Multi-field two-fluid and gyro-fluid simulations of Edge-Localized-Modes

BOUT++
Boundary Plasma Turbulence Code

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24th IAEA Fusion Energy Conference,

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Principal Results

Part one: two-fluid model

(1) **Fundamental model: 3-field 2-fluid model is a good enough model for P-B instability and ELM crashes.**

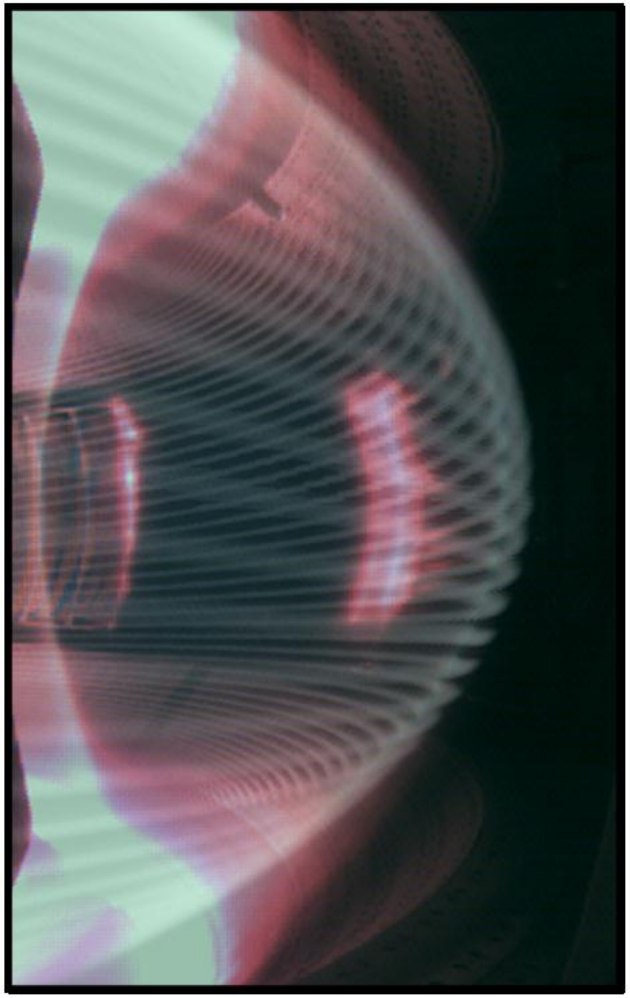
(2) **Multi-field 2-fluid models are necessary to describe heat transport.**

(3) **BOUT++ simulations show that bright stripes from visible camera on EAST match ELM filamentary structures.**

Part two: gyro-fluid model

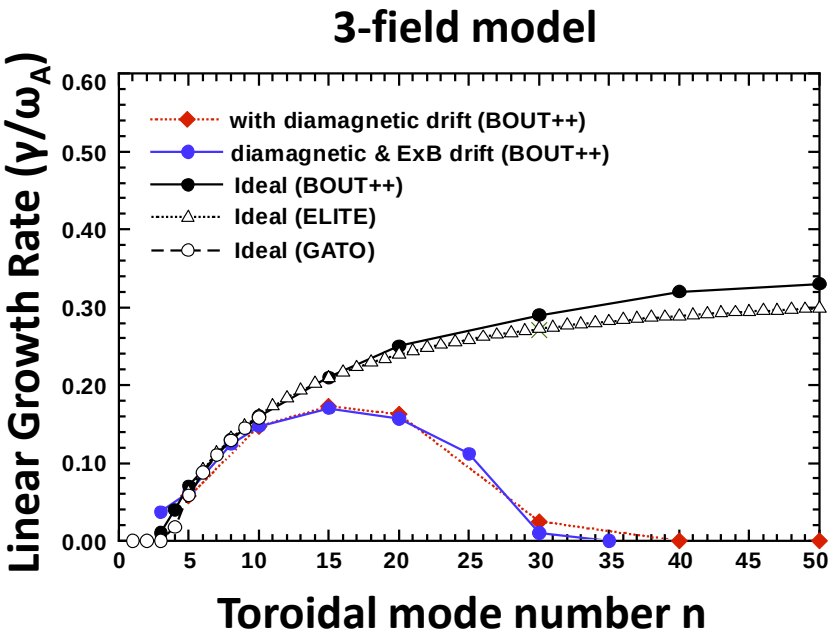
(1) **First order FLR corrections from "gyro-viscous cancellation" in two-fluid model are necessary to agree with gyro-fluid results for high ion temperature.**

(2) **Higher ion temperature introduces more FLR stabilizing effects, thus reduces ELM size.**



BOUT++ code for modeling tokamak edge ELMs and turbulence*

- **Framework for writing fluid / plasma simulations in complex tokamak geometry**
  - **Proximity of open+closed flux surface**
  - **Presence of X-point**
- **Written in C++, started from BOUT code, jointly developed by LLNL, Univ. York, other U.S. and international partners**
- **Well benchmarked with ELITE, GATO and other codes**



X.Q. Xu, B.D. Dudson, P.B. Snyder, M.V. Umansky, H.R.Wilson and T. Casper, Nucl. Fusion 51 (2011) 103040

** X.Q. Xu and R.H. Cohen, Contrib. Plasma Phys. 38, 158 (1998)*

- Umansky, Xu, Dudson, et al., , Comp. Phys. Comm. V. *180 , 887-903 (2008).*
- Dudson, Umansky, Xu et al., Comp. Phys. Comm. V.180 (2009) 1467.

