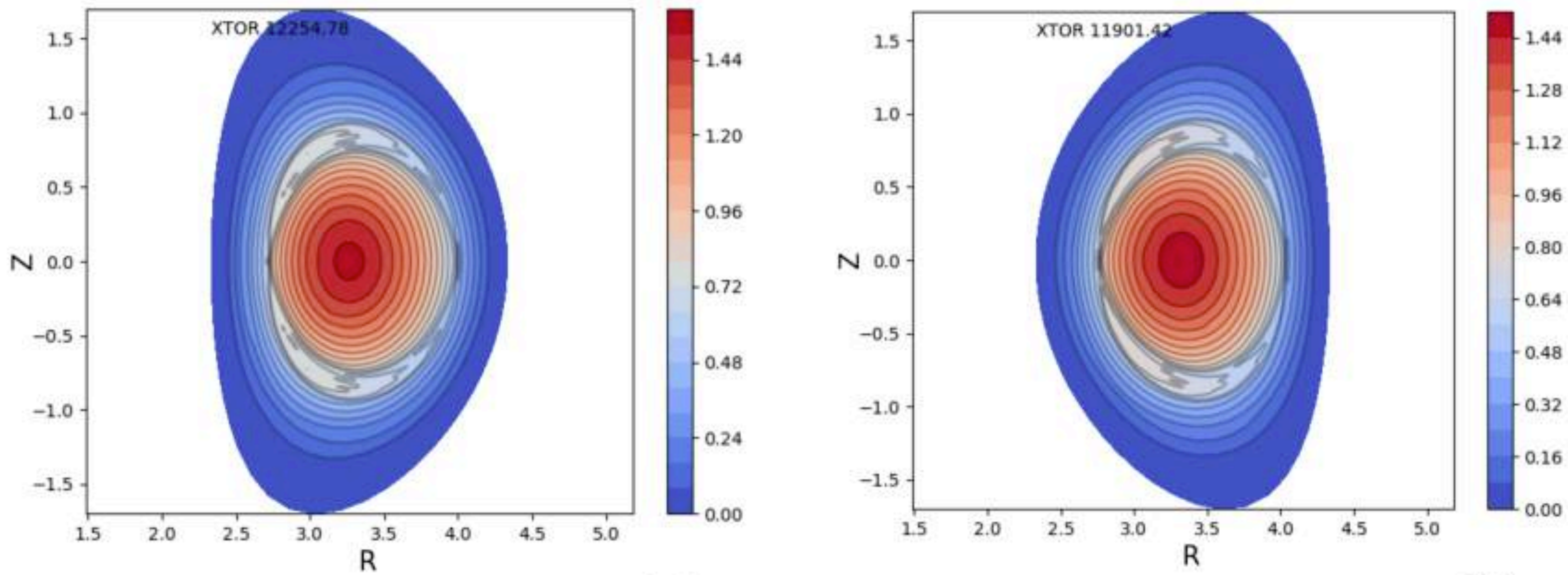
Further work important

Stability of tearing modes

[1] H. Lutjens, et al. *Nucl. Fusion* (1992).
[2] A. Bondenson, et al. *Phys. Plasmas* (1992).
[3] H. Lutjens, et al. *Phys. Plasmas* (2001).

- Significant code improvements to XTOR-K resulted in a ~10x speedup and porting to GPUs underway with ACH collaboration

- Preliminary NT versus PT simulations of 2/1 tearing mode display little direct impact of plasma shape on linear growth rates, nor saturated island size



- Consistent with past analytic work indicating weak destabilization by NT[1-3]

- Impact of L-mode profiles (as opposed to H-mode) expected to dominate

Physics takeaways

- GK finds better confinement in NT and we now believe we understand why
- NT may degrade confinement in spherical tokamaks (testable on SMART)
- Profile shearing and electromagnetic effects appear similar in PT and NT, suggesting confinement improvement will scale to a reactor
- Good agreement between ASTRA-TGLF and GENE
- Interpretative and predictive SOL simulations indicate that λ_q in NT will be between PT L-mode and PT H-mode
- NT and PT similar for fast ion physics, Alfven eigenmodes, tearing modes

Areas of priority for future work

- Electromagnetic turbulence — verify that conventional aspect ratio differs from spherical tokamaks
- Impurity transport — little work done thus far
- Core integrated modeling — important to include $\rho_{tor} > 0.9$ (strengthen ties with relevant TSVVs)
- Detachment — TCV experiments suggest that this is more difficult in NT than PT L-mode
- MHD stability — investigate impact of L vs. H-mode profiles

Thank you to EUROfusion for their support.

This work has been carried out within the framework of the EUROfusion Consortium, partially funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). The Swiss contribution to this work has been funded by the Swiss State Secretariat for Education, Research and Innovation (SERI). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union, the European Commission or SERI. Neither the European Union nor the European Commission nor SERI can be held responsible for them.

Appendix:
Summary of
milestones and deliverables

Green text — Task accomplished
Orange text — Task partially accomplished
Red text — Task not accomplished
Grey text — Task scheduled for the future

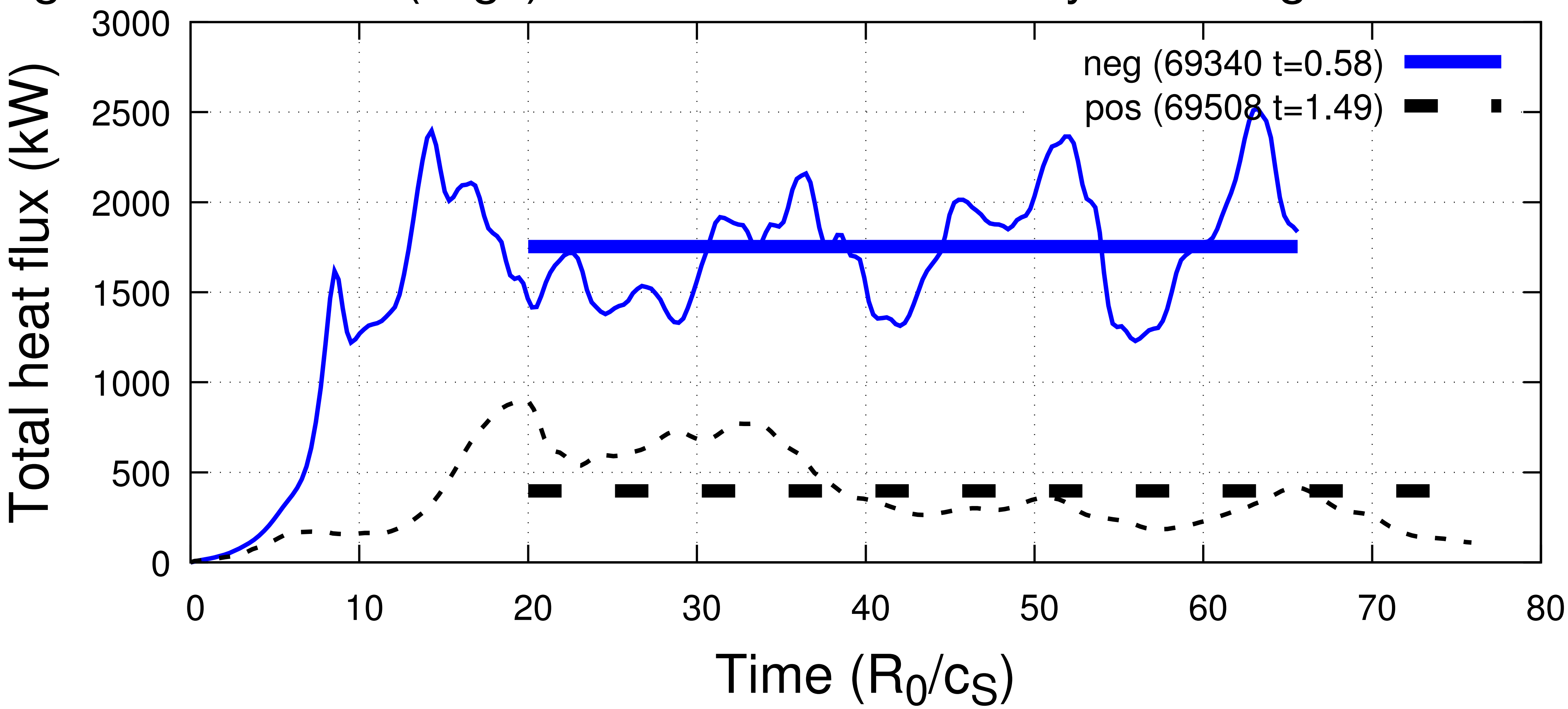
Deliverable 1 summary — turbulent transport

Milestone	Description	Participants	Target date
M1.1.1	Use local electrostatic GK simulations to assess magnetic equilibria and plasma profiles for consistency with design objectives	J. Ball	02.2021
M1.1.2	Perform local electrostatic GK simulations of PT and NT equilibria and swap individual geometric coefficients and plasma parameters to identify the dominate terms	J. Ball	08.2021
M1.1.3	Perform comprehensive study of critical gradient and stiffness as a function of minor radius using local GK simulations	J. Ball	12.2021
M1.1.4	Investigate possibility of further improvements using other plasma shapes	J. Ball, G. Di Giannatale	12.2025
M1.2	Integrate findings from the ERG on global flux driven GK simulations of TCV-like NT discharges (including impurity transport) into this TSVV; specifically comparing trends against the GENE results when possible	P. Donnel, J. Ball	8.2022
M1.3.1	Perform GBS simulations to understand the effect of plasma triangularity on single-null configurations with no neutrals	K. Lim	12.2021
M1.3.2	Perform GBS simulations to understand the effect of plasma triangularity on double-null configurations with no neutrals	K. Lim	12.2022
M1.3.3	Perform GBS simulations to understand the role of neutral dynamics on single- and double-null configurations in negative-triangularity plasmas, exploring the detachment regimes	K. Lim	12.2023
M1.3.4	Perform GBS simulations to understand the effect of plasma triangularity on alternative exhaust configurations	K. Lim	12.2025
M1.4	Predictive simulations using SOLEDGE3X for power exhaust on NT DTT L-mode discharges	P. Muscente	6.2024

Deliverable	Description	Participants	Target date	Evidence of achievement
D1.1	Report on properties of core and pedestal turbulent transport in NT as compared to PT, in particular identifying the important physical effects responsible for the difference	J. Ball, G. Di Giannatale	12.2022	See pinboard IDs 36044, 34331, 32978, paper, conference proceeding, conference contribution
D1.2	Report on properties of power exhaust in current NT experiments as compared to PT	K. Lim, P. Muscente	12.2022	See pinboard ID 34453 and conference contribution
D1.3	Report on power exhaust prospects for NT reactors as compared to PT	K. Lim, P. Muscente	12.2024	N/A
D1.4	Report on using understanding of NT to optimize the plasma shape further	J. Ball, G. Di Giannatale	12.2025	See pinboard ID 34331

M1.1.1: Use local GK to assess exp. consistency

- Initial simulations of TCV equilibria dramatically disagreed with experiment, but agreement within (large) error bars was found by including collisions



Description	Constants of comparison	Machine	Discharge	Time (sec)	elong	delta	betaN	P_nbi (kW)
Diverted, PT	Ip, betaN, ne	TCV	69508	1.49	1.43	+0.28	1.12	735
Diverted, NT	Ip, betaN, ne	TCV	69340	0.58	1.42	-0.28	0.97	362

M1.1.2: Swap geo. coeff. to find dominant terms

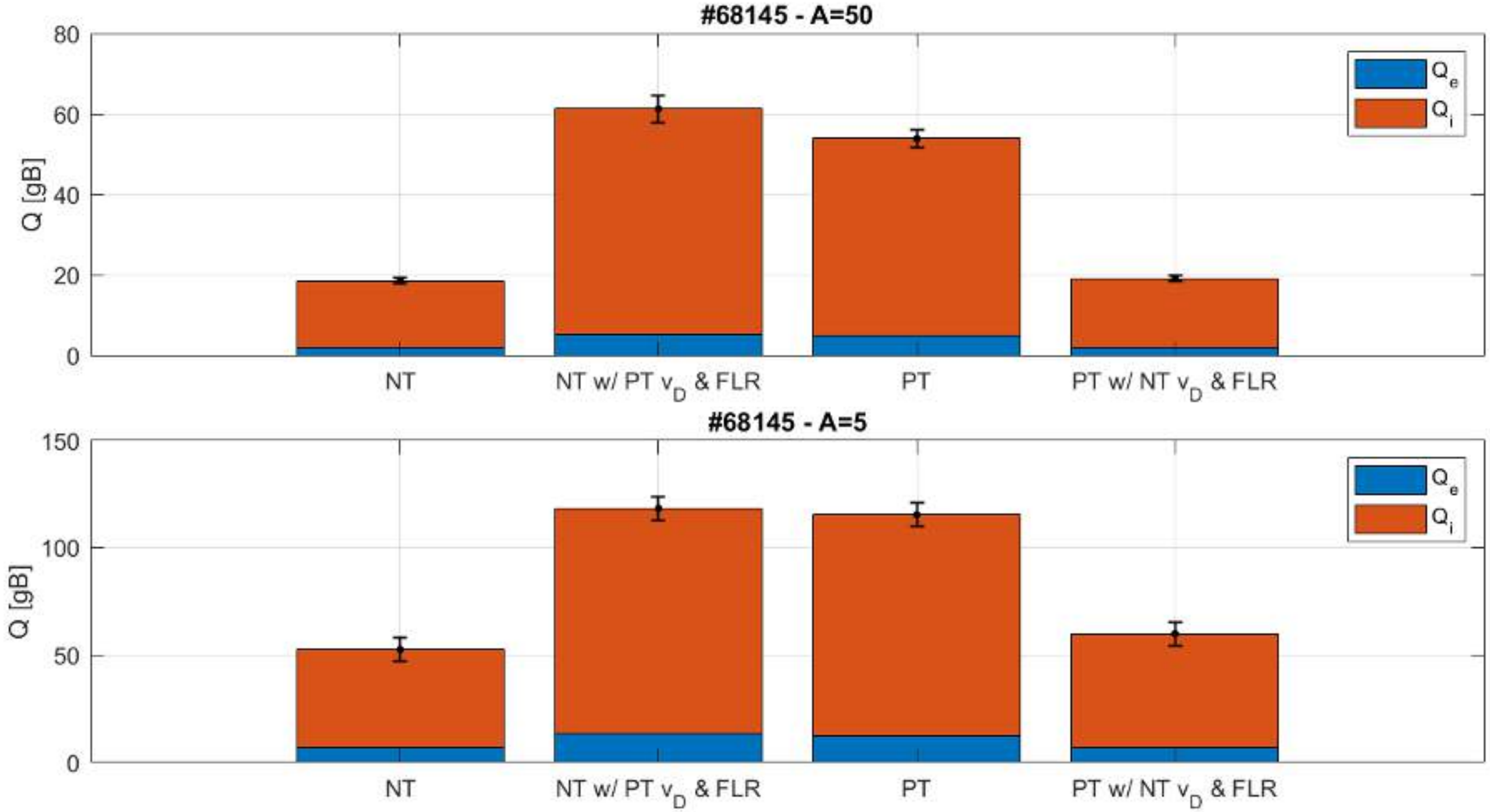
A. Balestri, et al. EPS (2023).

J. Parisi, et al. *Nucl. Fusion* (2020).

- Crucial step was to first look in the large aspect ratio limit

- Physical picture shows that magnetic drifts and FLR effects are dominant

- Also studied aspect ratio A dependence, revealing NT can be harmful in spherical tokamaks

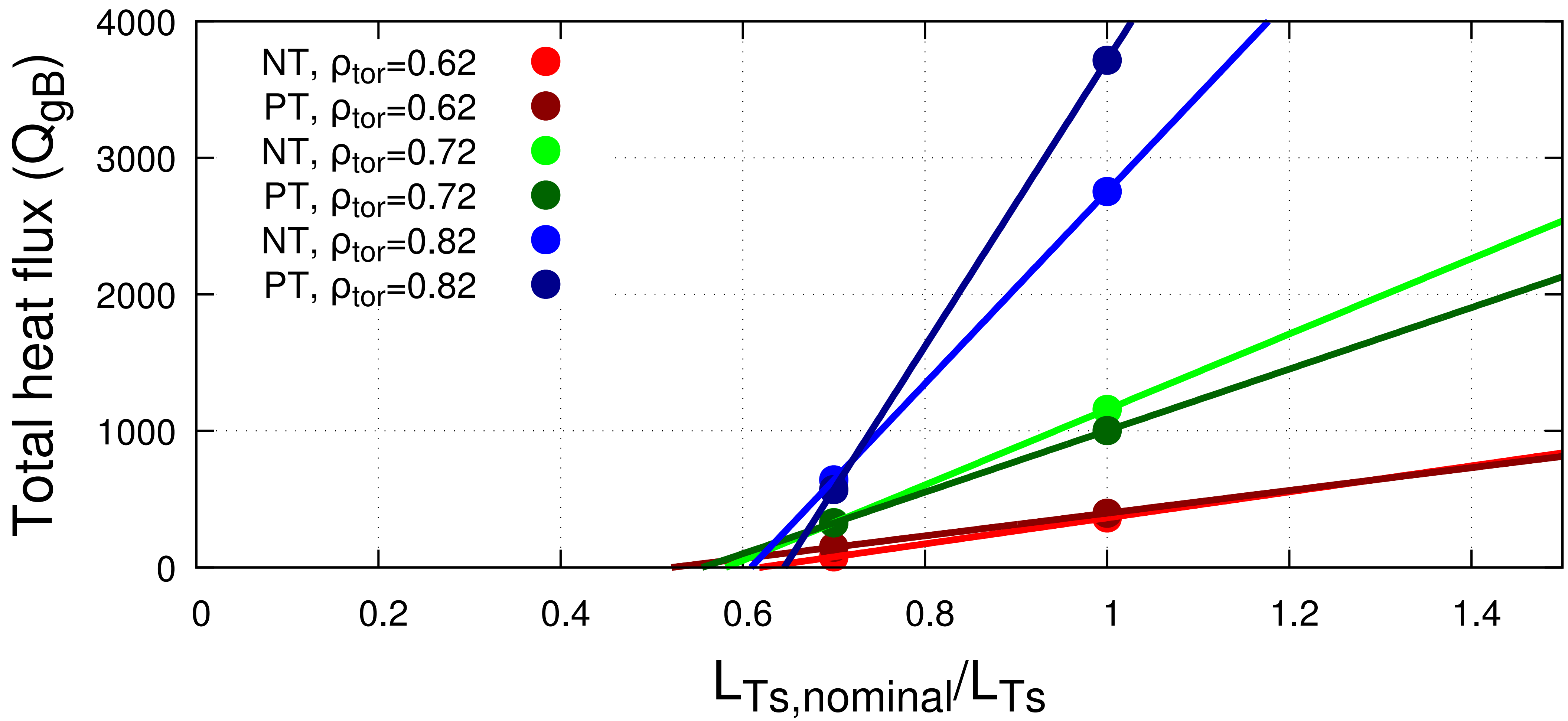


M1.1.3: Critical gradient and stiffness study

J. Ball. PMI-5.2.1-T050 (2020).

G. Merlo, et al. *PPCF* (2015).

- When effect of δ is isolated, profile stiffness is similar, critical gradients differ
- True for ITG-dominated EU DEMO scenarios (below), idealized pure ITG cases, DTT cases, and Merlo's original TEM TCV cases



