Role of Beta-Induced Alfven Eigenmodes in DIII-D high β_p scenario

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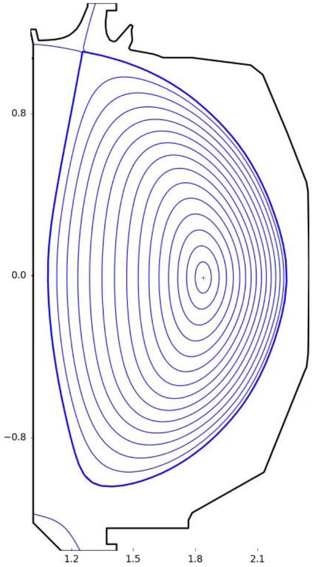
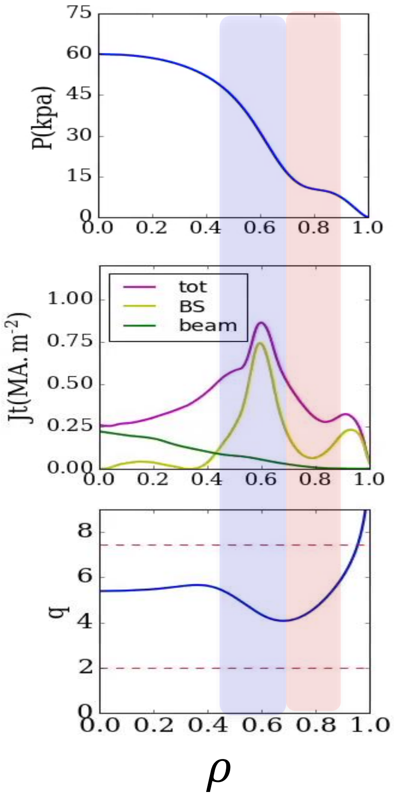
High β_p scenario is an advanced scenario for fully non-inductive operation with excellent compatibility of high confinement and f_{BS}