Multi-field two-fluid Peeling-Ballooning modes simulation with BOUT++

T. Y. Xia[1,2], X. Q. Xu[2], Z. X. Liu[1], S. C. Liu[1], B. Gui[1,2], W. Meyer[2], G. Q. Li[1] and J. G. Li[1]

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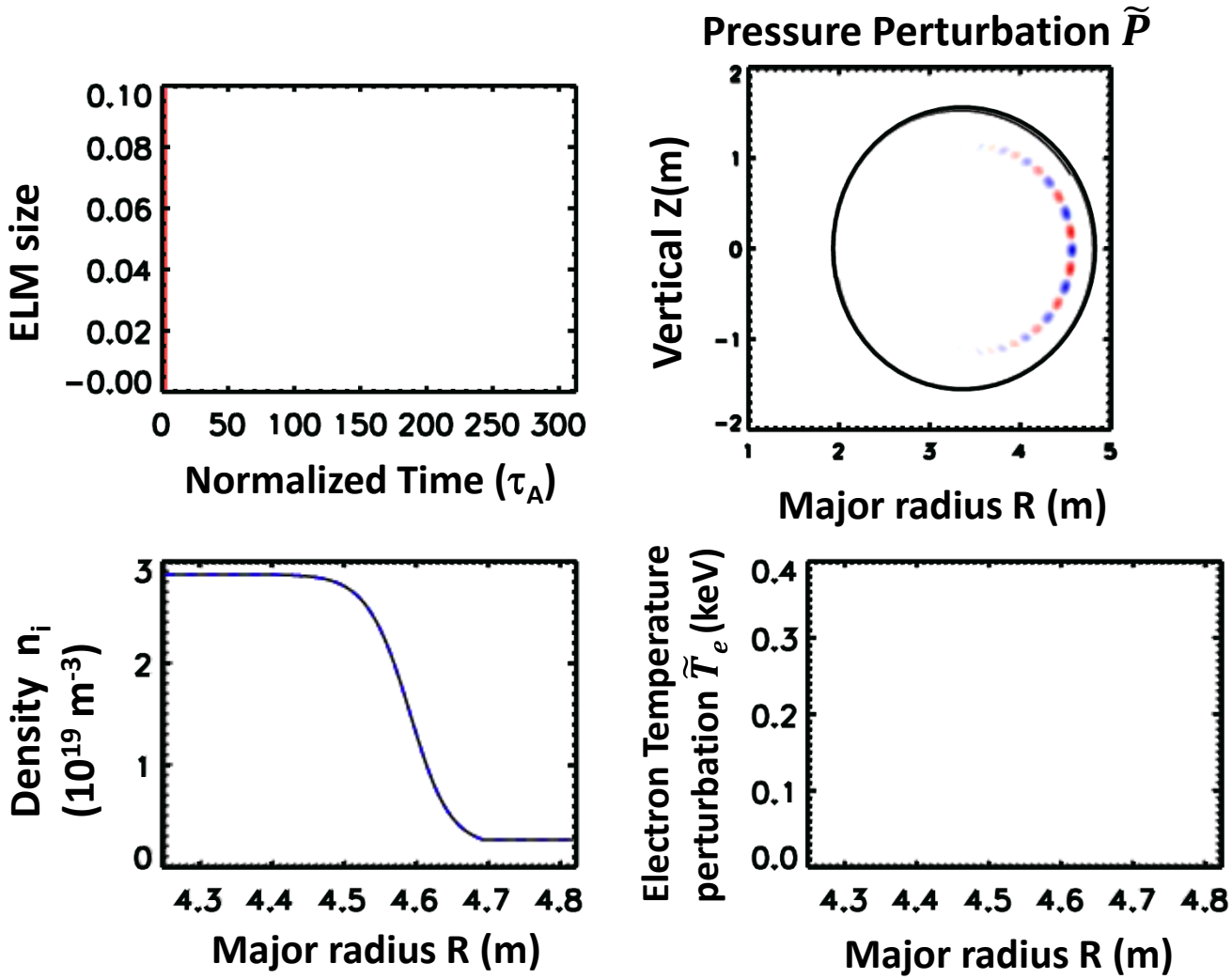
Multi-field two-fluid model in BOUT++

- Three-field (ϖ, P, $A_{||}$): peeling-ballooning model.
- Four-field (ϖ, P, $A_{||}$, $V_{||}$): include sound waves.
- Five-field (ϖ, n_i, T_i, T_e, $A_{||}$): parallel thermal conductivities
- Six-field (ϖ, n_i, T_i, T_e, $A_{||}$, $V_{||}$): combine all the models together, based on Braginskii equations, the density, momentum and energy of ions and electrons are described in drift ordering[1].

[1]X. Q. Xu et al., Commun. Comput. Phys. **4**, 949 (2008).

ELM crash in BOUT++ simulations



Five-field model: low density leads to larger stabilizing effects by diamagnetic drifts, and density gradient drives larger ELM size

3-field:

$$\frac{\partial P}{\partial t} + \mathbf{V}_E \cdot \nabla P = 0 \quad (previous\ model)$$

5-field

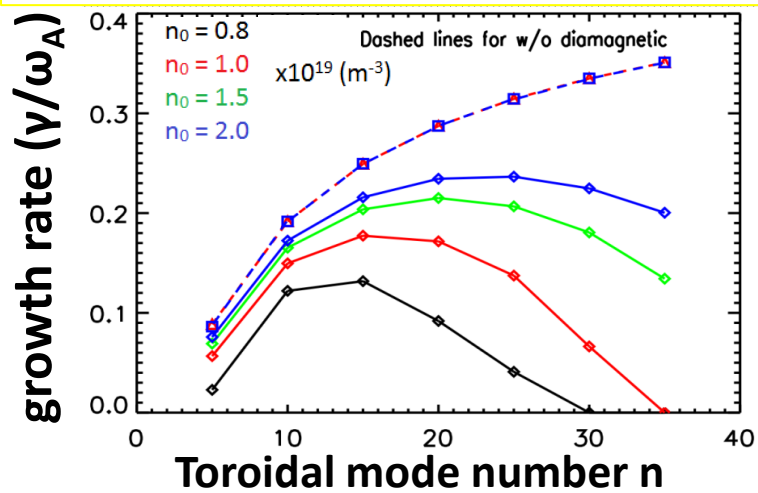
$$\frac{\partial n_i}{\partial t} + \mathbf{V}_E \cdot \nabla n_i = 0,$$

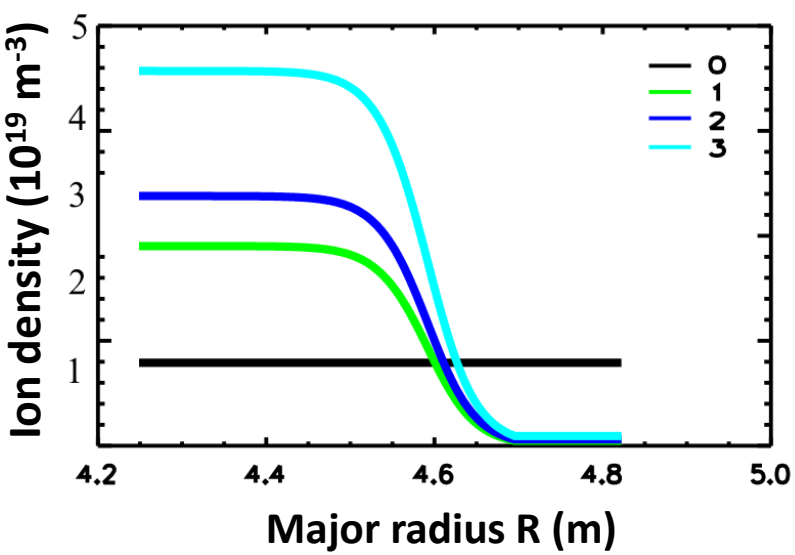
$$\frac{\partial T_j}{\partial t} + \mathbf{V}_E \cdot \nabla T_j = \nabla_\parallel \left(\kappa_{\parallel j} \nabla_\parallel T_j\right)$$

