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66<sup>th</sup> Annual Meeting of the APS Division of Plasma Physics

Atlanta, GA (USA)

10<sup>th</sup> October, 2024

# Kinetic Ballooning Modes as a Potential Candidate to Reconcile core- $T_e$ Measurement Discrepancy in High Temperature Plasmas

**S. Mazzi**<sup>1</sup>, G. Giruzzi<sup>1</sup>, R. Dumont<sup>1</sup>, M. Fontana<sup>2</sup>, E. de la Luna<sup>3</sup>, F. P. Orsitto<sup>4</sup>, L. Senni<sup>5</sup>,  
K. Aleynikova<sup>6</sup>, S. Brunner<sup>7</sup>, Y. Camenen<sup>8</sup>, B. J. Frei<sup>9</sup>, J. Garcia<sup>1</sup>, A. Zocco<sup>6</sup>,  
JET contributors<sup>a</sup> and EUROfusion Tokamak Exploitation Team<sup>b</sup>

<sup>1</sup>CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France

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<sup>a</sup> See the author list of C. F. Maggi *et al.*, *Nucl. Fusion* 64, 112012 (2024)

<sup>b</sup> See the author list of E. Joffrin *et al.*, *Nucl. Fusion* 64, 112019 (2024)

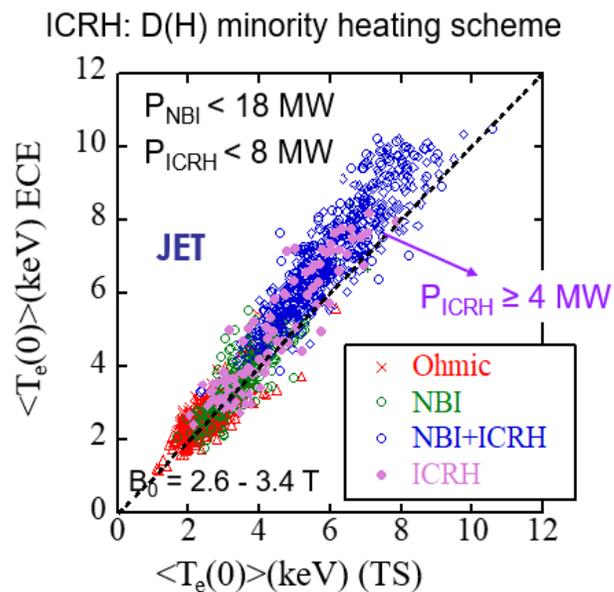




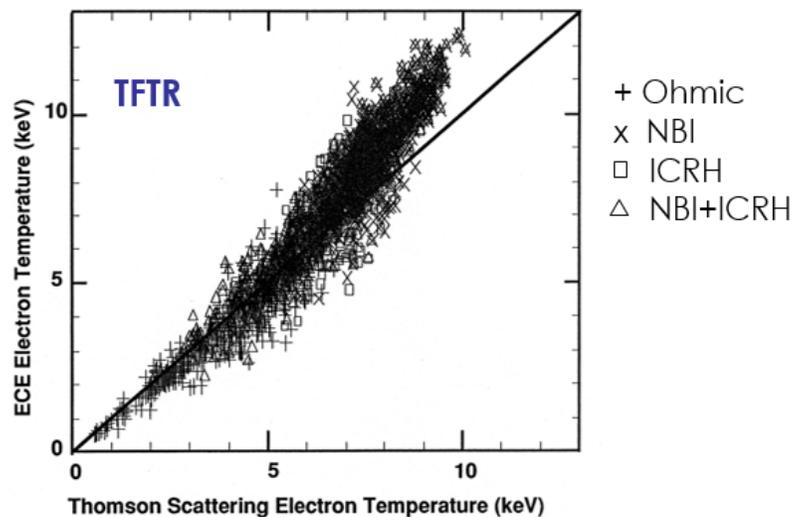
# ECE—Thomson Discrepancy in High-Temperature Plasmas: Long-Standing Issue

- Systematic observation of discrepancy between Electron Cyclotron Emission (ECE) and Thomson Scattering (TS) measurements at high  $T_e$ :
  - On multiple devices
  - With multiple diagnostic technologies

[Taylor FST(2009)]  
[de la Luna RSI(2003)]  
[Pucella NF(2022)]



[de la Luna HTPD(2002)]  
[de la Luna EC-15(2008)]



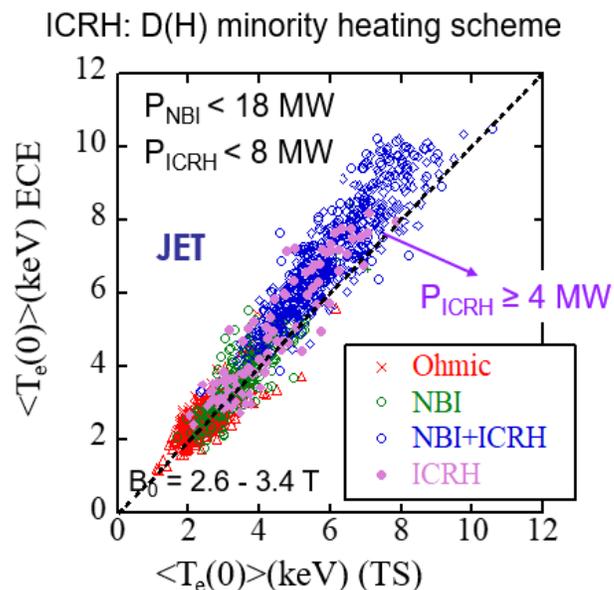
[Taylor EC-Workshop(1993)]



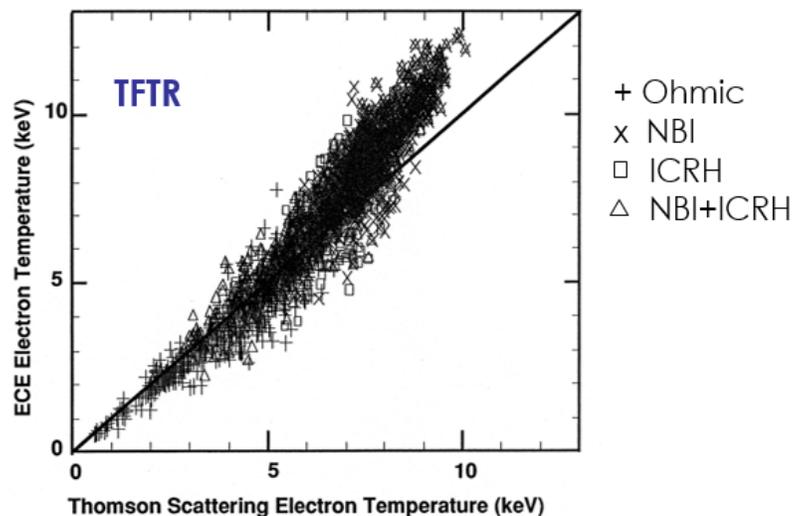
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[Taylor EC-Workshop(1993)]

**JET**

Is the issue still present?

- Building JET database of ECE vs. TS from C38B (DD 2019) to C41 (DT 2022)
  - >250 pulses, ~1400 samples
  - Rich variety of plasma conditions

**Discrepancy clearly still present!**

[Fontana EC-Workshop(2022)]  
 [Fontana PoP(2023)]