#176125@2600ms



Large Shafranov Shift
H_{98} = 1.5



- High f_{BS}

$$f_{BS} \sim \beta_p \sim q\beta_N$$

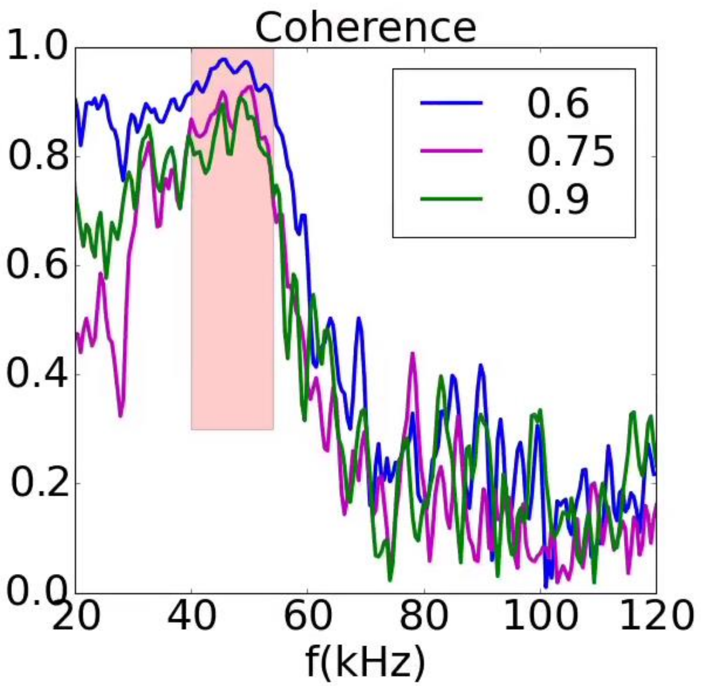
- High q & α

$$\alpha \sim -q^2 R \frac{8\pi}{B^2} \frac{dp}{dr}$$

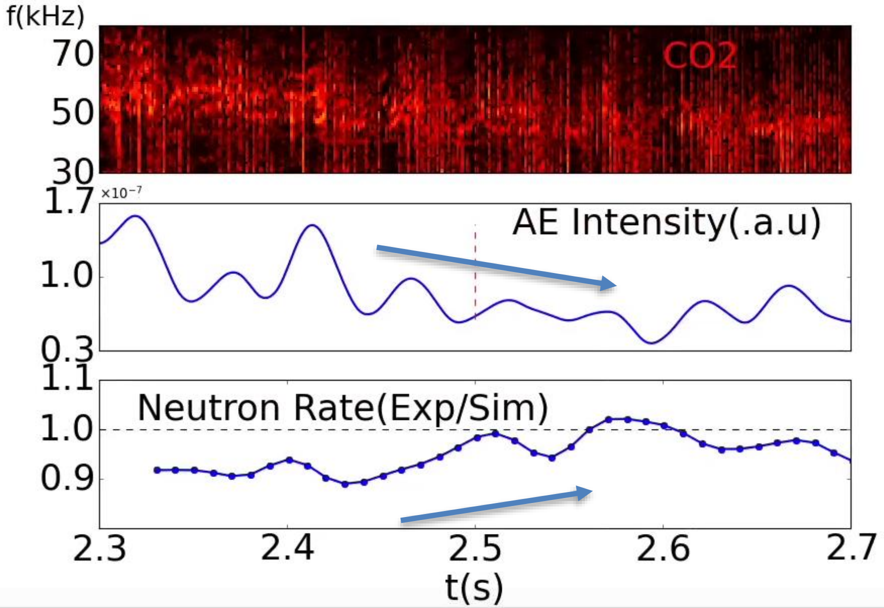
- Intensive efforts were put in the ITB region[1,2,3], while the outer core region (ρ~[0.65,0.85]) has not been systematically studied

Garofalo, NF, 2015
Staebler, POP, 2018
Jian, PRL, 2019

A coherent mode in the outer core region is observed experimentally and correlated with fast ion confinement

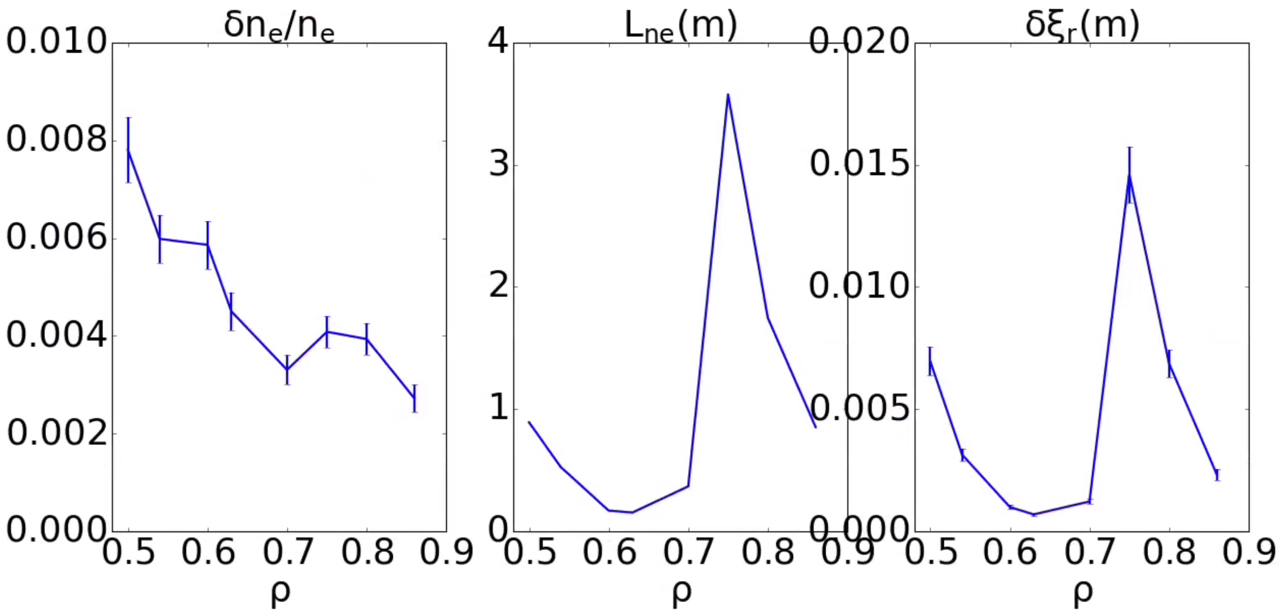


BES coherence



Ylim =0

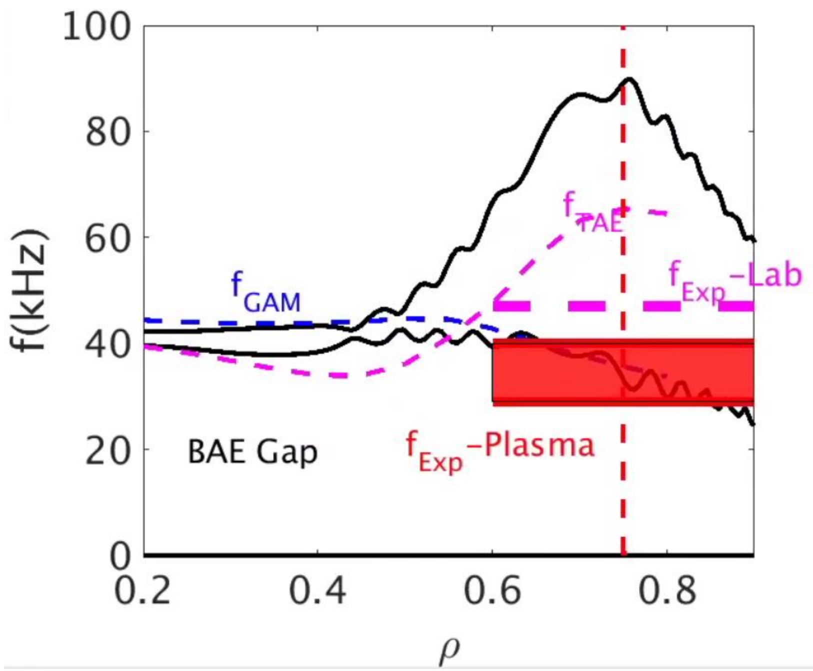
Experimental analysis shows the mode intensity peaks at ρ=0.75

