Turbulent transport driven by kinetic ballooning modes in the inner core of JET hybrid H-modes

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NSTX-U / Magnetic Fusion Science Meeting : August 10, 2020

Personal details

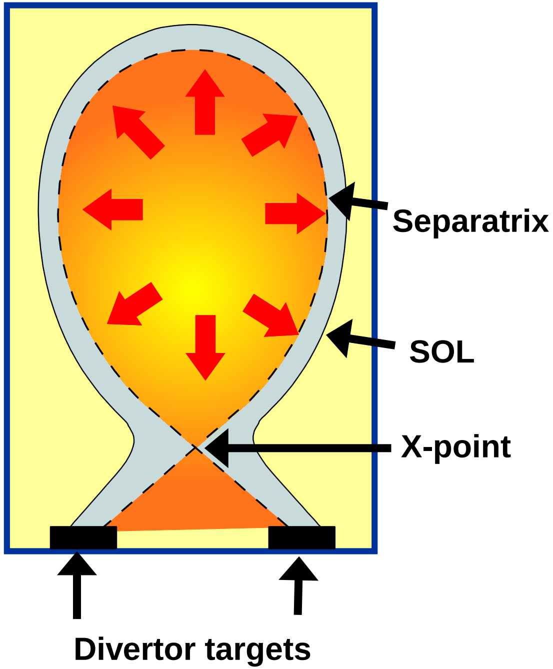
- Bachelor of Science Honours (B.Sc. (H)) in **Physics** ➔ University of Delhi, India, 2013
- Master of Technology (M.Tech) in **Nuclear Science and Technology** ➔ Department of Physics and Astrophysics, University of Delhi, India, 2016
- PhD in **Plasma Physics** ➔ Aix-Marseille University/ITER Organization, France, Dec 2017-Present
  - Thesis Title: **Analysis of Energy and Particle Transport in the Central part of ITER Plasmas**
  - Thesis Supervisors: **Yann Camenen, Alberto Loarte, Clarisse Bourdelle, Sadruddin Benkadda**
- **Research Interests:** Plasma modeling and simulations, turbulence transport

Outline

- **Background and motivation**
  - Tungsten (W) accumulation issue in ITER
  - Transport of W -> need to predict n and T in the inner core
- **Investigation of turbulent transport using gyrokinetic code GKW**
  - Linear analysis in the inner core of JET plasmas
  - Non-linear simulations the inner core of JET plasmas
- **Test of quasilinear approximation in the inner core of JET plasmas**
- **Summary**

ITER divertor and tungsten (W) accumulation issue

- Large heat loads on the walls and divertor ($\sim < \mathbf{10}\ \boldsymbol{MW/m^2}$)
- Use of materials that do not retain much tritium → **W**
- Large radiative power losses from the plasma
- W develops very peaked core density profiles in some conditions (JET, ASDEX Upgrade)
- Will there be W accumulation in ITER?



Transport of W Impurity

- **1D Transport equation: Continuity equation**

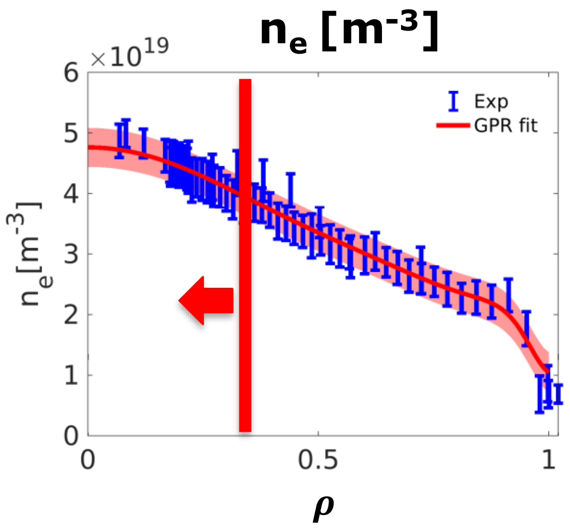
$$\frac{\partial n_w}{\partial t} + \nabla.\Gamma_w = S_w$$

- **W particle fluxes: Neoclassical + Turbulent**

  - $\Gamma_W^\rho = \Gamma_{NEO} + \Gamma_{TURB}$

$$= -(D_{NEO} + D_{TURB})\nabla n_w + (V_{NEO} + V_{TUR})\, n_w$$

$$V_{NEO} \propto Z n_W \left(\frac{\nabla n_i}{n_i} - 1/2\,\frac{\nabla T_i}{T_i}\right)$$



- Turbulent diffusion depends on main ion density and temperature profiles
- To predict $n_w(\rho)$ for $\rho < 0.3$, one needs to know main ion profiles $\frac{\nabla n_i}{n_i}$ and $\frac{\nabla T_i}{T_i}$

To predict n and T in the inner core

- To predict n and T in the inner core ➔ need to know turbulent fluxes
- Turbulent transport ➔ GKW[1], QuaLiKiz   [1] A. Peeters et al, *CPC* 180 (2650), 2009
- GKW ➔ local gyro kinetic flux tube code ➔ to simulate micro instabilities and turbulence in tokamak plasmas
- Need to validate transport models and quasilinear approximation in the inner core
  - Perform linear simulations
    - Compute quasi-linear fluxes from these simulations
  - Perform non-linear simulations
    - Compare the non-linear fluxes to quasi-linear fluxes
    - Compare the non-linear fluxes to experimental values