# Toy Model of Electron Distribution Perturbation: Reconciling the Experimental Measurements

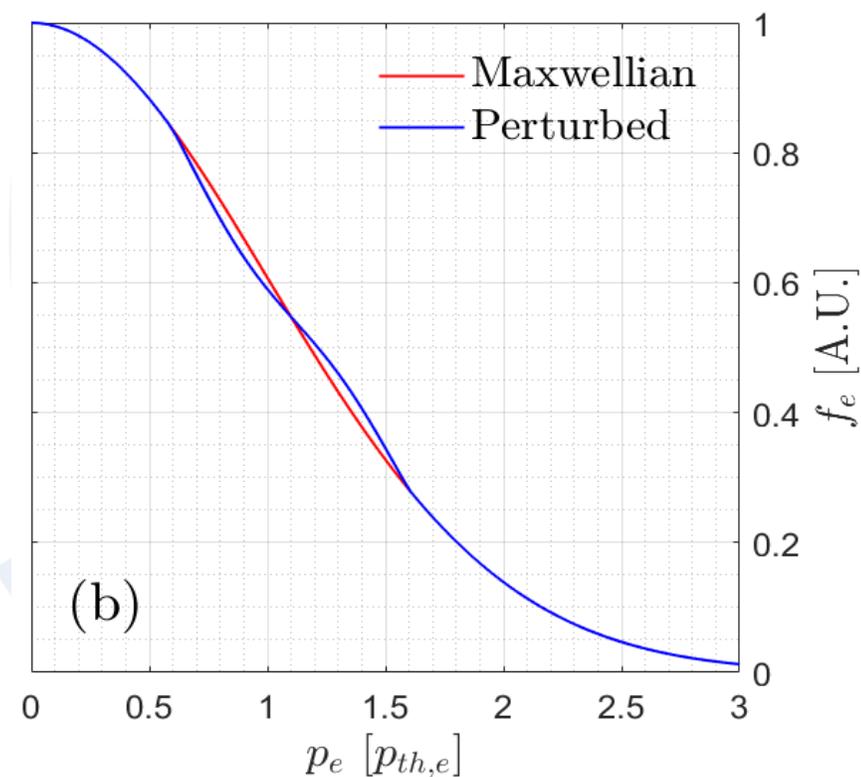
- To reconcile the experimental discrepancy → Heuristic model developed:
  - Adding bipolar perturbation to Maxwellian distribution function  $f_0$  [Krivenski FED(2001)]
  - Simple sinusoidal perturbation (over the infinite possibilities...)

$$f_1(p_e) = f_0 \sin\left(\frac{\pi}{\delta_0}(p_e - p_0)\right)$$

[Giruzzi EC-Workshop(2022)]  
[Fontana PoP(2023)]

Model Parameters:

Position →  $p_0/p_{th} = 1.1$   
Width →  $\delta_0/p_{th} = 0.5$   
Amplitude →  $f_0 = 0.03$



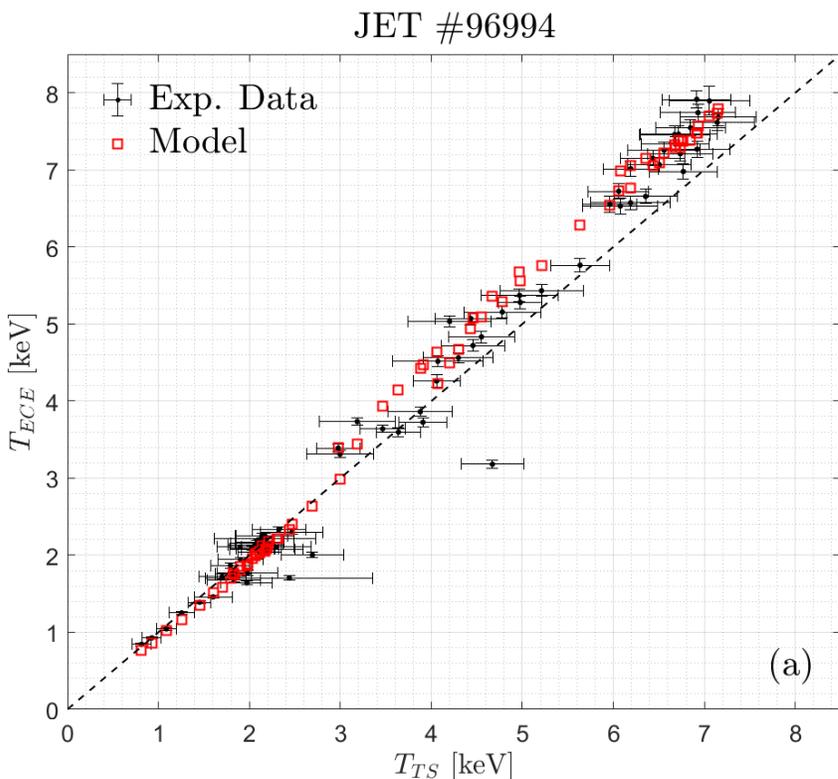


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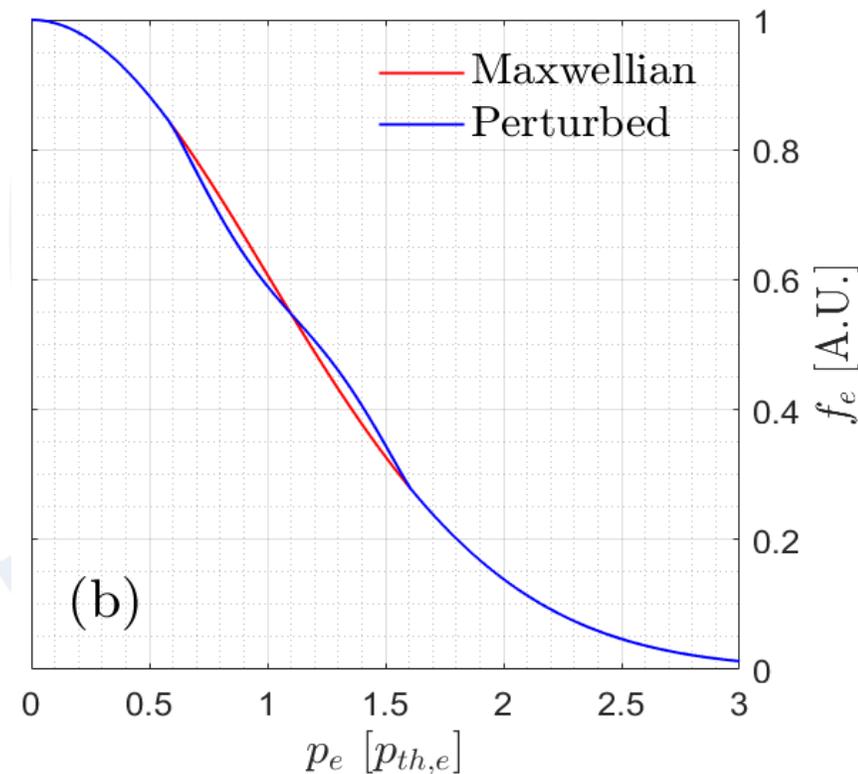
Perturbation in electron distribution impacts ECE measurement!

↓

Experimental measurements are reconciled!

Model Parameters:

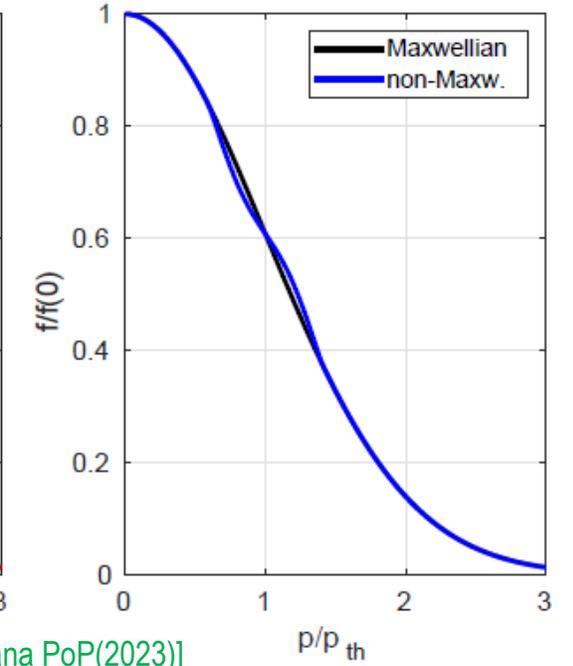
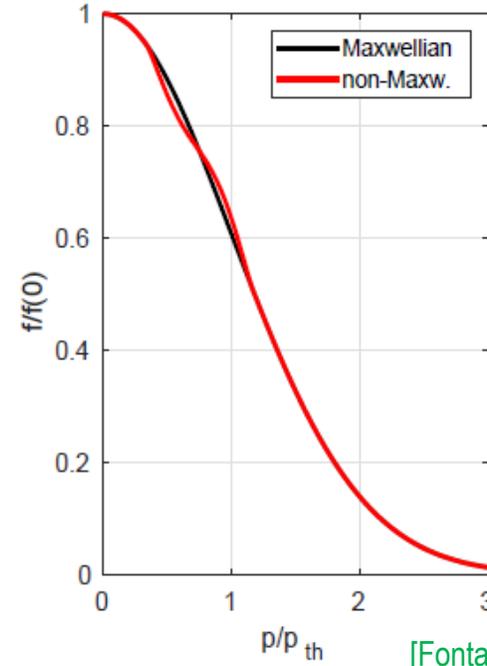
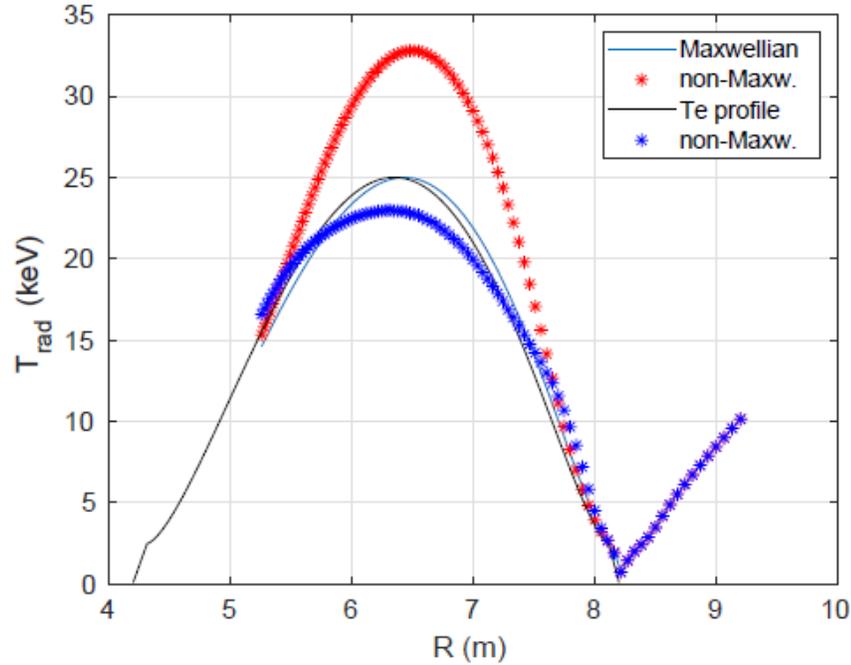
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# Very Large Impact on ITER ECE Measurements: Understanding is Crucial!

- If similar perturbations applied at ITER ECE measurements:
  - Very large impact on ECE measurements (up to >5 keV!)

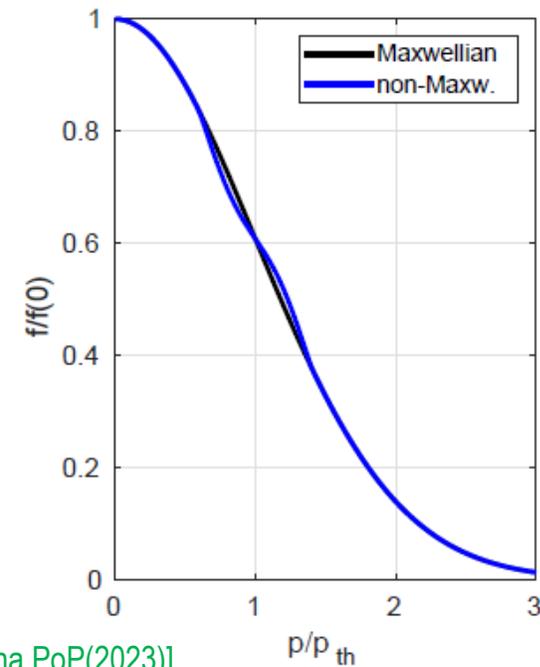
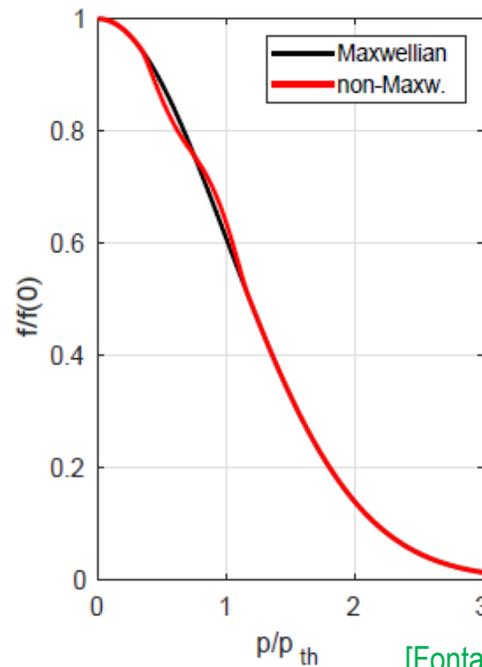
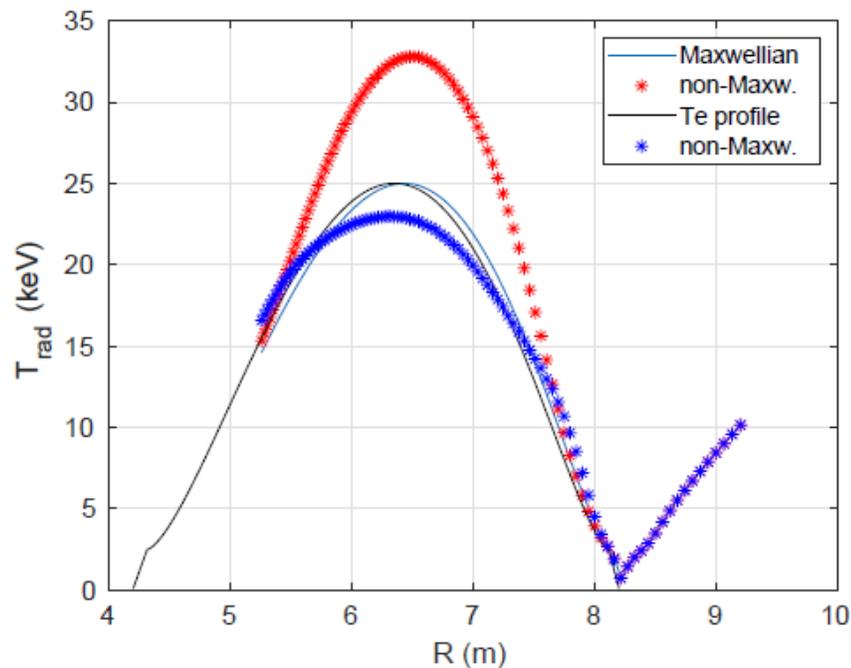


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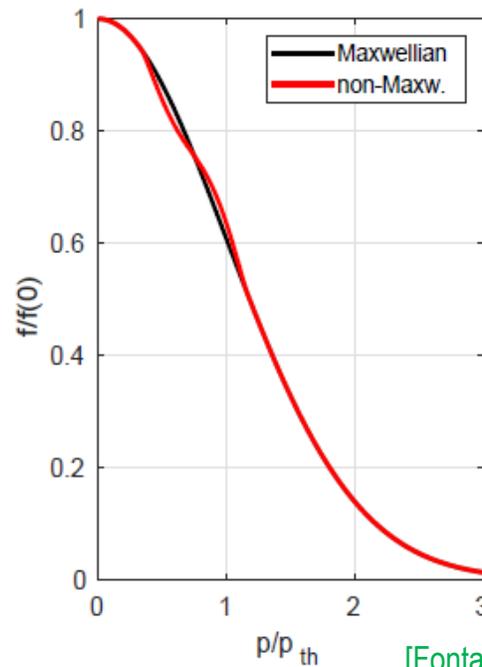
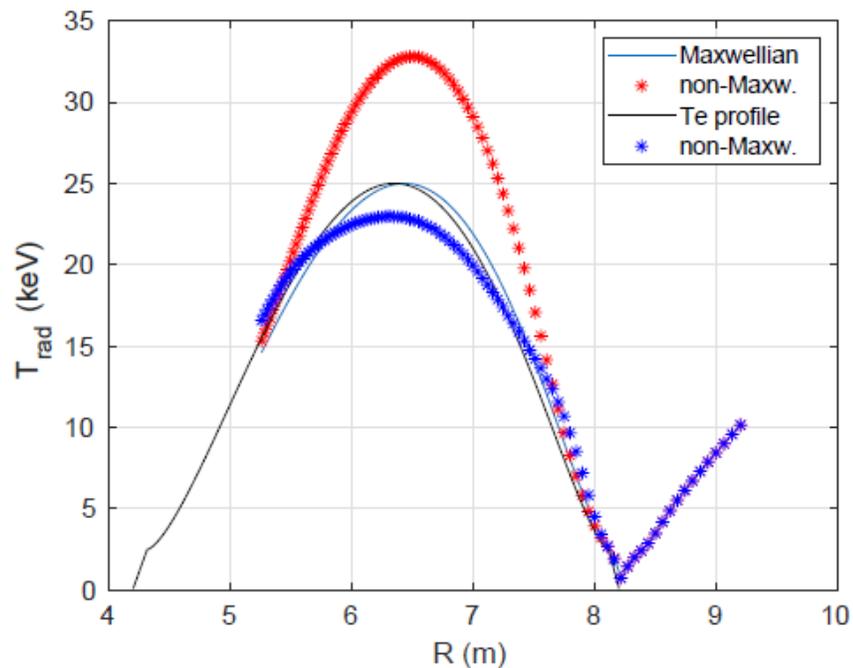
- Several mechanisms could be responsible of such a perturbation:
  - Collisional relaxation of fast ions [Dumont ITPA-EP(2022), Giruzzi IAEA-FEC(2023)]
  - Large-scale MHD activity (such as Kinetic Alfvén Waves or Kink modes)
  - Core-localized microinstabilities