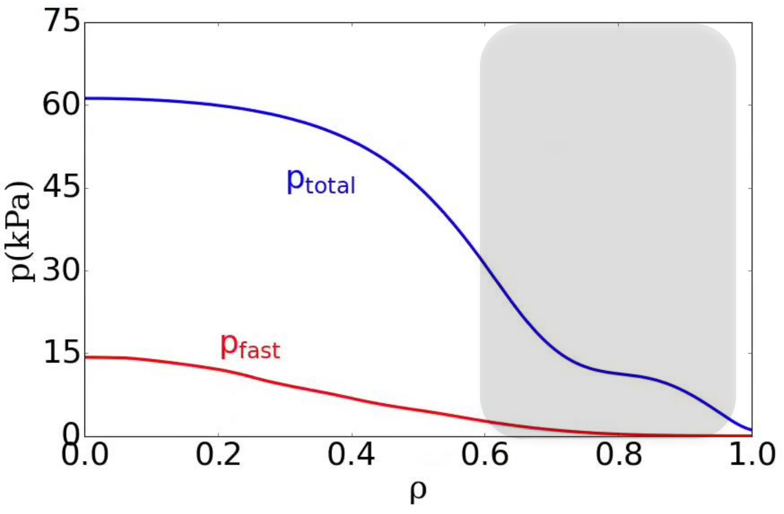


Ylim =0

$$\delta n_e = \delta\xi_r \frac{dn_e}{dr} => \delta\xi_r = \frac{\delta n_e}{n_e} * \left(\frac{n_e}{\frac{dn_e}{dr}}\right) = \frac{\delta n_e}{n_e} * L_{ne}$$

The mode is preliminarily identified to be an Beta Induced Alfven Eigenmode(BAE) based on its frequency characteristics