Outline

- **Tungsten (W) accumulation issue in ITER**
  - Issues with W
  - Transport of W -> need to predict n and T in the inner core
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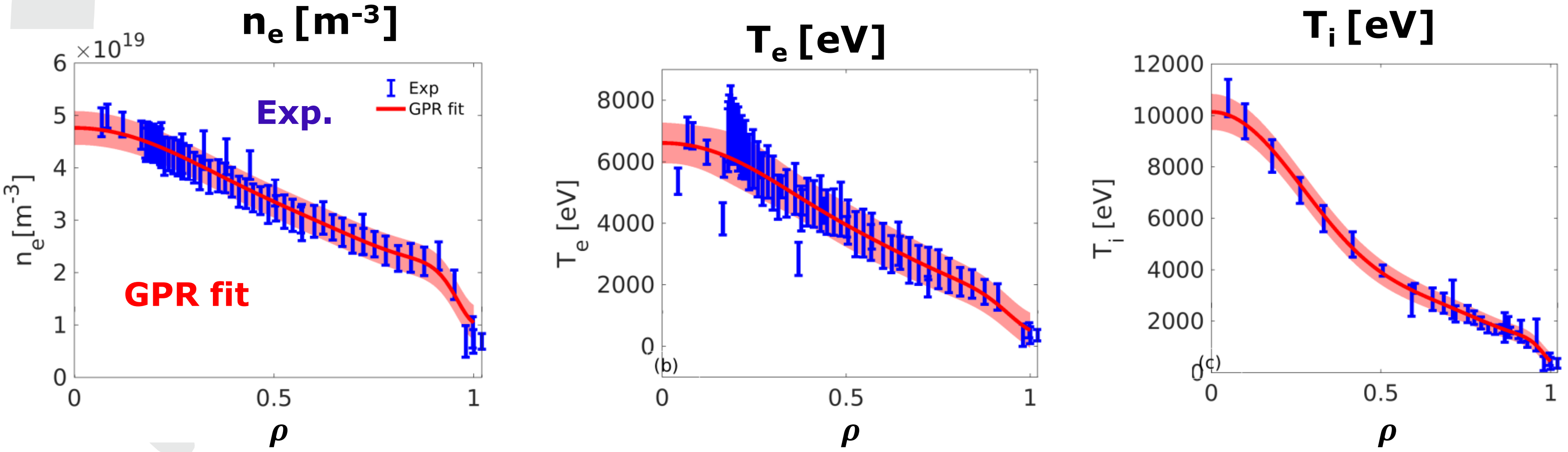
Input Profiles

- Target shot: JET hybrid #75225 with no sawteeth (C wall) [Citrin PPCF 2015, Moradi NF 2014]
- Simulations include: actual magnetic equilibrium (Miller), collisions, rotation, EM fluctuations ($A_{//}$ and $B_{//}$), and Carbon impurities



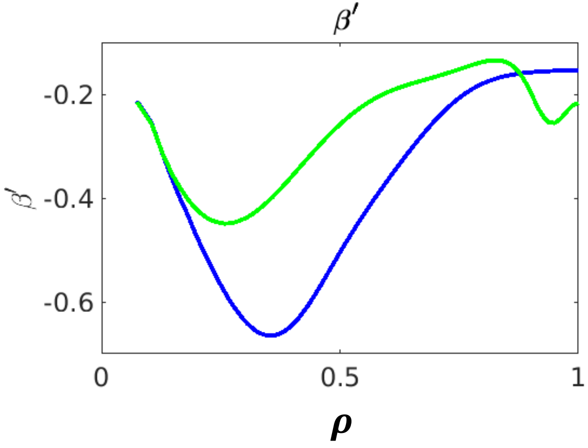
Normalized input parameters at various locations

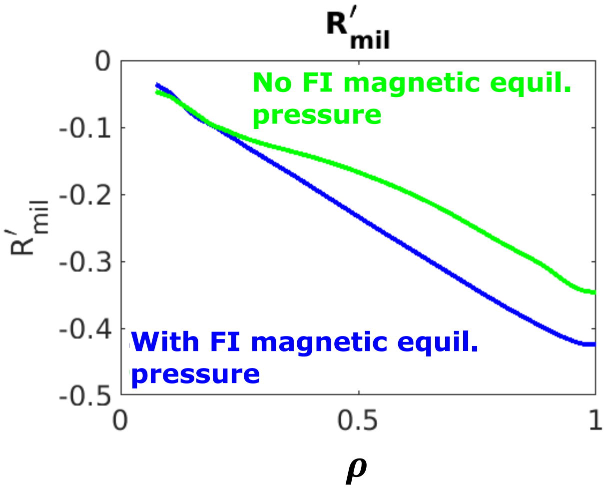
❖ Nominal value of s increased from 0.01 to 0.05 at $\rho = 0.15$

ρ	$\frac{R}{L_{Ti}}$	$\frac{R}{L_{Te}}$	$\frac{R}{L_{Tf}}$	$\frac{T_e}{T_i}$	$\frac{T_f}{T_i}$	$\frac{R}{L_{nC}}$	$\frac{R}{L_{ne}}$	$\frac{R}{L_{nf}}$	$\frac{n_C}{n_e}$	$\frac{n_f}{n_e}$	β_{ref} [%]	β'	$\hat{s}$	u	u′	ν x 10^{-2}
0.15	4.2	1.9	1.8	0.69	5.6	-0.70	1.5	0.80	0.01	0.12	4.6	-0.37	0.05	0.31	0.59	1.5
0.20	5.5	2.7	-0.6	0.72	6.1	-1.13	1.9	-0.88	0.01	0.12	3.8	-0.48	0.02	0.32	0.80	1.6
0.25	6.6	3.3	2.4	0.76	6.6	-1.45	2.3	1.84	0.01	0.13	3.3	-0.57	0.05	0.32	0.99	1.7
0.33	7.7	4.1	9.6	0.84	6.1	-1.51	2.7	8.97	0.01	0.10	2.6	-0.66	0.21	0.32	1.31	1.9
0.40	7.9	4.5	10.7	0.91	7.8	-0.87	2.9	10.2	0.02	0.07	1.9	-0.64	0.49	0.31	1.57	2.2
0.50	6.3	5.2	4.4	1.04	4.6	2.70	3.2	3.41	0.02	0.06	1.3	-0.50	0.98	0.29	1.88	2.7
0.60	5.9	5.5	9.6	1.05	4.6	4.41	3.3	7.96	0.02	0.06	1.0	-0.37	1.42	0.24	0.24	3.4