[Orsitto EPS(2023)]  
[Horvath PoP(2020)]

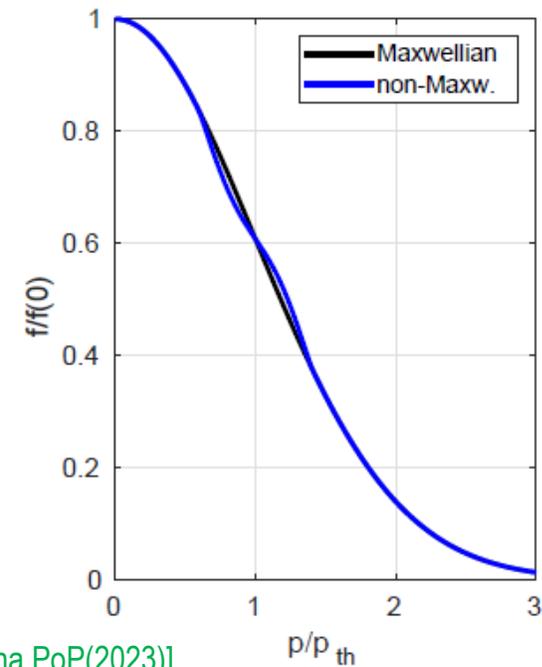


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# Gyrokinetic Analysis of JET Deep-Core: Unstable Kinetic Ballooning Modes

[Garcia PoP(2022)]

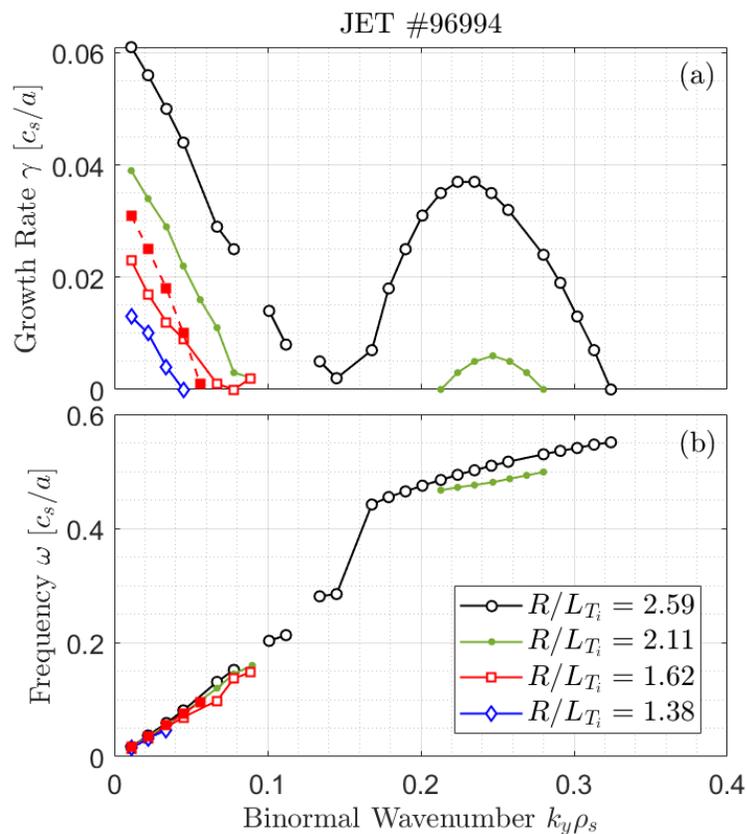
- Flux-tube GENE [Jenko PoP(2000)] simulations of selected pulse: JET #96994:
  - @  $\rho_{tor} = 0.15$  (within plasma center  $\pm 15$  cm)
  - Electrons and Bulk Deuterium (neglecting: impurities & fast ions )
  - Including collisions
- Baseline scenario ( $I_p=3$  MA,  $B_t=2.8$  T,  $q_{95}\sim 3.2$ , D plasma) with low gas and D pellet injection + small Ne injection (attached divertor) ---  $P_{NBI}=27$  MW,  $P_{ICRH}=4$  MW,  $\beta_N=2.2$ ,  $H_{98}(y,2)=1.1$
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## Linear outcomes

- Kinetic Ballooning Modes (KBM) found unstable (similar to [Moradi NF(2015), Kumar NF(2021)])
- Two KBM branches unstable
- KBMs unstable only at low magnetic shear

