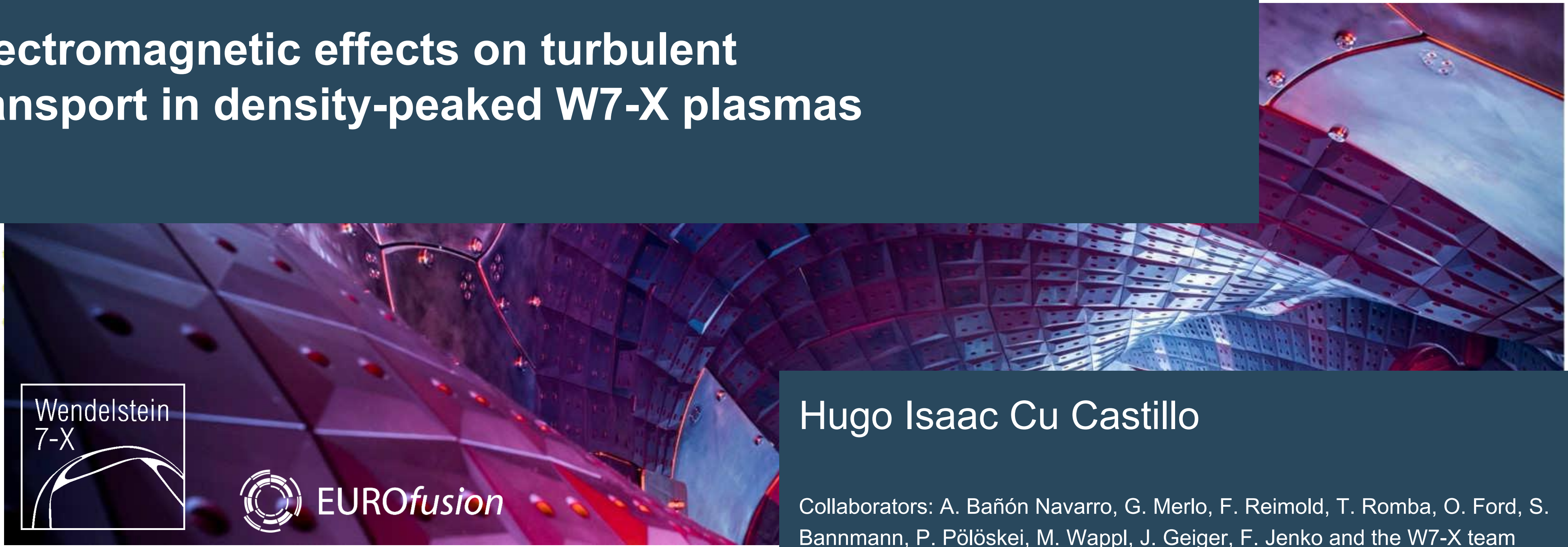
MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Electromagnetic effects on turbulent transport in density-peaked W7-X plasmas



Hugo Isaac Cu Castillo

Collaborators: A. Bañón Navarro, G. Merlo, F. Reimold, T. Romba, O. Ford, S. Bannmann, P. Pölöskei, M. Wappl, J. Geiger, F. Jenko and the W7-X team

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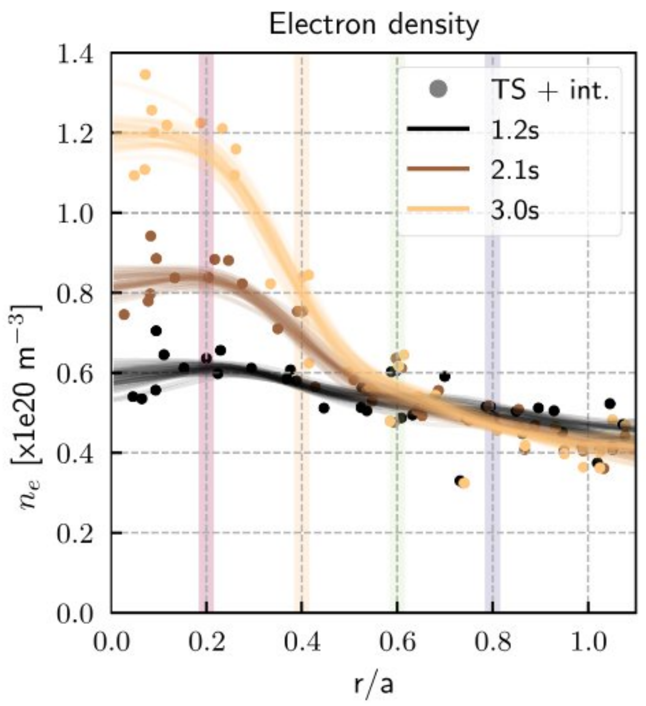
Motivation

In W7-X experiments with steep density gradients:

(pellets+ECHR) / (NBI+ECRH): high triple product[1], reduced turbulence [2]

(NBI): high particle and impurity confinement [3,4]→ <u>(my work: explain why with GENE)</u>

[3]



particle flux: $\Gamma \approx -D\,\nabla n + V\,n$

reduction of D_e by factor ~4
reduction of D_{C6+} by factor ~10

[1]: S.A. Bozhenkov et al 2020 Nucl. Fusion 60 066011
[2]: O.P. Ford et al 2024 Nucl. Fusion 64 086067
[3]: S. Bannmann et al 2024 Nucl. Fusion 64 106015
[4]: T. Romba et al 2023 Nucl. Fusion 63 076023

Outline

Motivation

Wendelstein 7-X

Gyrokinetics

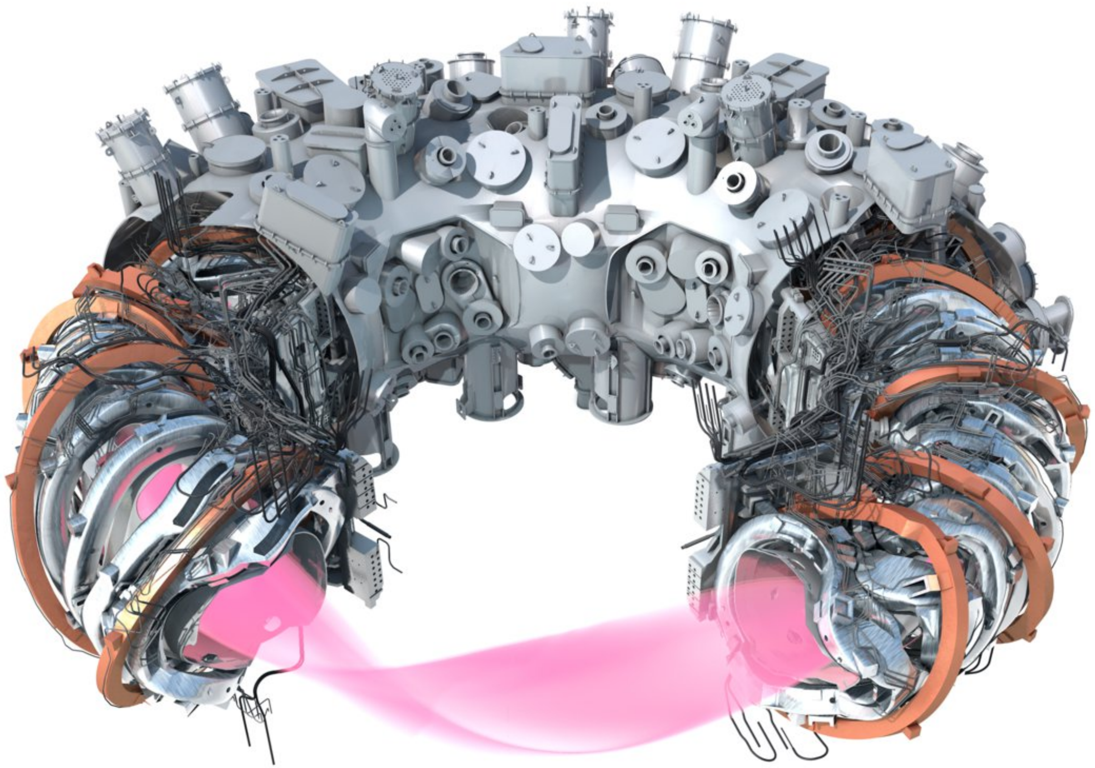
Theoretical understanding until now

Numerical results

Discussion

Conclusions

Wendelstein 7-X



MPI für Plasmaphysik

Stellarator:

- disruption-free
- long-pulse-compatible

W7-X optimization:

- MHD stability
- fast ion confinement
- (and other criteria)
- <u>low neoclassical transport</u>

Turbulence is main transport channel

Gyrokinetics

Gyrokinetic equation

|| streaming ExB grad-B curvature

$$\frac{\partial f_\sigma}{\partial t} + \left[v_\parallel \, \widehat{\boldsymbol{b}}_0 + \frac{B_0}{B_{0\parallel}^*} \left(\boldsymbol{v}_{\bar{\xi}} + \boldsymbol{v}_{\nabla B} + \boldsymbol{v}_c \right) \right] \cdot \left\{ \nabla f_\sigma - \left[q_\sigma \nabla \bar{\phi}_1 + \frac{q_\sigma}{c} \widehat{\boldsymbol{b}}_0 \dot{\bar{A}}_{1\parallel} + \mu \nabla \left(B_0 + \bar{B}_{1\parallel} \right) \right] \frac{1}{m_\sigma v_\parallel} \frac{\partial f_\sigma}{\partial v_\parallel} \right\} = 0$$

Assumptions:

- **Small fluctuations** $\frac{\delta n}{n} \ll 1$
- **Strong anisotropy** $k_\parallel \ll k_\perp$
- **Slow dynamics** $\omega_d \ll \Omega$

Solve self-consistently together with:

Poisson‘s equation

$$-\nabla^2 \phi_1(x) = 4\pi \sum_\sigma n_{1\sigma}(x) q_\sigma$$

Ampère‘s law

$$-\nabla_\perp{}^2 A_{1\parallel} = \frac{4\pi}{c} \sum_\sigma j_{1\parallel}(x)$$

Tool:

GENE

Theoretical understanding until now

geometry

QI+Max-J:

$$\frac{\partial J}{\partial \psi} < 0$$

$$J = \int_{l_1}^{l_2} m v_{||} \, dl$$

+

profiles

$$0 < \eta_a < 2/3$$

for all species,

$$\eta_a = \left(\frac{1}{T}\frac{dT}{dr}\right) / \left(\frac{1}{n}\frac{dn}{dr}\right)$$

=

Trapped Electron Mode (TEM):

- electrostatic
- driven by density gradient

No TEM [1]

Universal instability (UI) appears [2,3,4,5]

Limitations: <u>collisionless</u> and <u>electrostatic</u> analyses (in majority of cases with $\frac{1}{T_e}\frac{dT_e}{dr}$=0)

↳ What actually happens in the experiment?

[1]: J. Proll et al 2012 PRL 108 245002
[2]: J. Proll et al 2022 JPP 88 905880112
[3]: P. Costello et al 2023 J. Plasma Phys. 89 905890402
[4]: Helander et al 2015 Phys. Plasmas 22, 090706
[5]: Thienpondt et al 2025 Nucl. Fusion 65 016062

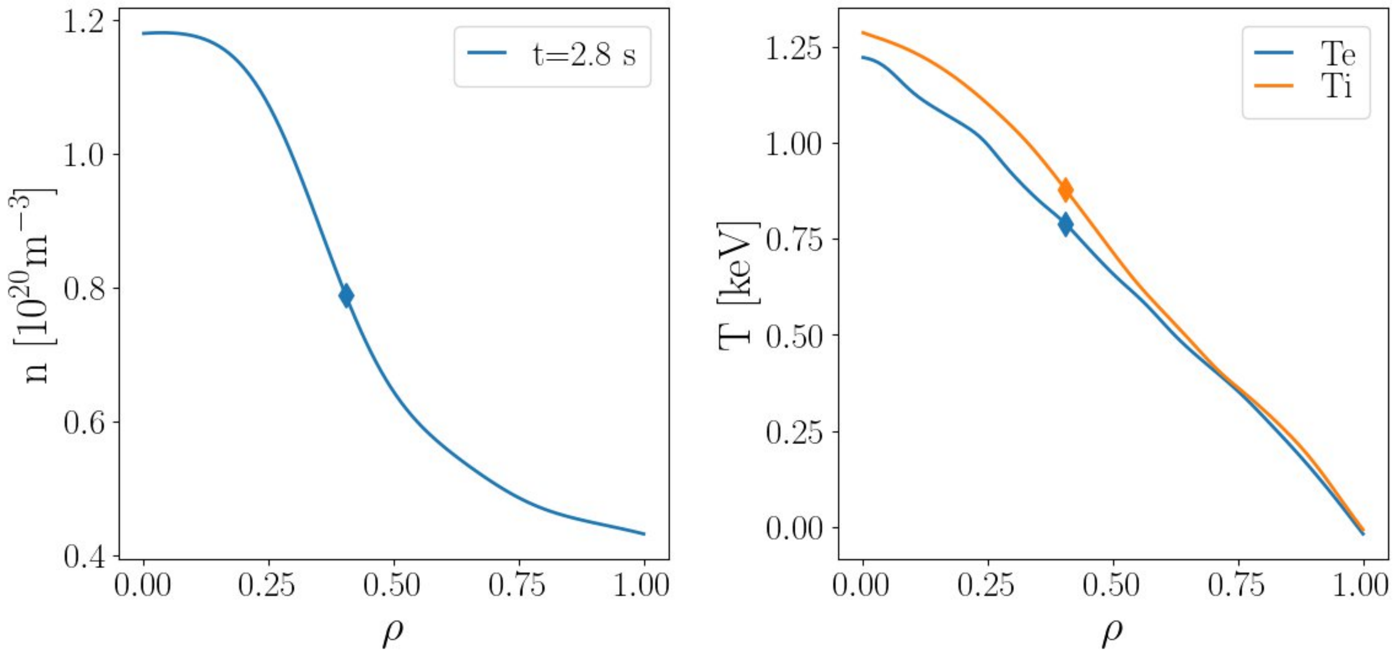
Numerical setup

NBI phase of discharge 20181009.034

$$\frac{a}{L_x} = -\frac{a}{x}\frac{dx}{dr}$$

$$\eta_a = \left(\frac{1}{T}\frac{dT}{dr}\right) / \left(\frac{1}{n}\frac{dn}{dr}\right)$$

$$\beta_e = \frac{8\pi n_{e0} T_{e0}}{{B_{ref}}^2}$$



$a/L_n = 2.36$ $T_i/T_e = 1.1$

$a/L_{T_e} = 1.54$ $\beta_e = 5 \times 10^{-3}$

$a/L_{T_i} = 1.9$

$\eta_i = 0.8$

$\eta_e = 0.65$

expected stabilization of both ITG and TEM

Numerical setup

NBI phase of discharge 20181009.034

$$\frac{a}{L_x} = -\frac{a}{x}\frac{dx}{dr}$$

$$\eta_a = \left(\frac{1}{T}\frac{dT}{dr}\right)/\left(\frac{1}{n}\frac{dn}{dr}\right)$$