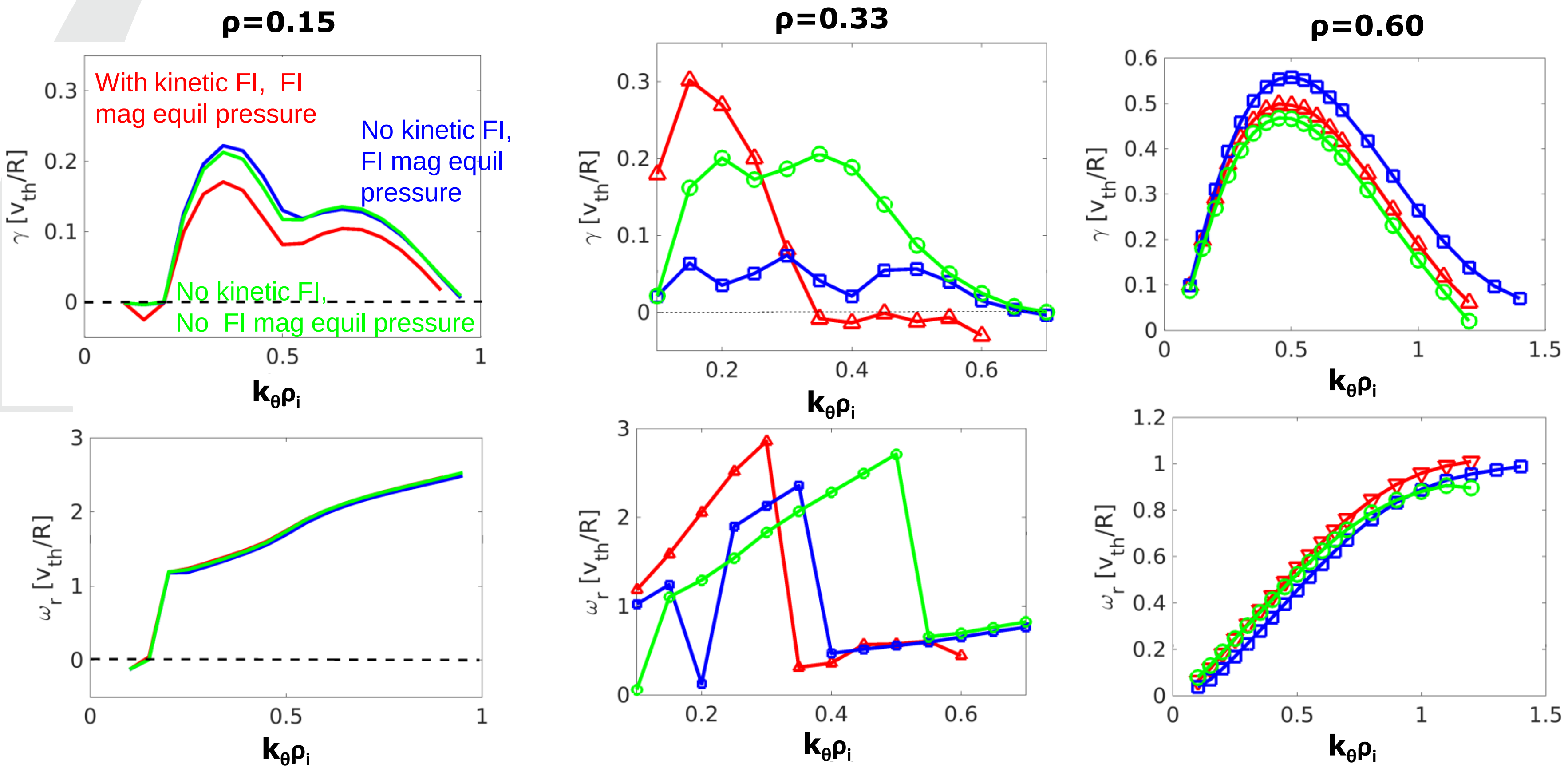
Impact of fast ions

- Kinetic fast-ions from NBI with Maxwellian distribution function
- Impact of fast ion population by performing three set of simulations
  - 1) kinetic fast ions and fast ion magnetic equilibrium pressure
  - 2) without kinetic fast ions and magnetic equilibrium include fast ion pressure
  - 3) without kinetic fast ions and without fast ion magnetic equilibrium pressure