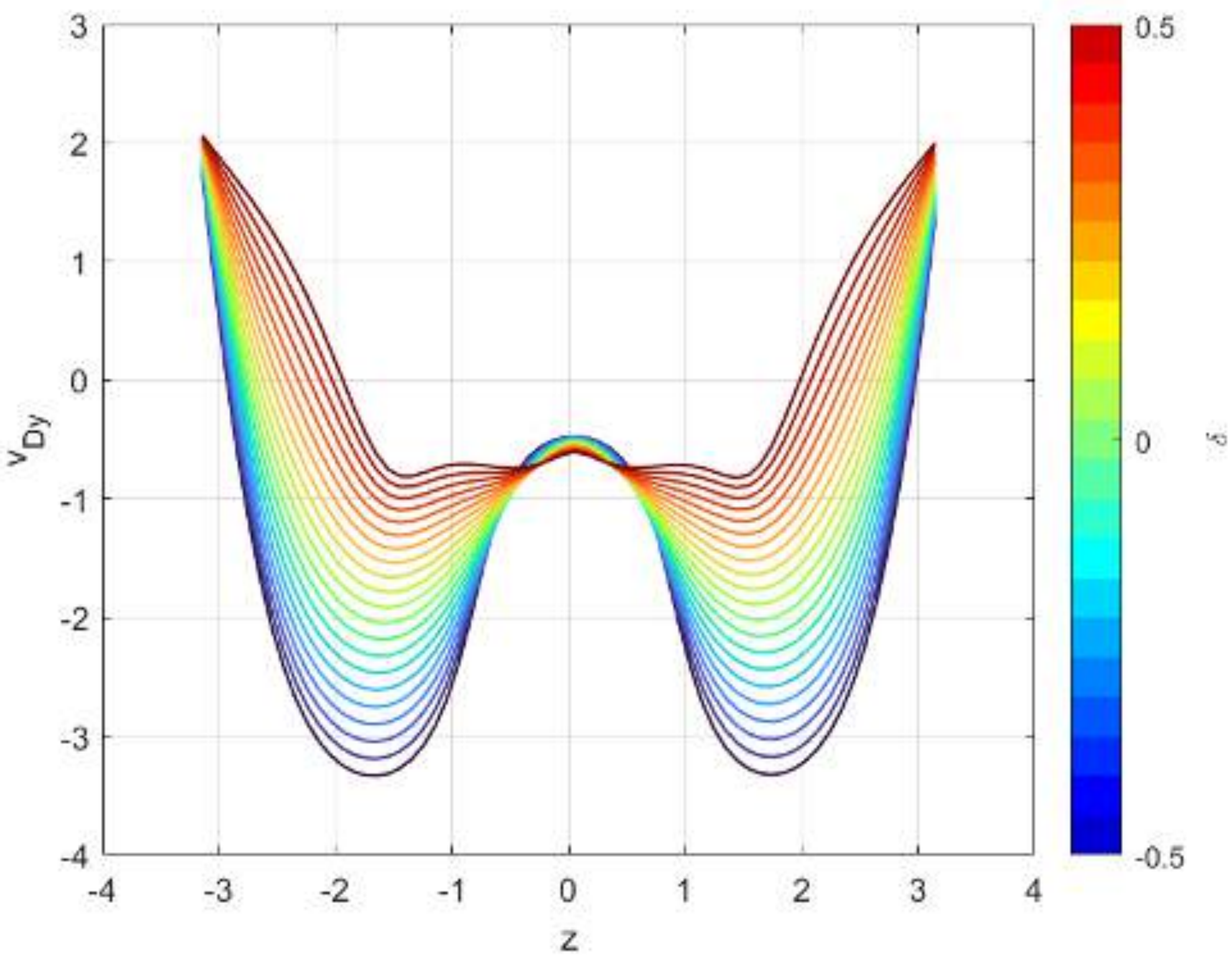
M1.1.4: Investigate improvements beyond NT

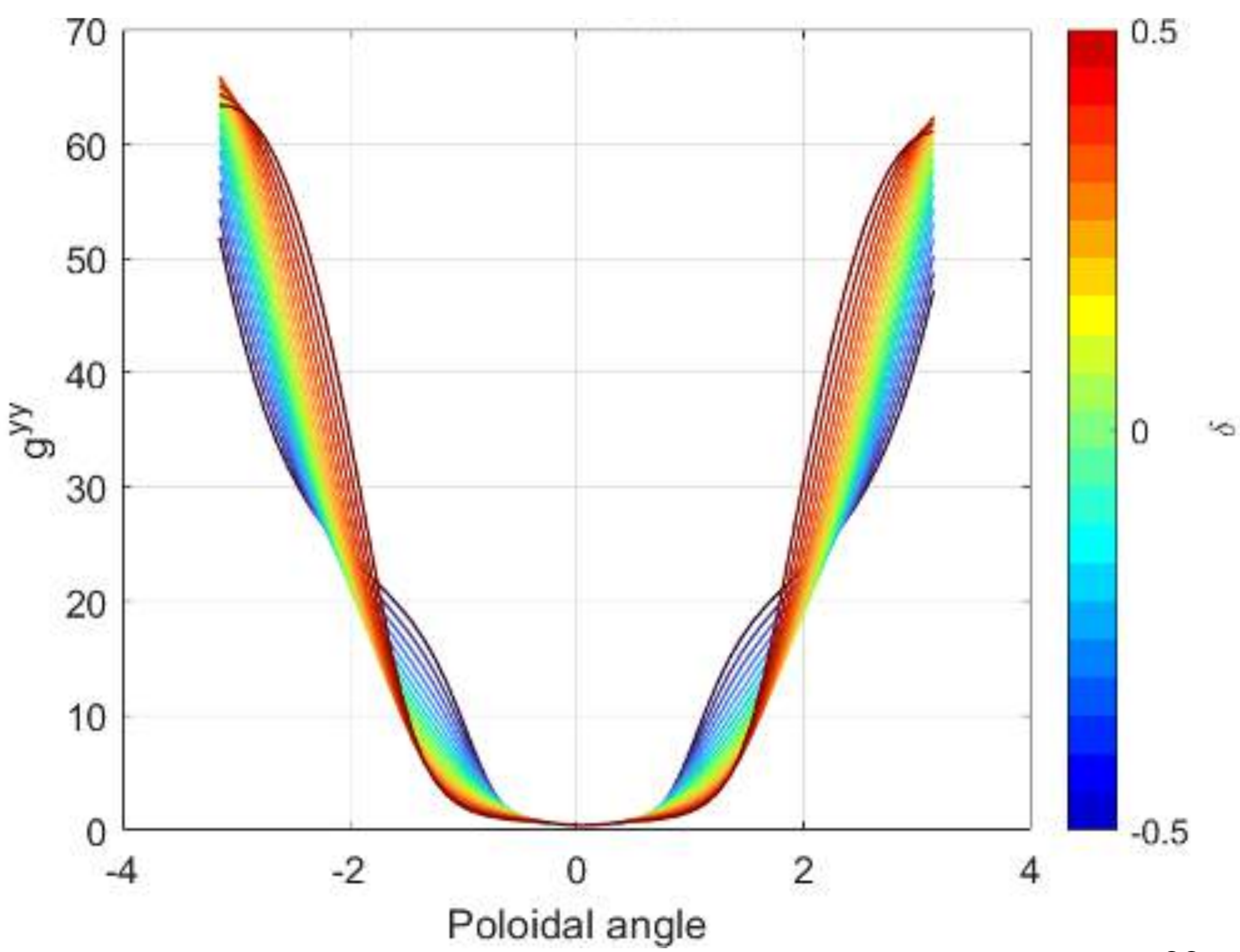
[A. Balestri, et al. EPS (2023).](#)

J. Parisi, et al. *Nucl. Fusion* (2020).

- Physical picture from M1.1.2 can be used to quickly evaluate other shapes in the large aspect ratio limit

- So far nothing obviously better, but haven't looked too much

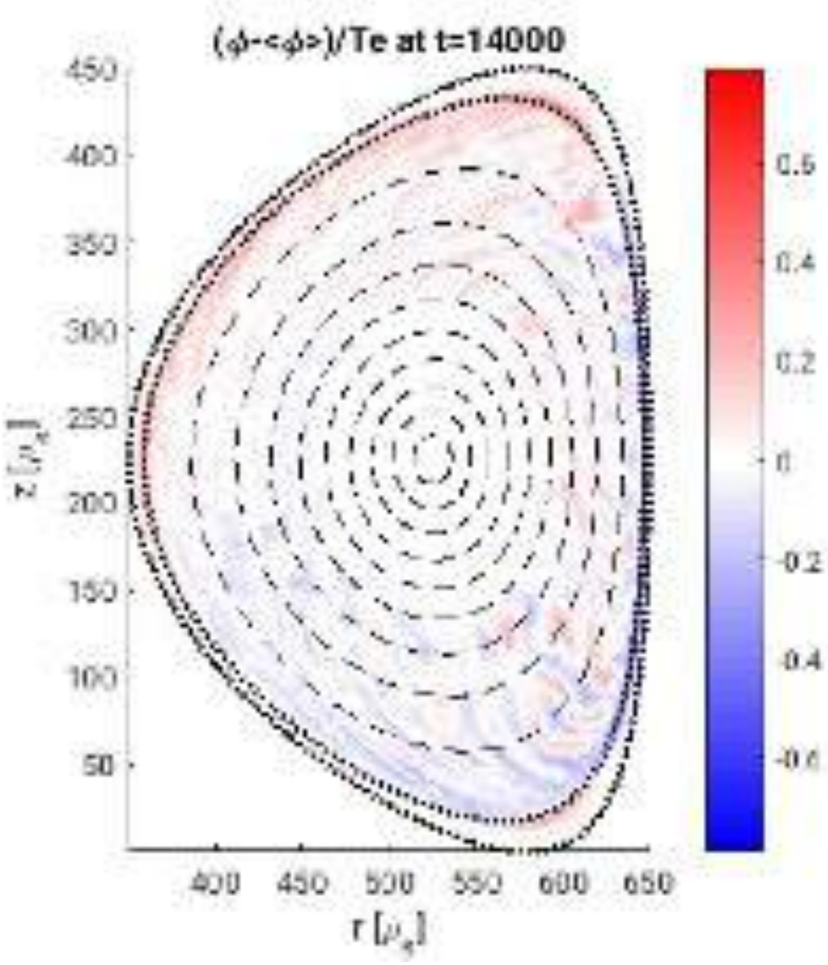


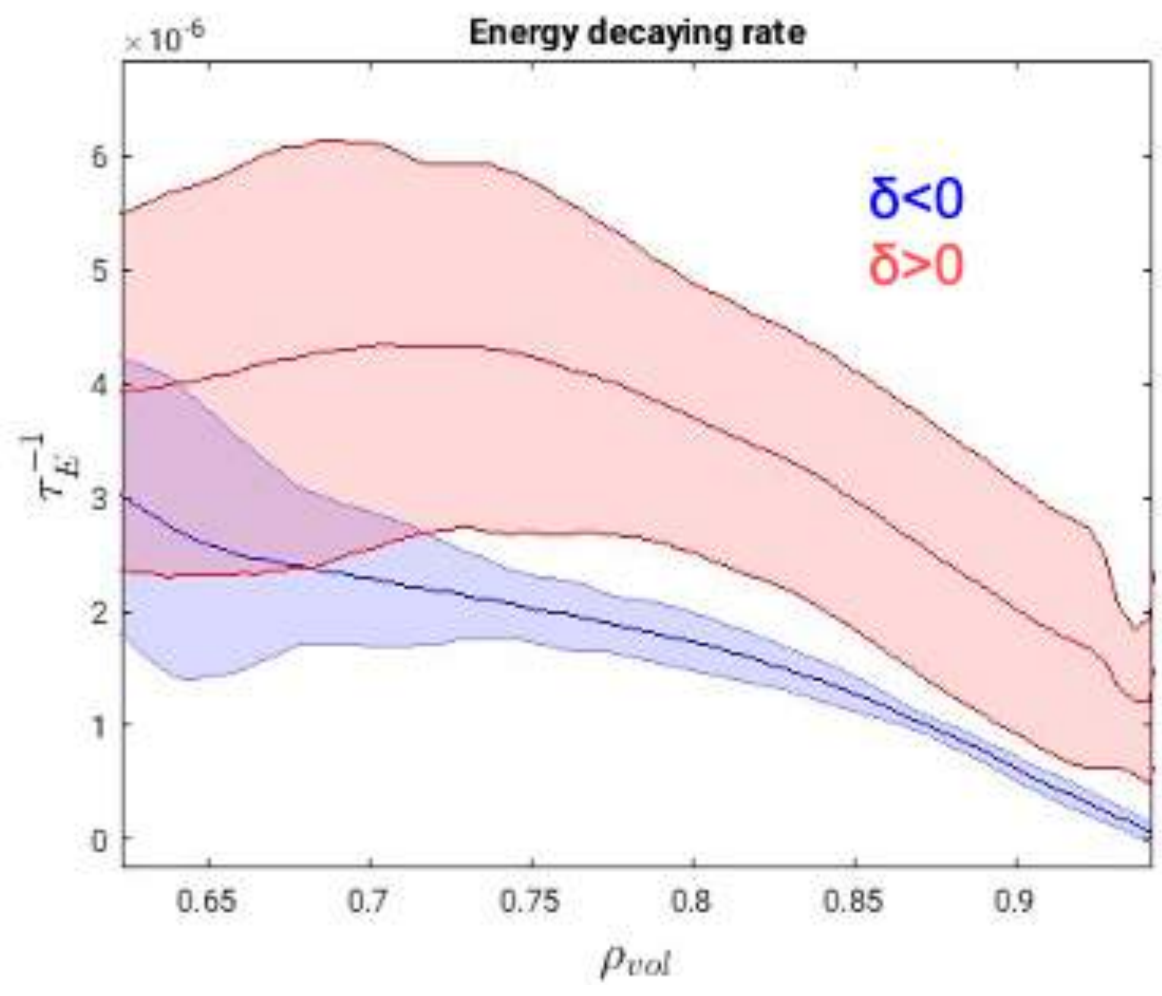


M1.2: Integrate findings of ERG

P. Donnel. EUROfusion IDM TRA-ERG.AWP20.EPFL (2022).

- Initial ORB5 simulations indicated improved confinement in NT, but needed to model at least trapped electrons kinetically and collisions were also important
- Not in quasi-steady state and no results for impurity transport

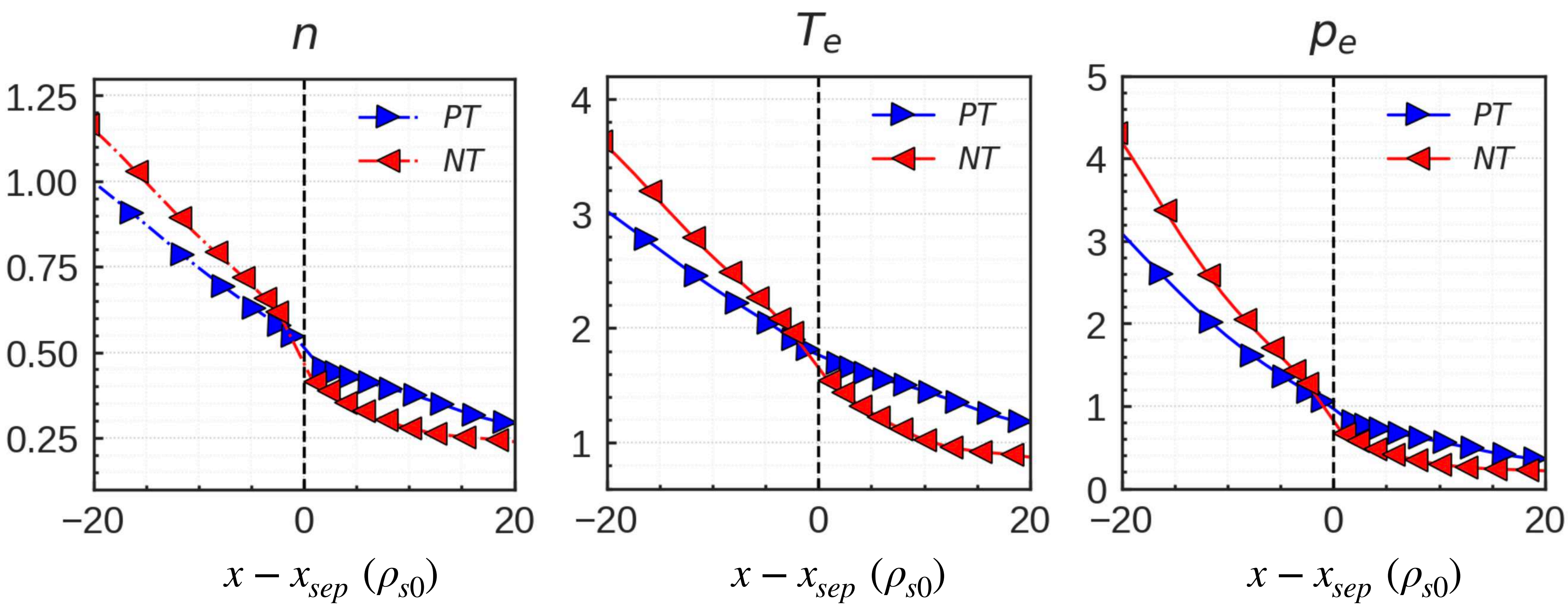




M1.3.1: GBS single-null simulations

K. Lim, et al. PPCF (2023).

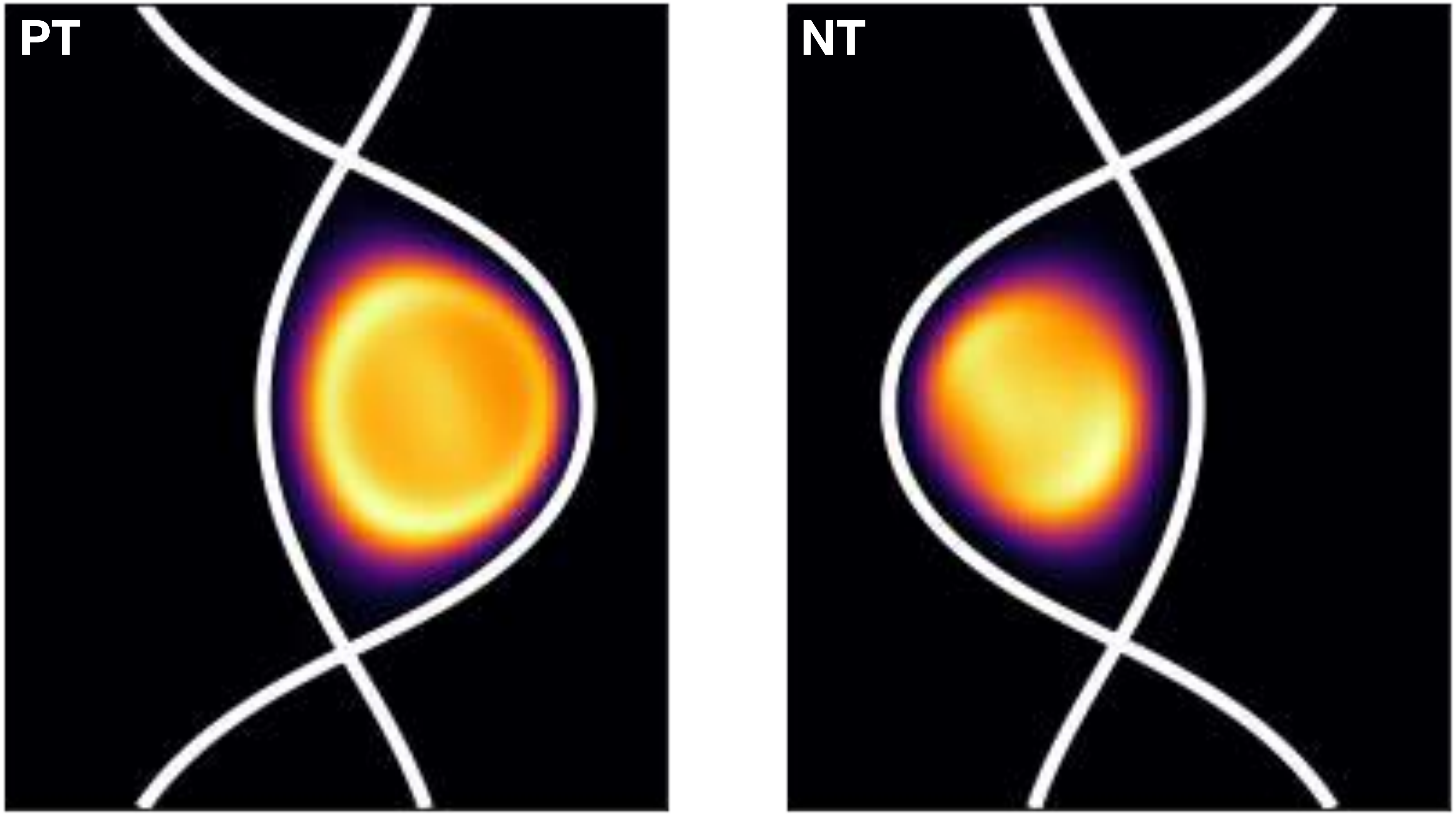
- GBS using $\delta = \pm 0.3$ finds that NT improves the energy confinement time, but steepens the profile gradients at the separatrix, thereby reducing λ_q by ~30%