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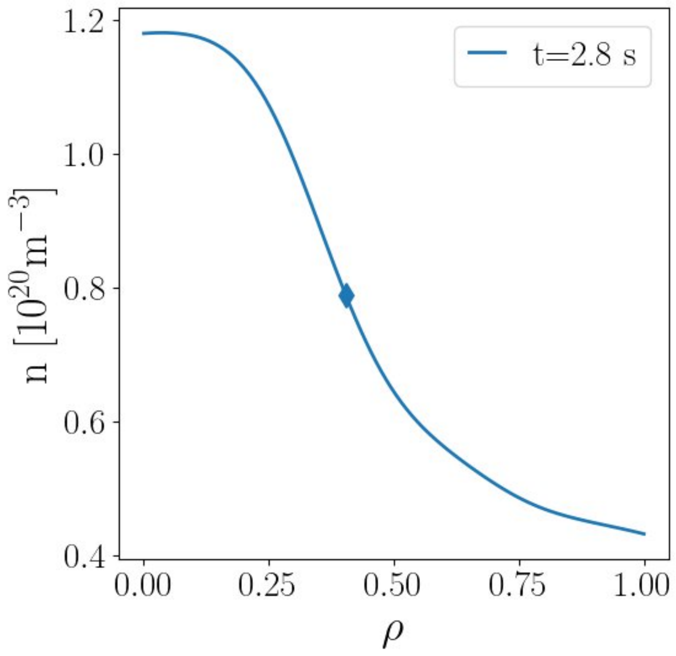

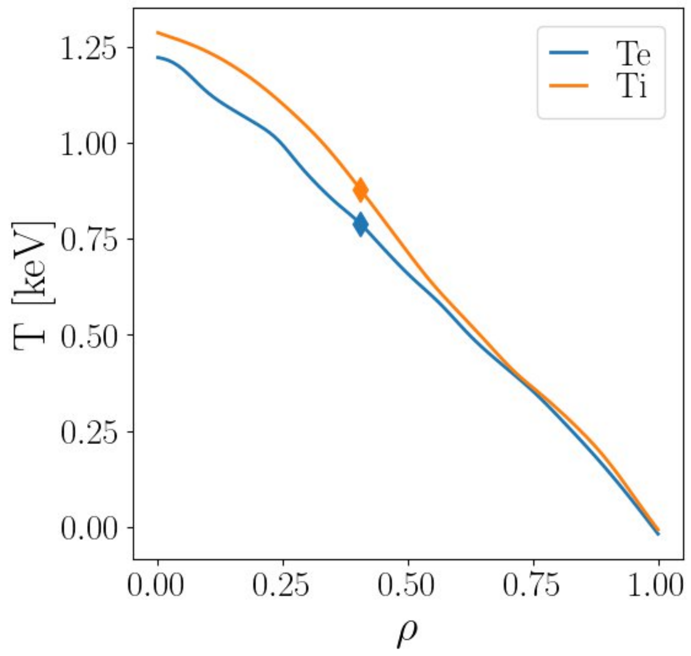

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$\eta_i = 0.8$
$\eta_e = 0.65$
expected stabilization of both ITG and TEM

outline for GENE flux tube simulations, two species:

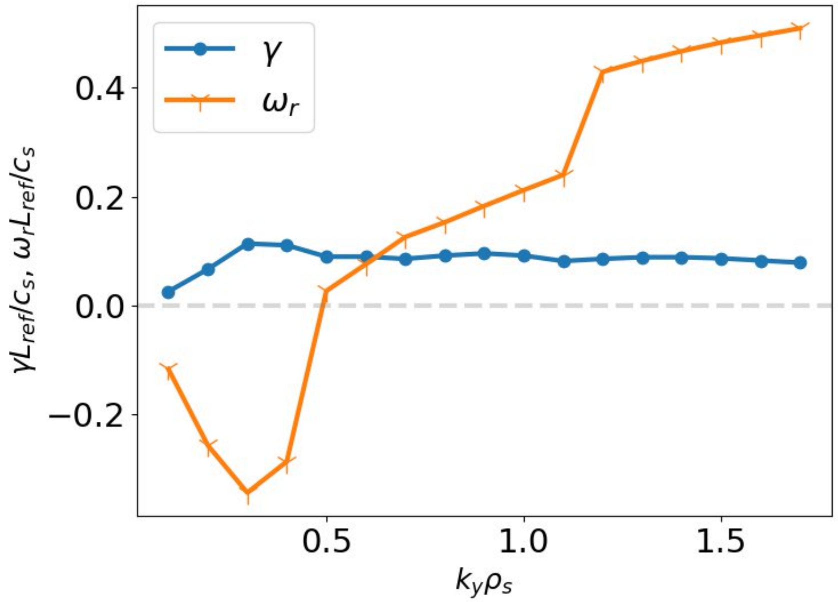
		collisions	
		T	F
beta	T	[Experiment]	?
	F	?	?

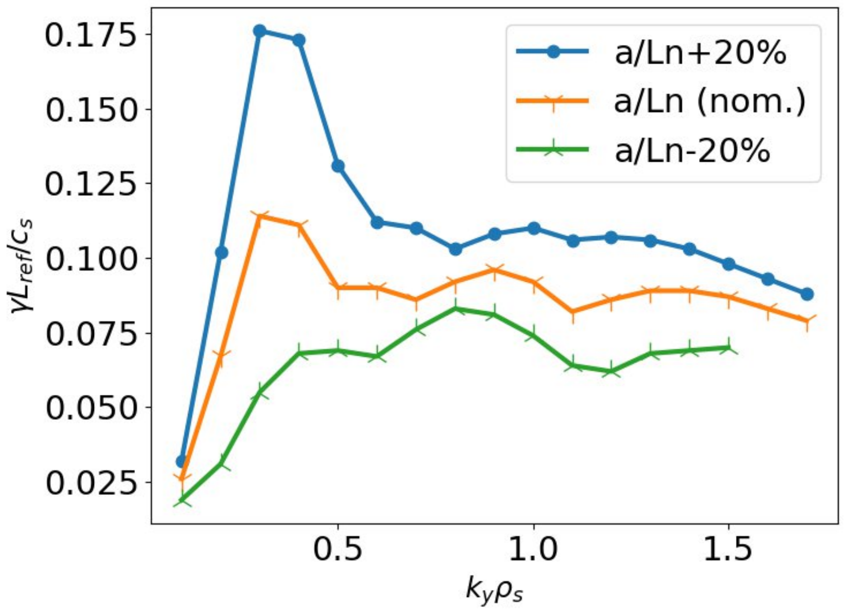
		collisions	
		T	F
beta	T	[Exp.]	?
	F	?	UI/iTEM

Beta scan without collisions

$\vec{B} = C\,\nabla x \times \nabla y$
x = flux surface label
$y = q\theta^* - \phi$
z = arc length along $\vec{B}$

no beta $(\beta_e = 10^{-6})$: UI+iTEM





Universal Instability (UI):
- destabilized by a/Ln
- ω_r <0
- driven by passing electrons [1,2]
  - **stabilized by beta [4]**

ion-driven Trapped Electron Mode (iTEM):
- destabilized by a/Ln
- $\omega_r \gtrapprox 0$ [3]
- driven by trapped particles-> localization of Q at |B| wells

[1]: Helander et al 2015 Phys. Plasmas 22, 090706
[2]: P. Costello et al 2023 J. Plasma Phys. 89 905890402
[3]:G. Plunk et all 2017 J. Plasma Phys. 83 715830404
[4]:J.M. Duff et al 2025 Nucl. Fusion 65 046020

		collisions	
		T	F
beta	T	[Exp.]	iTEM/ TEM
	F	?	UI/iTEM

Beta scan without collisions

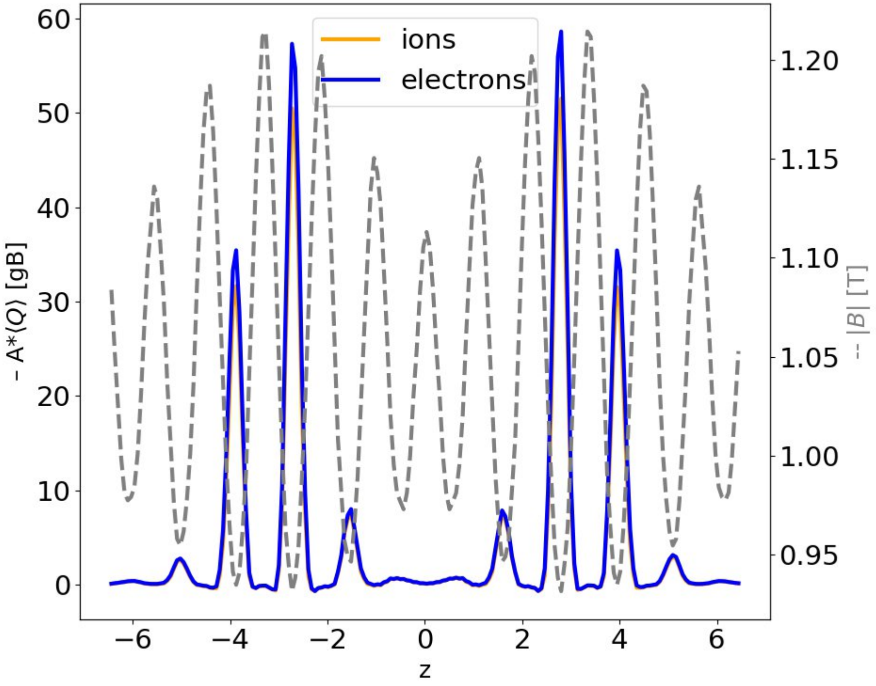
$\vec{B} = C\, \nabla x \times \nabla y$

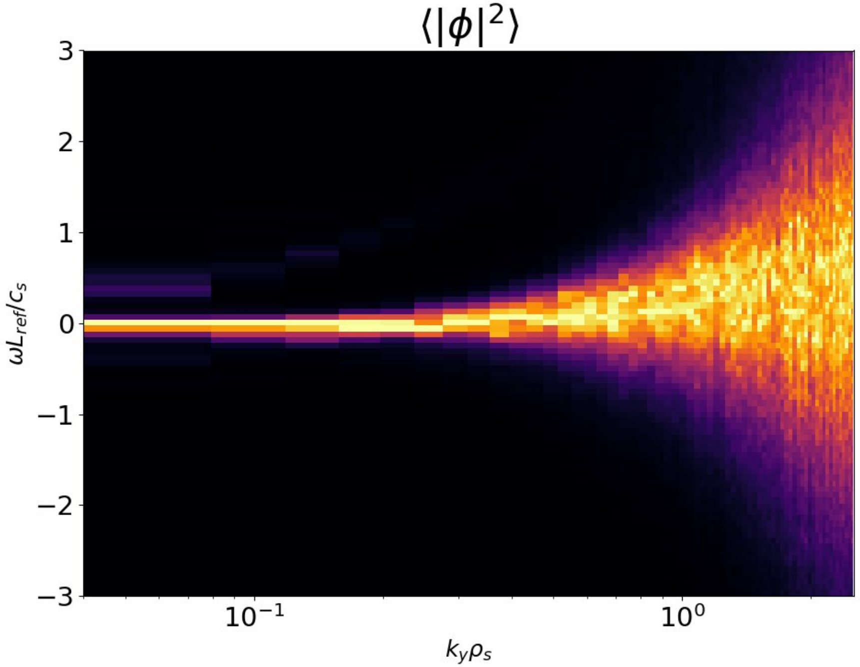
x = flux surface label

$y = q\theta^* - \phi$

z = arc length along $\vec{B}$

nominal beta $(\beta_e = 5 \times 10^{-3})$: **iTEM/TEM**





Universal Instability (UI):

- destabilized by a/Ln
- ω_r <0
- driven by passing electrons [1,2]
  - **stabilized by beta [4]**

ion-driven Trapped Electron Mode (iTEM):