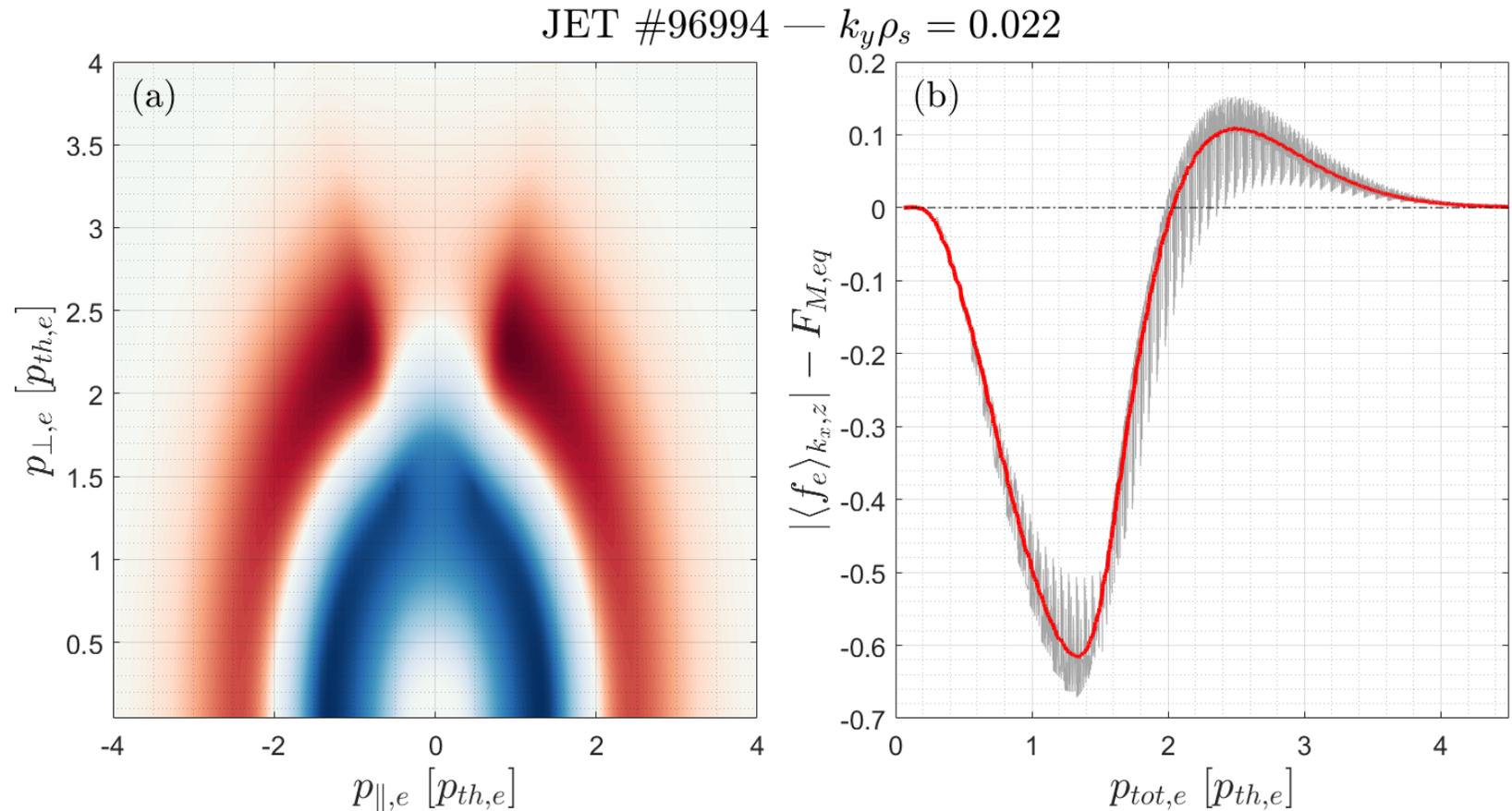


# KBM Induce Bipolar Perturbation on Electron Distribution Function

- Analysing the linear electron distribution function at KBM-dominated wavenumbers:

- The Maxwellian is strongly perturbed
- Bipolar structure emerging in the momentum space
- Similar structure found in moment-based approach flux-tube simulations [Frei JPP(2023)]
- Generalized KBM effects on electron distribution

Striking similarity with heuristic model perturbation!





# Analysing the Perturbation Causes: Electron Diamagnetic Frequency

- Investigating the role of the electron diamagnetic frequency in the bipolar perturbation

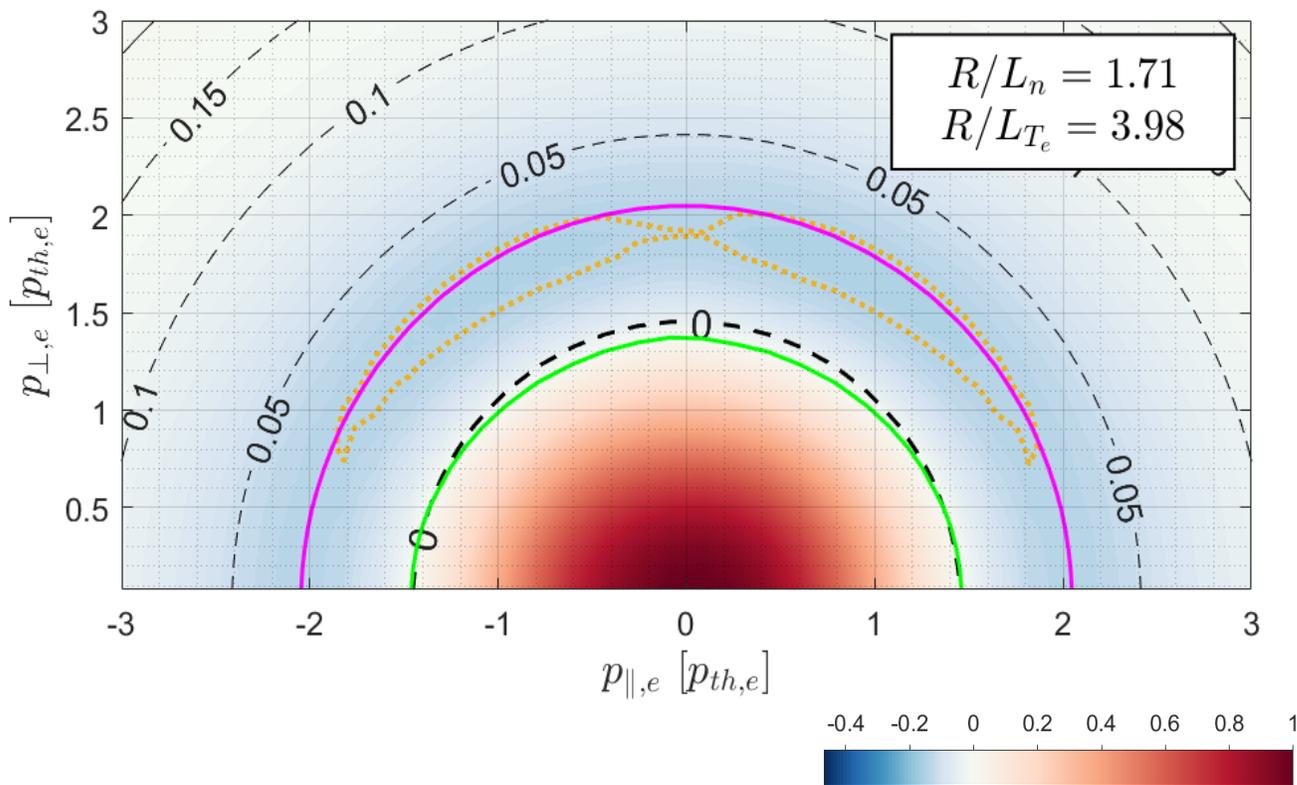
$$\omega_e^* = \left[ R/L_{n_e} + R/L_{T_e} \left( p_{\parallel}^2 + p_{\perp}^2 - \frac{3}{2} \right) \right]$$



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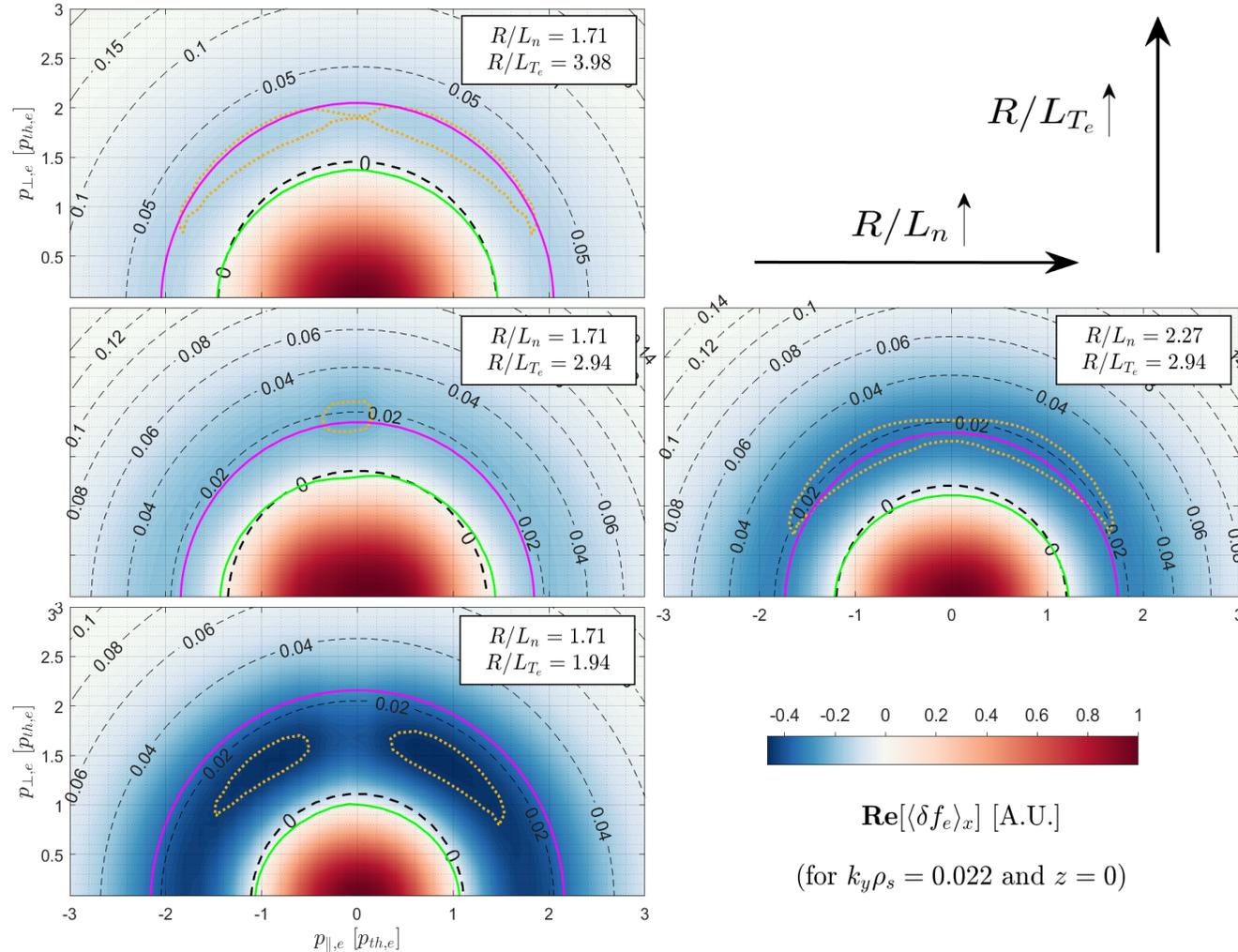
- Clear link between  $\omega_e^*$  and  $f_e$ :
  - $\omega_e^* = 0 @ f_e = 0$  (green line)
  - $\omega_e^* = \omega_{\text{KBM}}$  (pink line) @  $\max(|f_e|)$  (yellow line)