- Similarly, a theory-based scaling law that was developed predicts 40% lower λ_q for NT

M1.3.2: GBS double-null simulations

- A series of double-null simulations using the equilibria below are currently being performed with GBS, but are not yet complete



Deliverable 2 summary — MHD stability

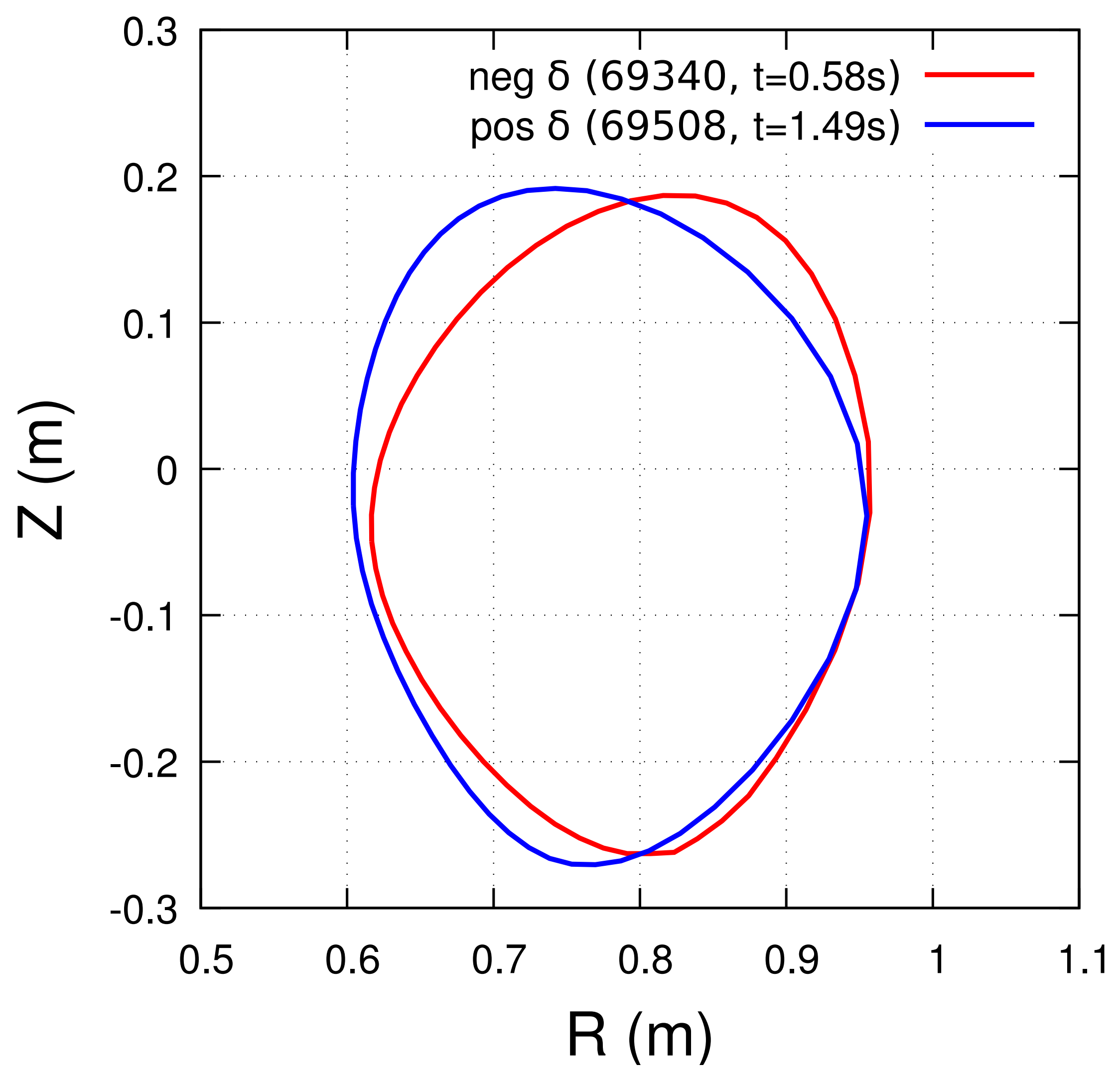
Milestone	Description	Participants	Target date
M2.1.1	Use KINX calculations to assess magnetic equilibria and plasma profiles for consistency with design objectives	O. Sauter	6.2021
M2.1.2	Study ideal n=0, n=1 MHD stability with KINX	O. Sauter	12.2022
M2.1.3	Study NT pedestal stability using EPED (after validating the empirical constants)	O. Sauter	12.2025
M2.2.1	Use HYMAGYC to investigate kinetic corrections to MHD	G. Fogaccia	12.2021
M2.2.2	Use HYMAGYC to investigate Alfvénic modes driven by energetic particles, with particular reference to DTT NT equilibria	G. Fogaccia	12.2023
M2.2.3	Use HYMAGYC to investigate the kinetic effects of energetic particles and core ions on the renormalized plasma inertia (compressibility) in scenarios of interest to plasmas close to ignition	G. Fogaccia	12.2025
M2.3.1	Influence of NT on the stability limits of tearing modes and NTMs with XTOR-K	H. Luetjens	12.2021
M2.3.2	Nonlinear interactions between fast ions, tearing and NTMs in NT plasmas	H. Luetjens	12.2022

Deliverable	Description	Participants	Target date	Evidence of achievement
D2.1	Report on properties of tearing modes in NT as compared to PT	H. Luetjens	12.2022	Delayed for technical reasons due to upgrades to XTOR-K
D2.2	Report on MHD stability properties of NT equilibria, including non-ideal effects in NT DTT equilibria and pedestal studies	O. Sauter, G. Fogaccia	12.2023	N/A

M2.1.1: Consistency of equilibrium with objectives

TSVV 2 wiki.

- Due to experimental constraints, we did not fix proximity to MHD stability limits, but instead created multiple pairs of equilibria with different quantities (e.g. P_{heat}, $\langle n_e \rangle$, β_N) kept fixed between NT and PT

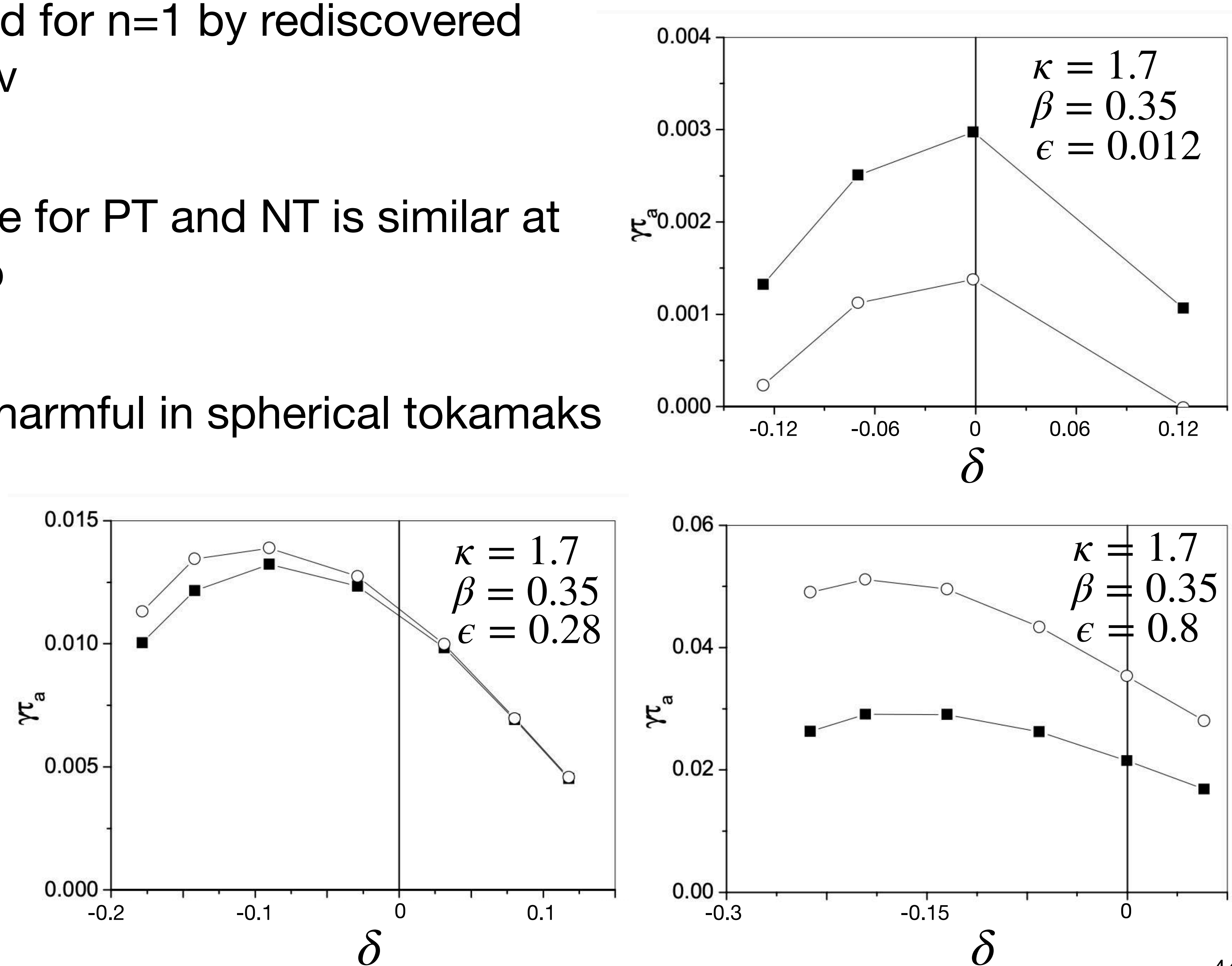


Comp. Num.	Description	Constants of comparison	Discharge	Time (sec)	elong	delta
1	Diverted, PT	q95, betaN	69515	1.02	1.43	+0.29
1	Diverted, NT	q95, betaN	69340	0.58	1.42	-0.28
2	Diverted, PT	q95, ne, Pheat	69515	1.02	1.43	+0.29
2	Diverted, NT	q95, ne, Pheat	69271	1.60	1.42	-0.27
3	Diverted, PT	Ip, betaN, ne	69508	1.49	1.43	+0.28
3	Diverted, NT	Ip, betaN, ne	69340	0.58	1.42	-0.28
4	Limited, PT	Ip, betaN, ne	69511	1.50	1.34	+0.35
4	Limited, NT	Ip, betaN, ne	69273	0.85	1.29	-0.29
5	Limited, PT	Ip, Pheat	69511	1.50	1.34	+0.35
5	Limited, NT	Ip, Pheat	69273	1.70	1.26	-0.26
-	Diverted, PT	-	69515	1.58	1.43	+0.34
-	Diverted, NT	-	69340	1.60	1.40	-0.27

M2.1.2: Study n=0, n=1 MHD stability

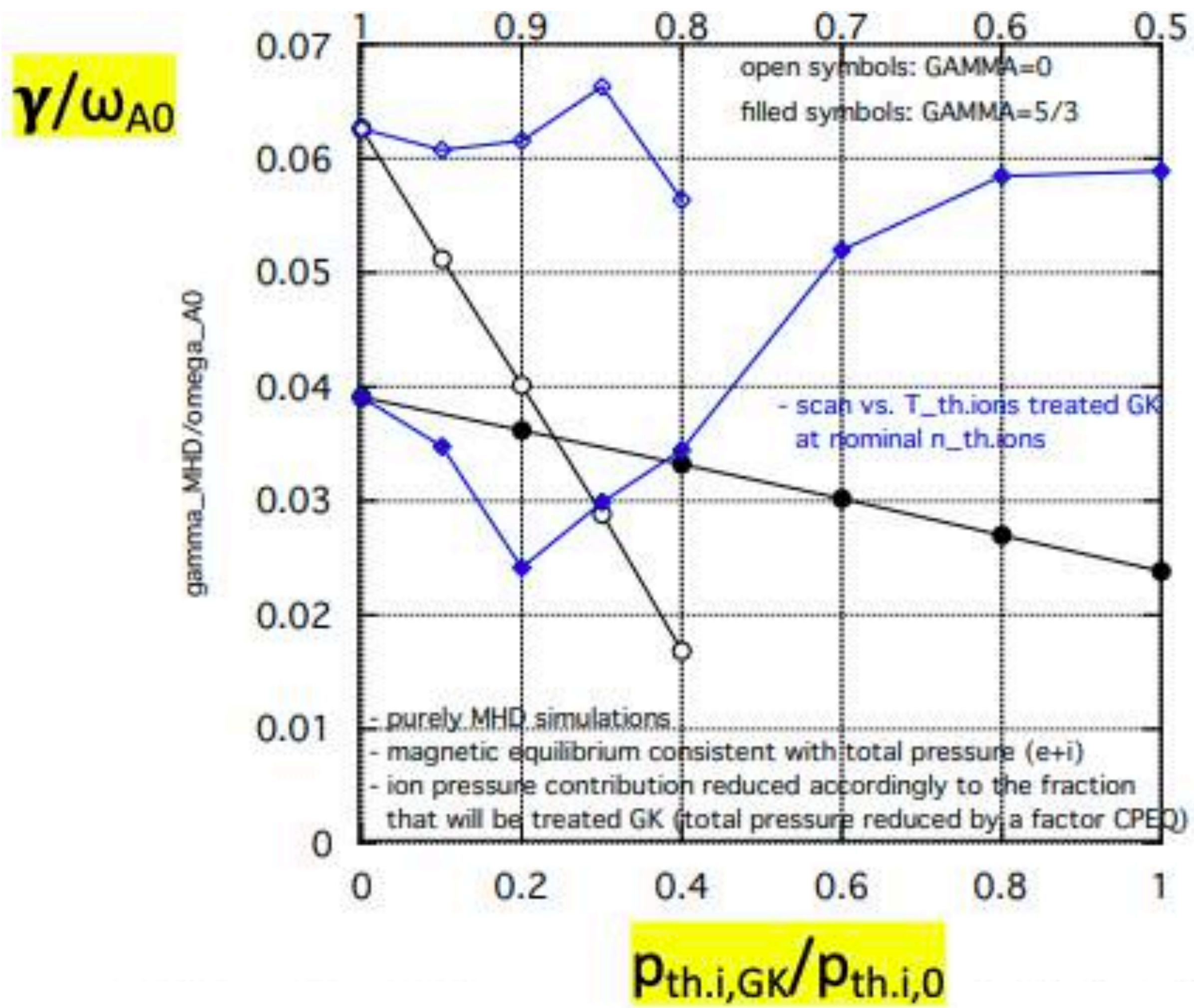
A. Martynov. EPFL PhD Thesis (2005).