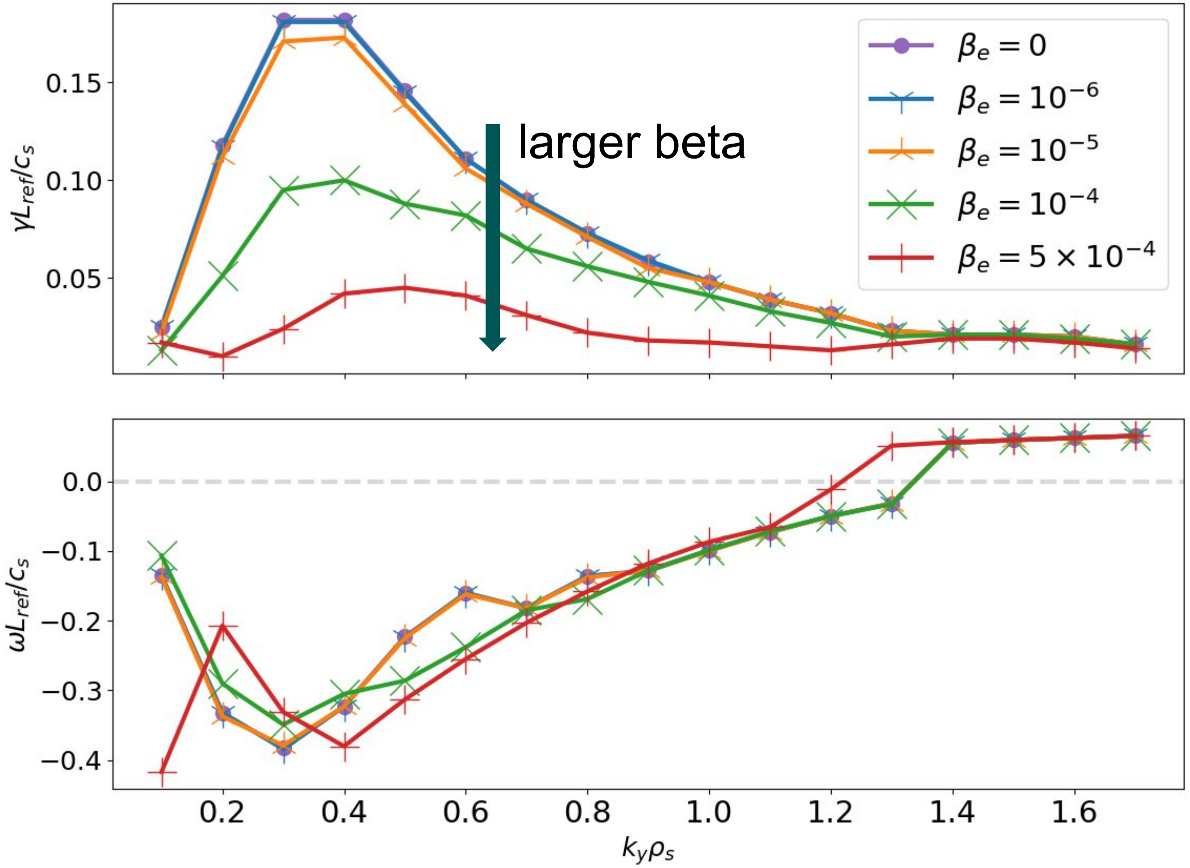
- destabilized by a/Ln
- $\omega_r \gtrsim 0$ [3]
- driven by trapped particles-> localization of Q at |B| wells

[1]: Helander et al 2015 Phys. Plasmas 22, 090706
[2]: P. Costello et al 2023 J. Plasma Phys. 89 905890402
[3]:G. Plunk et all 2017 J. Plasma Phys. 83 715830404
[4]:J.M. Duff et al 2025 Nucl. Fusion 65 046020

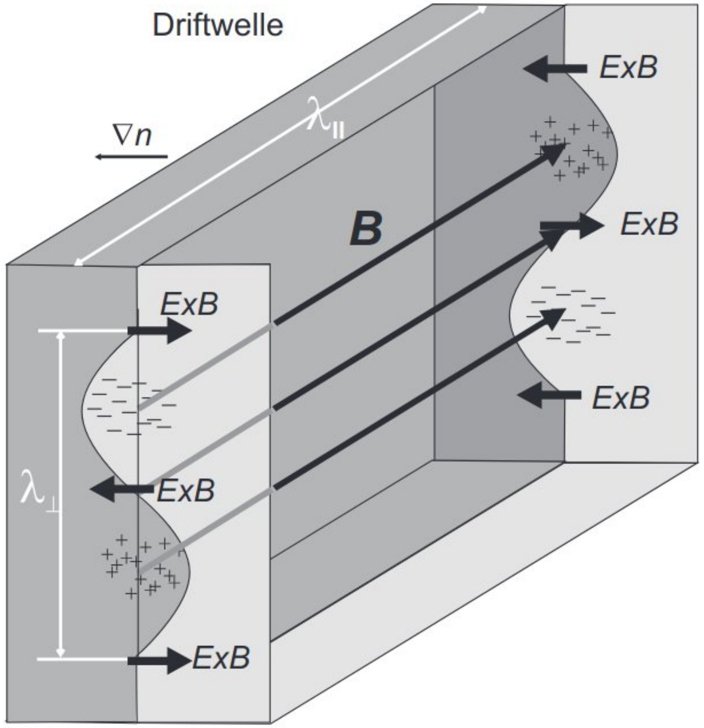
Beta scan with collisions

		collisions	
		T	F
beta	T	[Exp.]	iTEM/TEM
	F	UI	UI/iTEM

linear stabilization



1. increase of beta
2. increase of $\vec{B}$ fluctuations
3. decrease of passing e^- mobility
4. smaller potential ϕ
5. lower ExB

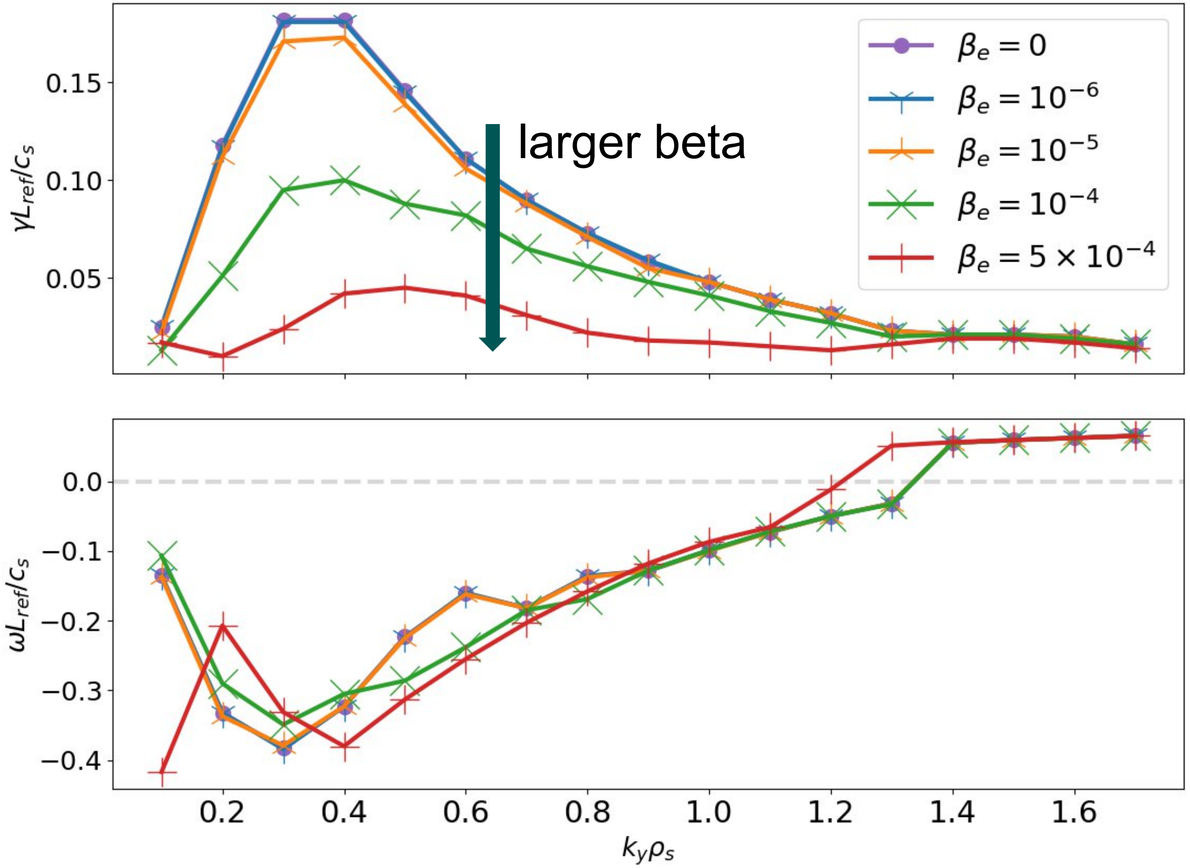


U. Stroth Plasmaphysik 2018

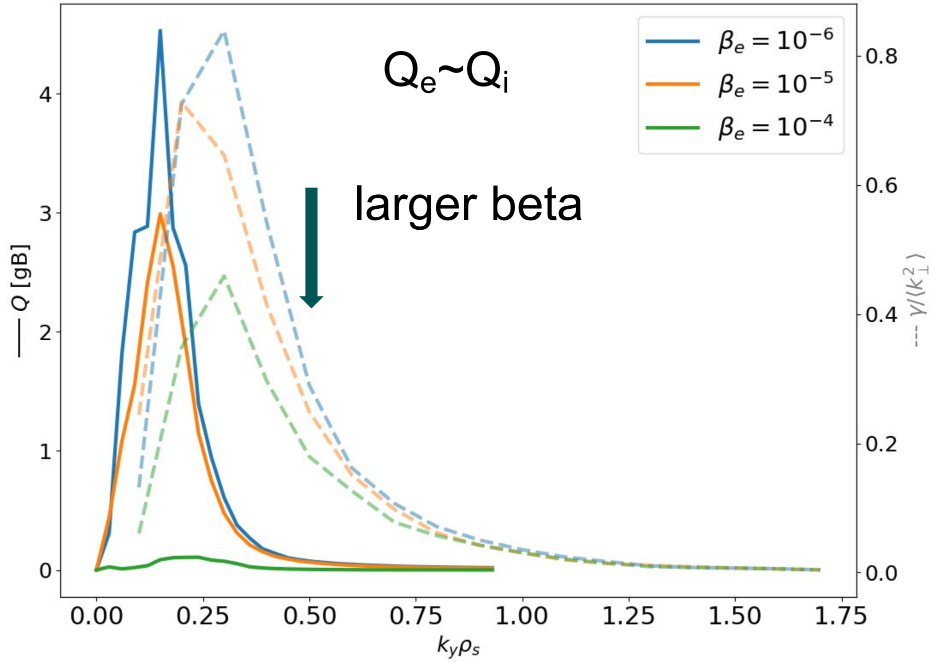
		collisions	
		T	F
beta	T	[Exp.]	iTEM/TEM
	F	**UI**	UI/iTEM

Beta scan with collisions

linear stabilization



strong non-linear stabilization



$$\langle k^2{}_\perp \rangle = \frac{\int k_\perp{}^2 |\phi|^2 dxdz}{\int |\phi|^2 dxdz}$$

	$\frac{Q_{(\beta=10^{-5})}}{Q_{(\beta=10^{-4})}}$	$\frac{Q_{(\beta=10^{-6})}}{Q_{(\beta=10^{-5})}}$
QL	1.7	1.1
NL	**11.9**	1.3

Possible reasons for strong NL stabilization:

-beta increases triplet correlation time [1]

-low shear $\hat{s} = \frac{x_0}{q_0}\frac{dq}{dr} = 0.022$ facilitates NL energy transfer [2]

[1]: Whelan 2018 PRL 120 175002

[2]: Faber 2018 J. Plasma Phys. 80 905840503

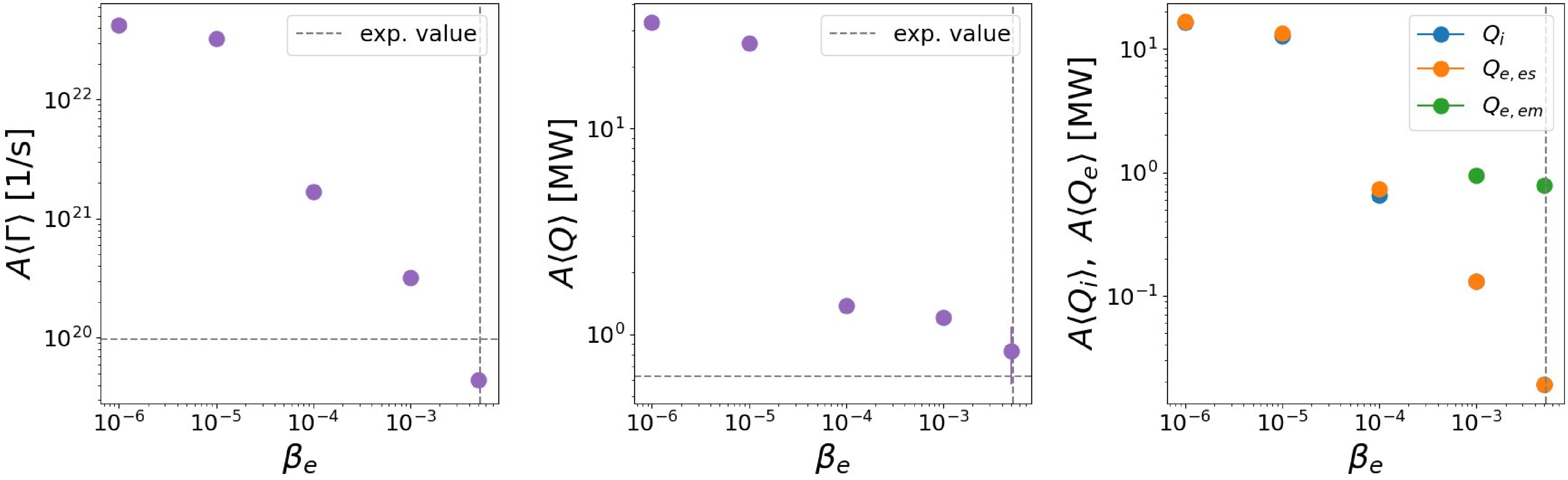
		collisions	
		T	F
beta	T	[Exp.]	iTEM/TEM
	F	UI	UI/iTEM