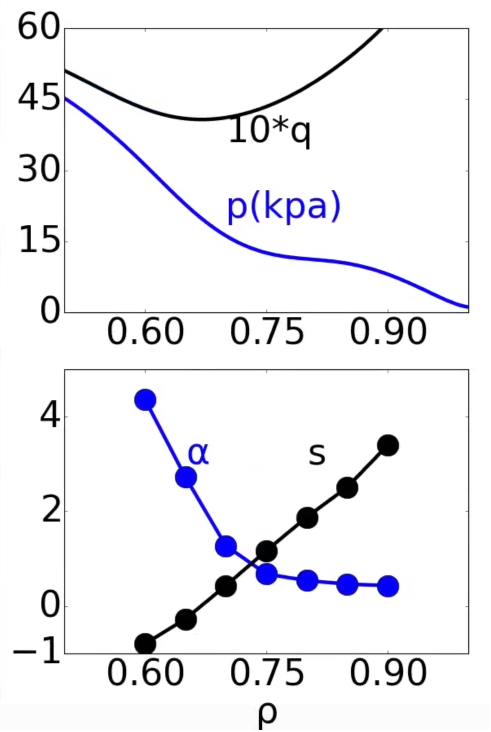


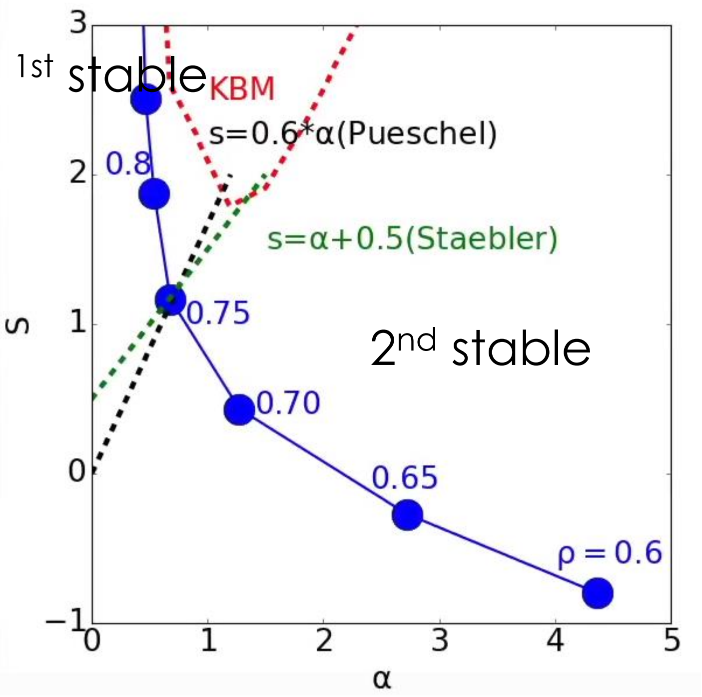


- Why can BAE be excited in the region where fast ions population is small?

W.Heidbrink-PRL-1993;
F.Zonca-PPCF-1996
A. Turnbull-PoP-1992

The outer core region is close to KBM boundary and may provide substantial free energy from thermal background profiles

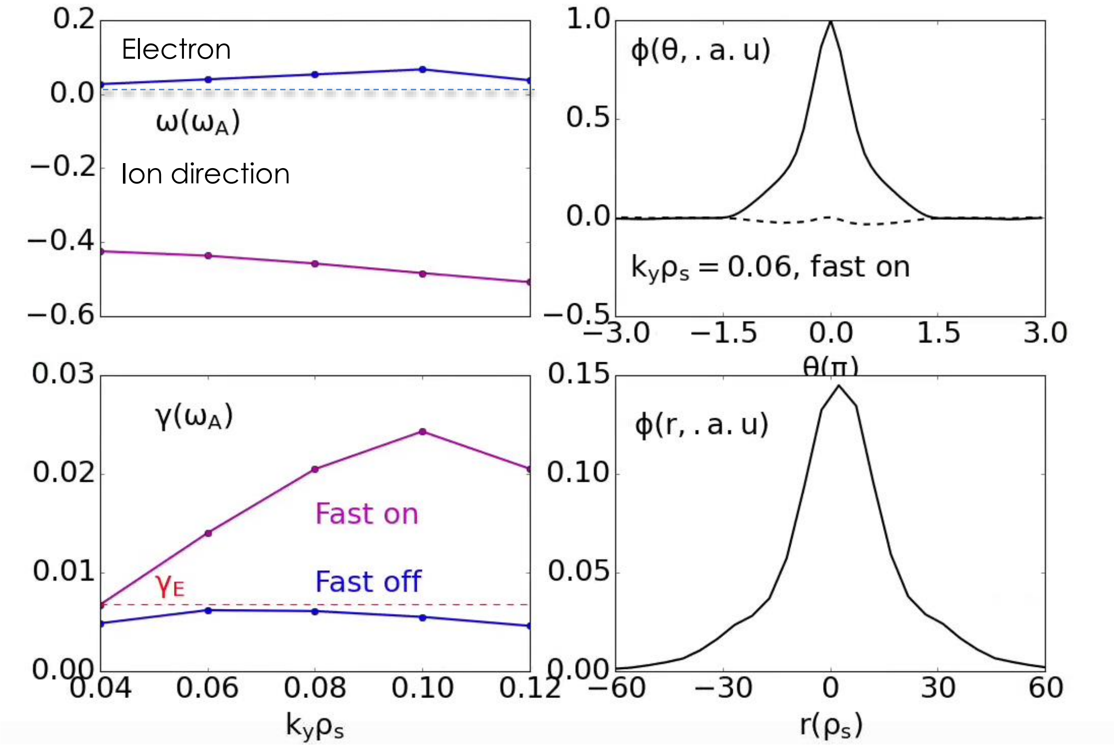




- Pueshel[1] & Staebler[2] curve defines the parameters set of most unstable KBM(kinetic ballooning mode);
- KBM and BAE are well **coupled** as long as $\eta_i \neq 0$[3]
  - Free energy for BAE excitation coming from background thermal profile can be significant