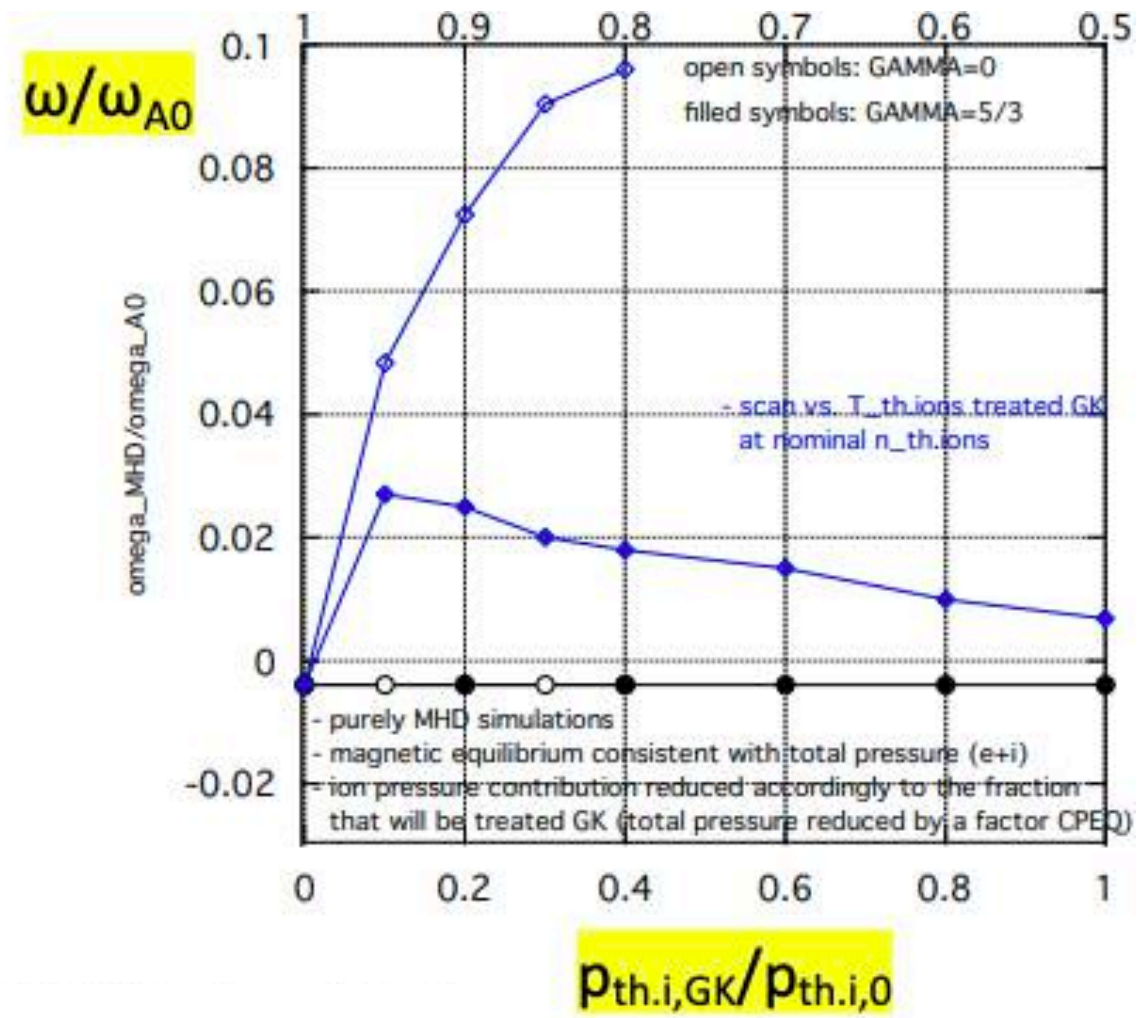
- Largely addressed for n=1 by rediscovered work by Martynov
- Linear growth rate for PT and NT is similar at large aspect ratio
- NT is somewhat harmful in spherical tokamaks
- Work on $n = 0$ modes on-going



M2.2.1: Kinetic corrections with HYMAGYC

- Kinetic corrections have been investigated, but not yet for NT versus PT





M2.3.1: Tearing stability with XTOR-K

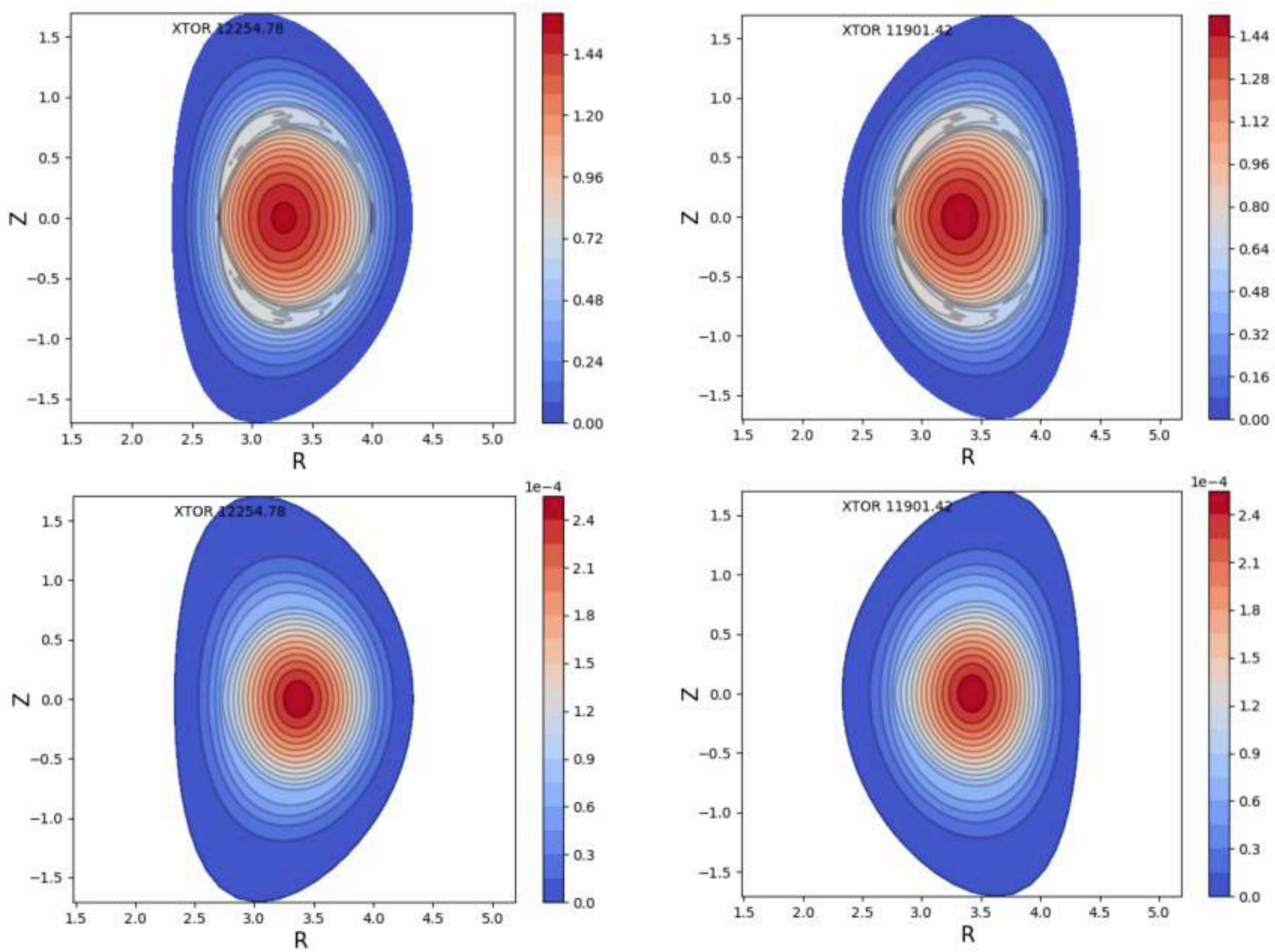
H. Lutjens, et al. *Nucl. Fusion* (1992).
A. Bondenson, et al. *Phys. Plasmas* (1992).
H. Lutjens, et al. *Phys. Plasmas* (2001).

- NT versus PT simulations of 2/1 tearing mode display little difference in linear growth rates, nor in saturated island size

- Consistent with past analytic work indicating weak destabilitization by NT

Toroidal current density:

Pressure:



M2.3.2: Fast particle & NTM interactions w/ XTOR

- Delayed for technical reasons due to upgrades to XTOR-K

Deliverable 3 summary — Experimental validation

Milestone	Description	Participants	Target date
M3.1	Establish initial magnetic equilibria and plasma profiles (a set based on existing experiment and a set based on DEMO) to be shared amongst the team	O. Sauter	1.2020
M3.2	Validation of trends from GK codes (local and global) using well-diagnosed TCV experiments	J. Ball, O. Sauter, G. Di Giannatale	12.2022
M3.3	Validation of SOLEDGE2D-EIRENE SOL simulations with experimental data (i.e. matching experimental observables by tuning cross-field diffusivities)	P. Muscente	6.2022
M3.4	Comparison of fast particle confinement and fast particle-driven modes between simulation and well-diagnosed TCV experiments	M. Vallar	6.2022
M3.5	Comparison between GBS single null simulations and TCV experimental measurements in the SOL	K. Lim	6.2023
M3.6.1	Validation of KINX global stability analysis against TCV experiments	O. Sauter	6.2022
M3.6.2	Validate empirical constants used for calculating local ballooning stability in EPED for NT	O. Sauter	12.2023

Deliverable	Description	Participants	Target date	Evidence of achievement
D3.1	Report on validation of core transport between gyrokinetic/TGLF simulations and present-day experiments	G. Di Giannatale, J. Ball, P. Mantica, O. Sauter	12.2023	See pinboard ID 36044, conference contribution
D3.2	Report on validation of pedestal MHD stability between EPED and TCV experiments	O. Sauter	6.2024	N/A

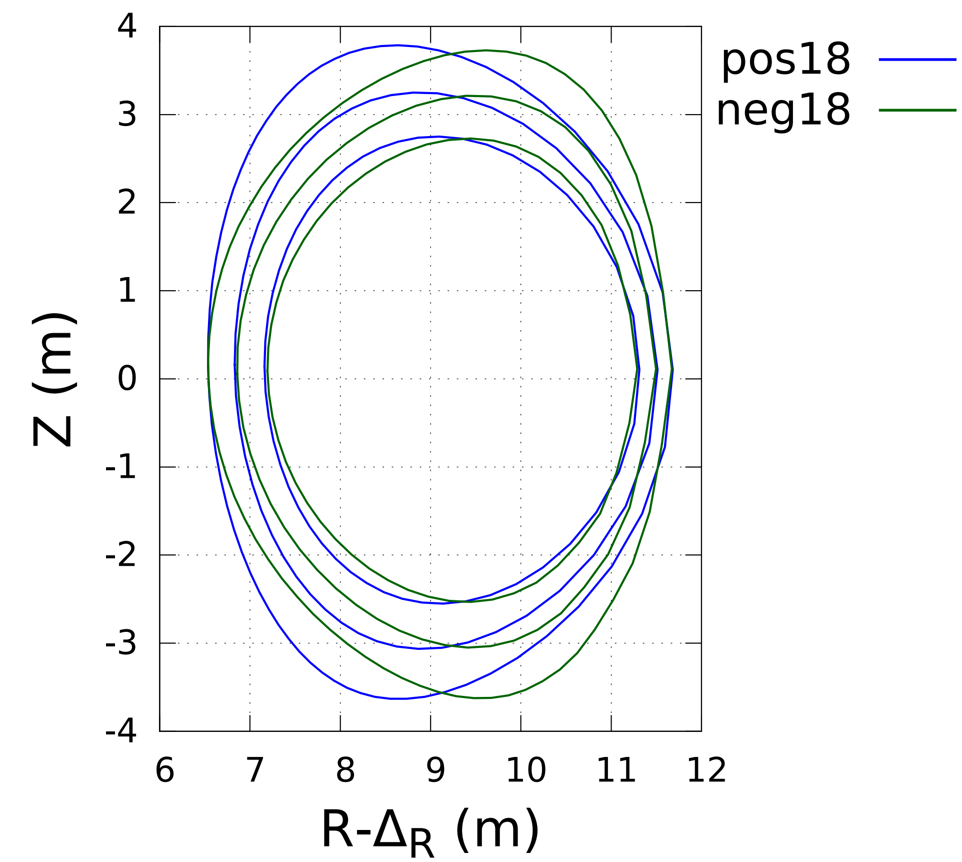
M3.1: Develop common set of NT/PT equilibria

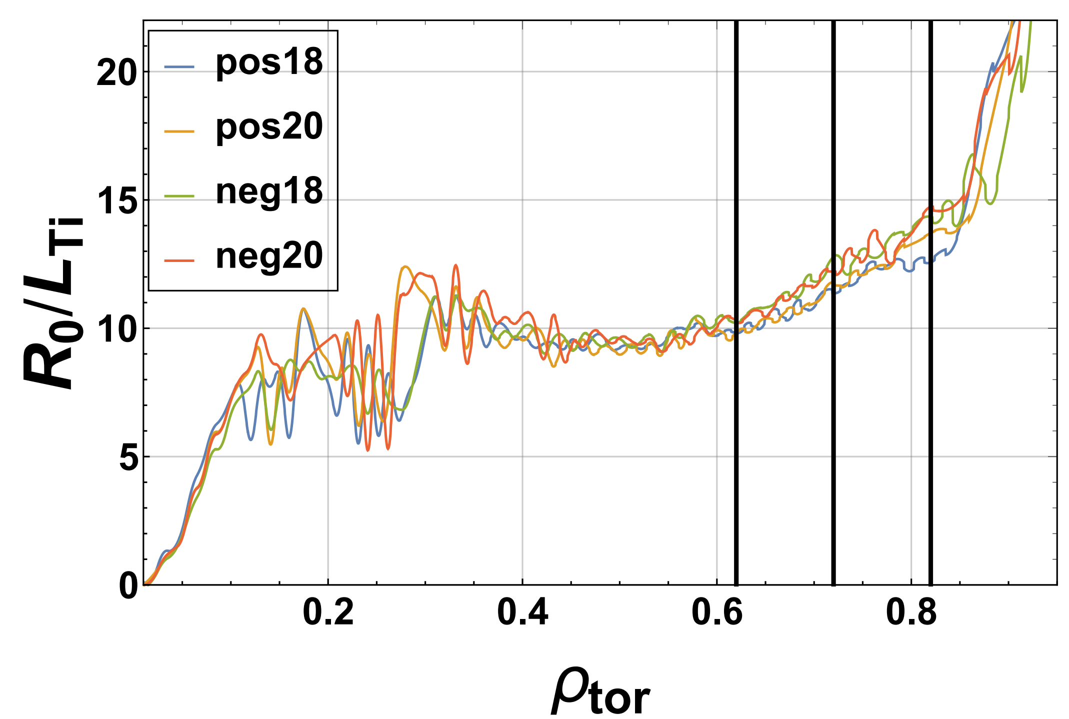
TSVV 2 wiki.

- 12 experimental TCV equilibria have been established and distributed to the team (and the wider community)

- 4 equilibria based on EU DEMO are available

Comp. Num.	Description	Constants of comparison	Discharge	Time (sec)	elong	delta
1	Diverted, PT	q95, betaN	69515	1.02	1.43	+0.29
1	Diverted, NT	q95, betaN	69340	0.58	1.42	-0.28
2	Diverted, PT	q95, ne, Pheat	69515	1.02	1.43	+0.29
2	Diverted, NT	q95, ne, Pheat	69271	1.60	1.42	-0.27
3	Diverted, PT	Ip, betaN, ne	69508	1.49	1.43	+0.28
3	Diverted, NT	Ip, betaN, ne	69340	0.58	1.42	-0.28
4	Limited, PT	Ip, betaN, ne	69511	1.50	1.34	+0.35
4	Limited, NT	Ip, betaN, ne	69273	0.85	1.29	-0.29
5	Limited, PT	Ip, Pheat	69511	1.50	1.34	+0.35
5	Limited, NT	Ip, Pheat	69273	1.70	1.26	-0.26
-	Diverted, PT	-	69515	1.58	1.43	+0.34
-	Diverted, NT	-	69340	1.60	1.40	-0.27



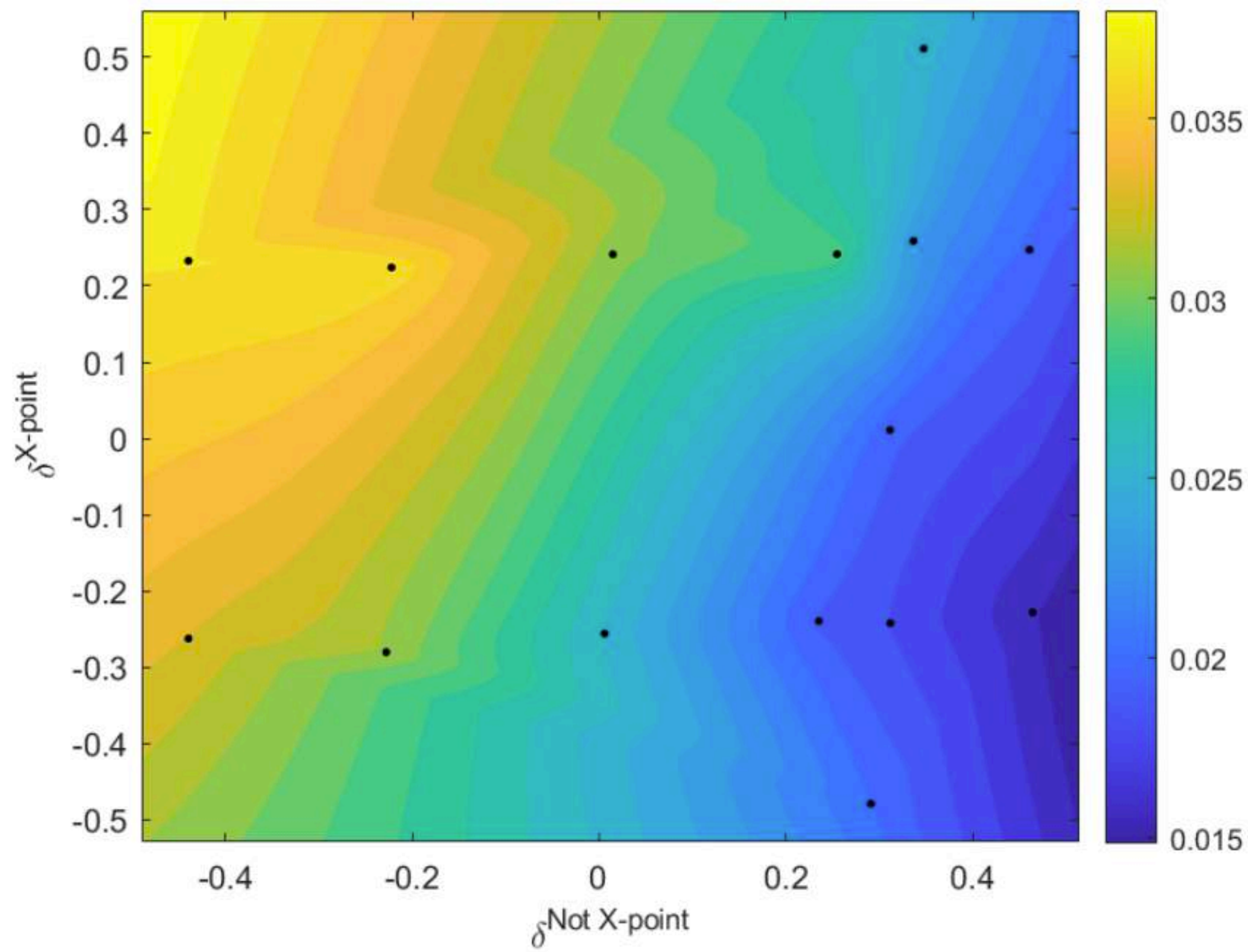


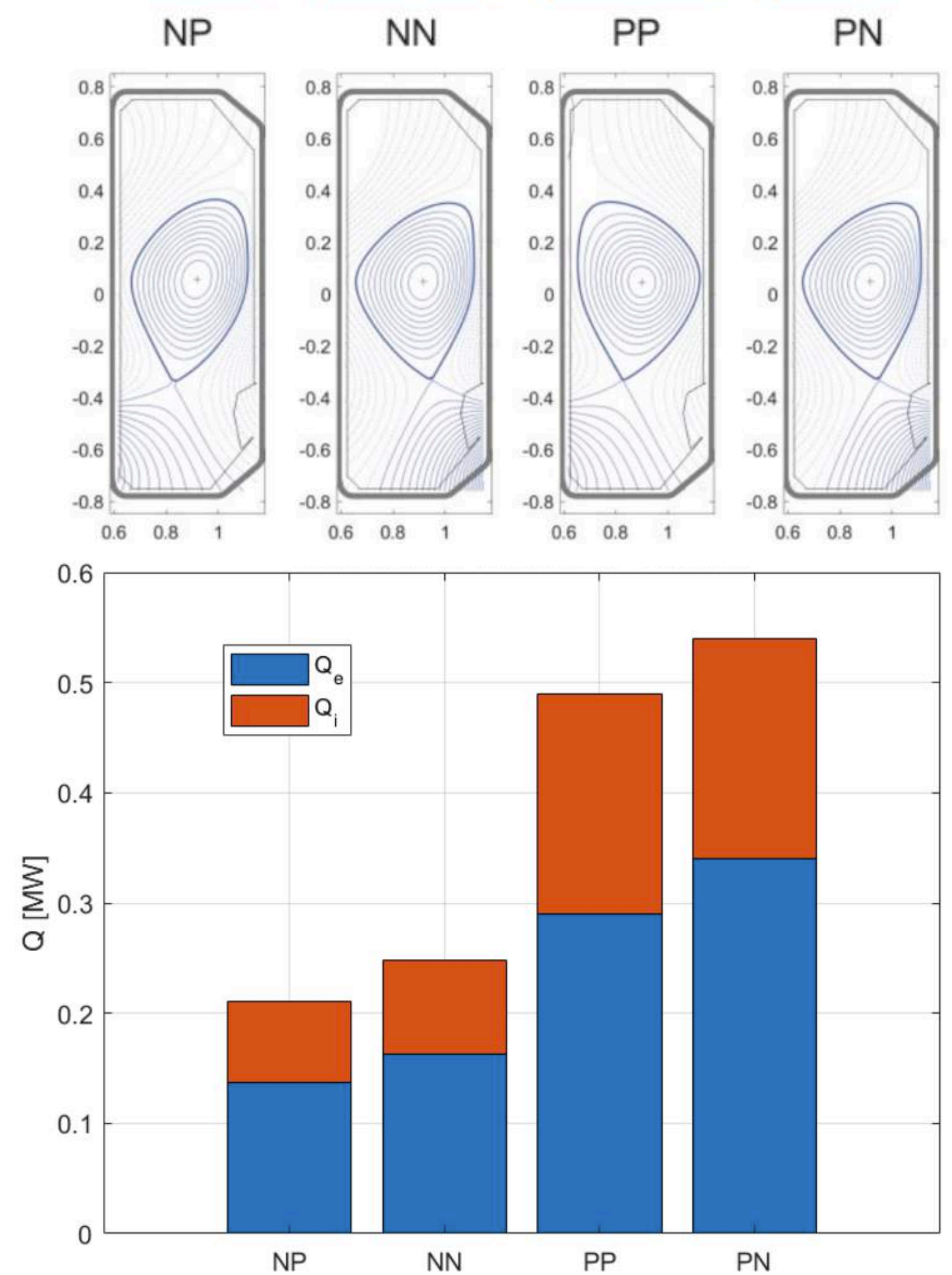
M3.2: Validate GK trends against TCV

S. Coda, et al. EPS (2023).

- Validated X-point versus non-X-point dependance for single-null TCV shots

- Also, GENE and ORB5 robustly find that NT is stabilizing relative to PT (when gradients are fixed between them)