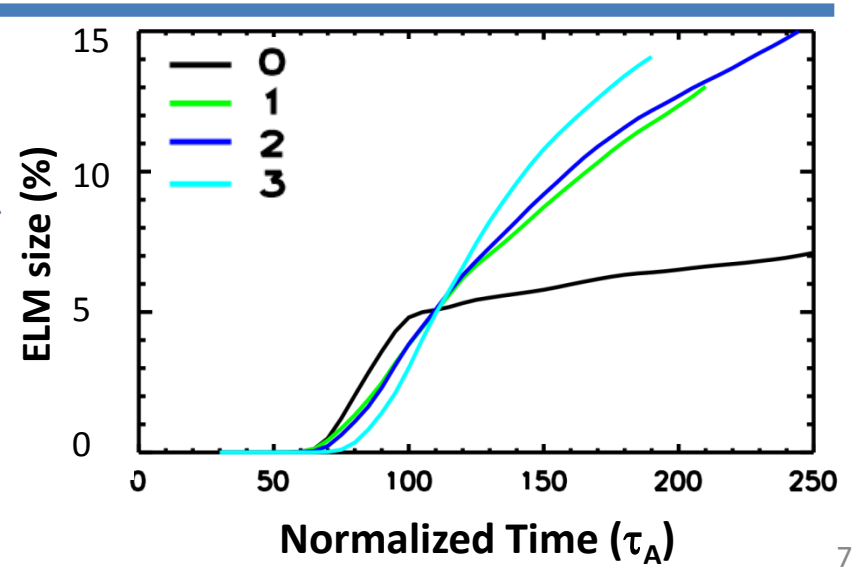
$$\varpi = n_{i0} \frac{m_i}{B_0} \left[\nabla_\perp^2 \phi + \frac{1}{n_{i0}} \nabla_\perp \phi \cdot \nabla_\perp n_{i0} + \frac{1}{n_{i0} Z_i e} \nabla_\perp^2 p_i \right]$$

With fixed pressure profile, ion density gradient leads to larger ELM size.

Density quantity affects linear growth rate through $\omega_* \propto 1/n_i$







Thermal conductivities suppress the energy transport at inner boundary

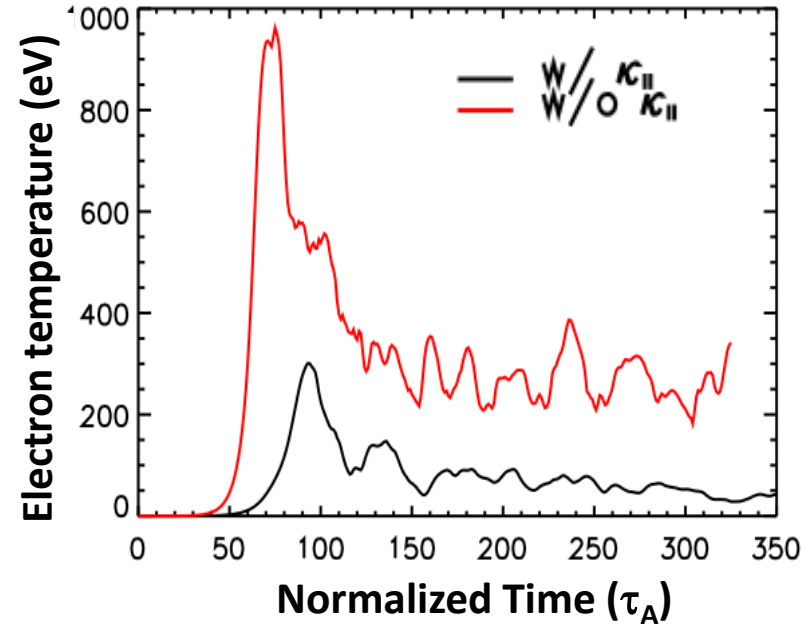
- Thermal conductivities with flux limited expressions suppress the increase of ELM

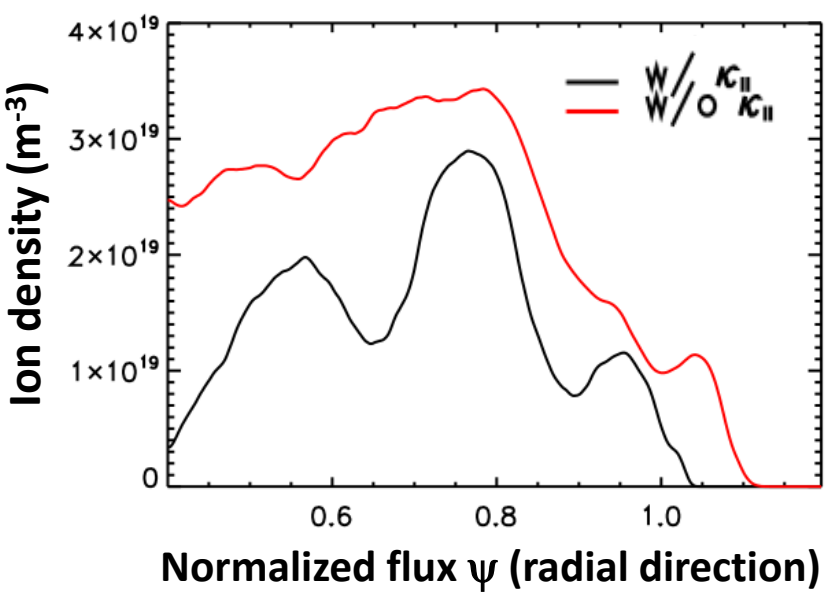
$$\kappa_{\|i} = 3.9\frac{v_{th,i}^2}{\nu_i} \quad \kappa_{\|e} = 3.2\frac{v_{th,e}^2}{\nu_e} \quad \kappa_{fl,j} = v_{th,j} q_{95} R_0$$

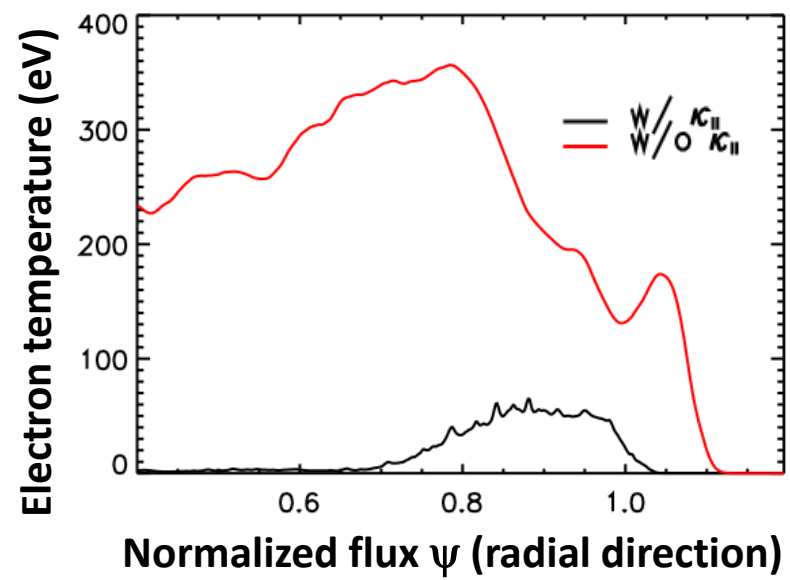
Flux limited expression:

$$\kappa_{\|j}^e = \left(\frac{1}{\kappa_{\|j}} + \frac{1}{\kappa_{fl,j}}\right)^{-1}$$

Electron temperature is most sensitive to $\kappa_{||}$.