Growth rate and frequency at three different radial locations



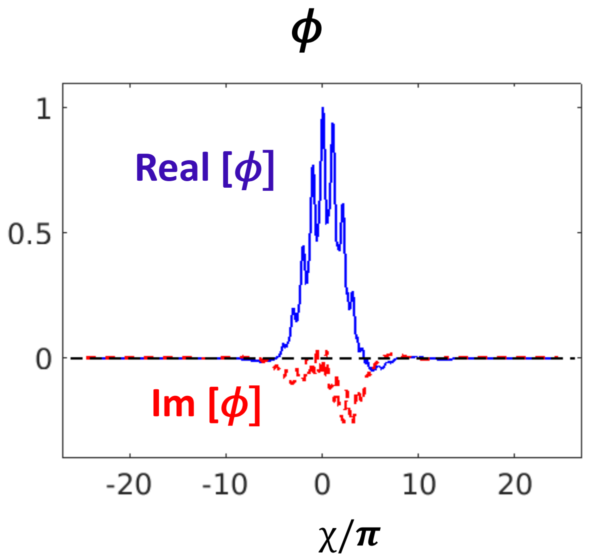
Conclusion:

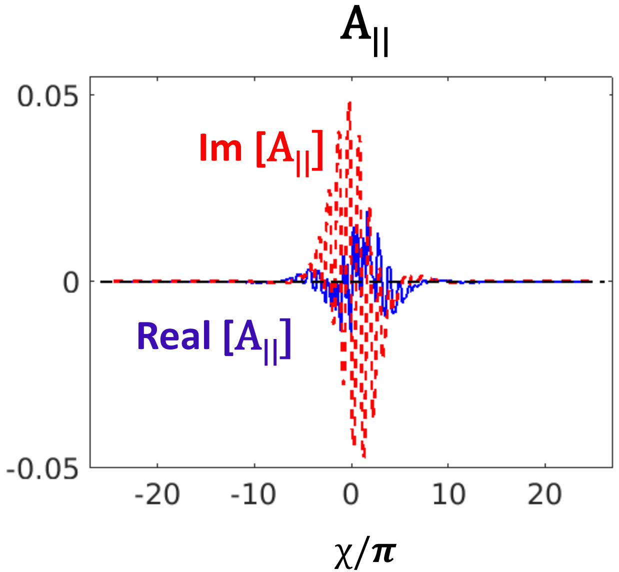
- Growth rate significantly reduces when kinetic fast ions included.
- Effect is independent of modification of magnetic equilibrium by fast ion pressure at $\rho = 0.15$
- Most unstable Kinetic ballooning mode (KBM) in inner core, propagating in diamagnetic drift direction at $\rho = 0.15$*

*** [Nkumar et al, submitted to NF 2020]**

- Next step: focus only at $\rho = 0.15$. Neglecting impact of fast ions,
  - All linear simulations performed without fast ions as kinetic species and with fast ions pressure in magnetic equilibrium.

Parallel mode structure of potential ϕ and $A_{||}$ at $\rho = 0.15$

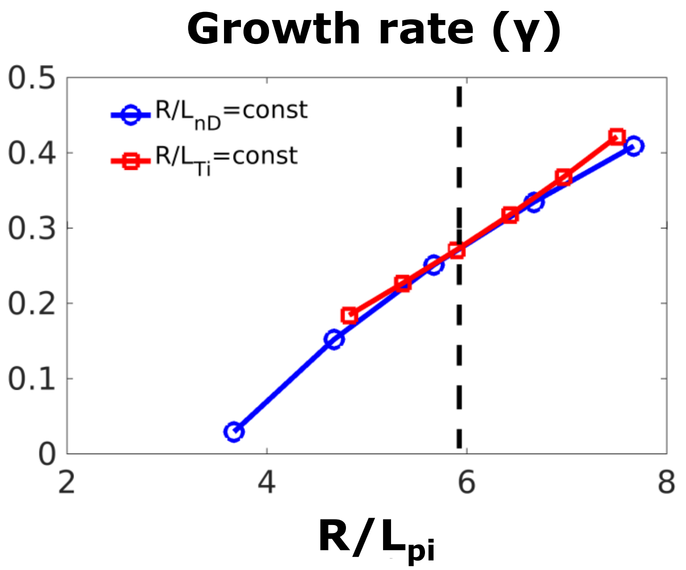




Conclusion:

- Mode structure for both electrostatic potential (ϕ) and magnetic potential ($A_{||}$) very unusual
- Mode structure extremely elongated along the field lines (10-50 poloidal turns at low $k_\theta \rho_i$)

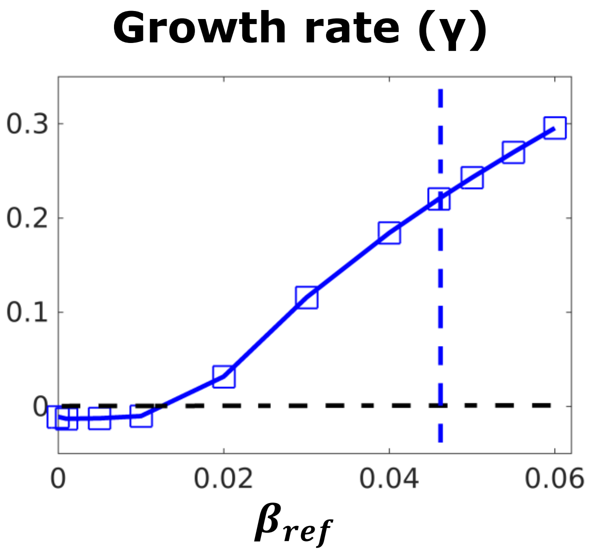
Growth rate as function of R/Lpi

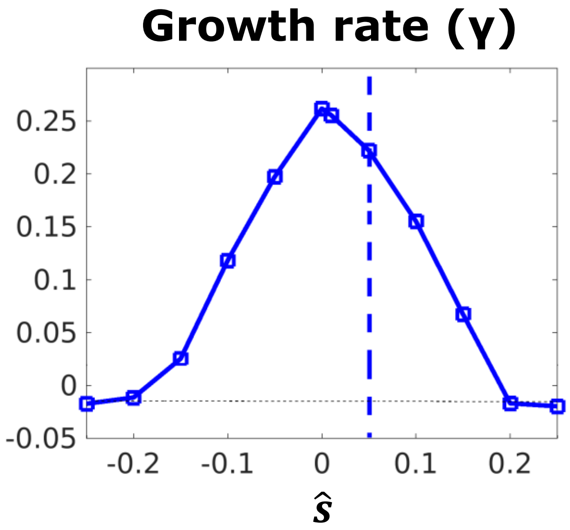


Conclusion:

❖ Growth rate curves are almost same for both the cases, indicates modes driven by pressure gradient.