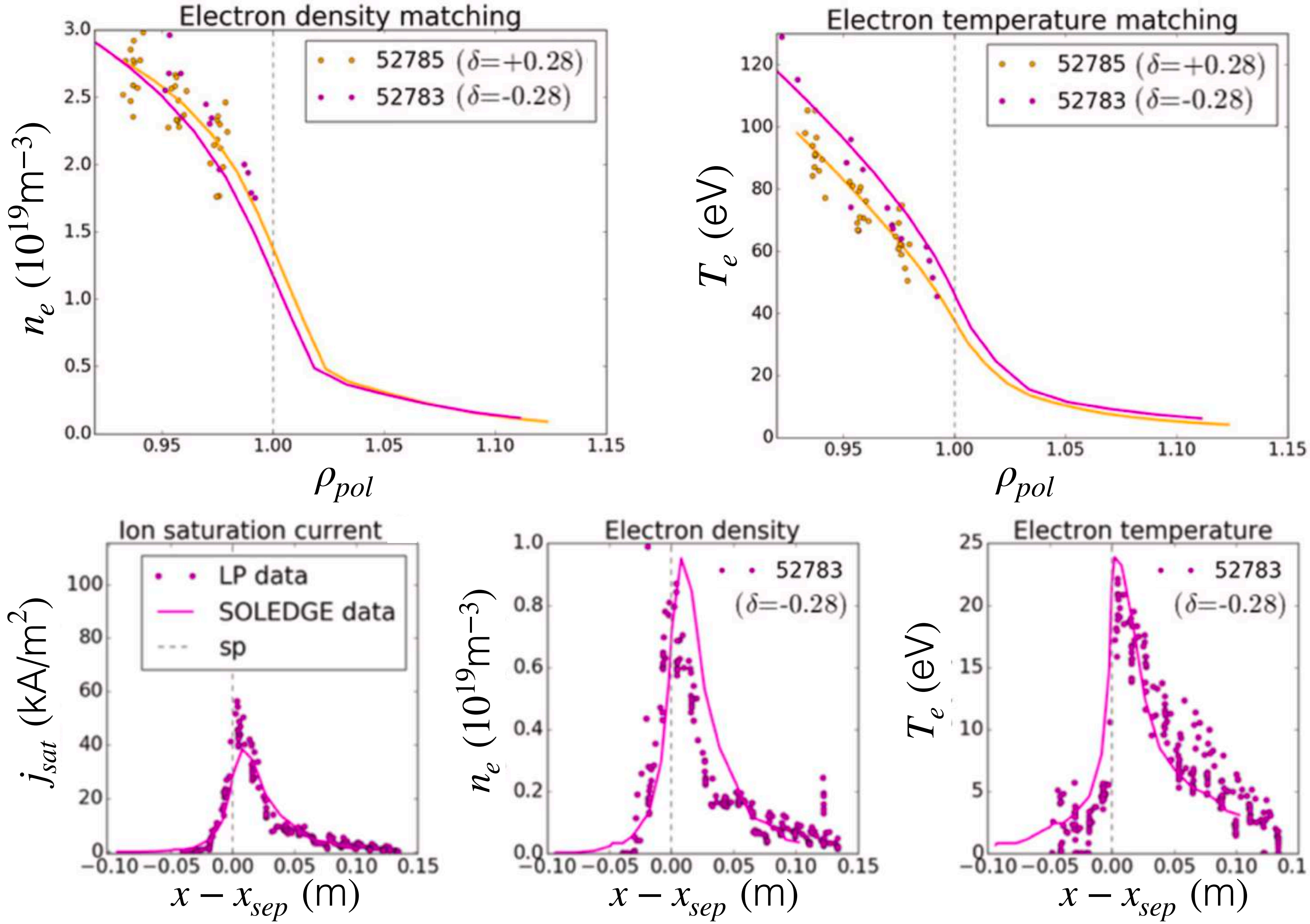




M3.3: Tune diffusivities in SOLEDGE to match TCV

[P. Muscente, et al. Nucl. Mat. Energy (2022).](#)

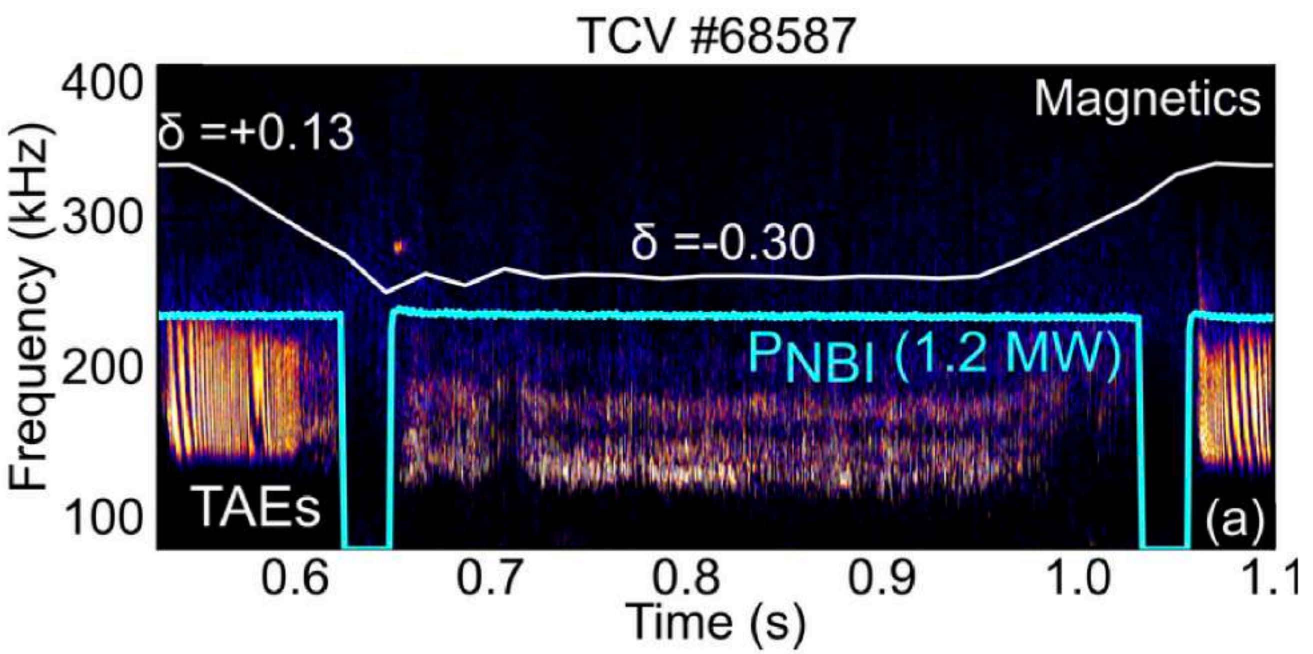
- Achieved reasonable agreement shown below, which required NT to have a lower particle diffusivity at the separatrix than in PT

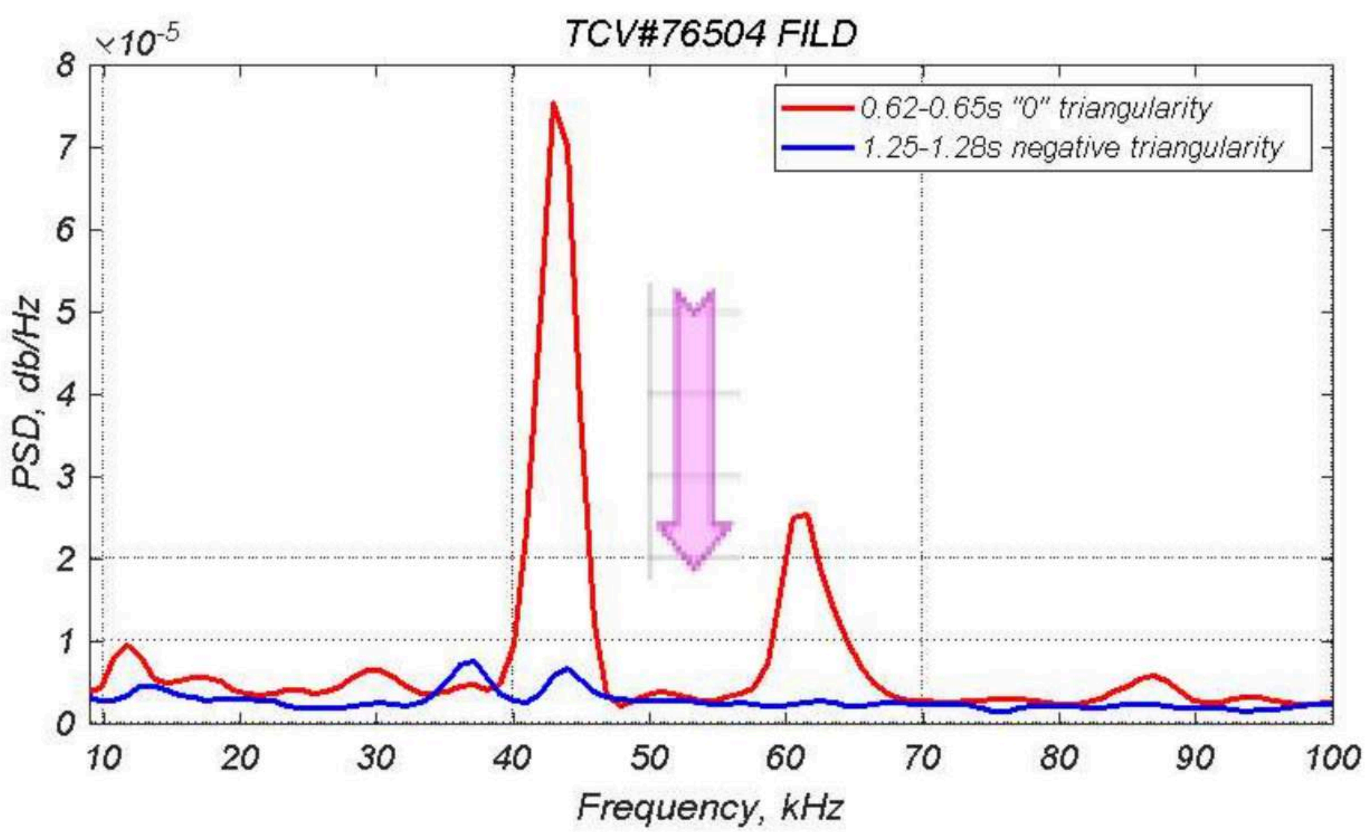


M3.4: Fast ion confinement & instabilities in TCV

P. Oyola, et al. IAEA (2023).
A. Karpushov, et al. *EPS* (2023).

- TCV experimental scenarios proved harder than expected to develop, so only qualitative comparisons were possible
- TAE signal increased with δ
- Fast Ion Loss Detector (FILD) signal increased with δ
- Both observations are good news for NT and consistent with simulation (see M5.1.1-3)

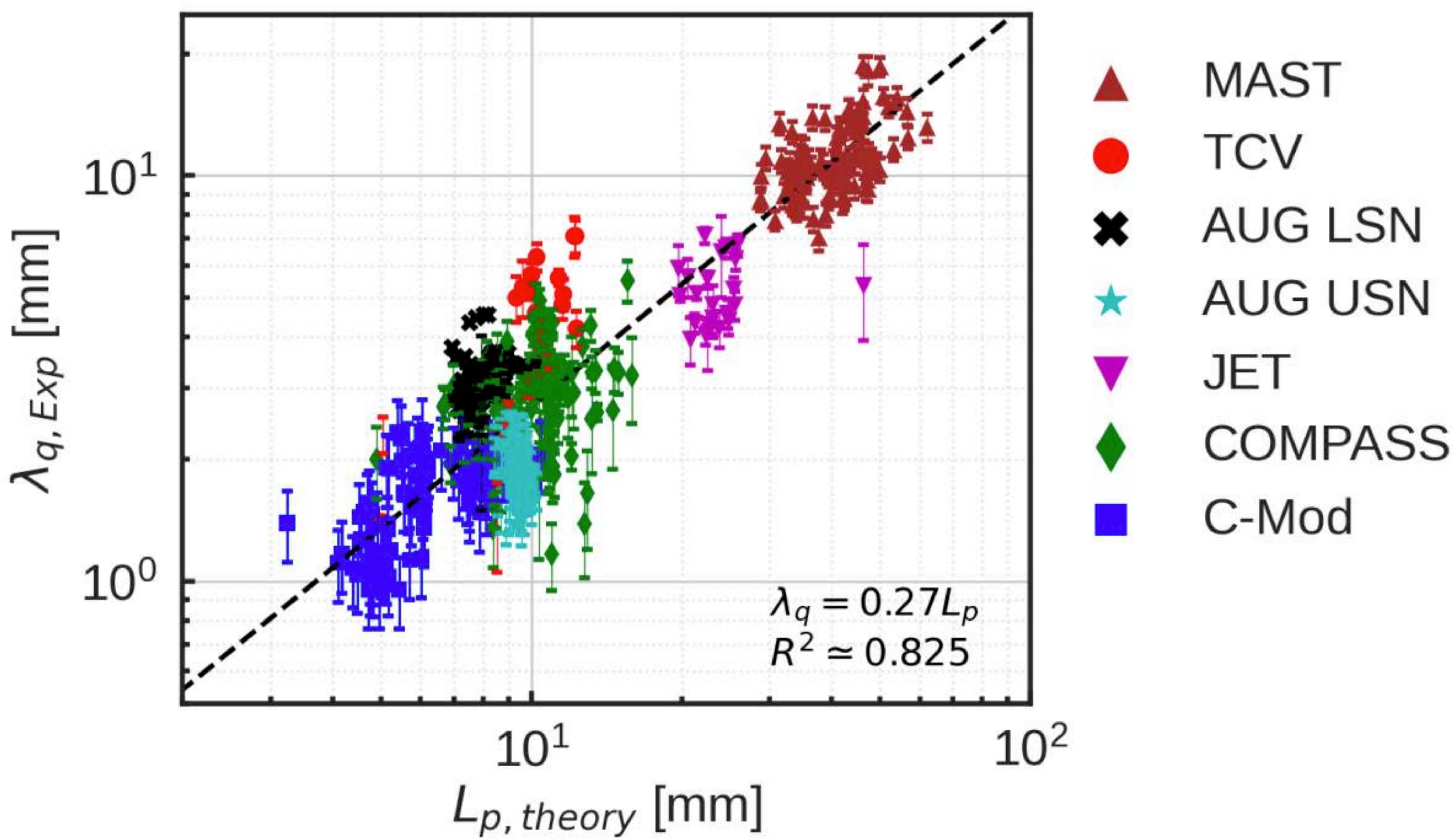




M3.5: SOL comparison between GBS and TCV

K. Lim, et al. PPCF (2023).

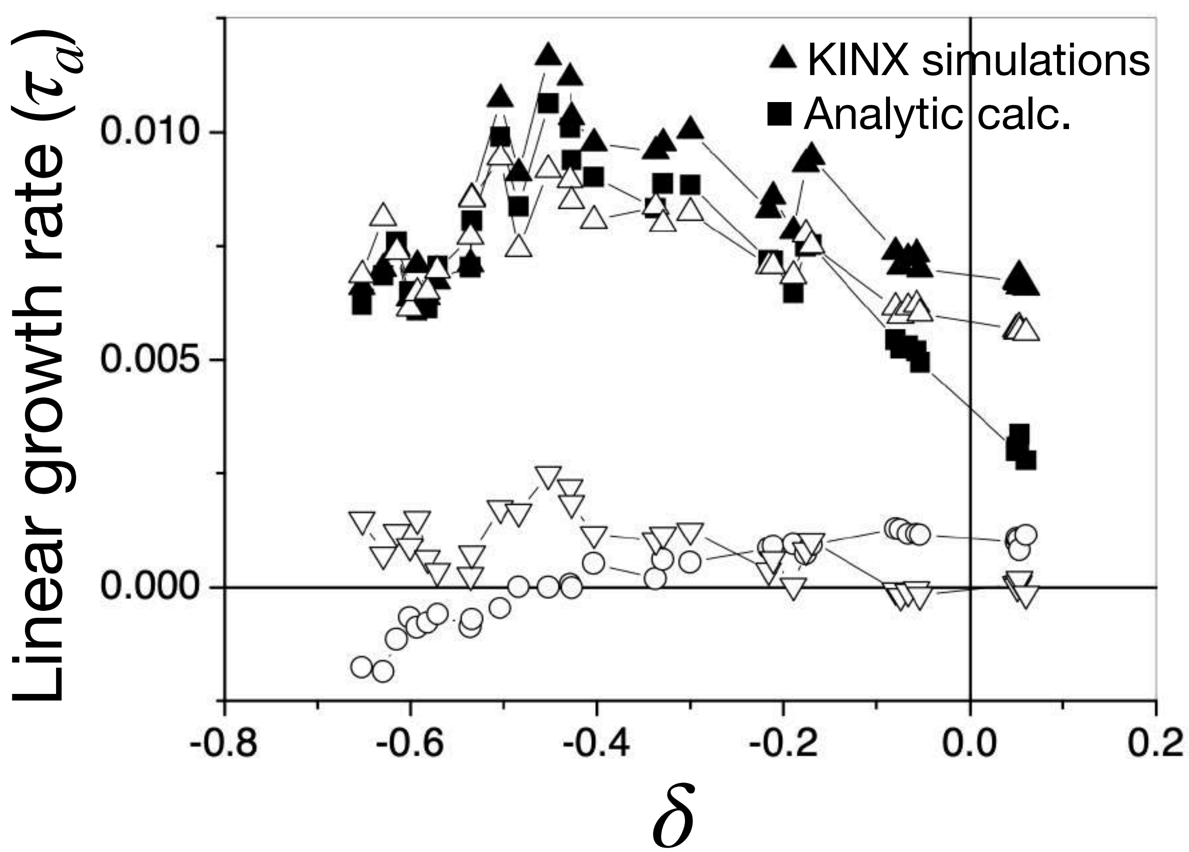
- A theory-based scaling law motivated from GBS results compared well against experimental measurements from a multi-machine database