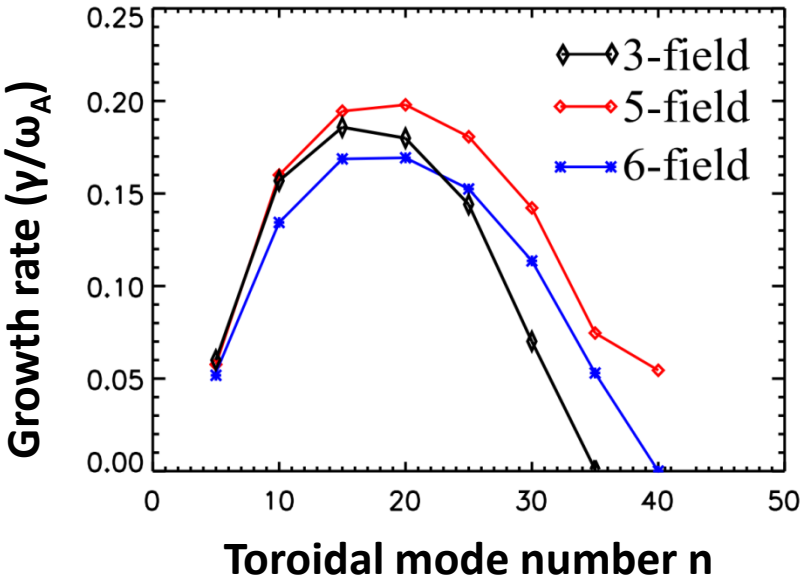
3-field 2-fluid model is good enough to simulate P-B stability and ELM crashes, additional physics from multi-field contributes less than 25% corrections

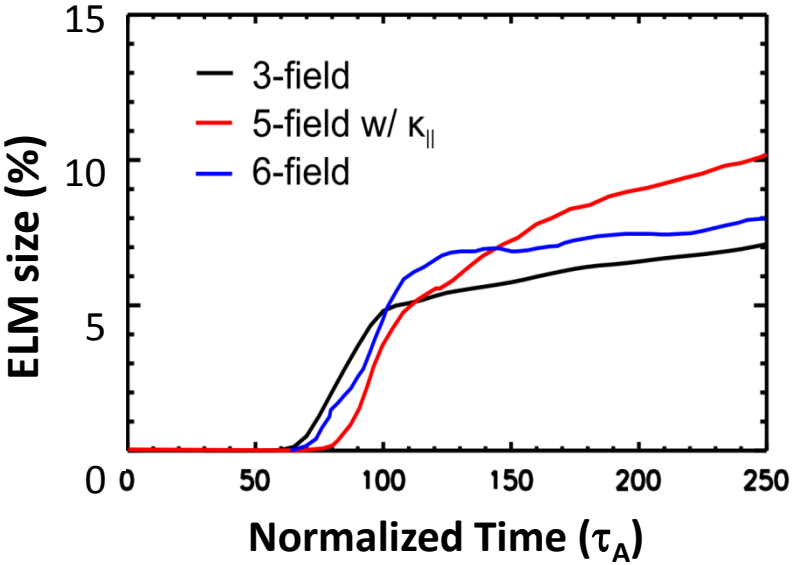
- **Fundamental physics in ELMs:**
  - ✓ Peeling-Ballooning instability
  - ✓ Ion diamagnetic stabilization
    - → kinetic effect
  - ✓ Resistivity and hyper-resistivity
    - → reconnection

- **Additional physics:**
  - Ion acoustic waves
  - Thermal conductivities
  - Hall effect
  - Compressibility
  - Electron-ion friction

change the linear growth rate less than 25%

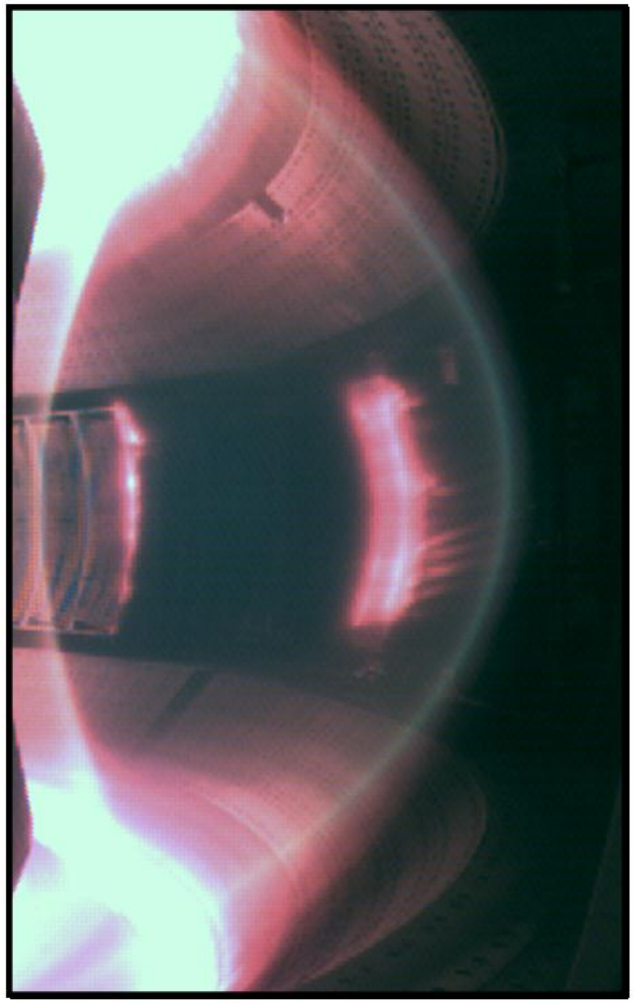
Power depositions on PFCs. Turbulence and transport



