Shot Analysis of Electron Transport in NSTX

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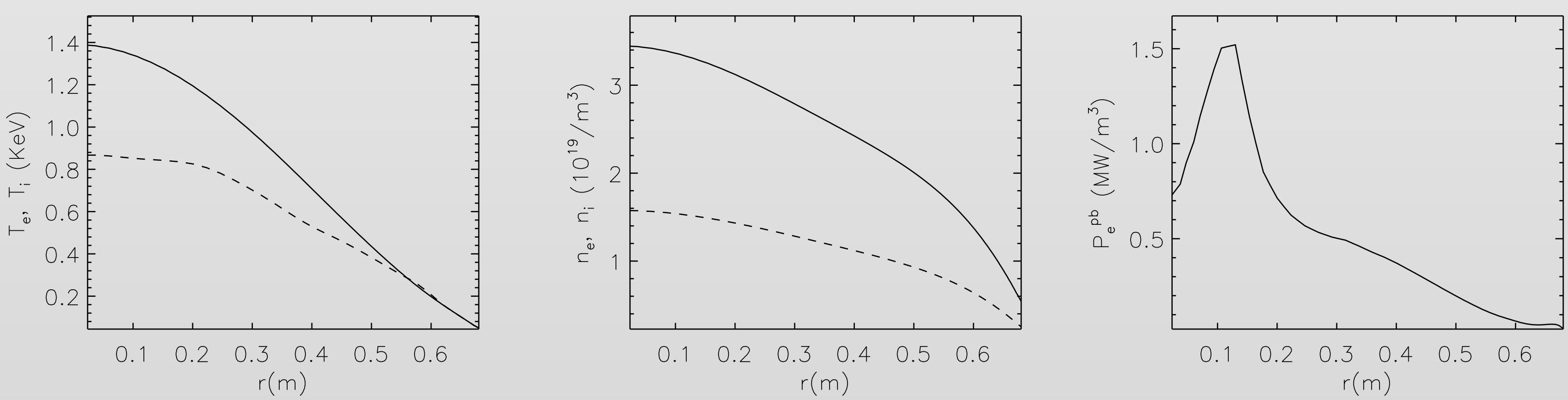
Overview

- NSTX 106194 Data Specification
- Power Balance Analysis
- Comparison of Power Balance with ETG and TEM
- ETG Model analysis and Nonlinear Simulation Result

Data Specification

NSTX 106194

- $R = 0.85$ m, $r = 0.68$ m and $B_0 \sim 0.45$ T, deuterium plasmas
- $\rho_e(0) = 0.2$ mm, $\rho_s(0) = 1.7$ cm and $d_e(0) = c/\omega_{pe} = 0.9$ mm at the core
- High Harmonic Fast Wave(HHFW) $P_e^{\mathrm{total}} = 2.4$ MW
- $\epsilon_n = L_{ne}/R$ ranges from 0.2 ($r = 0.6$ m) to 2.1 ($r = 0.1$ m)
- $\eta_e = L_{ne}/L_{Te} \geq 1.5$ and reach the maximum $\eta_e = 2.5$ at $r = 0.43$ m.



Power Balance Analysis

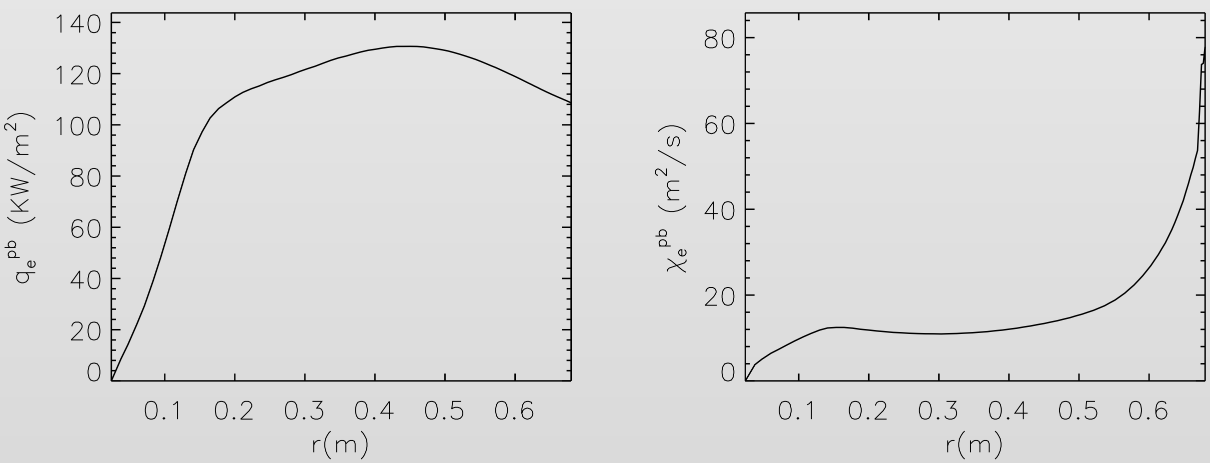
The heat flux, q_e, is from $\boldsymbol{\nabla} q_e = P_e$