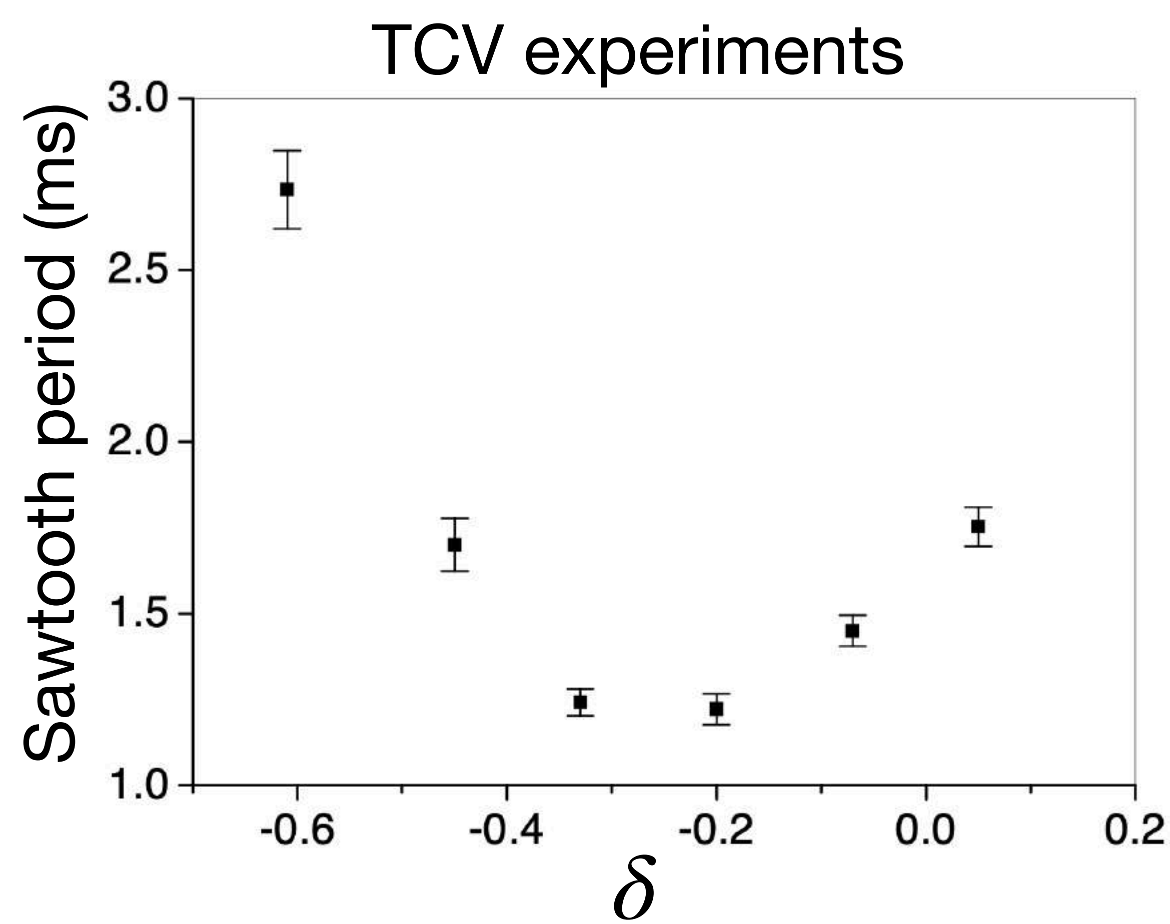


M3.6.1: Validating KINX and TCV for MHD stability

A. Martynov. EPFL PhD Thesis (2005).

- Existing thesis by Martynov shows good agreement between the ideal internal kink mode growth rate and the sawtooth period
- Indicates the sawtooth crash is triggered by the ideal internal kink





Deliverable 4 summary — Extrapolation to reactors

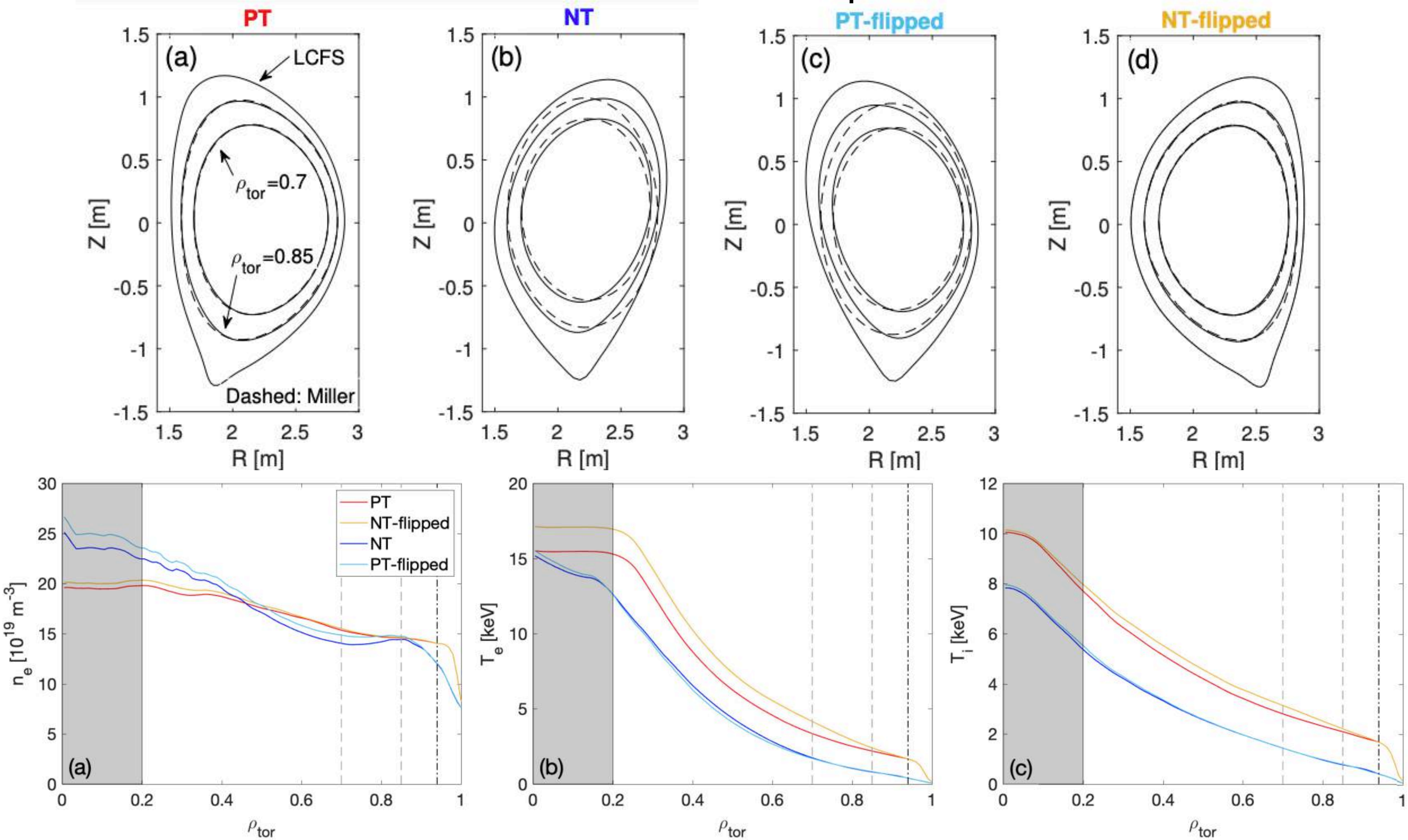
Milestone	Description	Participants	Target date
M4.1	TGLF integrated modeling of reactor-relevant DTT NT and present-day NT experiments to compare the effect of NT. In case no adequate TGLF setting is found, one can try to feed GK-deduced diffusivities into a transport code.	P. Mantica	12.2022
M4.2	Extrapolate to DTT and reactor-scales using SOLEDGE2D-EIRENE SOL simulations	P. Muscente	6.2023
M4.3.1	Perform electromagnetic local GK simulations to test impact at high β	J. Ball, M. Pueschel	12.2022
M4.3.2	Perform local GK simulations to extrapolate behavior to reactor scale devices	J. Ball	6.2023
M4.4	Use global flux driven simulations to extrapolate behavior to reactor scale devices	G. Di Giannatale	12.2023
M4.5	Use experimental-scale GBS simulations to study the scaling with size in order to extrapolate to reactor-scale devices	K. Lim	12.2024
M4.6	Extrapolate fast ion confinement to reactor-scale devices with neutral beams and alpha particles	M. Vallar	12.2023
M4.7	Synthesis of analysis results (e.g. transport, MHD) to optimize reactor-scale equilibria	O. Sauter, ALL	6.2023

Deliverable	Description	Participants	Target date	Evidence of achievement
D4.1	Report on feasibility of a NT reactor	ALL	6.2023	This presentation
D4.2	Report on fast particle confinement at reactor scales	M. Vallar	6.2024	N/A

M4.1: Integrated modeling of DTT with TGLF

A. Mariani, et al. Nucl. Fusion (2023).

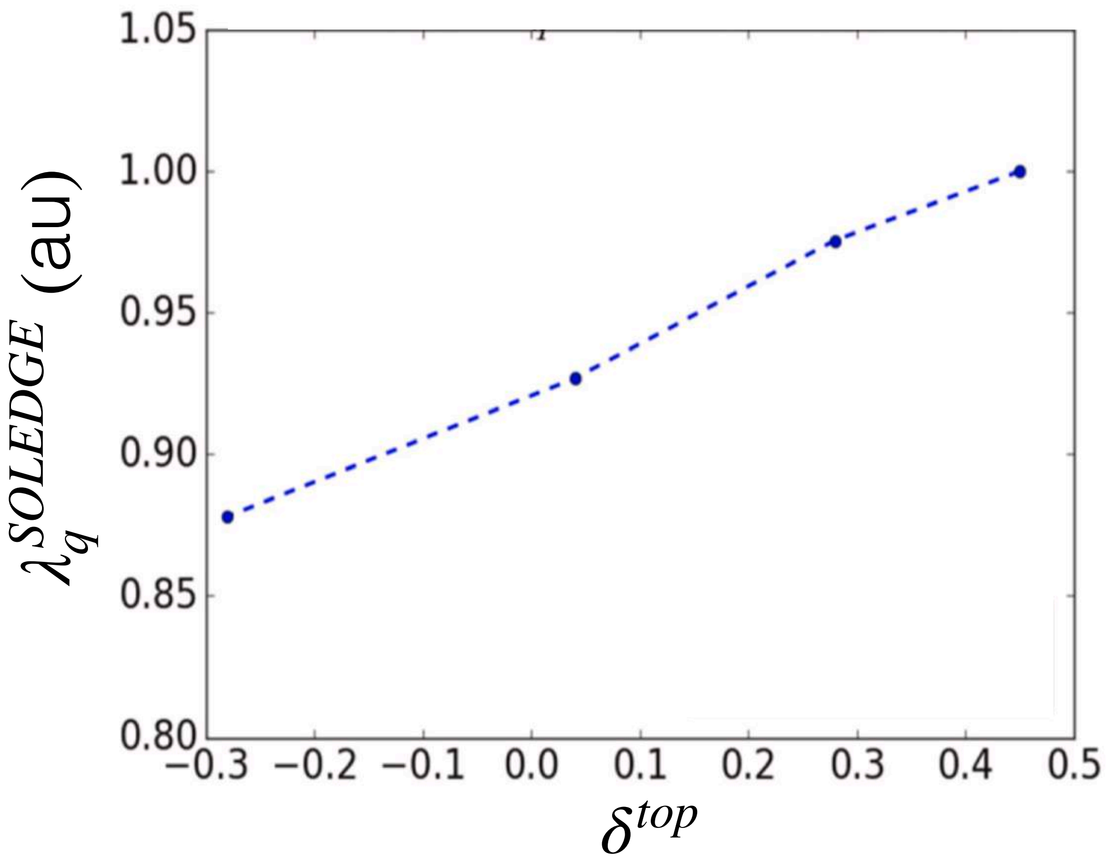
- Results indicate that NT is only beneficial at nominal DTT H-mode parameters and not at nominal DTT L-mode parameters

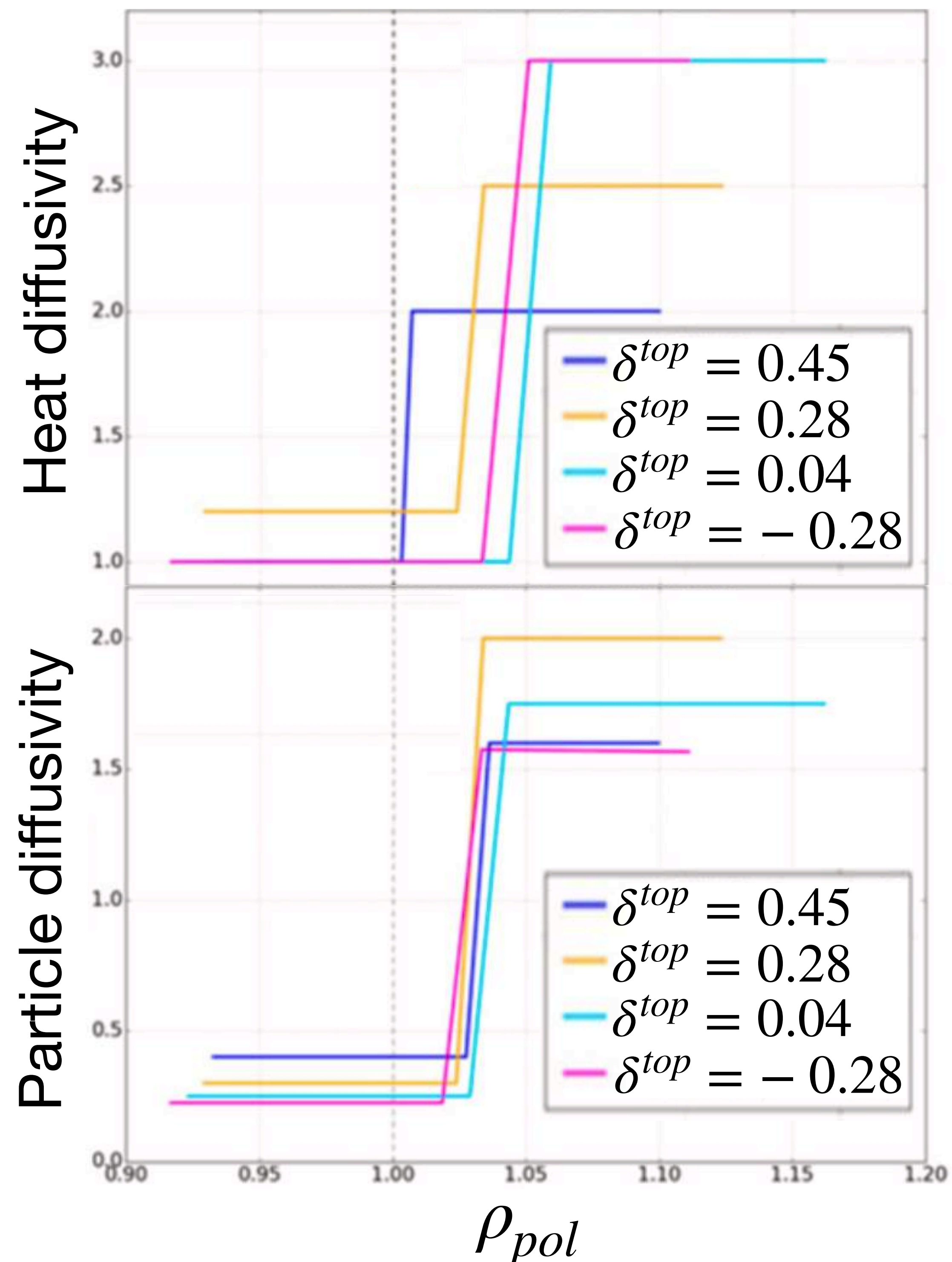


M4.2: Extrapolate SOL behavior with SOLEDGE

P. Muscente. J. Nucl. Mater. (2023).

- SOLEDGE-EIRENE has been successfully applied to TCV, but not yet DTT or reactors
- Matching experiment required a reduced separatrix particle diffusivity for NT (though heat diffusivity was less clear)
- Heat flux decay length at outer midplane measured in these simulations was lowered by NT