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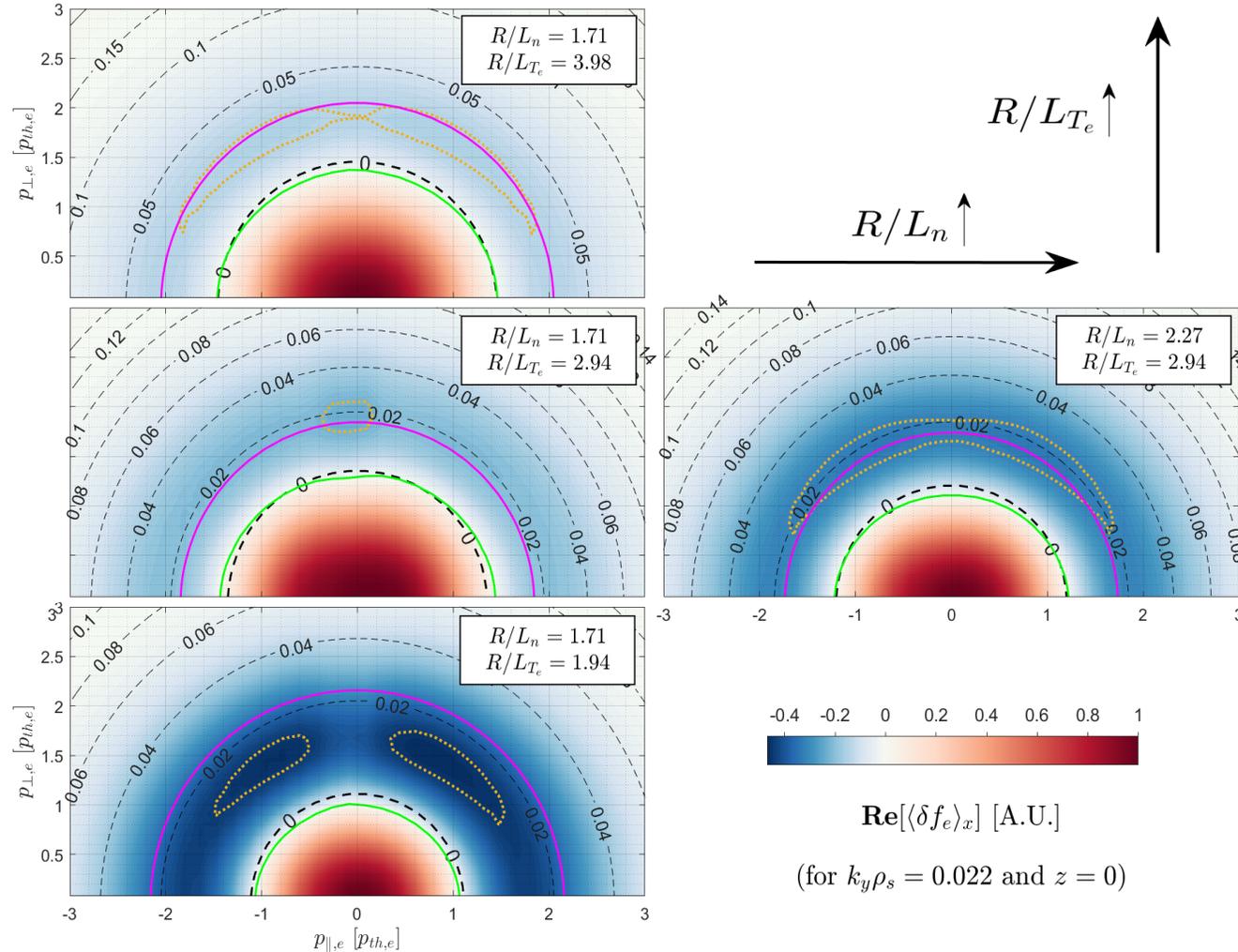
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$$\omega_e^* = 0 \leftrightarrow p_0 \text{ (heuristic model)}$$

Central position of the perturbation:

$$p_0 = \sqrt{\frac{3}{2} - \frac{R/L_{n_e}}{R/L_{T_e}}}$$

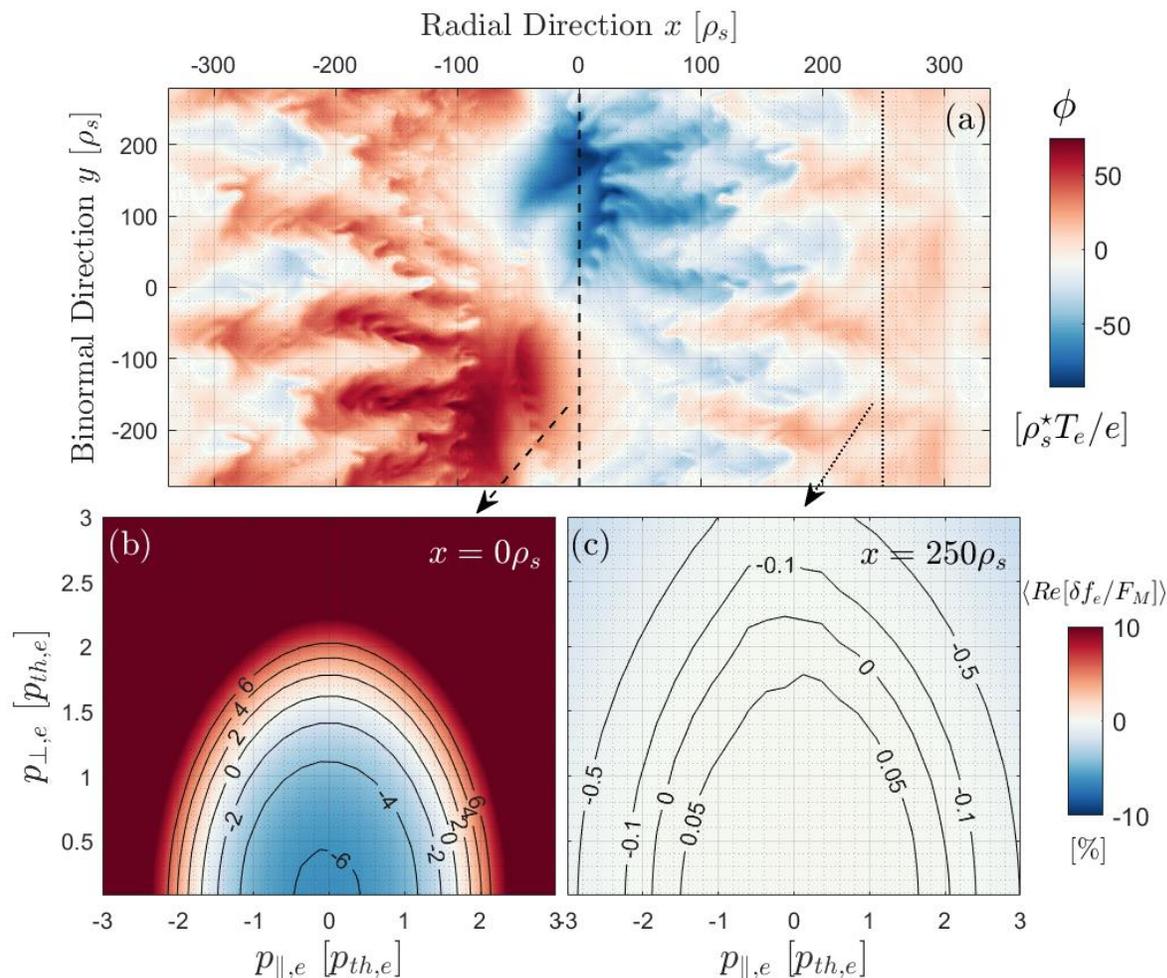


# Persistent and Localized Bipolar Perturbation on Electron Distribution in Time

- Nonlinear analyses are necessary to evaluate the persistency of the KBM-induced bipolar perturbation