Plasma beta and magnetic shear scans at ρ=0.15



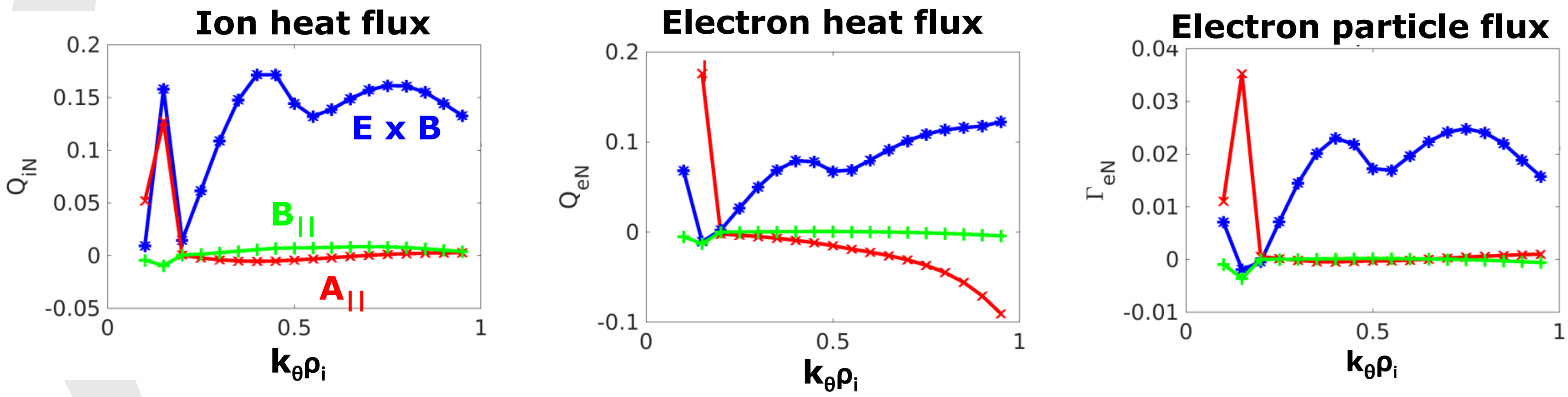


Conclusion:

➢ High plasma beta and low magnetic shear responsible for destabilization of KBMs in inner core

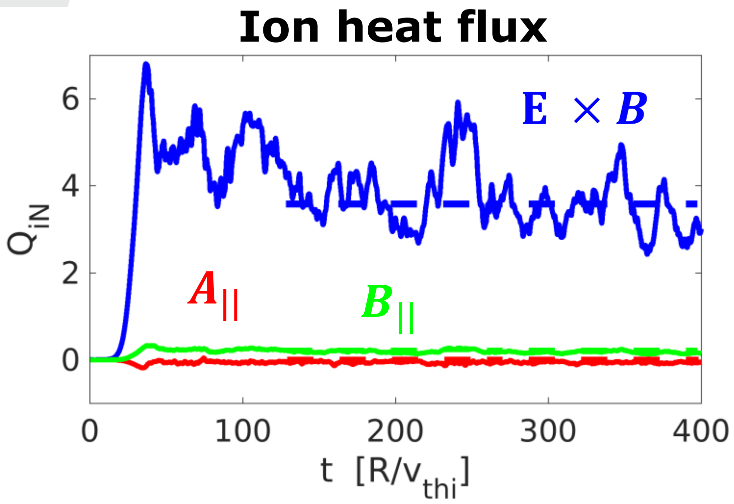
Normalized linear heat and particle fluxes

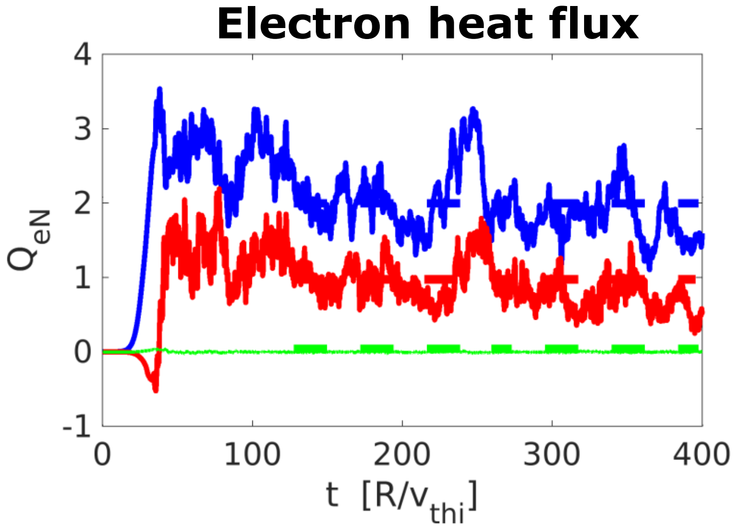
$$Q^N_{s,E\times B} = \frac{Q_{s,E\times B}}{\mathcal{A}_L^2} \qquad \mathcal{A}_L(t) = \sqrt{\int \left[|\phi|^2 + |A_\parallel|^2 + |B_\parallel|^2\right] \mathrm{d}s \Big/ \int \mathrm{d}s}$$