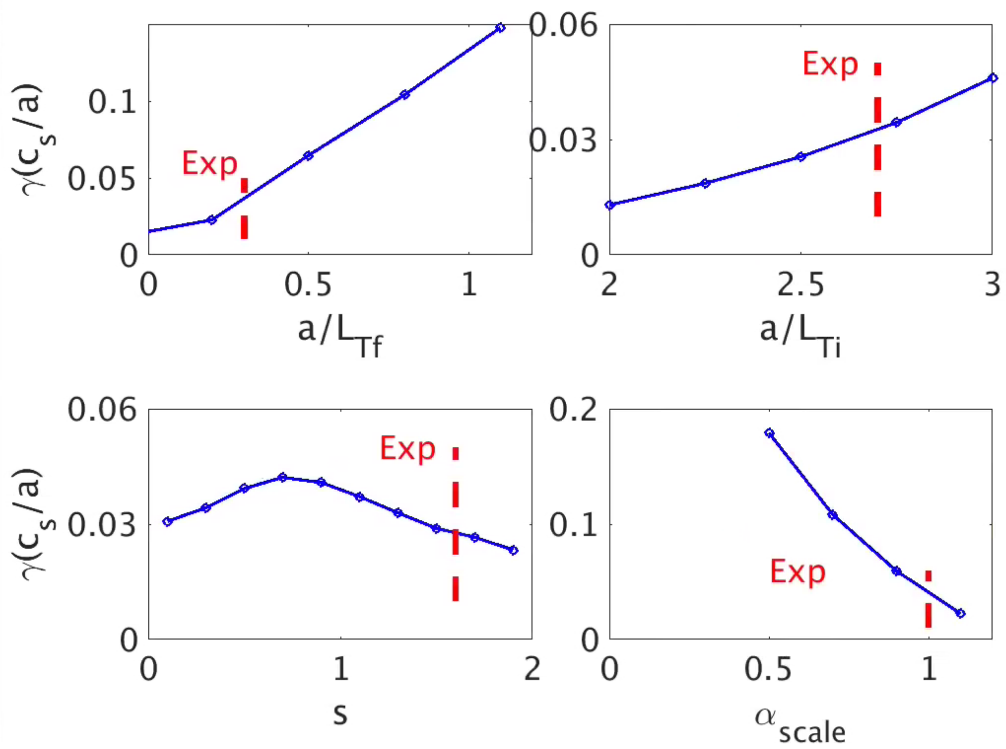
[1]Staebler, PoP, 2018
[2]Pueschel,PoP, 2008
[3] Zonca, PPCF, 1996

Flux-tube CGYRO calculation shows AE mode can be robustly unstable in the presence of fast ions



- Frequency is AE relevant;
- Eigenfunction is BAE-like
  - rather than doubled peaked TAE structure

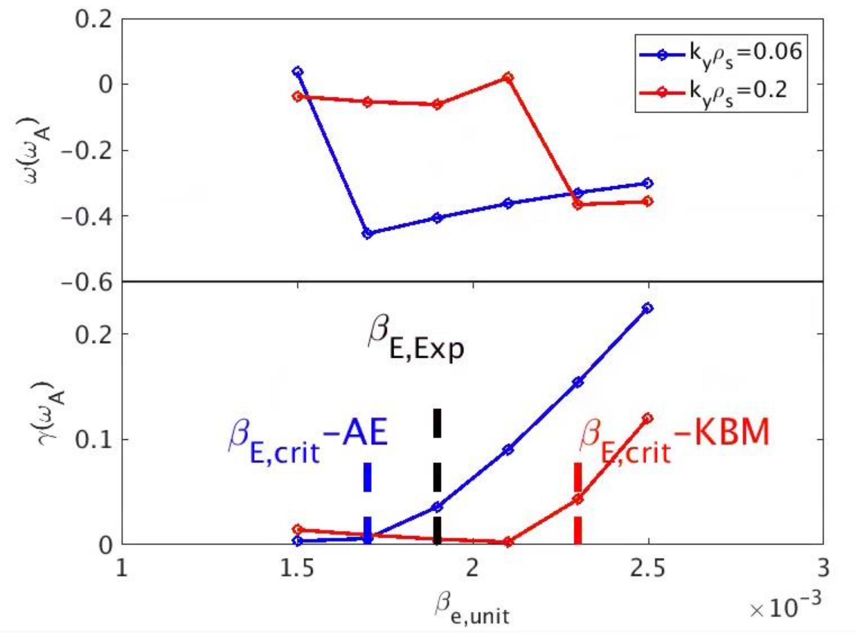
The parametric dependence of BAE is very similar to KBM, consistent with theoretical expectations



- Parameter regimes that favor KBM destabilization also facilitate the BAE excitation