➤ Clearly visible only where the KBM-induced (turbulent) fluctuations are large

KBM clearly the cause of the bipolar perturbation





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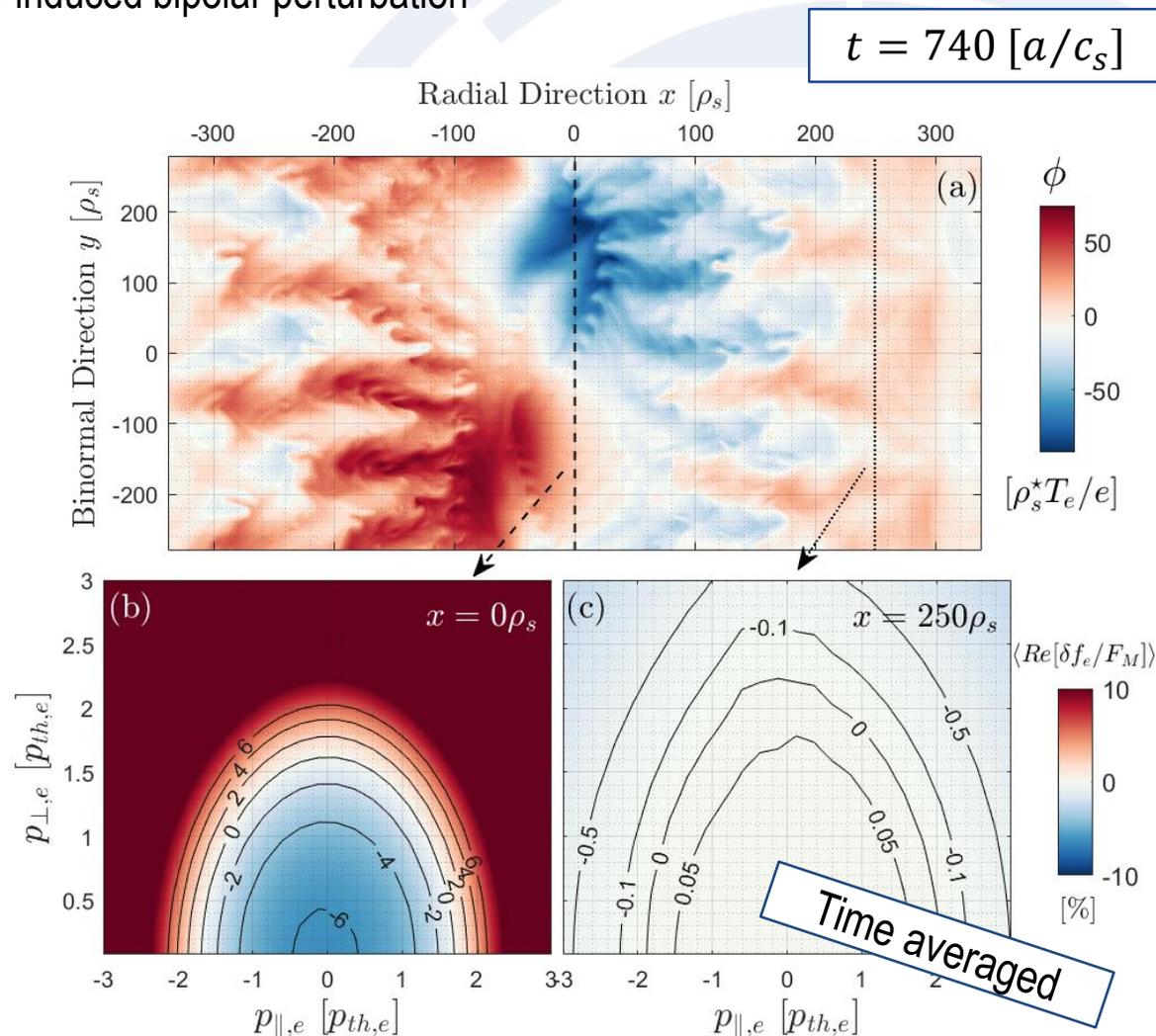
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- Remains along the simulations (after the KBM linear growth)

KBM-induced perturbation is persistent





# Conclusions & Perspectives

- Long-standing issue of ECE—TS discrepancy at high temperature ( $>5$  keV) → Reconciled by ad-hoc bipolar perturbation on the electron distribution function [Giruzzi EC-Workshop(2022), Fontana PoP(2023)]

*... Still physical causes missing!*



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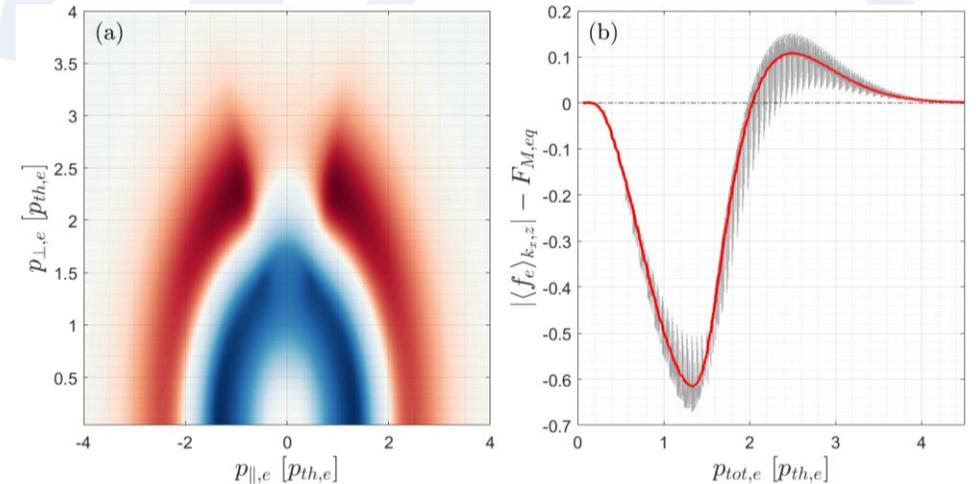
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- Analyzing deep-core of selected JET pulse → KBMs leading to bipolar perturbation as in the heuristic model!

- Position of the perturbation in momentum space linked with the electron diamagnetic frequency → Experimental validation?

$$p_0[p_{th}] = \sqrt{\frac{3}{2} - \frac{R/L_{n_e}}{R/L_{T_e}}}$$

- **Persistent** KBM-induced perturbation **localized** and dependent on the **KBM amplitude**