At low $k_\theta \rho_i = 0.1$, significant magnetic flutter contribution to electron heat flux

Time trace of heat and particle flux at beta=4.6%





Conclusion:

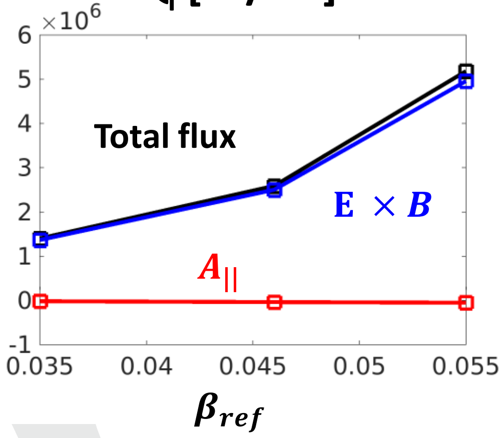
- ❑ Ion heat and particle flux dominated by $E \times B$ contribution, consistently with linear fluxes ratio
- ❑ Significant contribution from magnetic flutter to electron heat flux with opposite sign

Non-linear heat and particle fluxes in SI unit

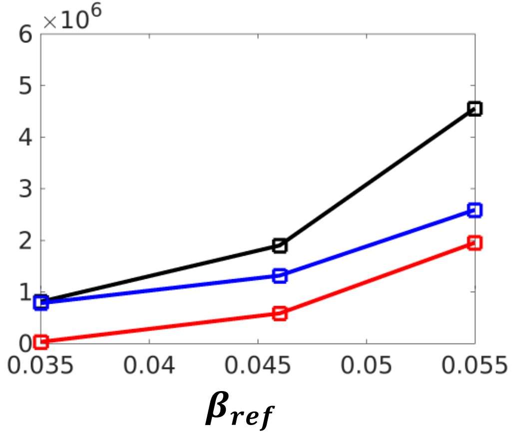
$$Q_{N,s} = \frac{Q_s^r}{n_s T_s \rho_*^2 v_{thi}} \quad \Gamma_{N,s} = \frac{\Gamma_s^r}{n_s \rho_*^2 v_{thi}}$$

$$\rho_*^2 = \rho_i / R_{ref} = 0.0033$$

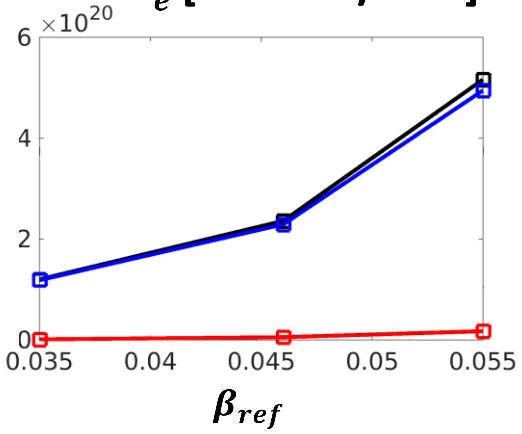
Q_i [W/m²]



Q_e [W/m²]



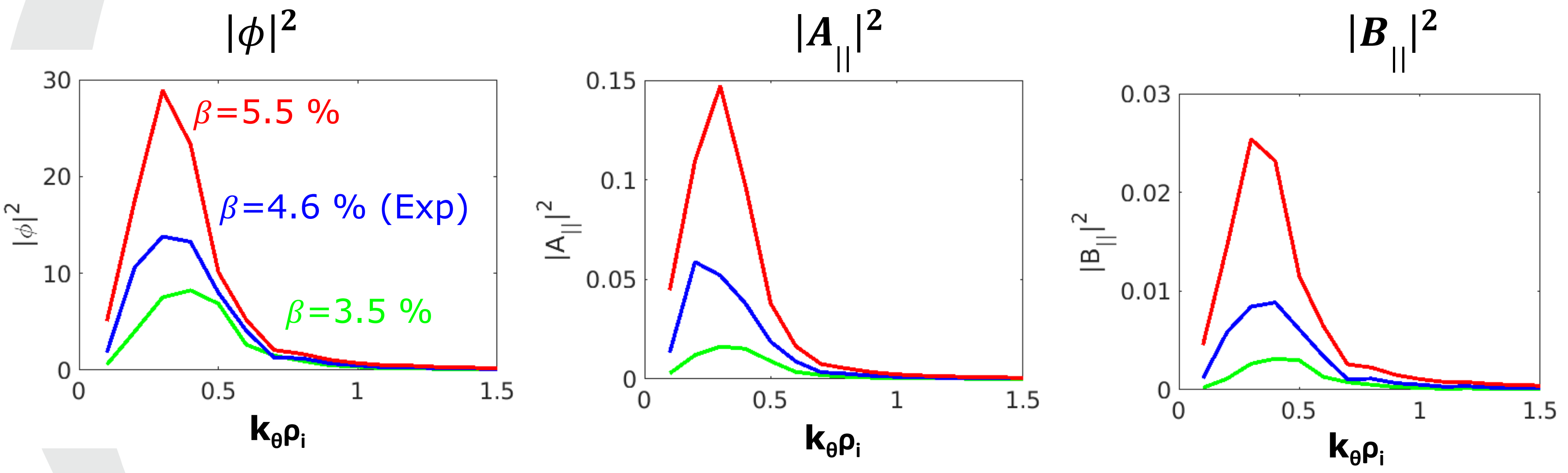
Γ_e [Particle /m² s]