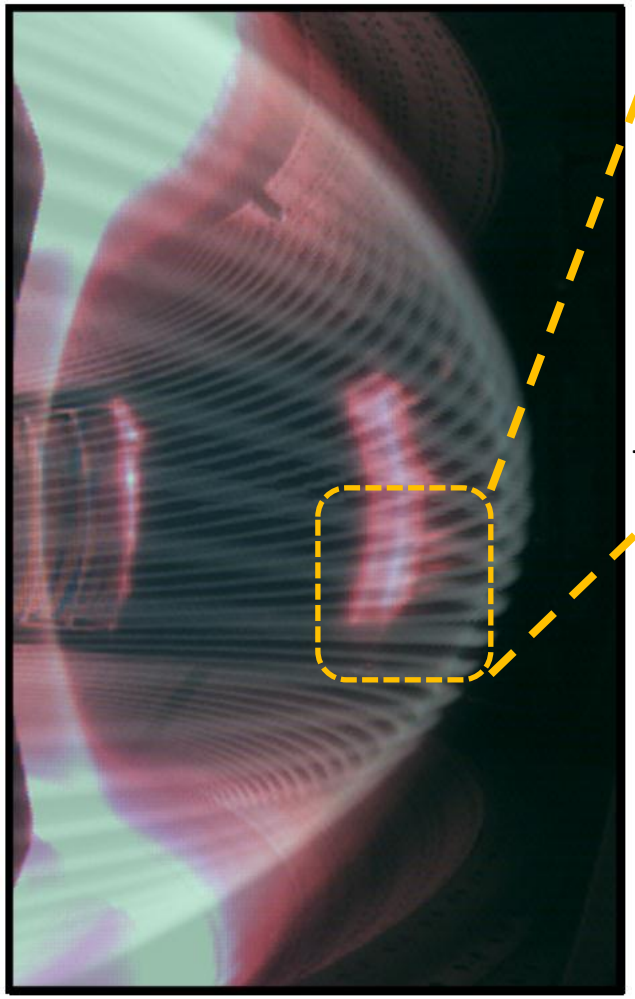


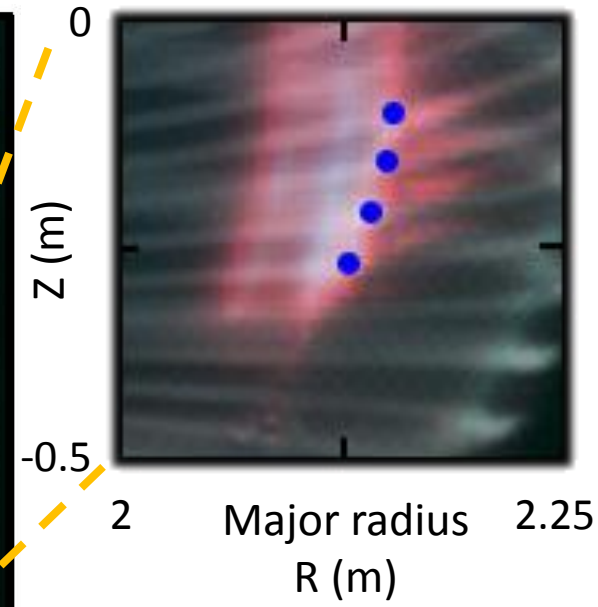
BOUT++ simulations show that the stripes from visible camera match ELM filamentary structures

EAST#41019@3034ms Visible camera shows bright ELM structure$



BOUT++ simulation shows that the ELM stripe are filamentary structures*

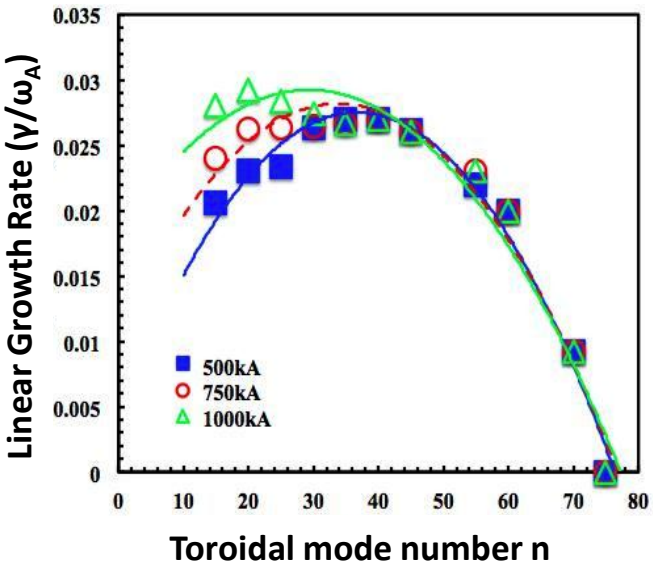


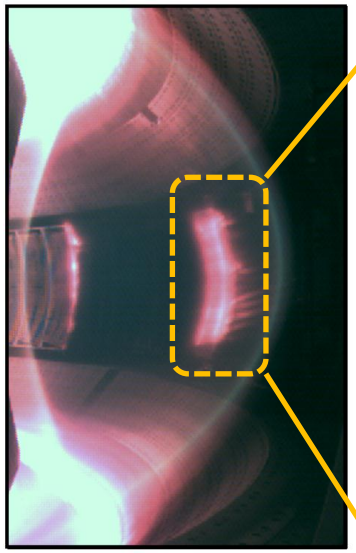


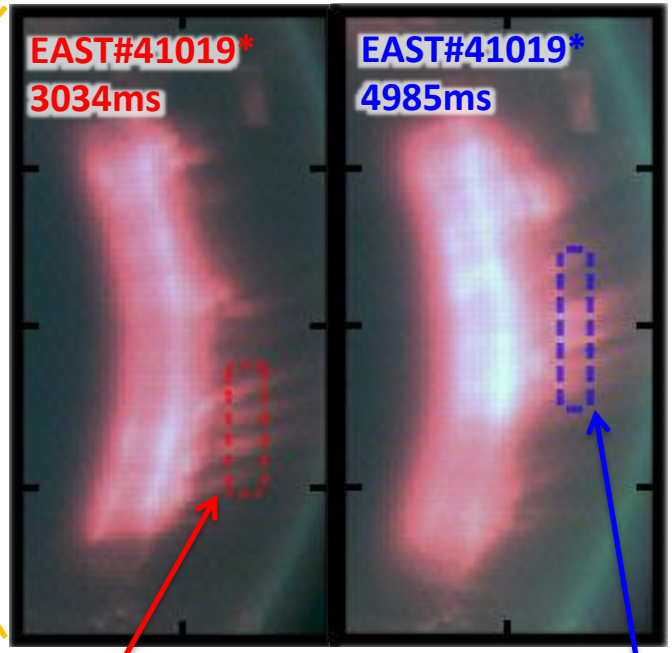
- Pitch match!
- Mode number match!

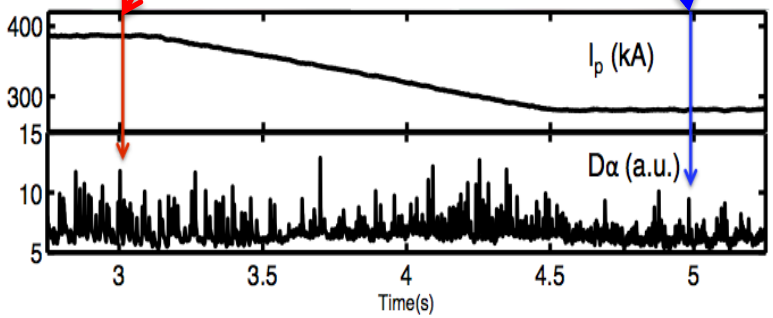
$Taken by J. H. Yang
*Figure by W.H. Meyer

EAST experiments verified BOUT++ predictions that low-n modes become dominant at high I_p









BOUT++:

- Higher current has lower n mode

Experiment:

- 400kA→n=25
- 300kA→n=30

Qualitatively consist

Z.X. Liu et al, Phys. Plasmas 19 102502 (2012).