Beta scan with collisions

Non-linear simulations, increase of β_e causes:

→Reduction of fluxes

→Transition from electrostatic to electromagnetic turbulence



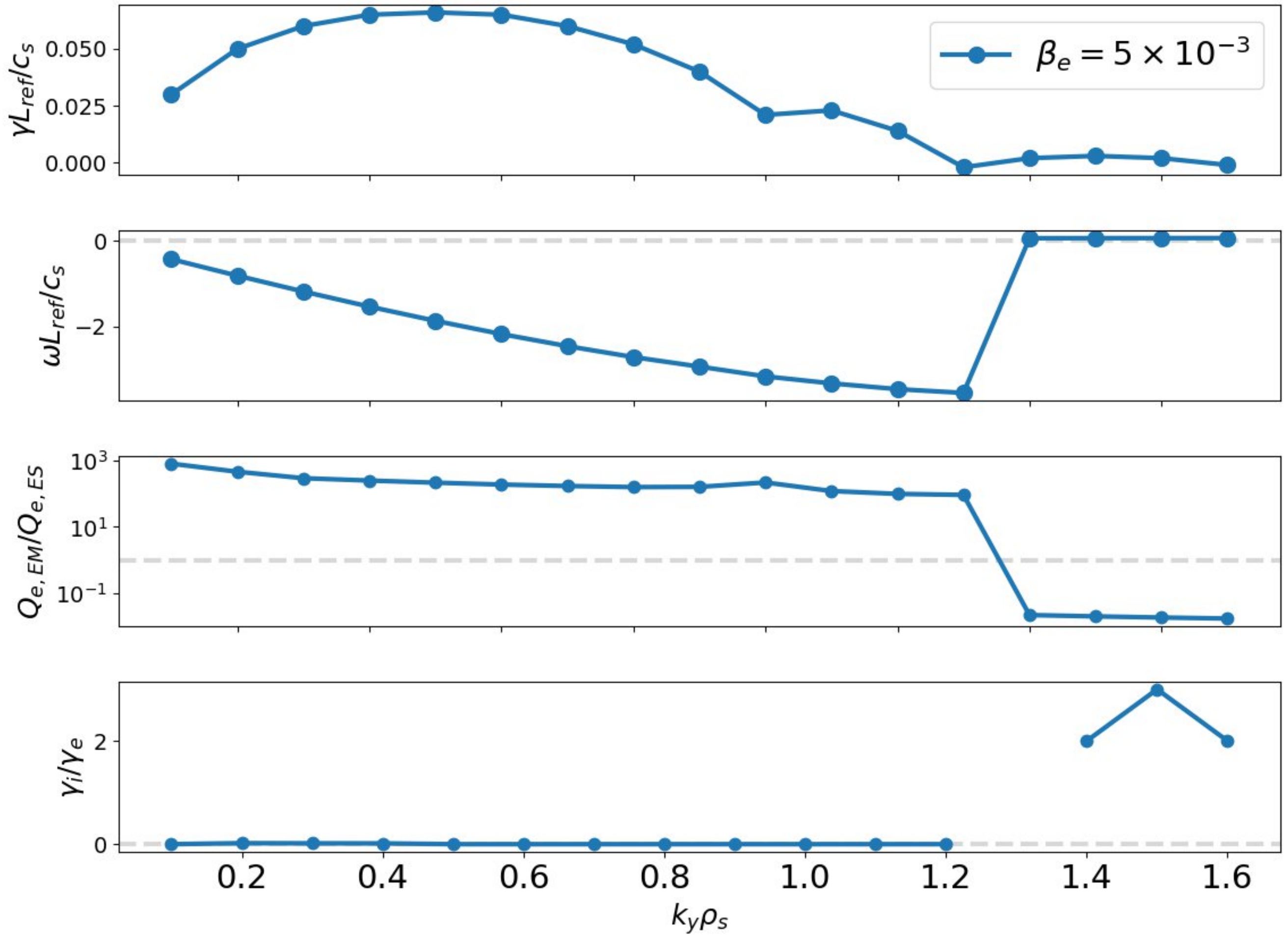
A=area

		collisions	
		T	F
beta	T	**MTM**	iTEM/TEM
	F	UI	UI/iTEM

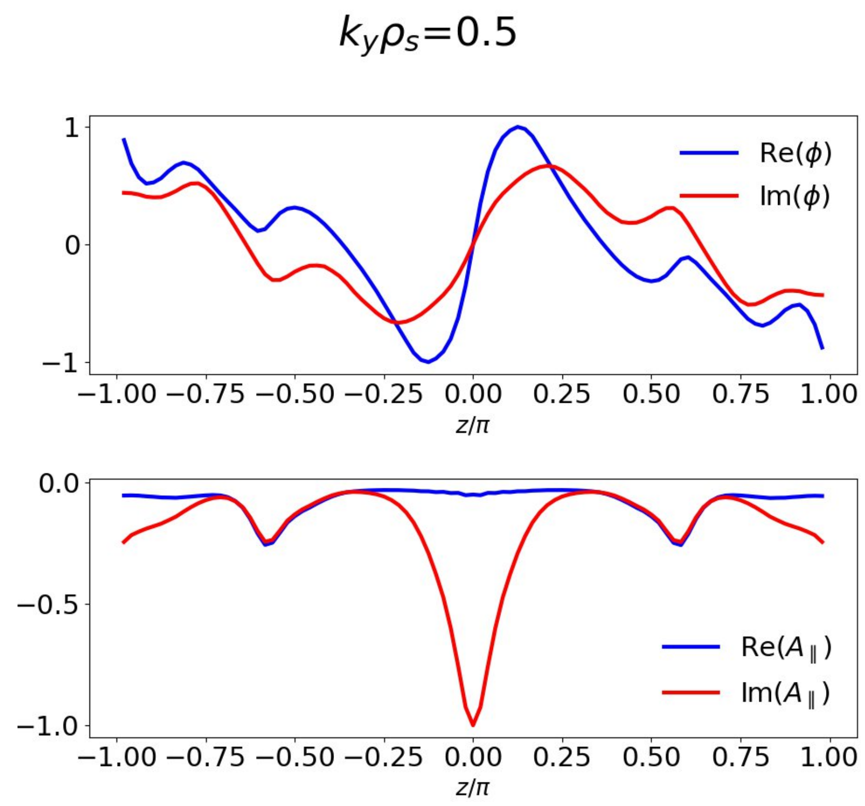
Nominal beta and collisions: Microtearing mode (MTM)

Linear simulations

MTM: electromagnetic, driven by a/LT$_e$ (and to lesser extent by a/L$_n$)



tearing parity



Nominal beta and collisions: Microtearing mode (MTM)

		collisions	
		T	F
beta	T	MTM	iTEM/TEM
	F	UI	UI/iTEM

Non-linear simulations

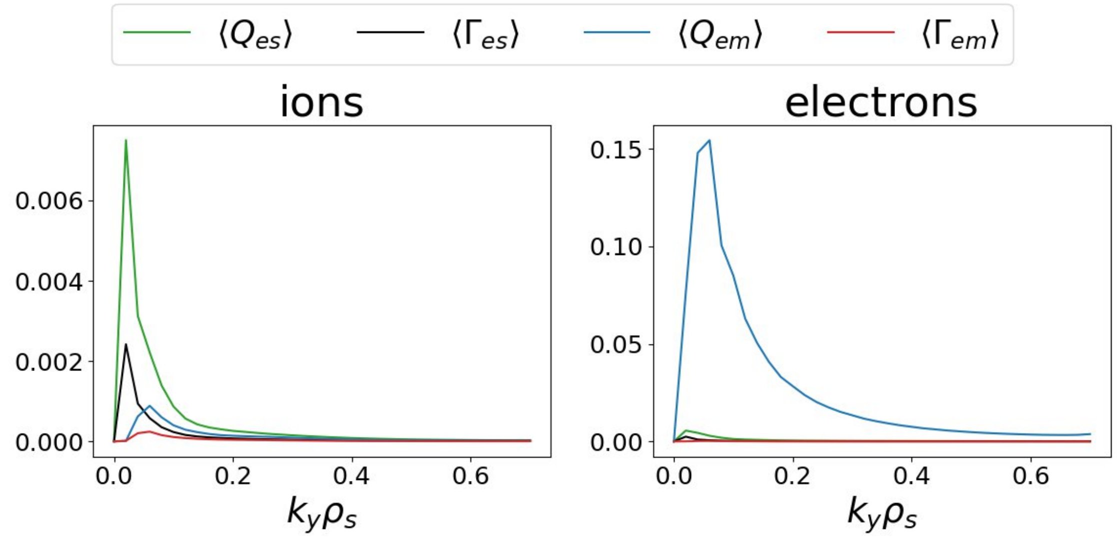
$\vec{B} = C\, \nabla x \times \nabla y$

x = flux surface label

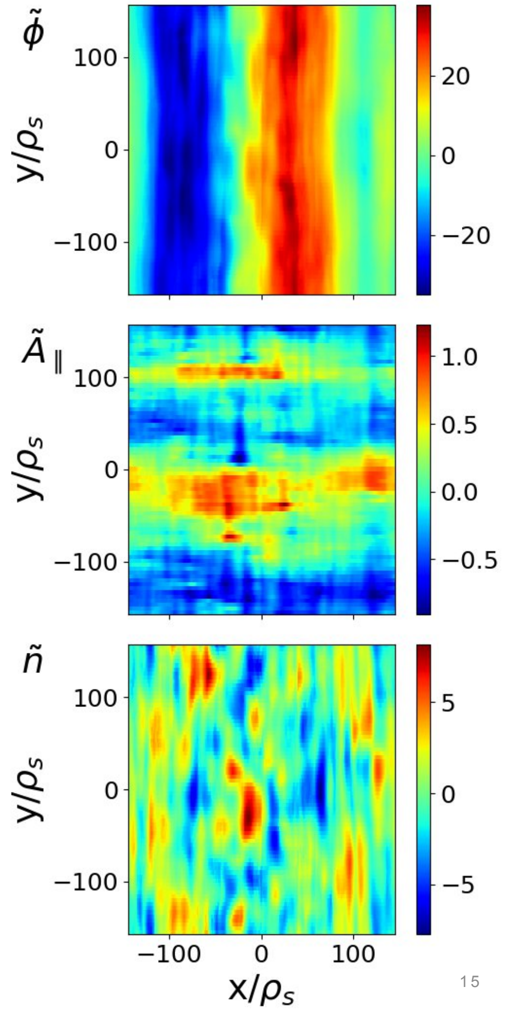
$y = q\theta^* - \phi$

z = arc length along $\vec{B}$

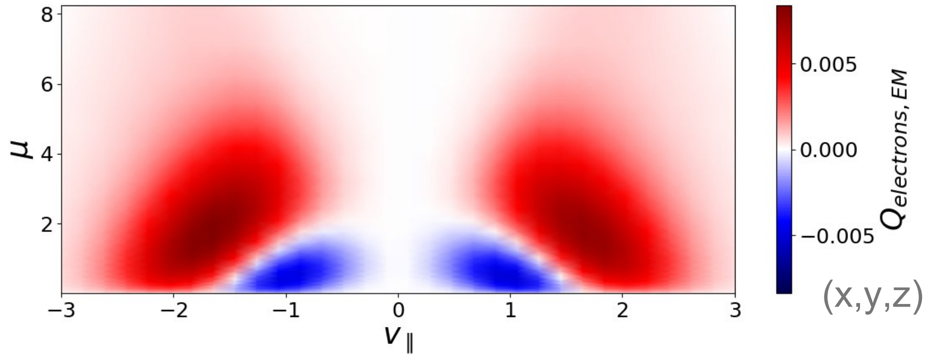
Electromagnetic mode



Elongated A|| structures



Effects at the trapped-passing particle boundary



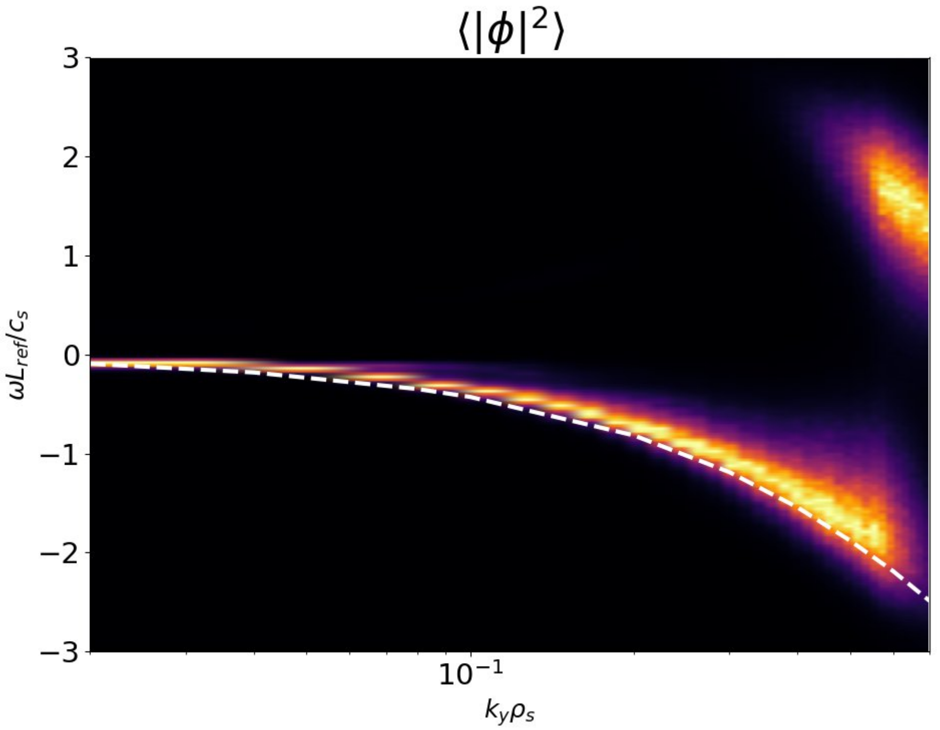
(x,y,z) averaged

		collisions	
		T	F
beta	T	**MTM**	iTEM/TEM
	F	UI	UI/iTEM

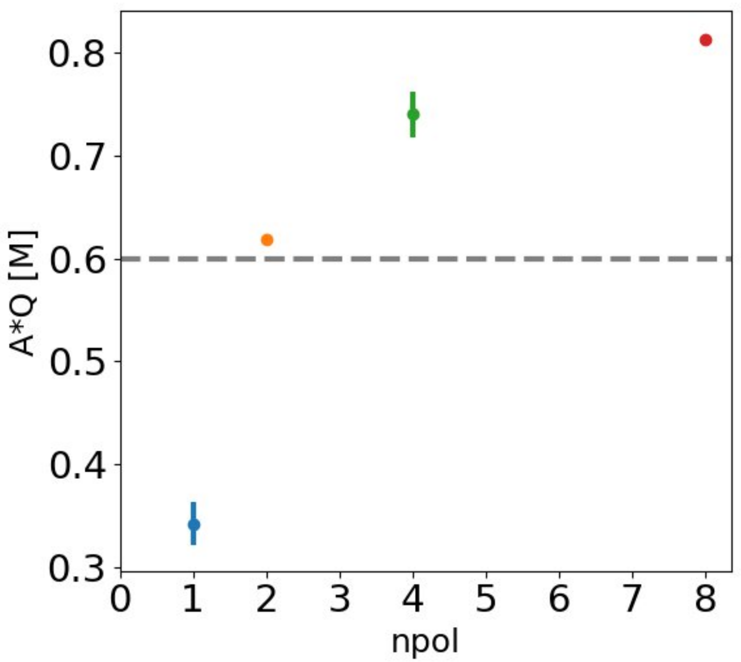
Nominal beta and collisions: Microtearing mode (MTM)