- The question is about which one comes first

AE mode is driven before KBM under experimental conditions

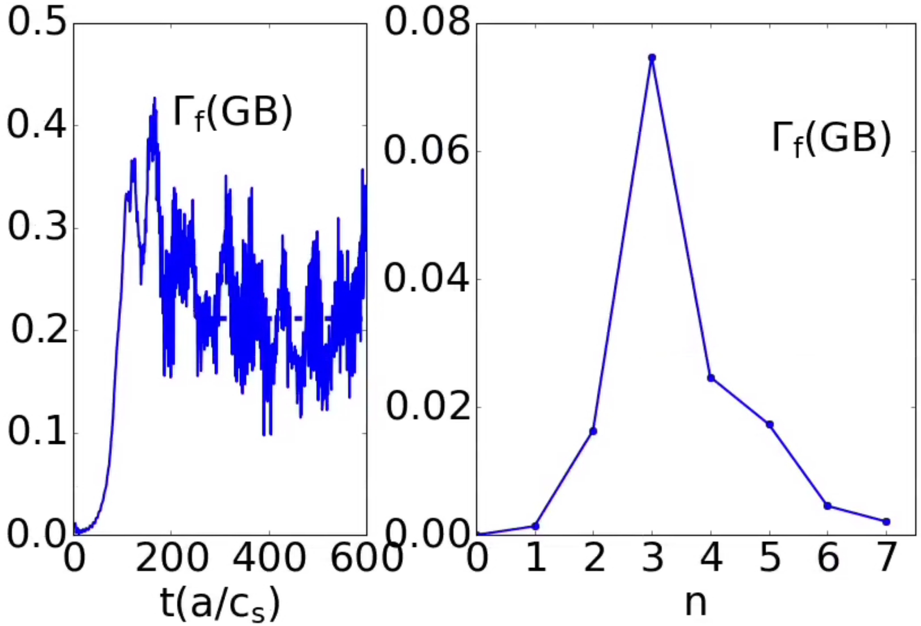


- $\beta_{E,crit}$(BAE) < β_E(Exp) < $\beta_{E,crit}$(KBM)

- BAE mode is excited (and kinetic profiles can be relaxed) before touching KBM
  - Consistent with absence of KBM under experiments
- Experimental condition is close to KBM threshold
  - Consistent with excitation of BAE under low fast ion population

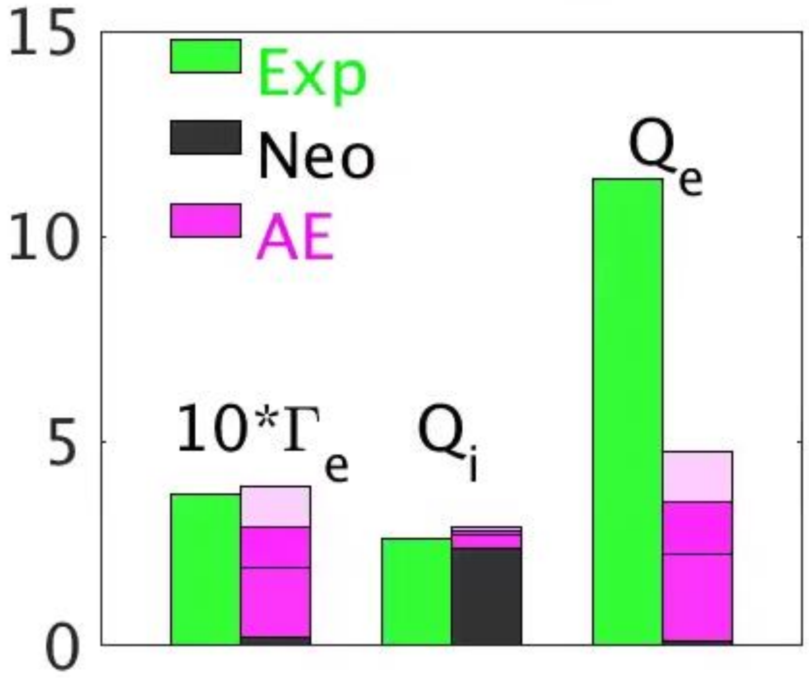
Role of BAE in transport? Nonlinear simulation is required.

Nonlinear CGYRO simulation on the AE-only wavelength predicts the mode peaks at n=3~4, consistent with experiments



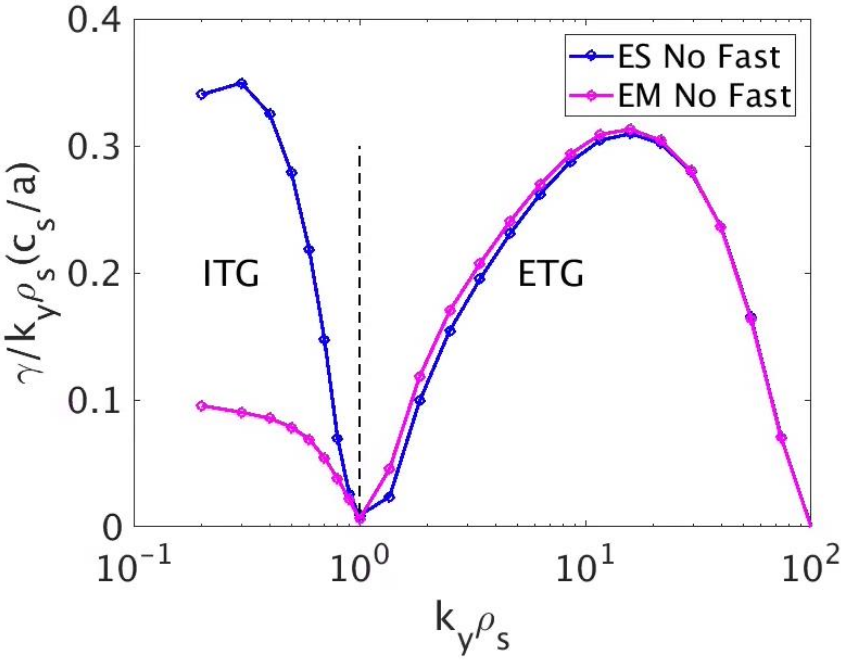
- Well Saturated State;
- Peaks at n=3~4
    - Consistent with experiments