Z.X. Liu et al, EX/p7-11, "Study of ELMy H-mode plasmas and BOUT++ simulation on EAST"

TH/5-2Rb

Theory and Gyro-fluid Simulations of Edge-Localized-Modes

BOUT++
Boundary Plasma Turbulence Code

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An isothermal electromagnetic 3-field gyro-fluid model

- We derived an isothermal electromagnetic 3-field gyro-fluid model with vorticity formulation generalized from Snyder-Hammett gyro-fluid model [1] for edge plasmas.

- Utilizing the Padé approximation for the modified Bessel functions, this set of gyro-fluid equations is implemented in the BOUT++ framework with full ion FLR effects,

- In long-wavelength limit, this set of gyro-fluid equations is reduced to previous 3-field two-fluid model with additional gyro-viscous terms resulting from the incomplete "gyro-viscous cancellation" in two-fluid model given by Xu et al [2].

- Higher ion temperature introduces more FLR stabilizing effects, thus reduces ELM size.

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[1] P. B. Snyder and G. W. Hammett, Phys. Plasmas 8, 3199 (2001).
[2] X. Q. Xu, R. H. Cohen, T. D. Rognlien, et.al., Phys. Plasma 7, 1951 (2000).

In the presence of large density gradient, gyro-fluid and two-fluid model show qualitative difference when $k_\perp \rho_i$ is large

$$\frac{d\varpi_G}{dt} + \mathbf{V}_E \cdot \nabla \varpi_{G0} - eB(\mathbf{V}_{\Phi T} - \mathbf{V}_{ET}) \cdot \nabla n_{iG} = B\nabla_\parallel J_\parallel + 2\mathbf{b}_0 \times \kappa \cdot \nabla \tilde{P}_G + \mu_{i,\parallel}\partial^2_{\parallel 0}\varpi_G$$

$$\frac{d\tilde{P}_G}{dt} + \mathbf{V}_E \cdot \nabla P_{G0} + T_0(\mathbf{V}_{\Phi T} - \mathbf{V}_{ET}) \cdot \nabla n_{iG} = 0$$

$$\frac{\partial A_\parallel}{\partial t} + \partial_\parallel \phi_T = \frac{\eta}{\mu_0}\nabla^2_\perp A_\parallel - \frac{\eta_H}{\mu_0}\nabla^4_\perp A_\parallel$$

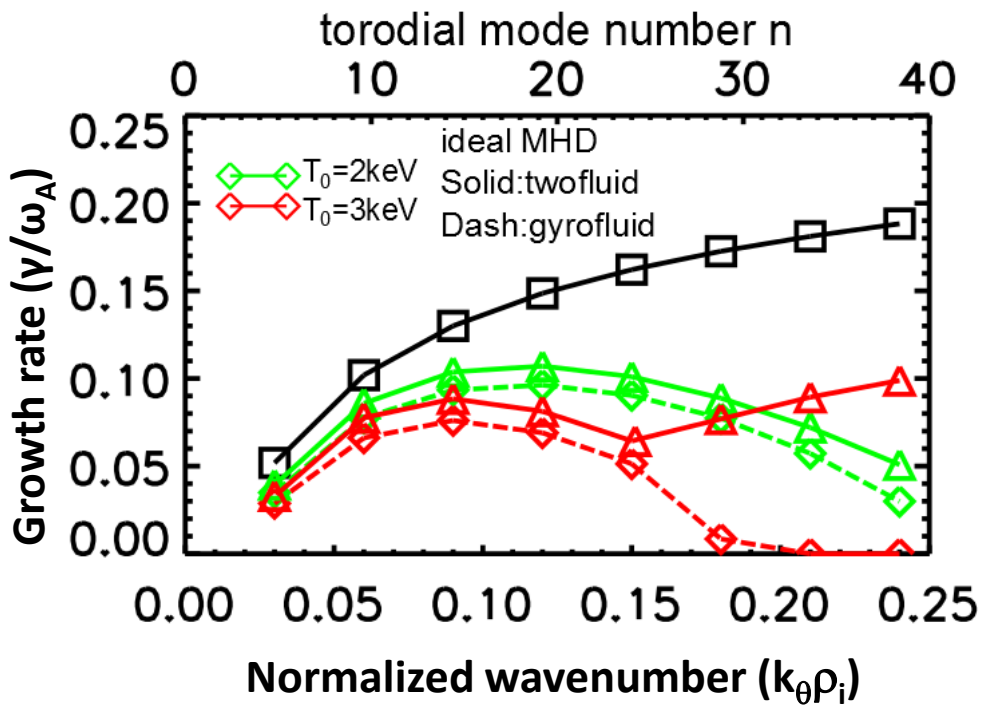
$$\varpi_G = eB(\Gamma_0^{1/2}\tilde{n}_{iG} - n_0(1-\Gamma_0)\frac{e\phi}{T_0} + \boxed{\frac{e\rho_i^2}{T_0}\nabla n_0 \cdot \nabla((\Gamma_0 - \Gamma_1)\phi)} - \tilde{n}_{iG})$$

$$\begin{cases} \tilde{P}_G = T_0(\tilde{n}_e + \tilde{n}_{iG}) \\ \varpi_G = eB(\tilde{n}_e - \tilde{n}_{iG}) \end{cases}$$

Consider the **large density gradient** at H-mode pedestal:

- Two-fluid model: **no stabilizing** on high-n modes,
- Gyro-fluid model: **strong FLR stabilizing** on high-n modes.

Simple ion diamagnetic effect in two-fluid model is not sufficient to represent FLR stabilizing if density gradient is large!



Gyroviscous terms are necessary to stabilize Ion-Density-Gradient modes, which appear in two-fluid model

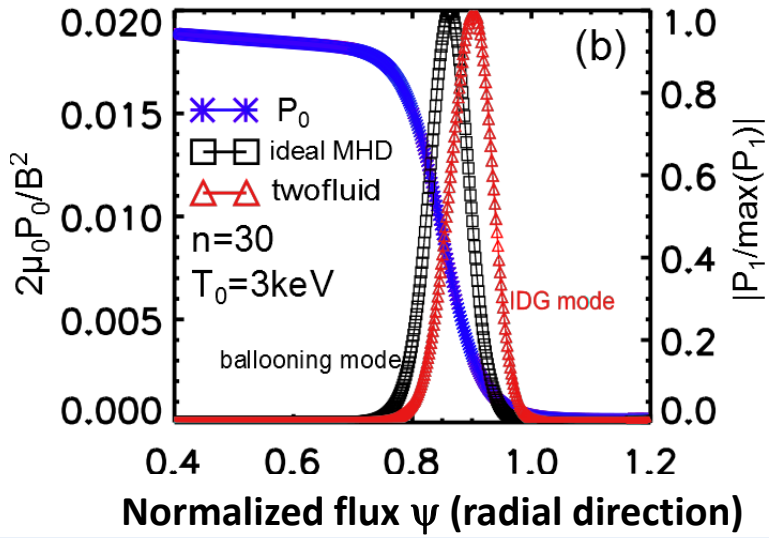
- **Two-fluid dispersion relation:**

ion diamagnetic stabilizing on ballooning modes

drift instability due to ion density gradient

$$\gamma = \frac{1}{\sqrt{C}}\left(\sqrt{\gamma_I^2 - \frac{\omega_{*i}^2}{4}}\cos\frac{\alpha}{2} + \frac{\omega_{*i}}{2}\sin\frac{\alpha}{2}\right)$$