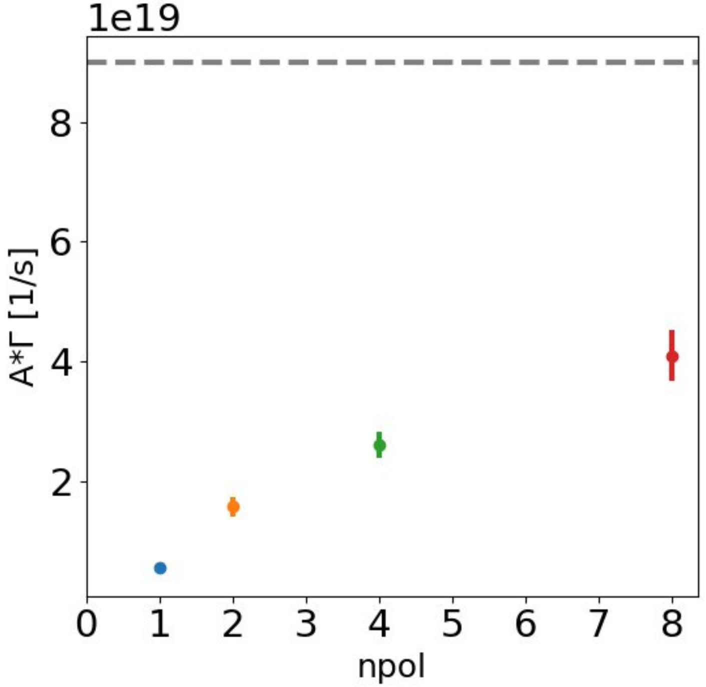
Non-linear simulations

Particle flux driven by MTM ($\omega_r < 0$) at large scales



Mode is very extended along the field line





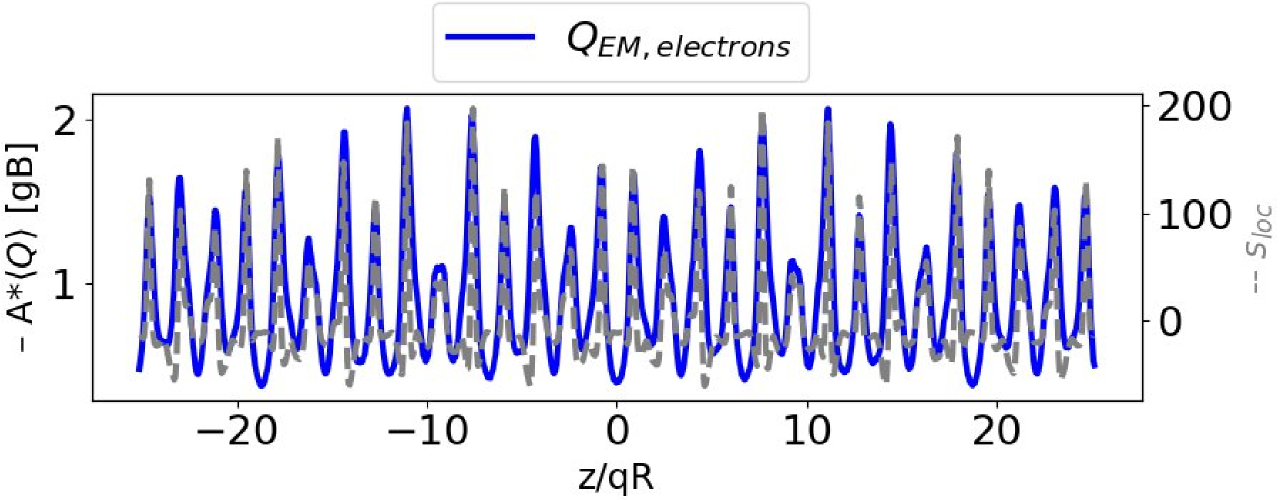
Nominal beta and collisions: Microtearing mode (MTM)

		collisions	
		T	F
beta	T	MTM	iTEM/TEM
	F	UI	UI/iTEM

Non-linear simulations

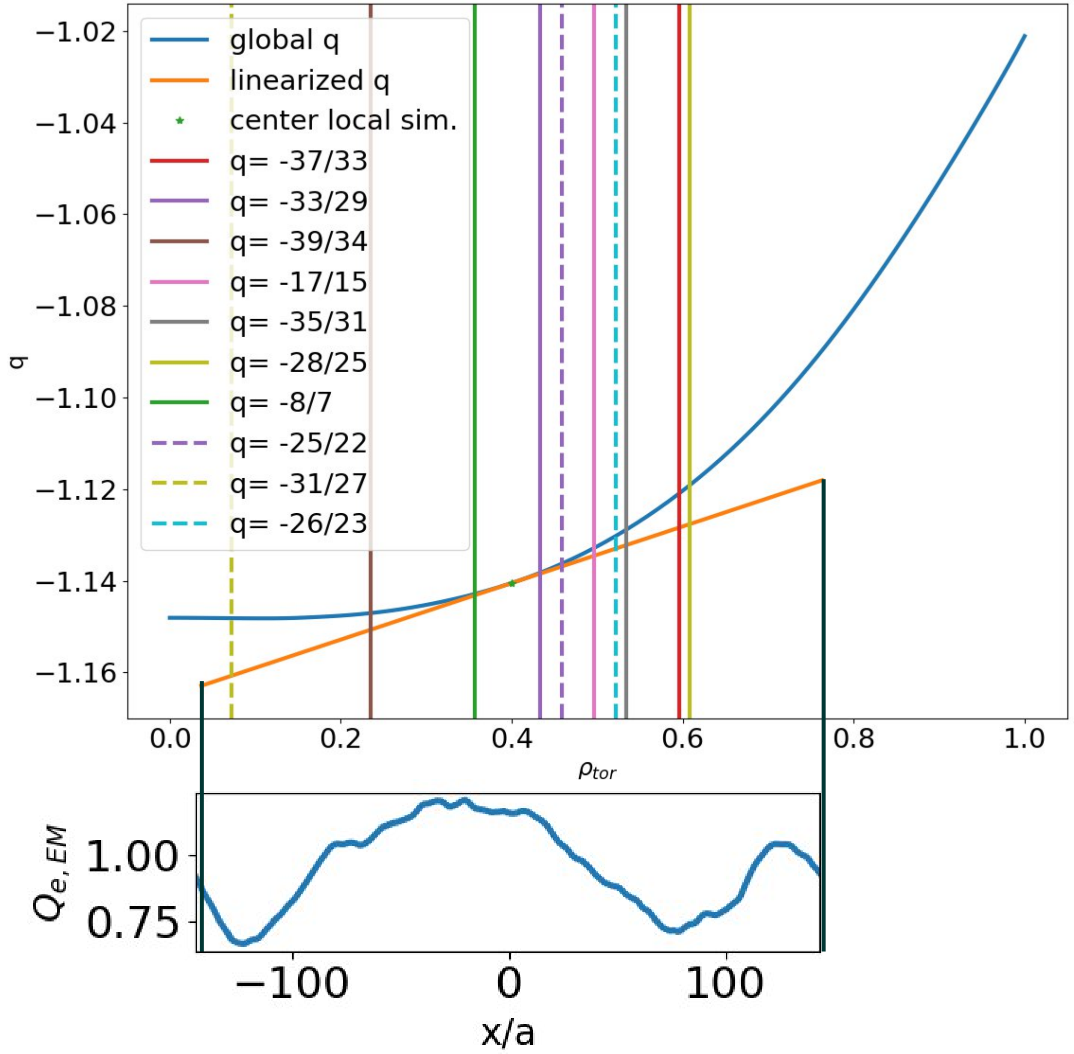
Dependence of $Q_{e,em}$ on local magnetic shear:

$$S = -\boldsymbol{X} \cdot \left(\nabla \times \boldsymbol{X}\right) = \boldsymbol{B} \cdot \nabla\left(\frac{\nabla\psi\cdot\nabla\alpha}{|\nabla\psi|^2}\right) \qquad \text{with } \boldsymbol{X} = \frac{\boldsymbol{B}\times\nabla\psi}{|\nabla\psi|^2} \qquad [1]$$



Dependence on x?

$$q(x) \approx q(x_0) + (x - x_0)\frac{dq}{dx}\Big|_{x_0}$$



Relation to global shear: $\langle S\rangle = -4\pi^2 \frac{d\iota}{dV}$

[1]: Helander 2014 Rep. Prog. Phys. 77 087001

Nominal beta and collisions: Microtearing mode (MTM)

		collisions	
		T	F
beta	T	**MTM**	iTEM/TEM
	F	UI	UI/iTEM

Non-linear simulations

stabilization by collisions

stabilization by beta

Experiment: $A\langle Q\rangle$ =**0.6 MW** $A\langle\Gamma\rangle$ =**9.6x10^{19} 1/s** A=area		collisions	
		T	**F**
beta	**T** ($\beta_e = 5\times10^{-3}$)	$A\langle Q\rangle$ =**0.84 MW** $A\langle\Gamma\rangle$ =**4.4x10^{19} 1/s**	$A\langle Q\rangle$ =6.7 MW $A\langle\Gamma\rangle$ =1.1 x10^{22} 1/s
	F ($\beta_e = 1\times10^{-6}$)	$A\langle Q\rangle$ =32.7 MW $A\langle\Gamma\rangle$ =4.2x10^{22} 1/s	$A\langle Q\rangle$ =25.6 MW $A\langle\Gamma\rangle$ =3.5x10^{22} 1/s

Experimentally:

1) **Q_i can drop to neoclassical levels [1]**
2) **NBI discharges: separation of Q_e and Qi difficult, since T_e~T_i [2].**
   Within error bars: Q=Q_e

[1]: S.A. Bozhenkov et al 2020 Nucl. Fusion 60 066011
[2]: O.P. Ford et al 2024 Nucl. Fusion 64 086067

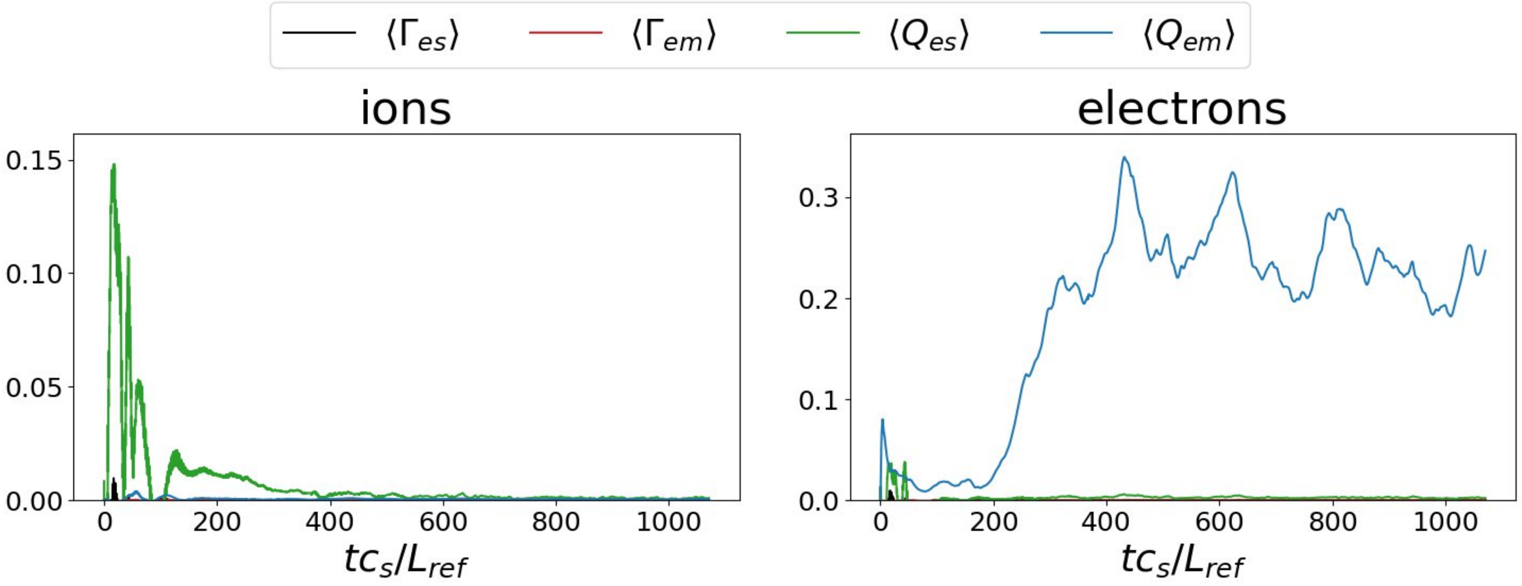
Open questions

„pre-accumulation“ -> likely also MTM

What causes then the reduction of D for ne and C6+?