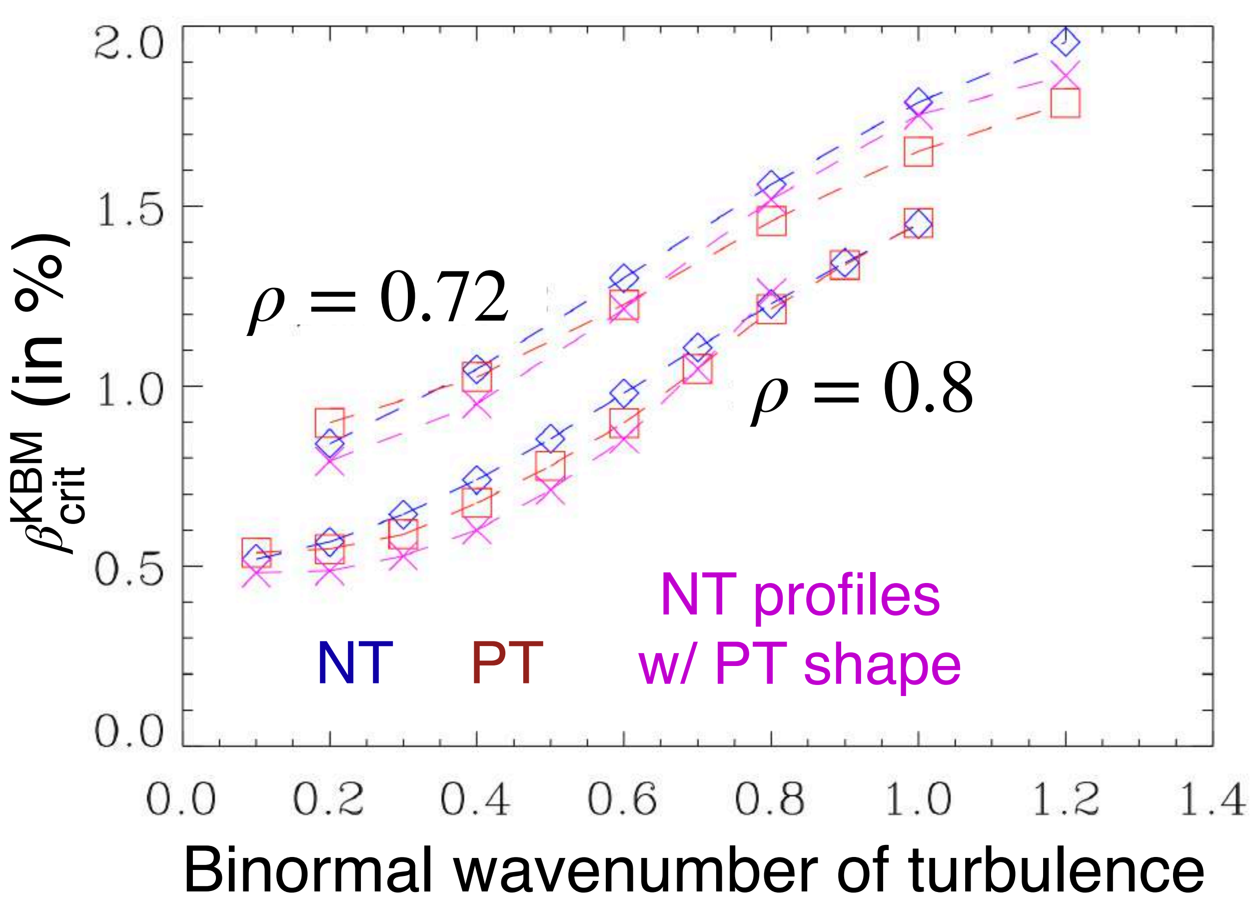


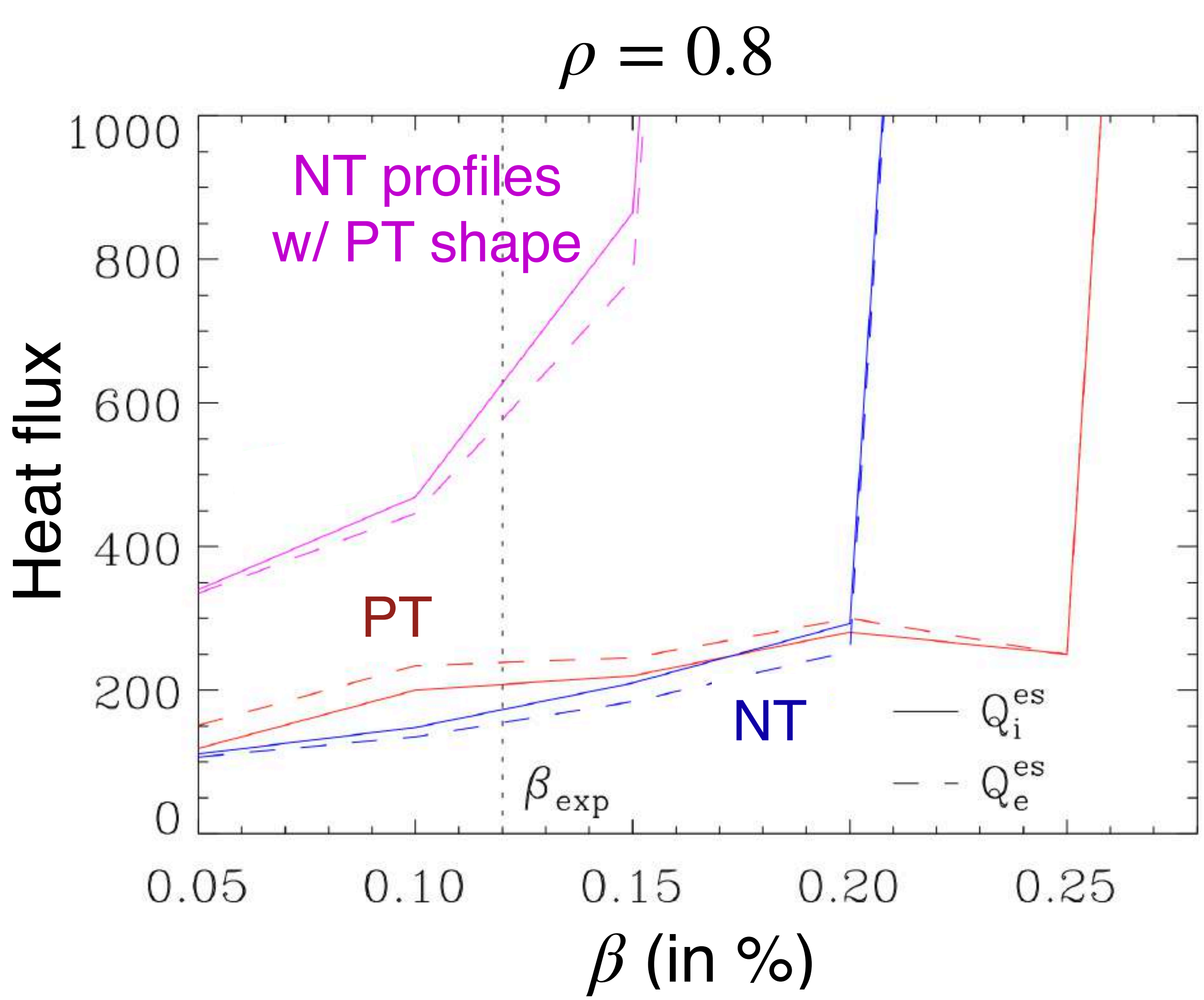
M4.3.1: Test impact of β on core turbulence

M.J. Pueschel. APS (2022).
A. Balestri, et al. EPS (2023).
R. Davies, et al. *PPCF* (2022).

- NT and PT TCV discharges scale similarly with β

- Critical β for the linear onset of KBM turbulence is similar as is the nonlinear effect of β on electrostatic turbulence





- MTM and KBM seems stronger for NT in spherical tokamaks

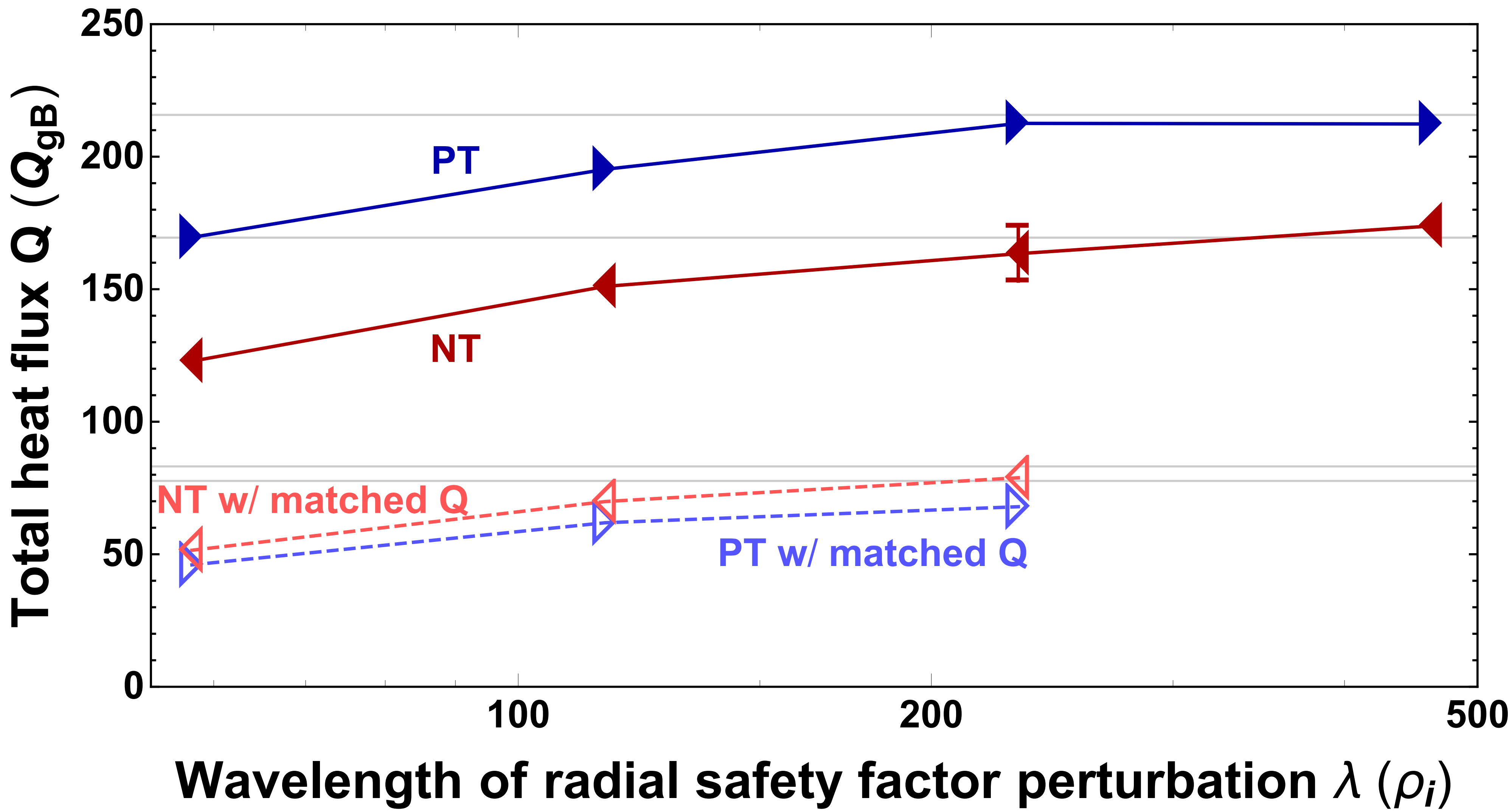
EUROfusion EPFL

M4.3.2: Extrapolate to reactors with local GK

J. Ball, et al. PPCF (2022).

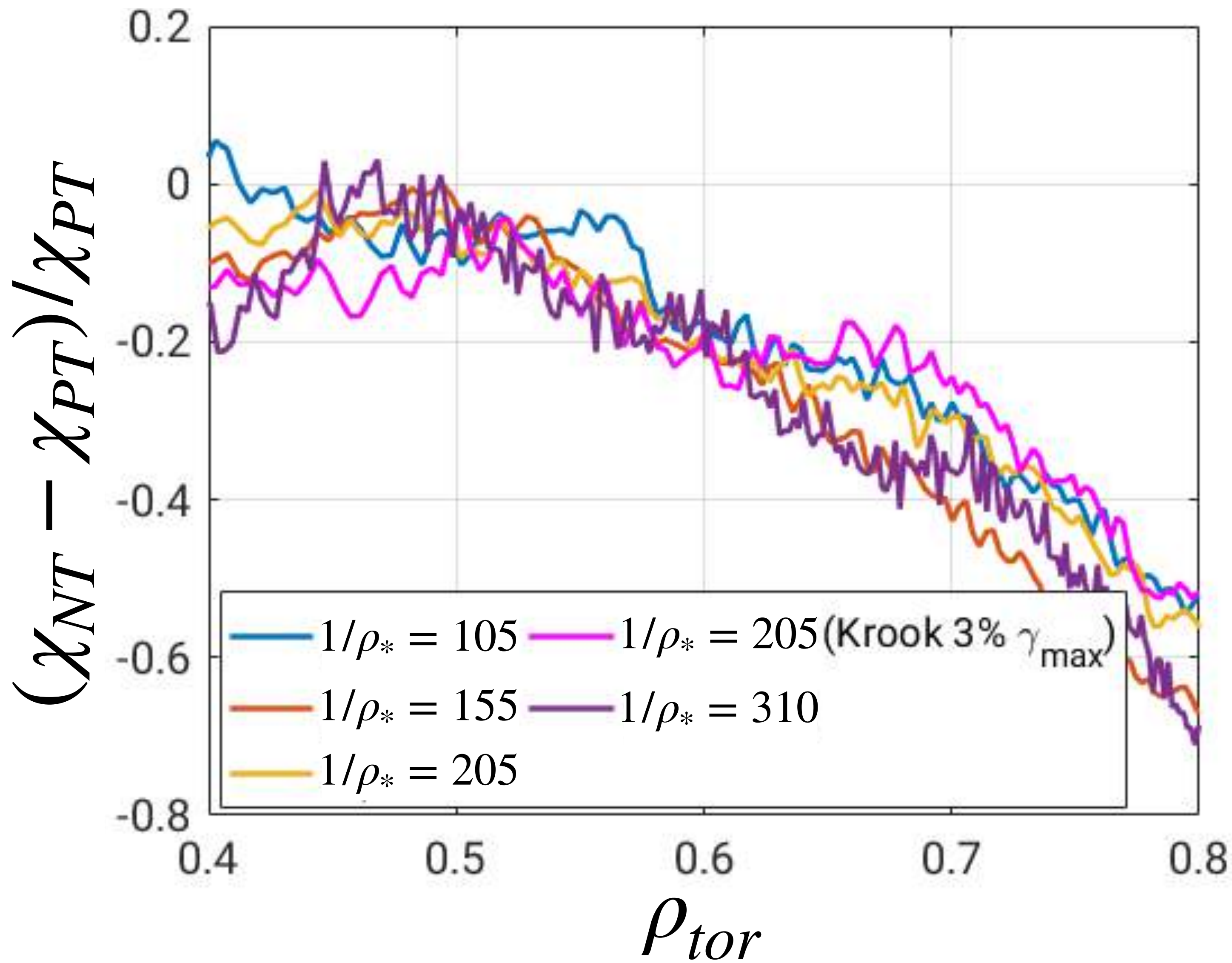
- We developed a novel flux tube incorporating profile shearing in safety factor profile in order to investigated impact of machine size

- NT and PT scale similarly to larger devices



M4.4: Extrapolate to reactors with global GK

- Using fully kinetic electrons was needed to reveal a distinction between NT and PT
  - Though artificially heavy electrons are used to reduce computational cost



M4.7: Synthesize results to optimize reactors

- A conventional aspect ratio single-null NT power plant looks most attractive:
    - confinement benefits appear to scale, plasma should remain in L-mode, SOL width appears wider than PT H-mode, and other considerations (e.g. MHD, fast particles, etc.) appear similar to PT
- A spherical tokamak NT power plant is more questionable as theory suggests confinement (due to electromagnetic and TEM turbulence) and MHD stability (due to ideal kink modes) might be worse
- A double-null NT power plant is more questionable as theory and experiment suggest that NT at the X-point degrades confinement

Deliverable 5 summary — Fast ion confinement

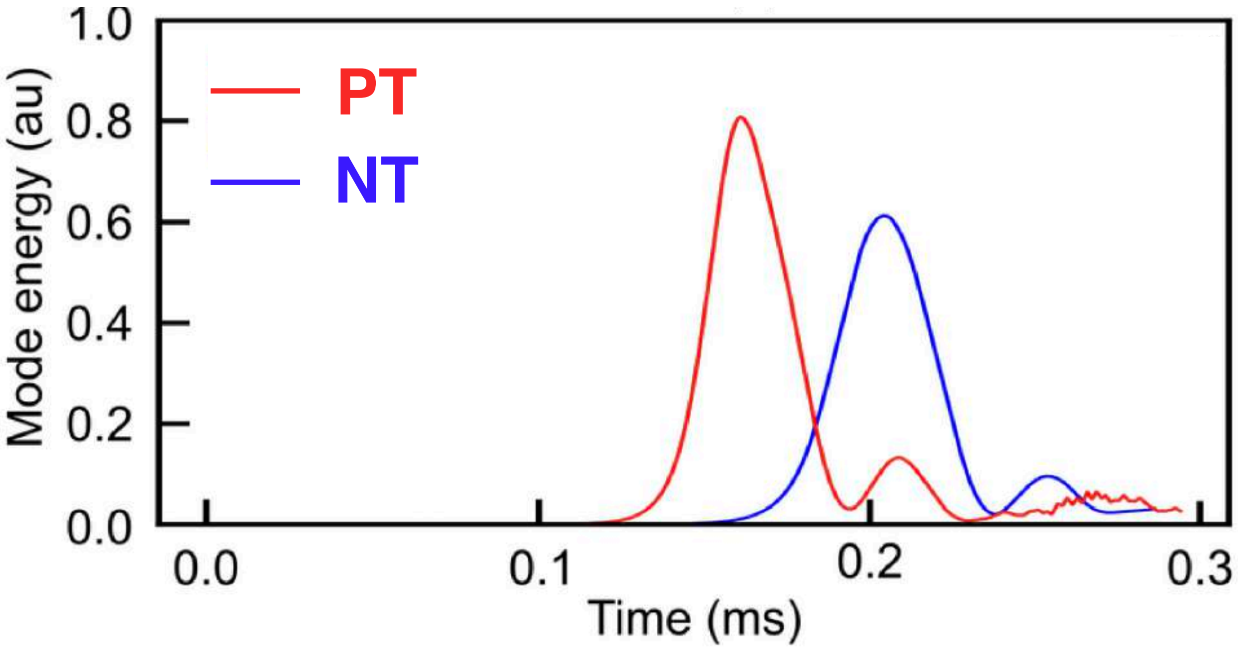
Milestone	Description	Participants	Target date
M5.1.1	Model fast ion transport using ASCOT and TRANSP/NUBEAM	M. Vallar	6.2021
M5.1.2	Model energetic particle-driven modes using LIGKA	M. Vallar	12.2021
M5.1.3	Model the impact of energetic-particle driven modes on fast ion confinement	M. Vallar	12.2022
M5.2	Fast ion confinement studies with XTOR-K	H. Luetjens	12.2022

Deliverable	Description	Participants	Target date	Evidence of achievement
D5.1	Report on fast particle confinement and fast particle driven instabilities in NT	M. Vallar, G. Fogaccia	12.2023	See pinboard ID 34289