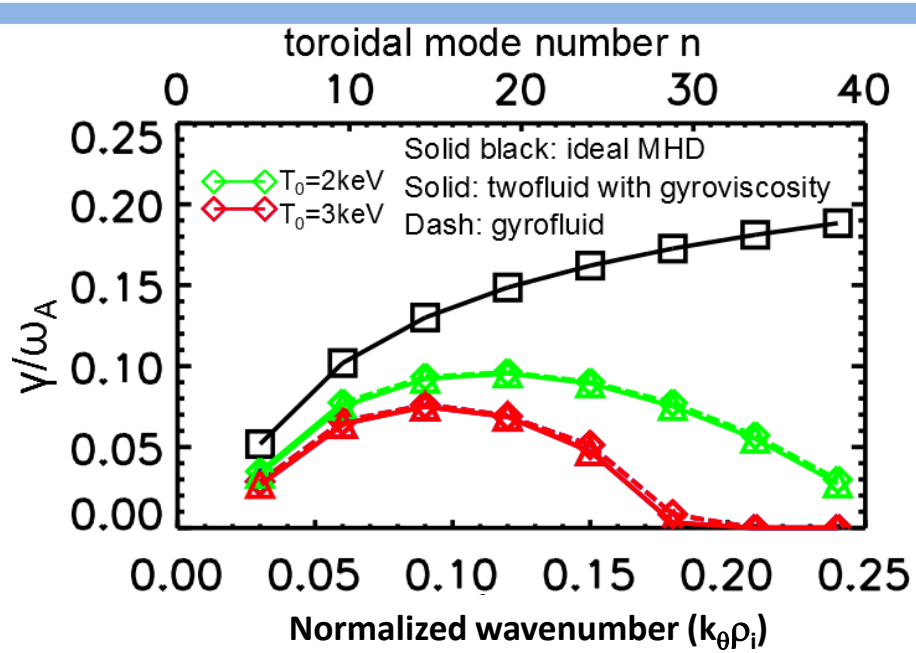
$$C^2 = 1 + \frac{k_x^2}{k_\perp^4 L_n^2}, \quad \cos\alpha = \frac{1}{C}, \quad \sin\alpha = \frac{1}{C}\frac{k_x}{k_\perp^2 L_n}$$



- **At long wavelength limit, gyro-fluid goes back to two-fluid but with additional gyroviscous terms**

$$\frac{d\varpi_G}{dt} + \mathbf{V}_E\cdot\nabla\varpi_{G0} - eB(\mathbf{V}_{\Phi T} - \mathbf{V}_{ET})\cdot\nabla n_{iG} =$$

$$\frac{d\varpi}{dt} + \boxed{\frac{1}{2\omega_{ci}}\{\nabla_\perp^2[\phi,P] - [\nabla_\perp^2\phi,P] - [\phi,\nabla_\perp^2 P]\}}$$

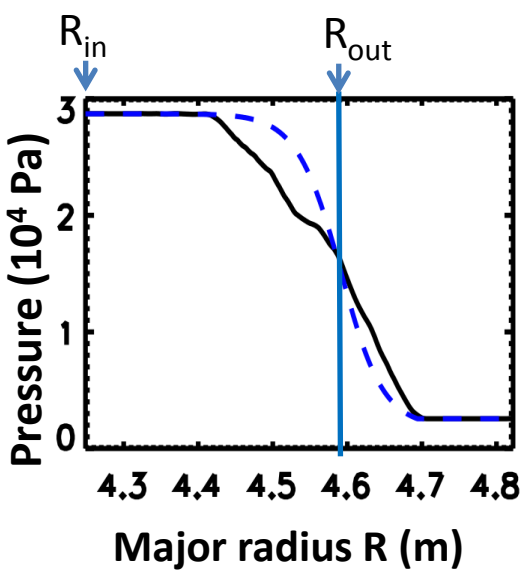


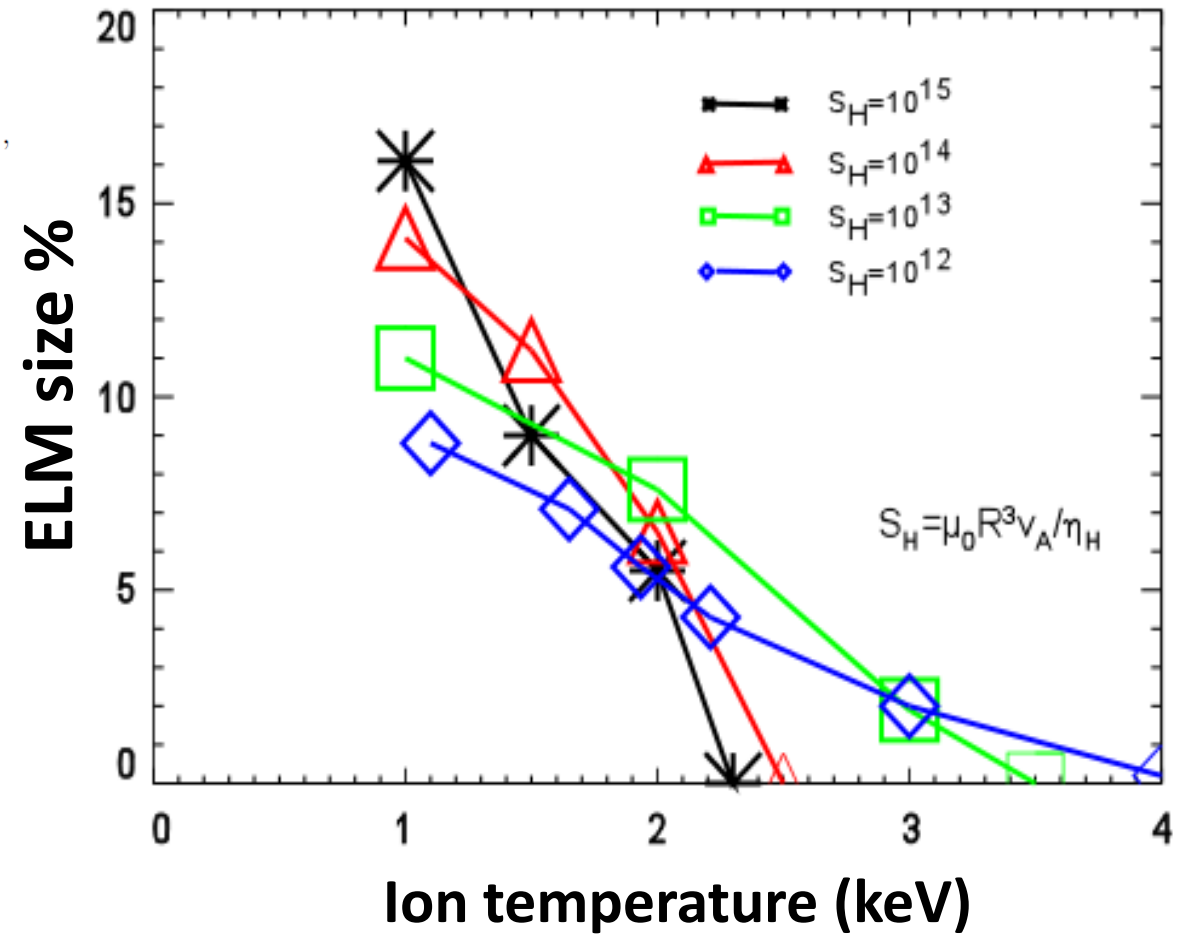
Higher ion temperature introduces more FLR stabilizing effects, thus reduces ELM size