Nonlinear simulation predicts the BAE induced flux consistent with transport fingerprints



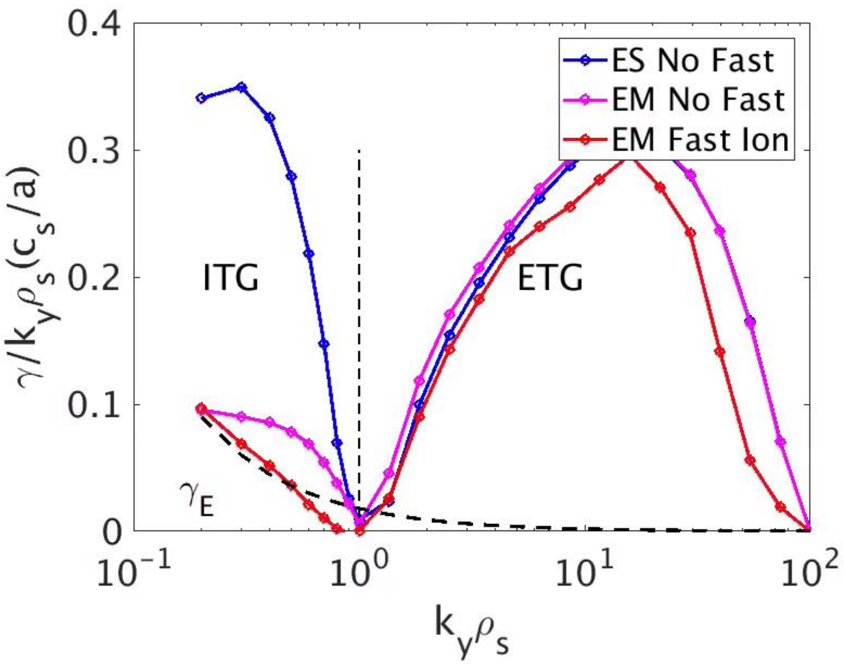
- Q_i is mostly neoclassical;
- BAE accounts for
  - Γ_e transport fully;
  - 1/3~1/2 of Q_e;
    - Additional transport mechanism for Q_e is required.
- Drift wave instability simulation is required

ITG and ETG dominates in low-k and high-k region, respectively



- ITG is heavily suppressed by EM stabilization while ETG is robustly unstable;
  - Strong EM stabilization on ITG is consistent with experimental condition (which is close to KBM boundary)

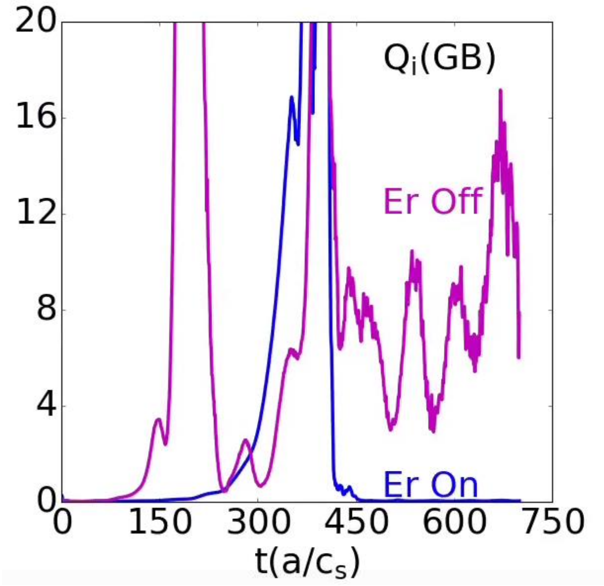
ITG is heavily suppressed while ETG is robustly unstable



- ITG is heavily suppressed by EM stabilization while ETG is robustly unstable;
  - Strong EM stabilization on ITG is consistent with experimental condition (which is close to KBM boundary)