Conclusion:

- ❑ Heat and particle fluxes increases with beta due to destabilization of KBM consistently with linear values

$k_\theta\rho_i$ spectrum of $|\phi|^2$, $|A_{||}|^2$ and $|B_{||}|^2$ for different beta



Conclusion:

- ❑ $|A_{||}|^2$ values much lower than $|\phi|^2$ but have similar shape

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Test of Various QL rules in the inner core

- **Mixing length model [1]:**

$$W1 = \mathcal{A}_{QL}^2 = C1 \frac{\gamma}{\langle k_\perp^2 \rangle}$$

QL fluxes computed as:

$$Q_{s,E\times B}^{QL} = \sum_{k_r,k_\theta} Q_{s,E\times B}^{N} \mathcal{A}_{QL}^2$$

$$Q_{s,A_\parallel}^{QL} = \sum_{k_r,k_\zeta} Q_{s,A_\parallel}^{N} \mathcal{A}_{QL}^2$$

- **Qualikiz Model [2]:** Saturated mode amplitude

$$W_n = C_n \mathcal{S}_k \max \left[\frac{\gamma}{\langle k_\perp^2 \rangle} \right]$$

$k_\theta \rho_i^{max}$ **wave vector at max**$(\frac{\gamma}{k_\perp^2})$

$$\mathcal{S}_k = \left(\frac{k_\theta \rho_i}{k_\theta \rho_i^{max}} \right)^{x_n} \quad \text{for} \quad k_\theta \rho_i < k_\theta \rho_i^{max}$$

$$\mathcal{S}_k = \left(\frac{k_\theta \rho_i}{k_\theta \rho_i^{max}} \right)^{-3} \quad \text{for} \quad k_\theta \rho_i > k_\theta \rho_i^{max}$$

$W2$ with $\mathbf{x_2 = 1}$

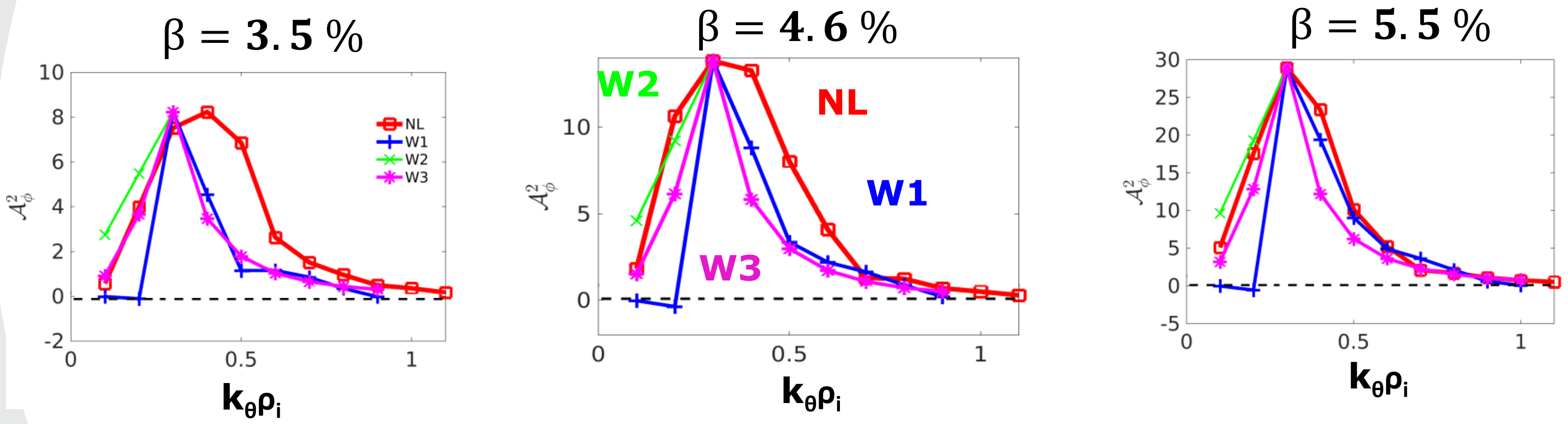
$W3$ with $\mathbf{x_3 = 2}$

[1] T. Dannert et al, *PoP* **12** (072309), 2005

[2] C. Bourdelle, et al, *PoP* **14** (112501), 2007

Comparison of ∅ spectra for non-linear and various quasi-linear weights

QL spectra normalized to maximum of non-linear spectra



Conclusion:

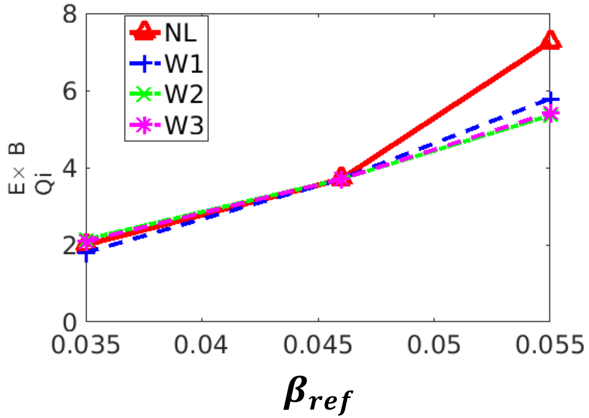
- Standard mixing length model not capture the finite amplitude of fields for $k_\theta\rho_i<0.3$
- Qualikiz-like model perform better to this respect, especially for W3