Maybe just a change in cross phases, i.e. Phi x n?

Certainly: more simulations needed



Back-of-the-envelope calculation of α_{MHD} for t=2.8 and t=1.5 s

$$\alpha_{MHD} = -Rq^2 \frac{d\beta}{dr}$$

$$\alpha_{MHD} \approx q^2 \frac{R}{a} \beta_e \left(\frac{a}{L_n} + \frac{a}{L_T} \right)$$ **(using $n_e = n_i$ and $T_e = T_i$)**

$$\beta_e = \frac{8\pi n_{e0} T_{e0}}{B_{ref}^2}$$

β_e in cgs units

q=-1.14

R/a=10 (W7-X)

t=1.5 s

$a/L_n = 0.98$ $\quad T_i/T_e = 1.1$

$a/L_{T_e} = 1.55$ $\quad \beta_e = 4 \times 10^{-3}$

$a/L_{T_i} = 1.12$

$$\alpha_{MHD} \approx 2 \cdot (-1.14)^2 \cdot 10 \cdot 4 \times 10^{-3} (0.98 + 1.55)$$

$$\alpha_{MHD} \approx 0.26$$

t=2.8 s

$a/L_n = 2.36$ $\quad T_i/T_e = 1.1$

$a/L_{T_e} = 1.54$ $\quad \beta_e = 5 \times 10^{-3}$

$a/L_{T_i} = 1.9$

$$\alpha_{MHD} \approx 2 \cdot (-1.14)^2 \cdot 10 \cdot 5 \times 10^{-3} (2.36 + 1.54)$$

$$\alpha_{MHD} \approx 0.50$$

Note: α_{MHD} is a figure of merit for pressure-driven instabilities

Limitations of flux tube model

Double check:

- (possible) cross-field interaction $\rightarrow$ FFS simulation
- linearization of safety factor $\rightarrow$ global simulation

Which is the cheapest, yet good-enough model?

Conclusions

Using GENE, microtearing mode (MTM) has been found in W7-X experimental scenarios which are

- ~~**highly density-gradient-driven.**~~
- **not so temperature-gradient-driven.**

MTM appears to exist in a „sweet region“ of beta, collisionality and moderate/low values of η_i, η_e

$$\eta_a = \left(\frac{1}{T}\frac{dT}{dr}\right) / \left(\frac{1}{n}\frac{dn}{dr}\right)$$

previous understanding

QI + Max-J
+low η_i & η_e

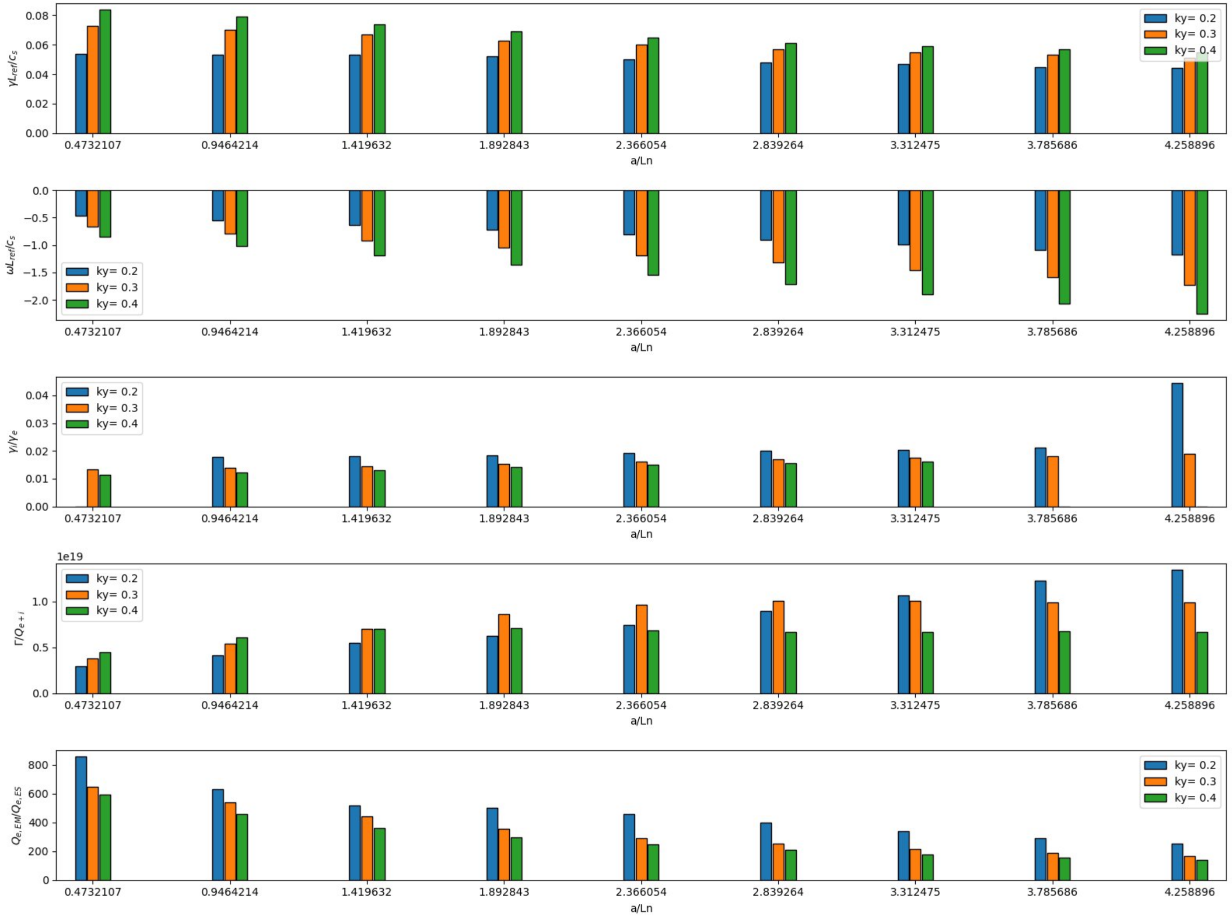
absence of TEM

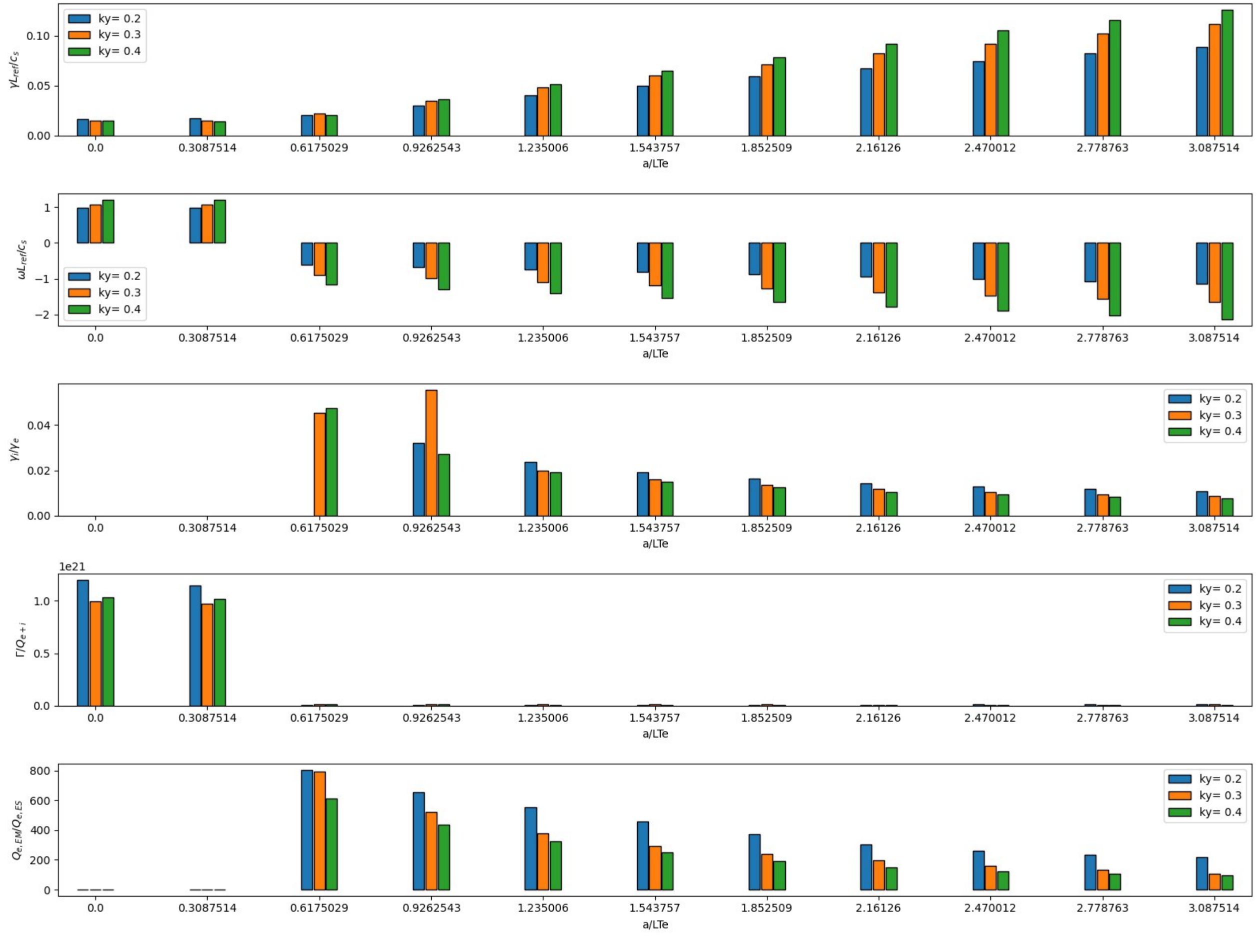
+collisions
+beta:
transition UI/iTEM->MTM