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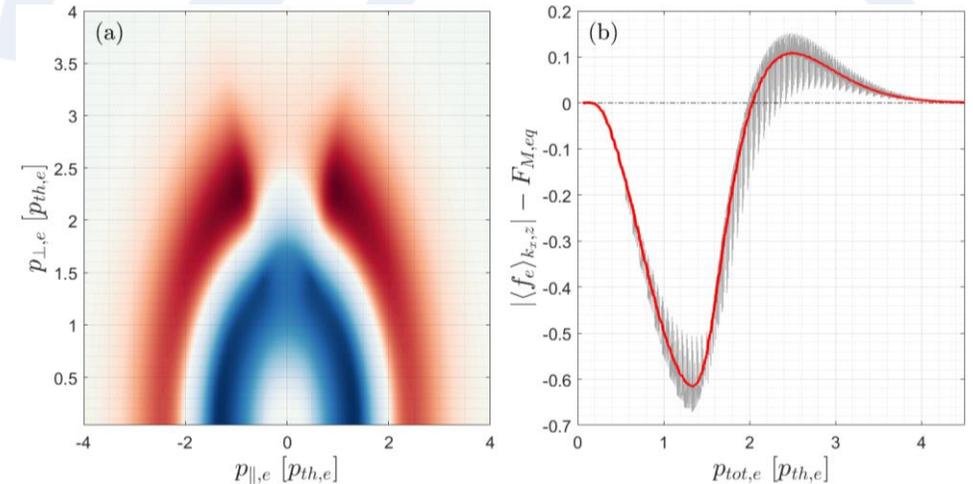
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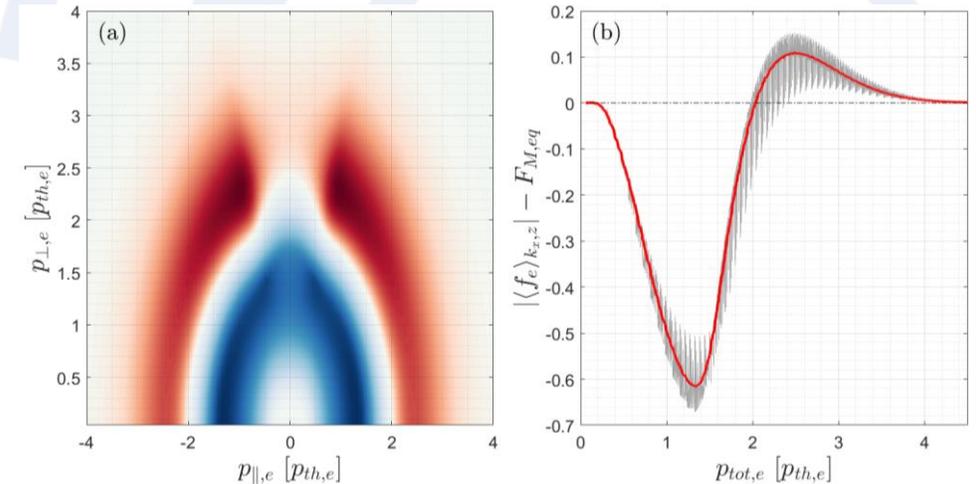
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This is work summarized in a *Nuclear Fusion* paper under review

ITPA Working Group on High Temperature Measurements  
(multi-device coordination efforts by F. P. Orsitto & L. Senni)

66<sup>th</sup> Annual Meeting of the APS Division of Plasma Physics

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# Backup Slides

**S. Mazzi**<sup>1</sup>, G. Giruzzi<sup>1</sup>, R. Dumont<sup>1</sup>, M. Fontana<sup>2</sup>, E. de la Luna<sup>3</sup>, F. P. Orsitto<sup>4</sup>, L. Senni<sup>5</sup>,  
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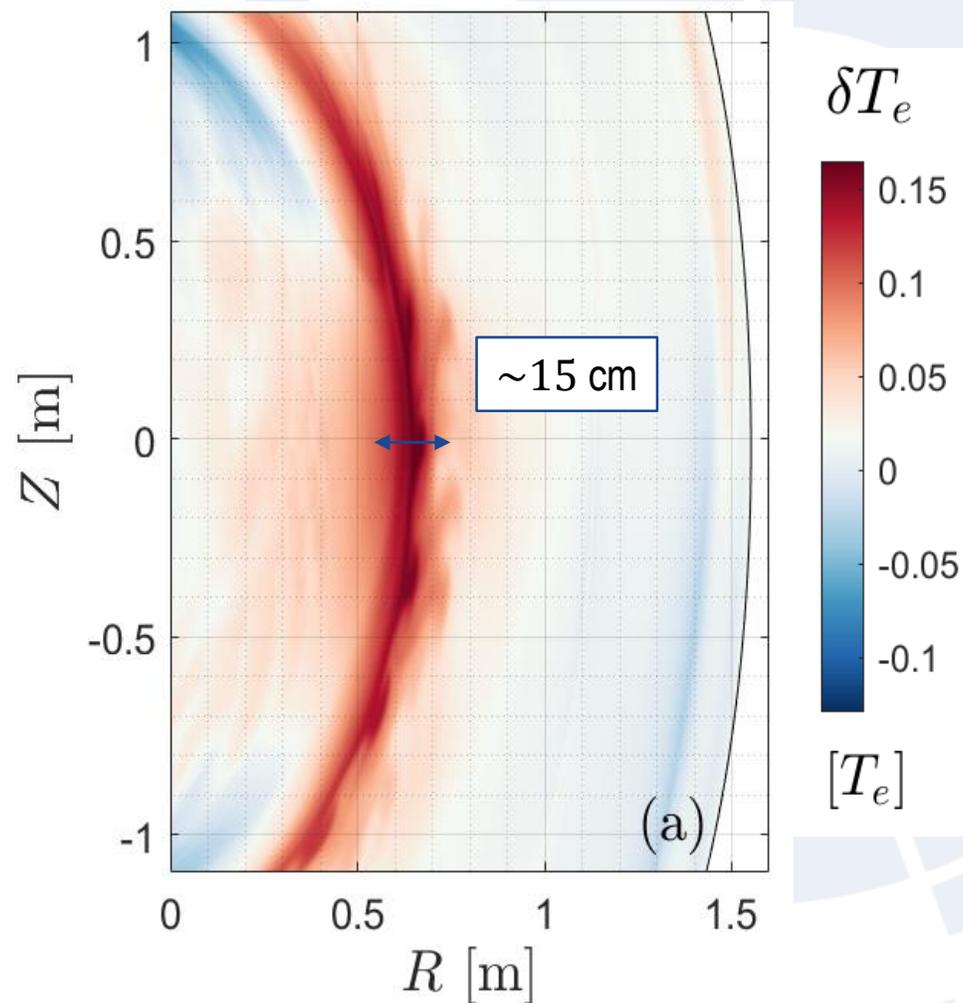
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- When KBM unstable, the radial width of the structure is small

KBM-induced perturbation is localized

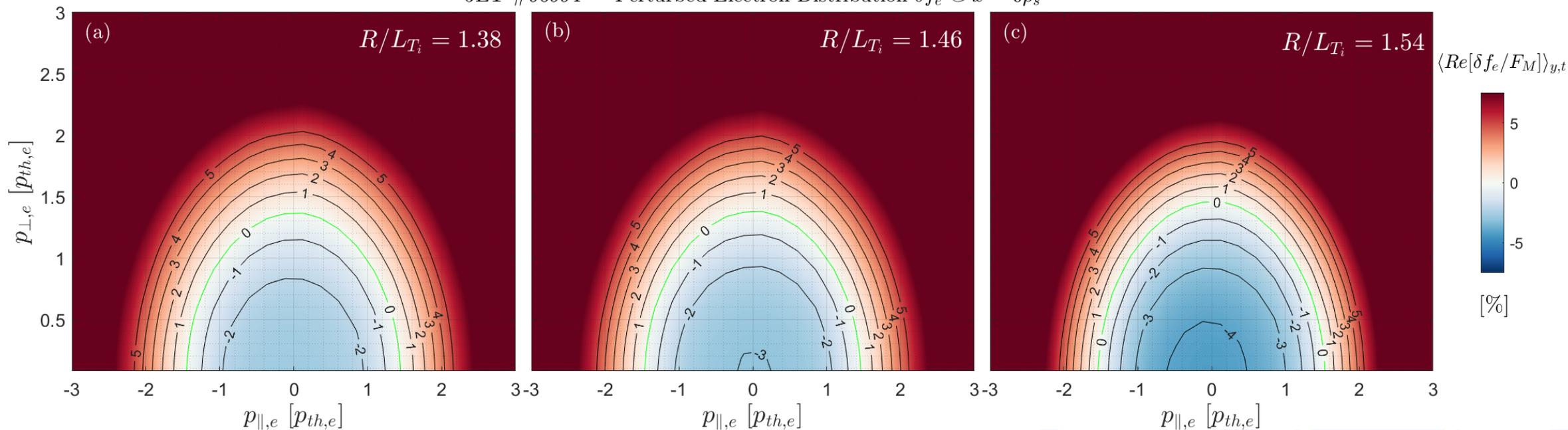




# Bipolar Perturbation Amplitude: KBM Drive Strongly Impacts

- The amplitude of the KBM-induced bipolar perturbation depends on the KBM drive and KBM-driven turbulence

JET #96994 — Perturbed Electron Distribution  $\delta f_e$  @  $x = 0\rho_s$



The amplitude of the perturbation in the heuristic model is of the same order (3% vs. 5%)