- Hyper-resistivity is necessary to ELM crash, but ELM size is weakly sensitive to hyper-resistivity;
- With fixed pressure profile, high ion temperature introduce stronger FLR effect and thus leads to smaller ELM size

Definition of ELM size:

$$\Delta_{ELM}^{th} = \frac{\Delta W_{ped}}{W_{ped}} = \frac{\langle \int_{R_{in}}^{R_{out}} \oint dR d\theta (P_0 - \langle P \rangle_\zeta) \rangle_t}{\int_{R_{in}}^{R_{out}} \oint dR d\theta P_0},$$





Accurate non-Fourier methods for Landau-fluid operators

Tokamak edge:

- **kinetic effects important -> need Landau-fluid (LF) operators**

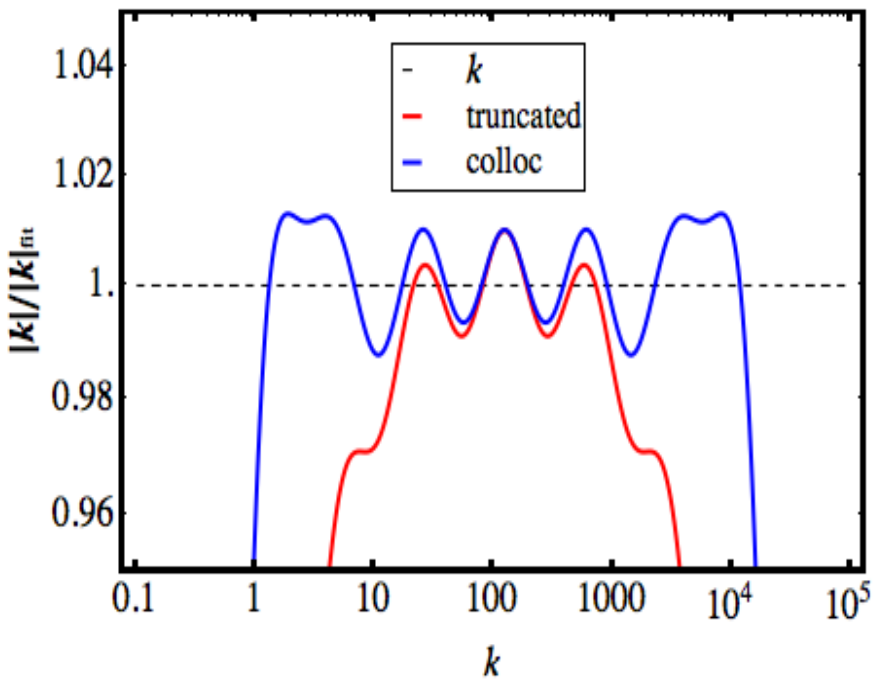
$$\gamma \propto -v_{\text{char}} \left| k \right|$$

- **Large spatial inhomogeneities & complicated boundary**
  - ➢ **need non-Fourier implementation**
  - ➢ **Useful accurate approximation:**

$$\frac{1}{\left|k\right|} \approx \sum_{n=0}^{N} \frac{\alpha^n k_0}{k^2 + \left(\alpha^n k_0\right)^2}$$

- **The new method has favorable Fourier-like computational scaling**

Ratio of fit to analytical operator vs. wavenumber



✓ **The error is less than 1.5%.**

Principal Results

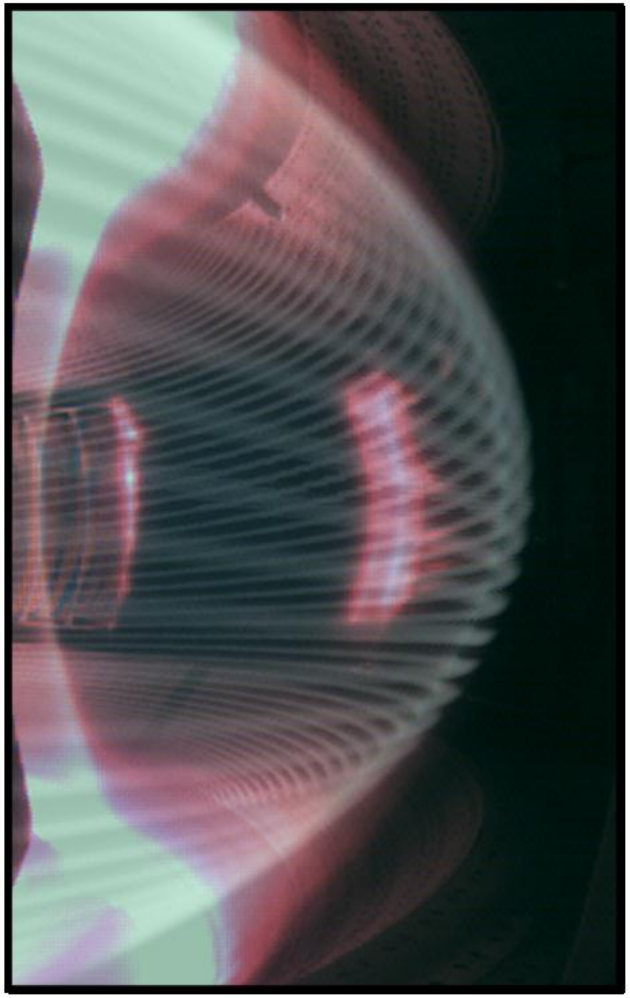
Part one: two-fluid model

(1) Fundamental model: 3-field 2-fluid model is a good enough model for P-B stability and ELM crashes.

(2) High-n P-B mode is strongly stabilized at low density by diamagnetic drifts at low temperature.

(3) BOUT++ simulations show that bright stripes from visible camera on EAST match ELM filamentary structures.

Part two: gyro-fluid model

(1) First order FLR corrections from "gyro-viscous cancellation" in two-fluid model are necessary to agree with gyro-fluid results for high ion temperature.

(2) Higher ion temperature introduces more FLR stabilizing effects, thus reduces ELM size.