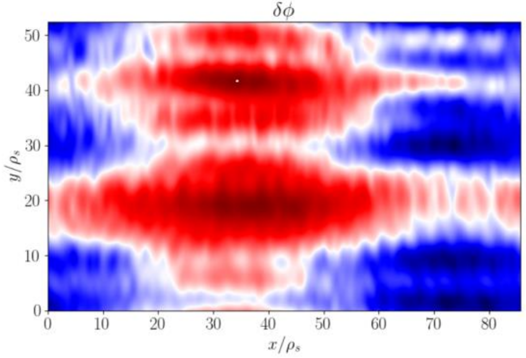
- Inclusion of fast ions further pushes the ITG growth rate to the Er shearing level;
  - Likely to be induced by geometrical α stabilization enhanced by inclusion of fast ions;

ITG turbulence is quenched by E_r shear as observed from nonlinear simulation, consistent with linear analysis

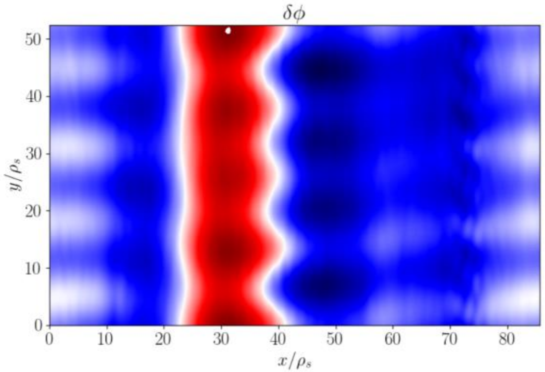


Simulation with fast ions off

Er Off

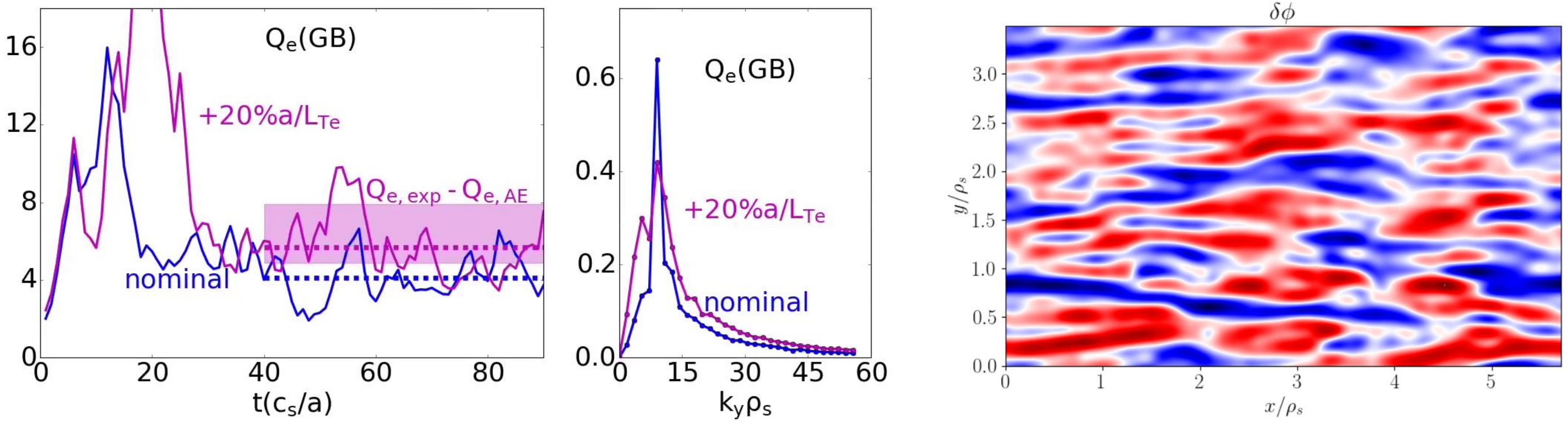


Er On



- Absence of ITG turbulence is consistent with experimental transport fingerprints
  - Instabilities for driving Γ_e & Q_i is **NOT** required;
- Will ETG be able to drive the residual Q_e?

ETG can provide missing Q_e



Caveat:

- No cross-coupling effect is considered;
- Multi-scale effect might be the future direction;

Saturated ETG eddies.

Conclusion

- High β_p outer core region is close to KBM boundary, which provides large free energy from thermal kinetic profiles and thus enables BAE to be excited by even a small fast ion population;
  - Potential solution: reduce fast ion deposition in that region

- Nonlinear CGYRO simulation suggests that Neoclassical, BAE and ETG can combined to drive experimental inferred particle and energy fluxes
  - Neoclassical transport accounts for most Q_i;
  - BAE can accounts for full Γ_e and 1/3~1/2 of Q_e;
    - Consistent with flat experimental n_e profile where BAE activity peaks;
  - ETG accounts for residual Q_e;
  - Fast ion impact on momentum transport is still under study

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The mode is correlated with fast ions confinement.