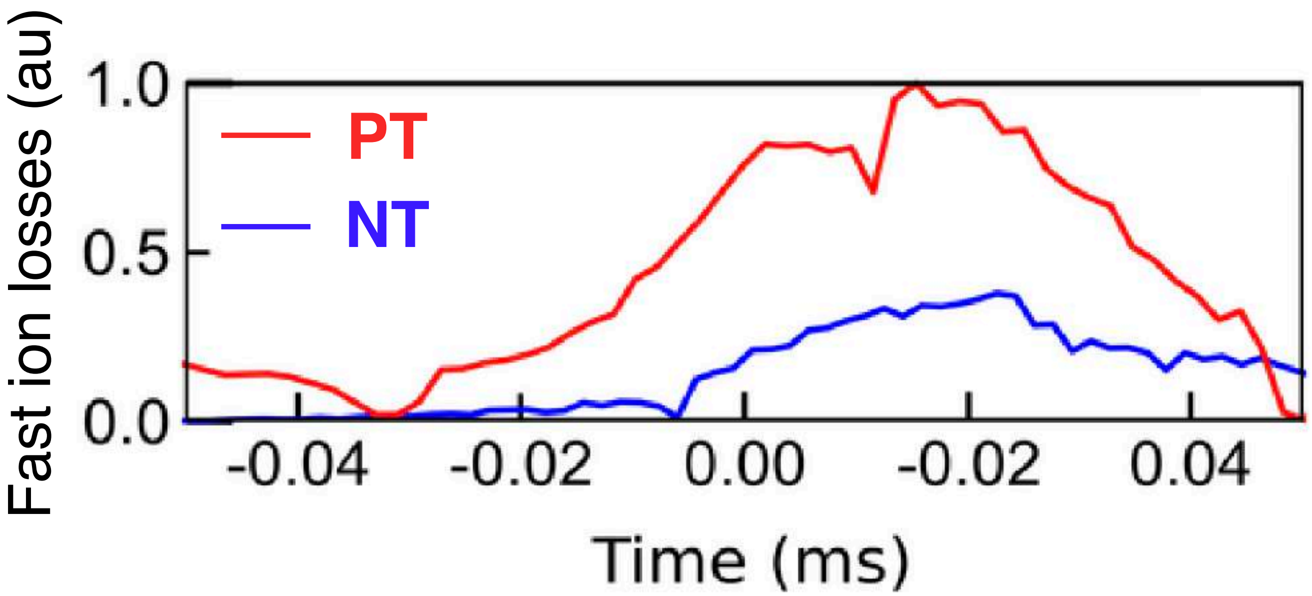
M5.1.1-3: Interplay of fast ion modes & transport

P. Oyola, et al. IAEA (2023).

- MEGA (not ASCOT) analysis of a pair of TCV equilibria show reduction in TAE amplitude by 30%



- Resulting TAE-induced fast ion losses to the wall are 3 times smaller in NT



M5.2: Fast ion confinement study with XTOR-K

- Delayed for technical reasons due to upgrades to XTOR-K

Deliverable 6 summary — Reduced modeling

Milestone	Description	Participants	Target date
M6.1	Detailed verification of TGLF SAT1 vs GK simulations and optimization of TGLF settings for standard DTT NT case and extreme NT DTT case	A. Mariani	12.2021
M6.2.1	Conduct encompassing linear and nonlinear gyrokinetic GENE flux-tube studies of PT and NT scenarios, specifically looking at saturation physics and nonlinear coupling, with a special focus on experimental cases	M. Pueschel	12.2021
M6.2.2	Test quasilinear gyrokinetics-based transport models for these cases against nonlinear scalings, and improve the models where necessary	M. Pueschel	12.2022
~~**M6.2.3**~~	~~Implement model in a bigger, possibly multi-physics framework (e.g. transport solver), and create a neural network that captures NT scalings~~	~~M. Pueschel (in collaboration with J. Citrin at DIFFER, and ACH support)~~	~~12.2023~~

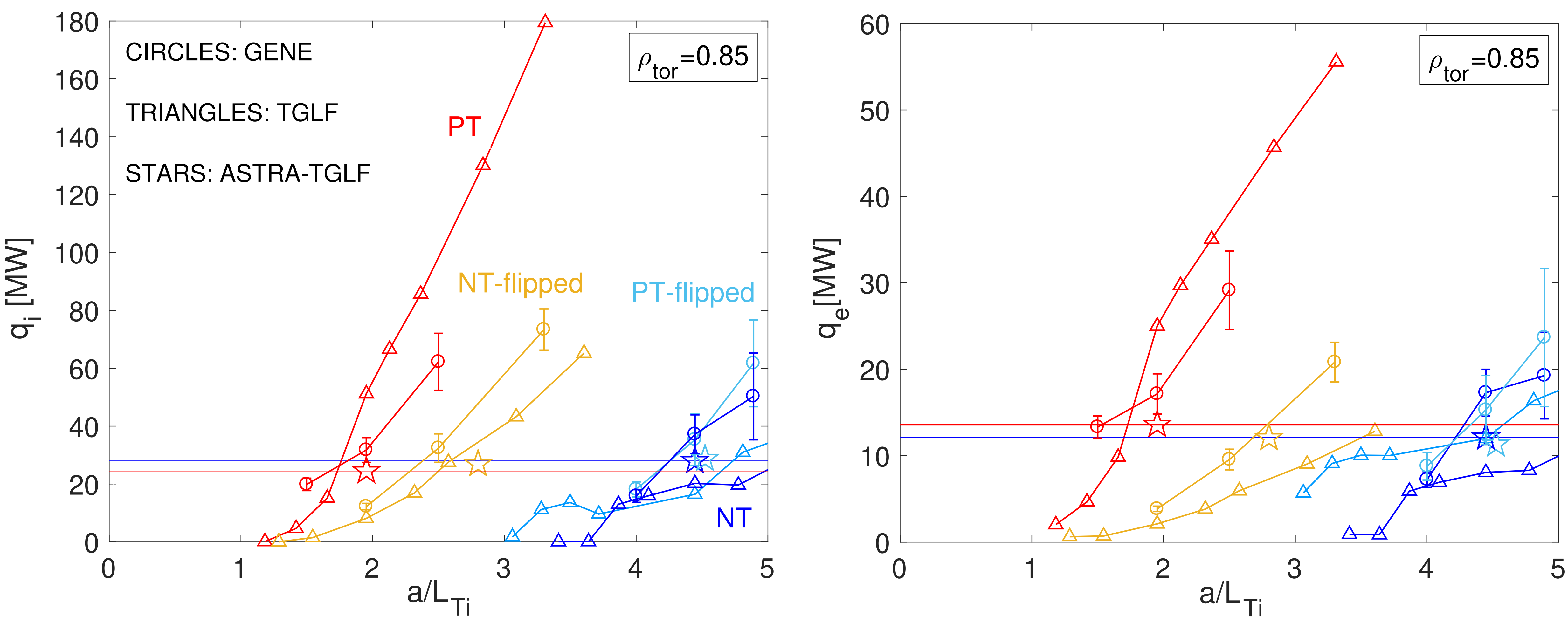
Deliverable	Description	Participants	Target date	Evidence of achievement
D6.1	Report on verification of TGLF with GENE for NT, detailing how to best simulate NT with the standard TGLF	A. Mariani, P. Mantica	12.2022	See pinboard ID 35620, 33950, conference contribution
D6.2	Report on linear instability and nonlinear saturation behavior for NT	M. Pueschel	12.2022	See pinboard IDs 36044, 30201
~~**D6.3**~~	~~Report on neural network for modeling NT~~	~~M. Pueschel~~	~~12.2024~~	Abandoned (given lack of DIFFER ACH)

M6.1: Verification of TGLF and GENE for DTT

[A. Mariani, et al. Nucl. Fusion (2023).](#)

- TGLF (using SAT2) coupled with ASTRA has been benchmarked against local GENE, but this was only successful for DTT case (and not TCV case)

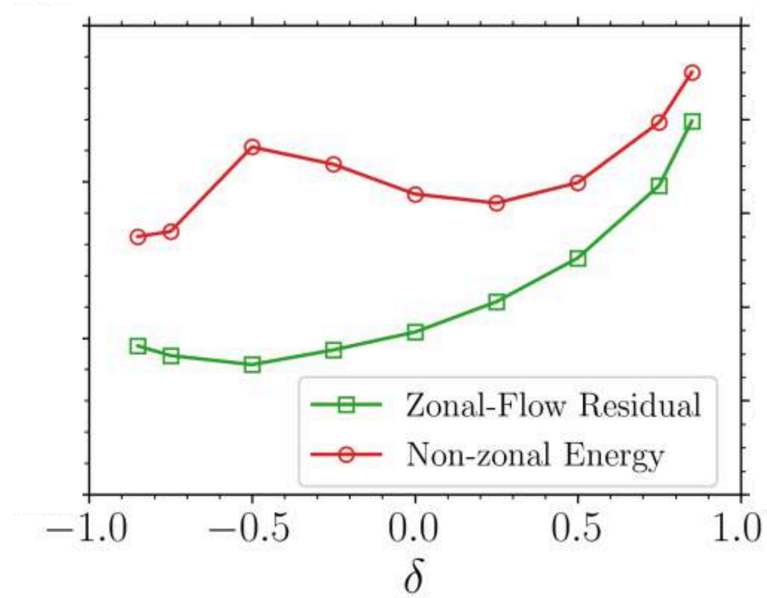
- Important effect seems to come from $\rho_{tor} > 0.95$, which is not included



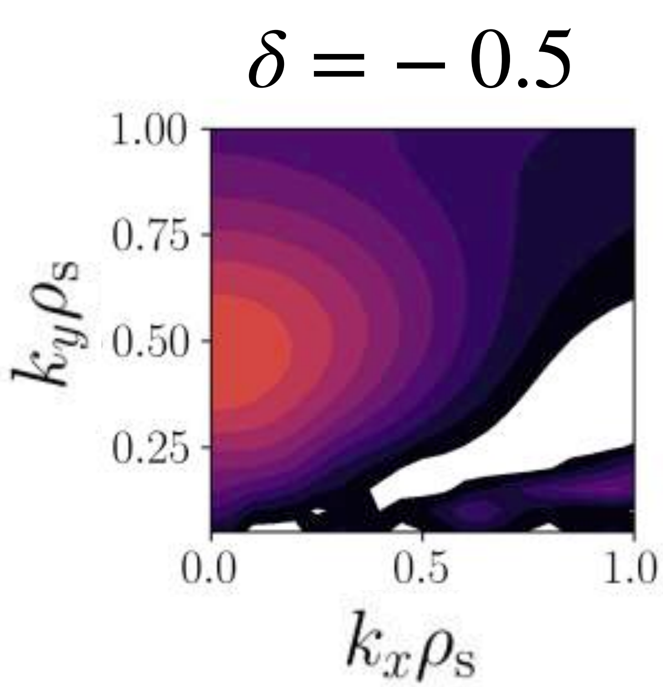
M6.2.1: Investigate saturation physics with GENE

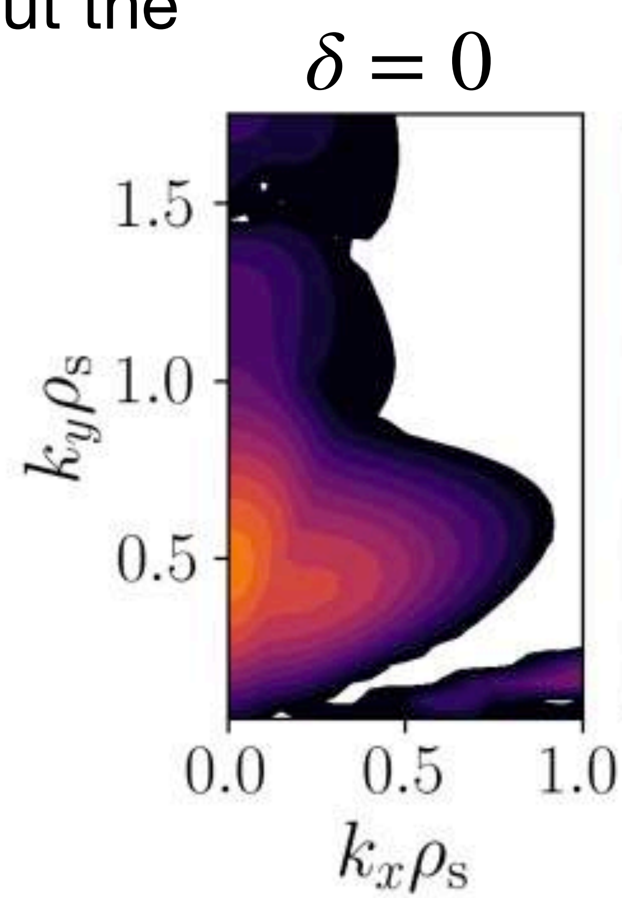
[M.J. Pueschel. Nucl. Fusion (special iss.).](#)
[J. Duff, et al. Phys. Plasmas (2021).](#)

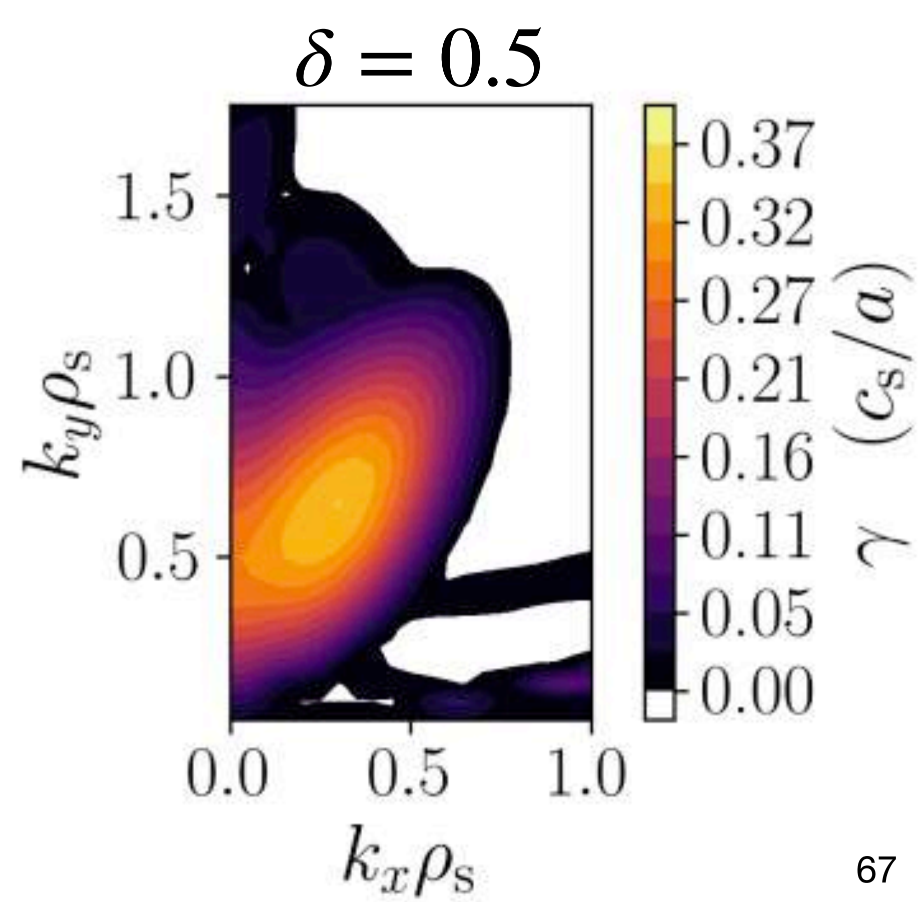
- Proxies for zonal flow damping and drive indicate that NT makes more efficient use of zonal flows for saturation



- NT has a broader spectrum in k_x due to its straight, flat shape about the outboard midplane



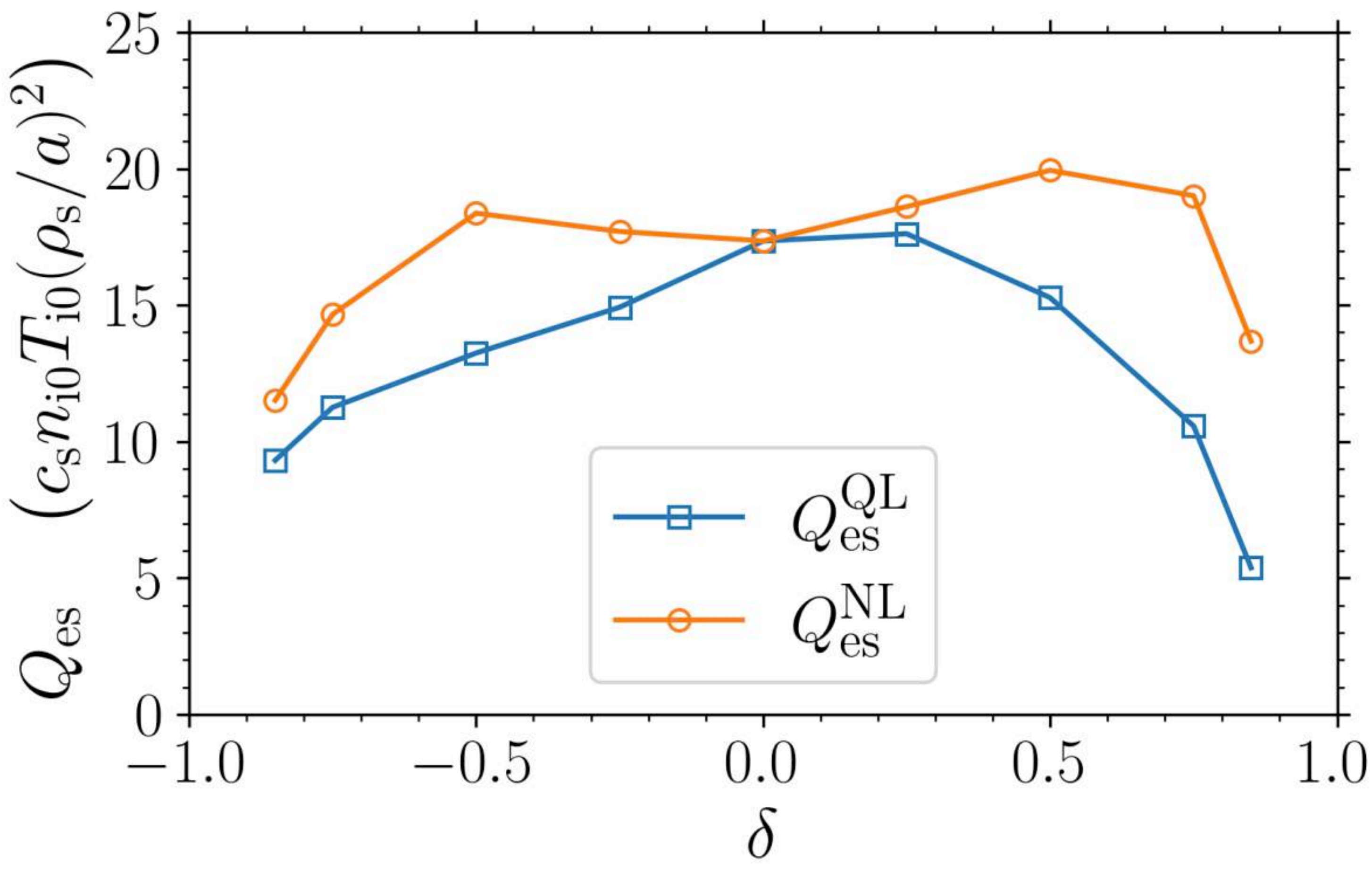




M6.2.2: Test quasilinear models against nonlinear

M.J. Pueschel. Nucl. Fusion (special iss.).
J. Duff, et al. Phys. Plasmas (2021).

- Standard mixing length quasilinear estimates can capture some of the variation with triangularity (e.g. strong decrease for $\delta > 0.5$), but overall only weak agreement



- SAT2 used in TGLF seems to do better