This work, using experimental values

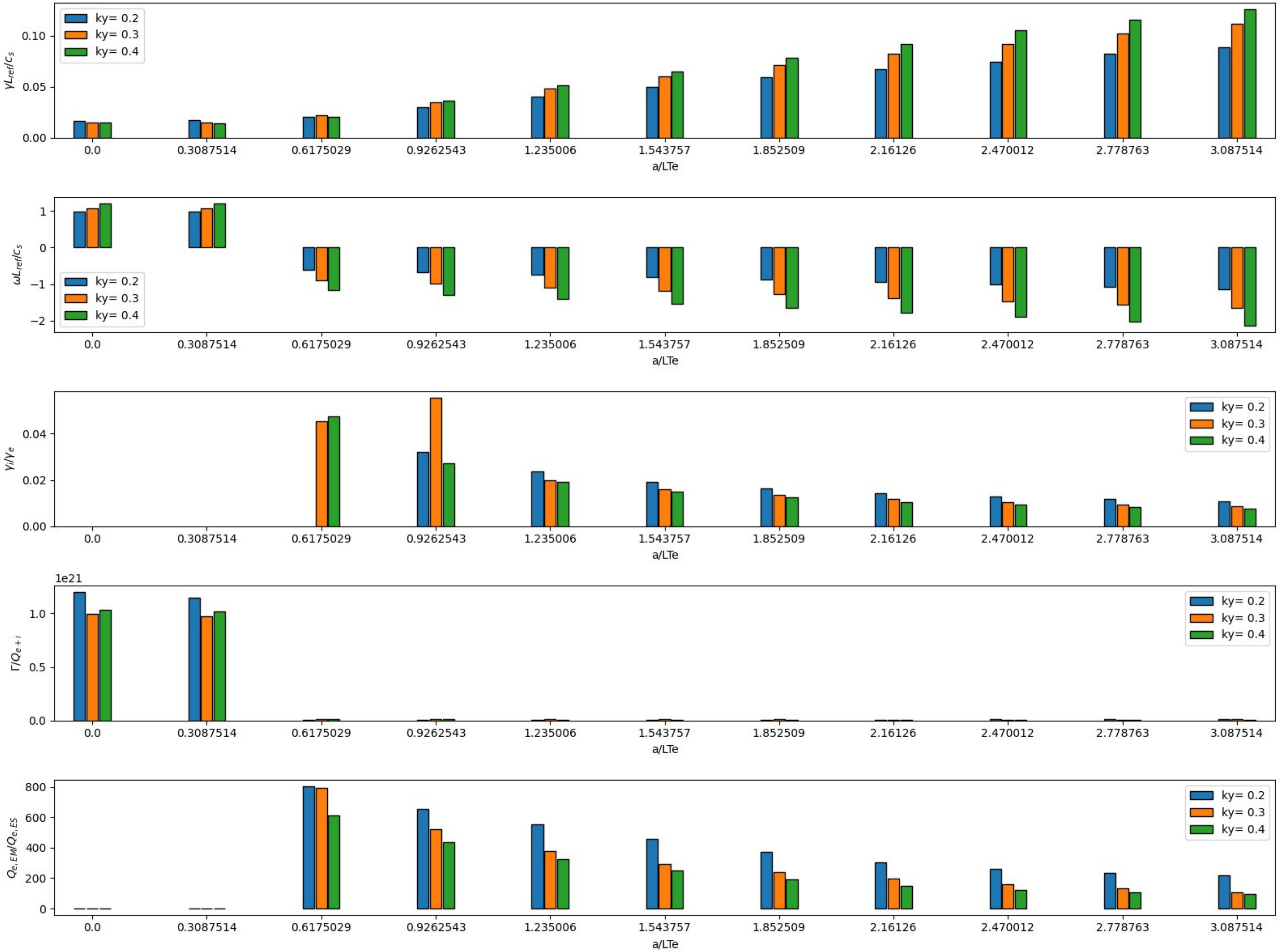
Back-up slides

Growth rate dependence on a/LTe,a/Ln

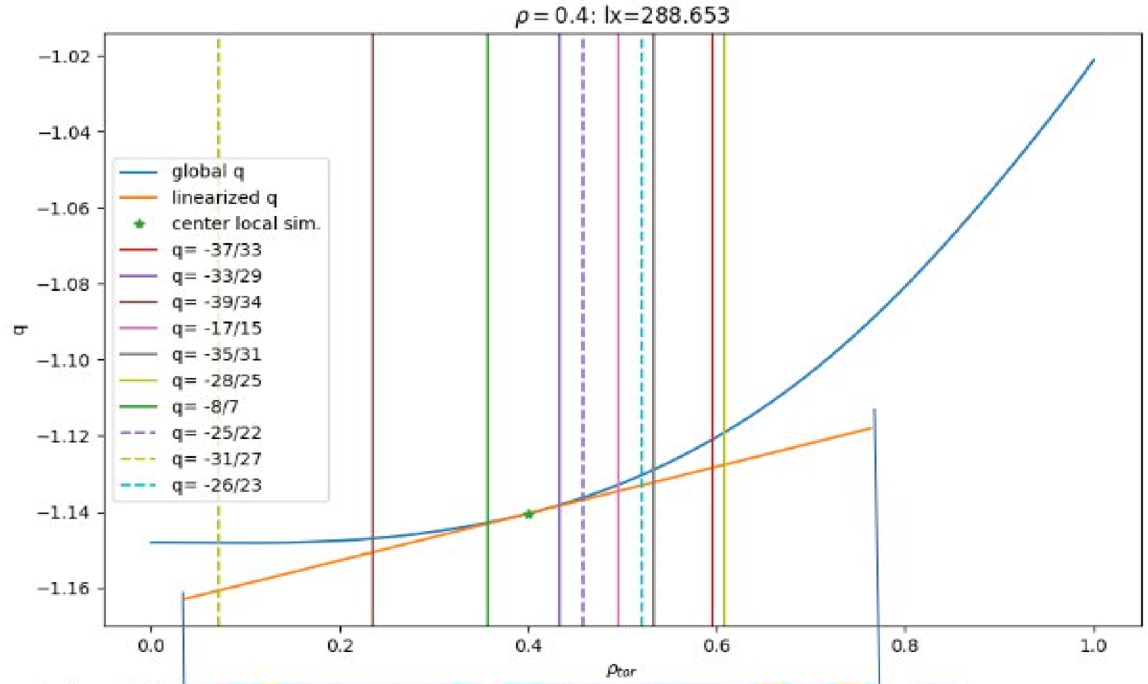


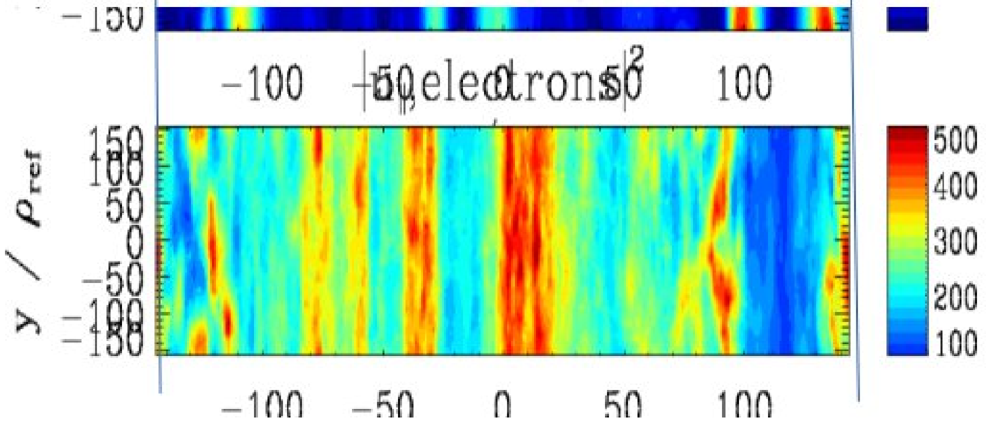


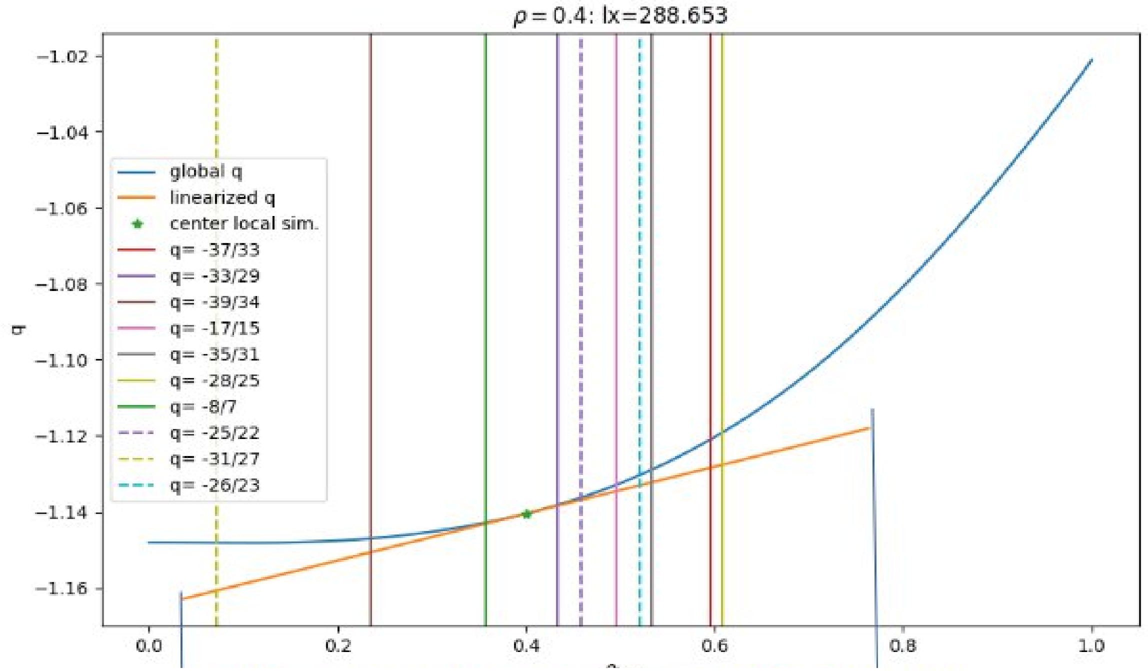
Growth rate dependence on a/LTi

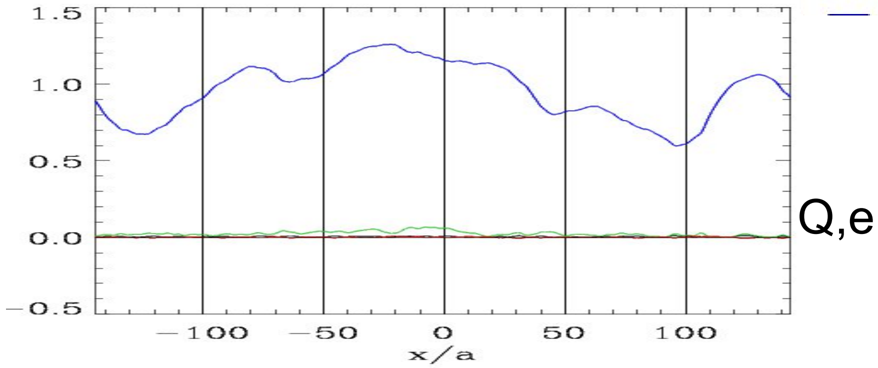


Contour plots, comparison with global and linearized safety-factor profile



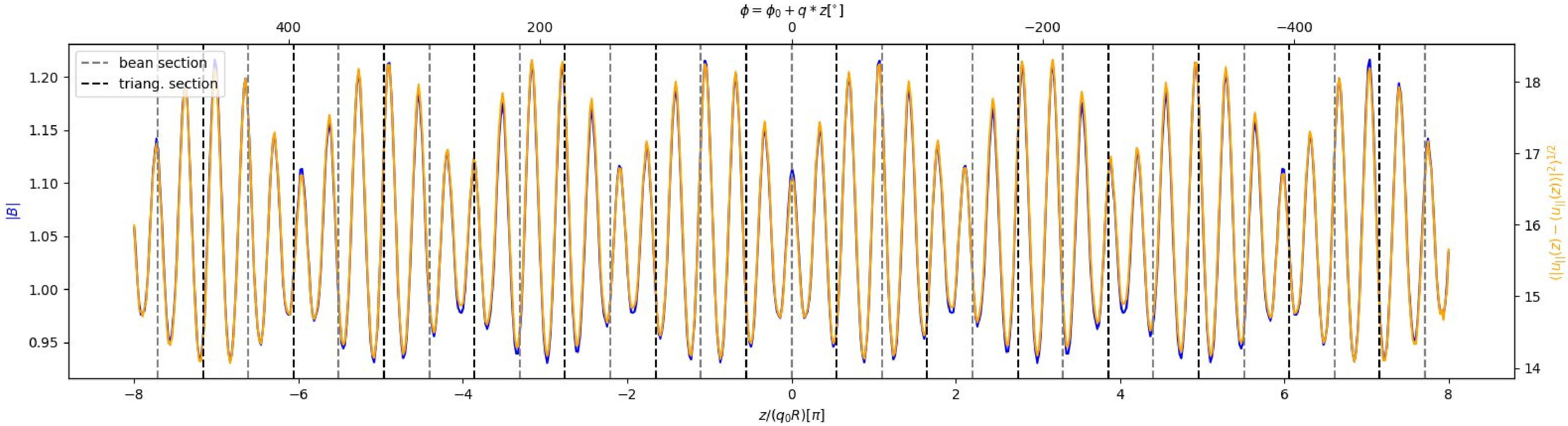




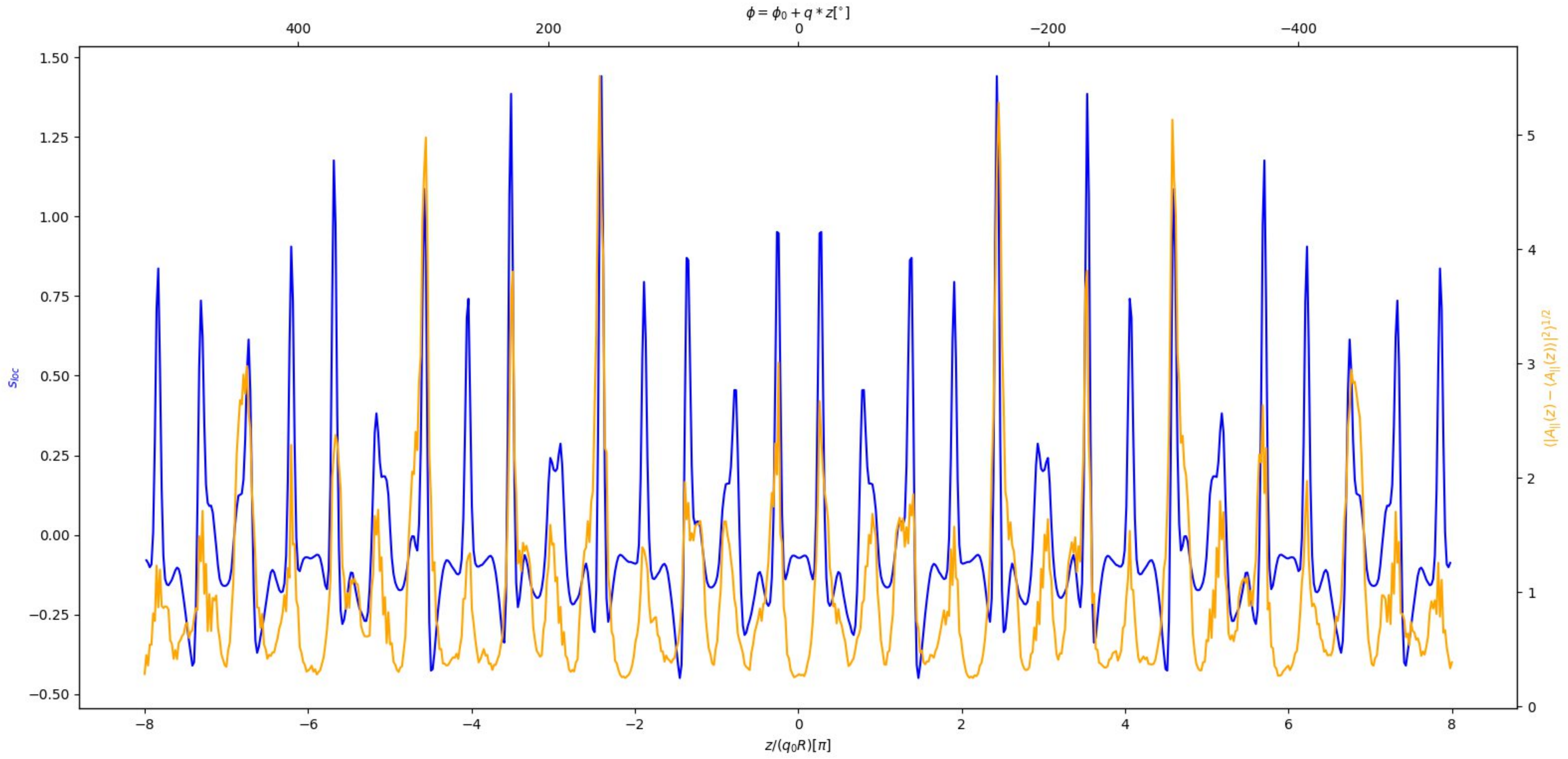


Q,e,EM

Dependence of u||² on |B|(z):