Comparison of non-linear and quasi-linear heat fluxes with beta for $E \times B$ part

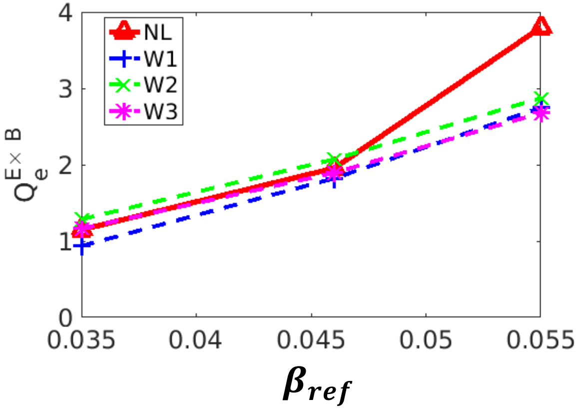
$$Q^{QL}_{s,A_{\parallel}} = \sum_{k_r,k_\zeta} Q^{N}_{s,A_{\parallel}} \mathcal{A}^2_{QL}$$

C1=12.4 ; C2=14.1; C3=14.4

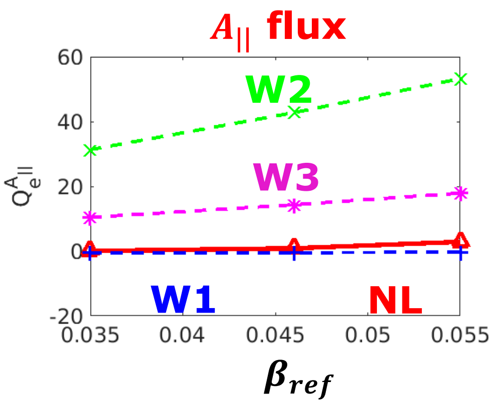
Ion heat flux



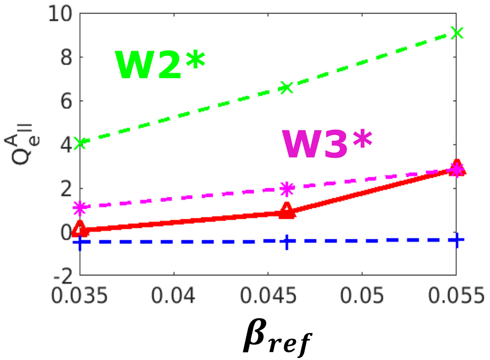
Electron heat fluxes



Comparison of non-linear and quasi-linear electron magnetic flutter heat fluxes with beta



$$Q^{QL}_{s,A_\parallel} = \sum_{k_r,k_\zeta} Q^N_{s,A_\parallel} \mathcal{A}^2_{QL}$$



$$A_\parallel^{\text{ratio}} = \frac{\mathcal{A}_L(k_\theta \rho_i)}{\mathcal{A}_{A_\parallel,L}(k_\theta \rho_i)} \frac{\mathcal{A}_{A_\parallel,L}(k_\theta \rho_i^{max})}{\mathcal{A}_L(k_\theta \rho_i^{max})}$$

$$Q^{QL}_{s,A_\parallel} = \sum_{k_r,k_\theta} Q^N_{s,A_\parallel} \mathcal{A}^2_{QL} A_\parallel^{\text{ratio}}$$

With $A_{||}^{ratio}$

Summary

- Turbulent transport level non-negligible for $r/a < 0.3$ provided $\hat{s}$ sufficiently low
- Non-negligible turbulence in inner core mitigate neoclassical inward pinch of W ➔ relevant for ITER
- KBMs instability is also present in the inner core of ITER plasma*
- Low $k_\theta \rho_i$ regions that are linearly stable can have a finite level of fluctuations in the non-linear regime
- Their excitation in the non-linear regime generates significant contribution to the magnetic flutter electron heat flux
- Standard quasilinear models fails to capture this part because ratio of $|A_{||}|$ to $|\emptyset|$ at low $k_\theta \rho_i$ different in linear and non-linear simulations
- By including $A_{||}^{ratio}$ magnetic flutter part capture better. Still further improvement required*

*** [N. kumar et al, submitted to NF 2020]**

Ongoing work

- Extend study to other ITER high Q-scenario, such as steady state Q=5 ➔predict impact of core profile flattening on fusion gain
- Compare turbulent heat and particle fluxes with neoclassical fluxes to predict W accumulation in inner core of ITER
- **Est. Thesis submission December 2020**

Publications and conferences

❖ Publications

❖ Manuscript submitted: N. Kumar, Y. Camenen, S. Benkadda, C. Bourdelle, A. Loarte, A.R. Polevoi, F. Widmer, and JET contributors, " Turbulent transport driven by kinetic ballooning modes in the inner core of JET hybrid H-modes", Nucl. Fusion.

❖ Conference Poster Presentations

- Poster presentation in the « 46th European Physical Society Conference on Plasma Physics (EPS 2019)», Milan, Italy, from July 8 to 12, 2019
- Abstract accepted for regular poster presentation, "28th IAEA Fusion Energy Conference (FEC 2021)", 10-15 May 2021, Nice, France (shifted to next year due to COVID-19)

❖ Poster Presentations

- Presented a poster in the Culham Plasma Physics Summer School, the UK from July 15 to 27, 2018.
- Poster in the ITER FuseNet PhD event 2018, France, from November 6 to 9, 2018.

Thank you. Any questions?

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