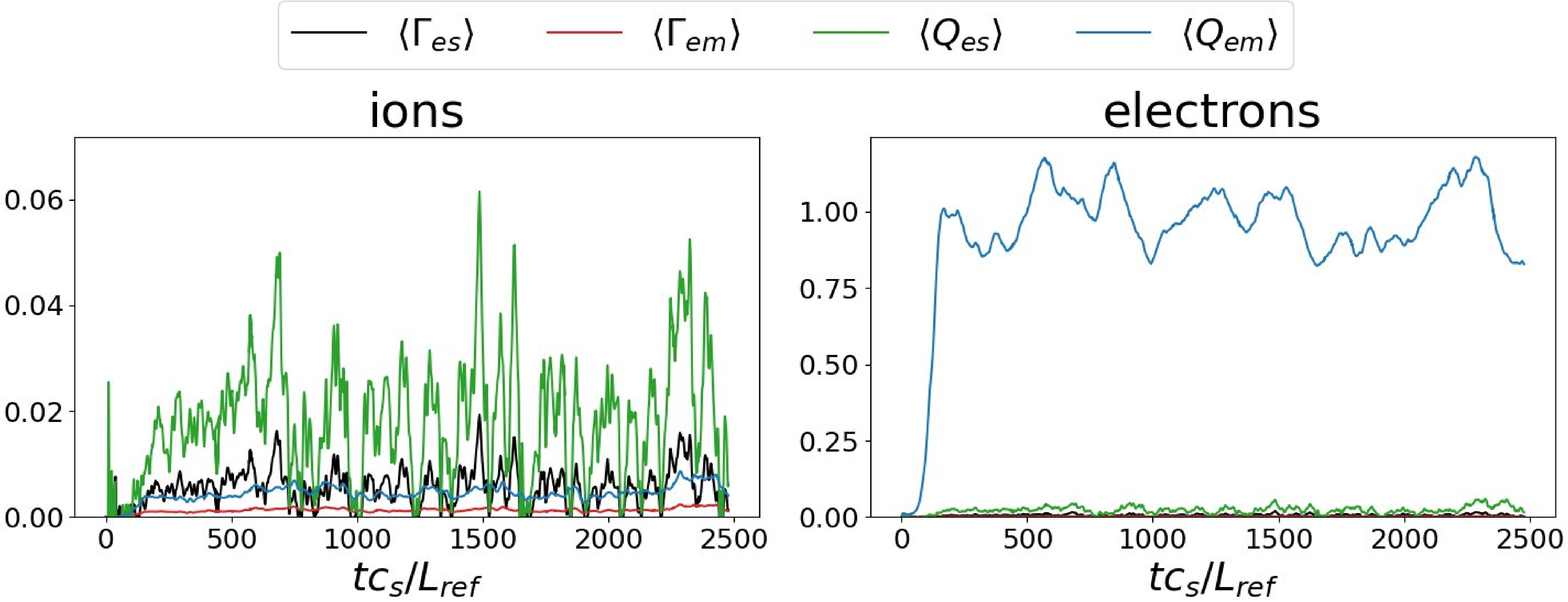


Dependence of A|| on local shear



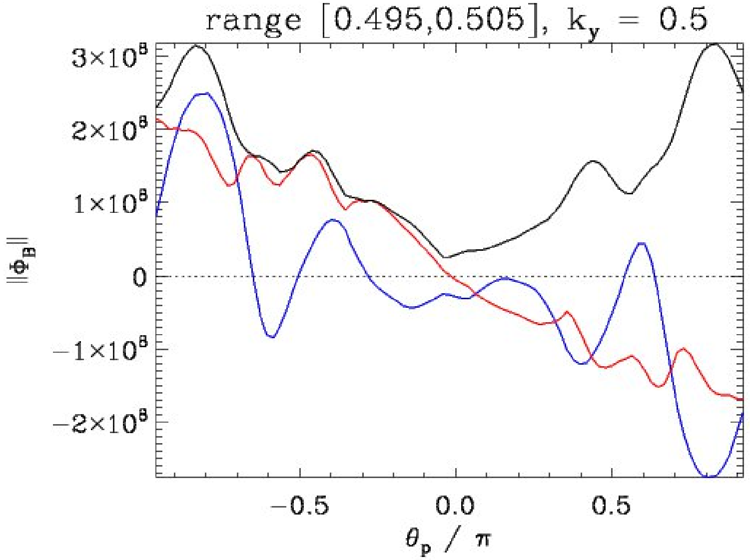
Time trace, beta=T,coll=T, t=2.8 s

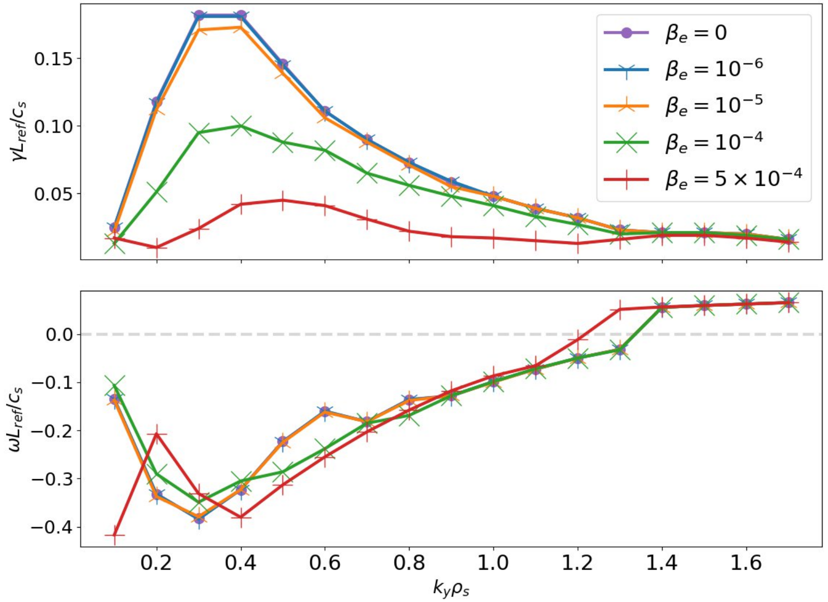
gB units



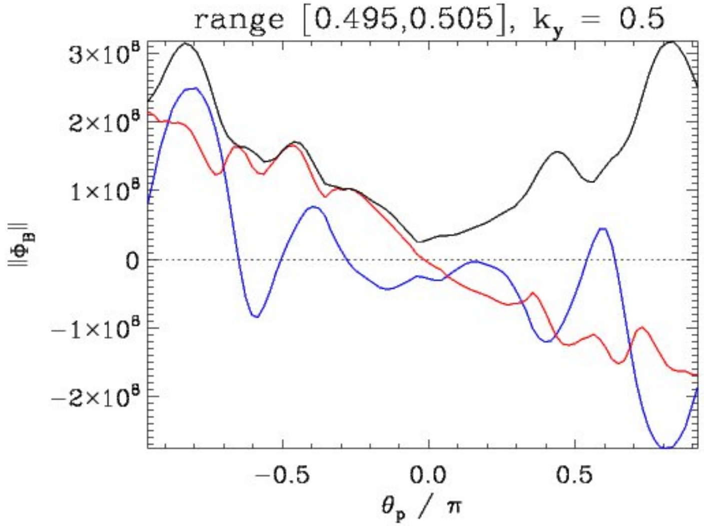
Universal instability also displays tearing parity

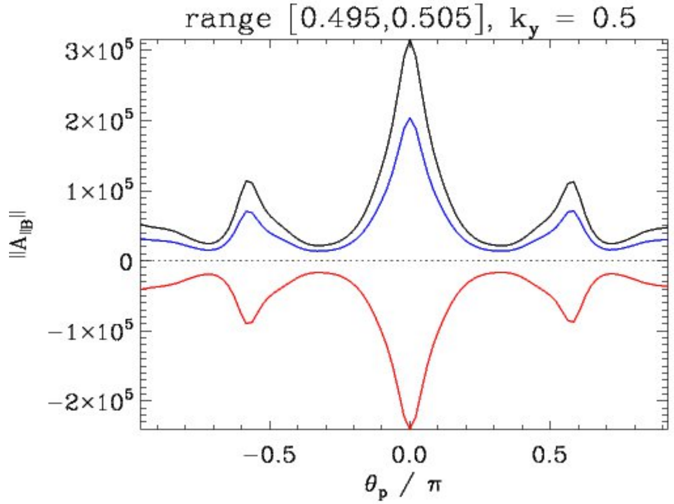
beta=0





beta=1E-6





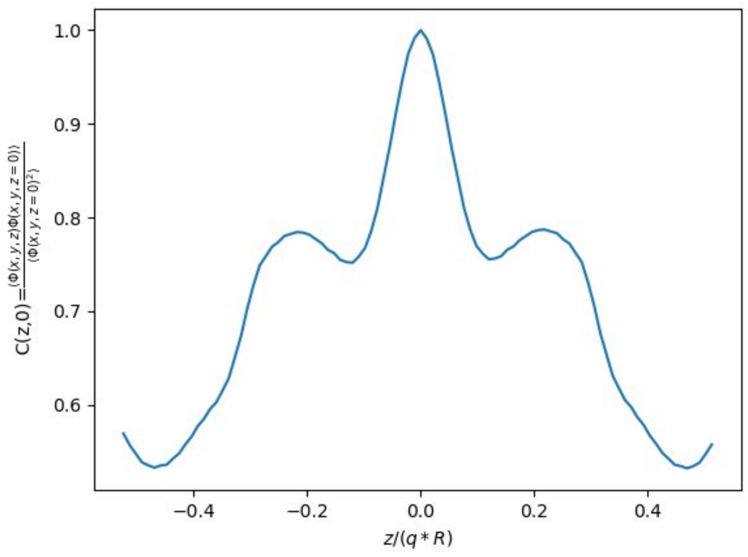
A simple figure of merit to quantify excessive || correlation for stellarators

Beer 1995, PoP

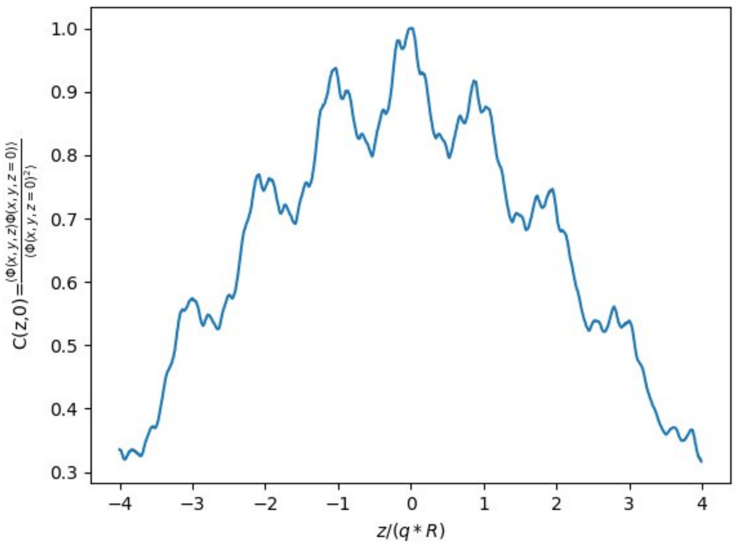
$$C(\theta,0)=\frac{\langle\Phi(x,y,\theta)\Phi(x,y,\theta=0)\rangle}{\langle\Phi(x,y,\theta=0)^2\rangle}$$

(modified) correlation function. <> means average over x,y and t. Only non-zonal components (ky=/=0) of phi are used here

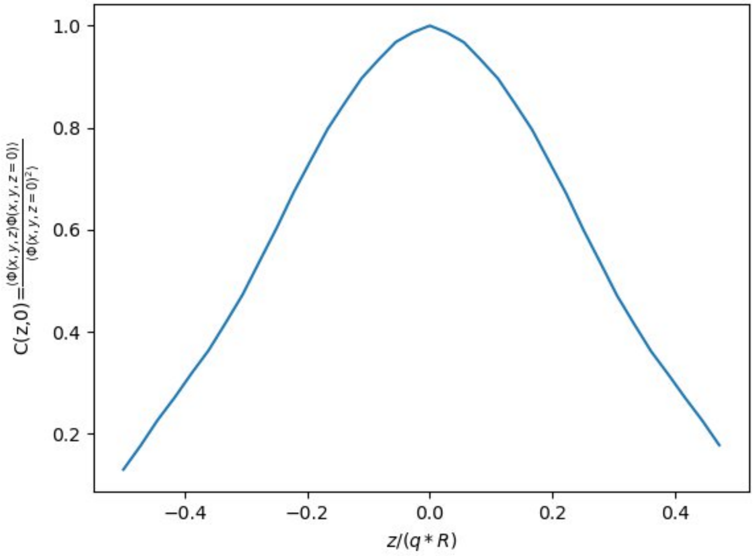
npol=1



npol=8



CBC, with KE, (npol=1, $\beta=10^{-4}$)



Limitations of flux tube model

Double check:

- (possible) cross-field interaction → FFS simulation
- linearization of safety factor → global simulation

Which is the cheapest, yet good-enough model?