$$q_e(r) = \frac{1}{r}\int_0^r r' P_e(r') dr' \qquad (1)$$

and the heat diffusity is

$$\chi_e^{pb} = \frac{-q_e}{n_e \, \nabla T_e} \qquad (2)$$

Energy confinement time $\tau_E = a^2/\chi_e^{pb} = 40$ ms,

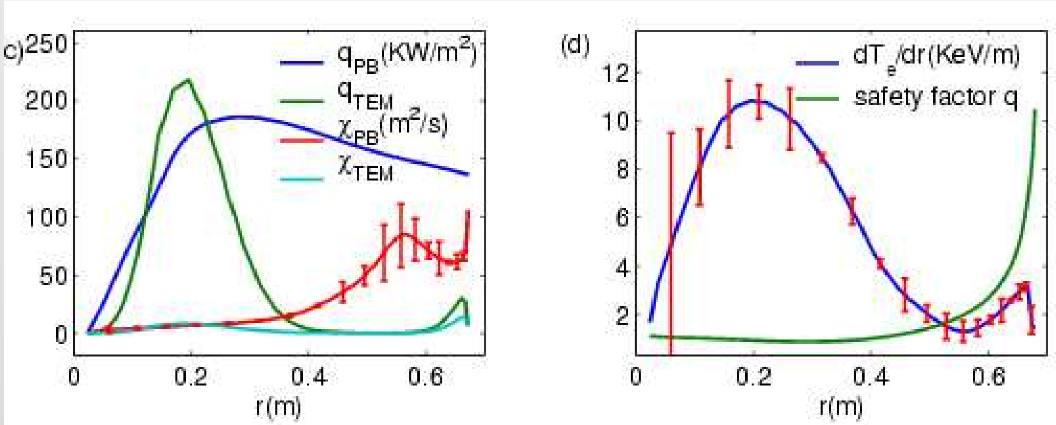


Trapped Electron Mode(TEM)

In the low-aspect ratio R/a like NSTX, there are the large pitch angle electrons with density fraction $\delta n_t = n_0 \delta$, where $\delta = (B_{\max}/B_{\min})^{1/2} - 1 \approx (2r/R)^{1/2}$ near the axis.
The particle and heat diffusivities are given by Kadomtsev and Pogutse(1970)

$$D_t = c_{TEM} D_{gB} \left(\frac{c_s R}{\nu_e L_n^2} \right) \tag{3}$$

$$\chi_e^{\text{TEM}} = \frac{3}{2} D_t \left(\frac{R}{L_{T_e}} \right) . \tag{4}$$



From Horton et. al. Nuclear Fusion 2005

Electron Temperature Gradient(ETG)

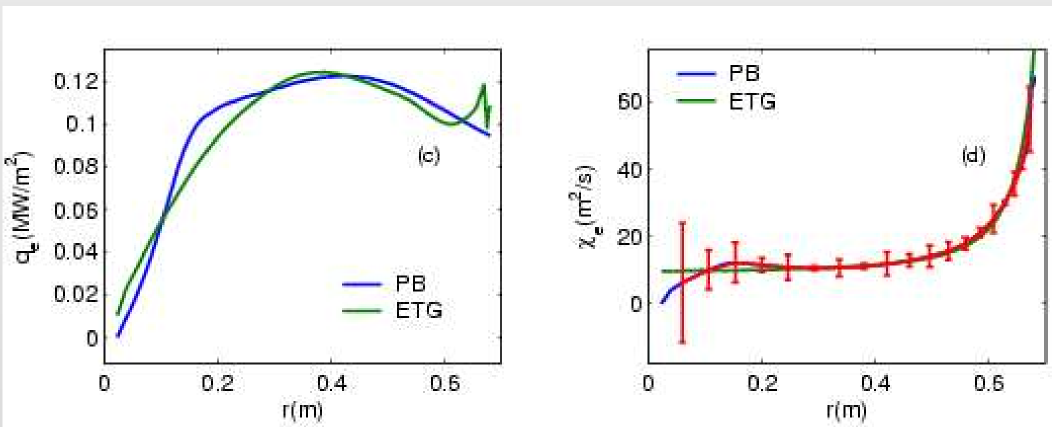
For ETG mode,

$$q_e = C_e^{em} n_e T_e q \frac{c^2}{\omega_{pe}^2} \frac{v_e}{R} \left(\frac{R}{L_{Te}} - \frac{R}{L_c} \right) \quad \beta_e > \beta_{e,cr} \tag{5}$$

$$q_e = C_e^{es} n_e T_e q^2 \left(\frac{\rho_e^2 v_e}{L_{Te}^2} \right) \left(\frac{R}{L_{Te}} - \frac{R}{L_c} \right) \quad \beta_e < \beta_{e,cr} \tag{6}$$

where $\beta_{e,cr} = (L_{Te}/qR)^2$ ETG mode is electromagnetic,

$\beta_e > \beta_{e,cr}$ where $r > 0.32$ m



From Horton et. al. Nuclear Fusion 2005

Critical Temperature Gradient

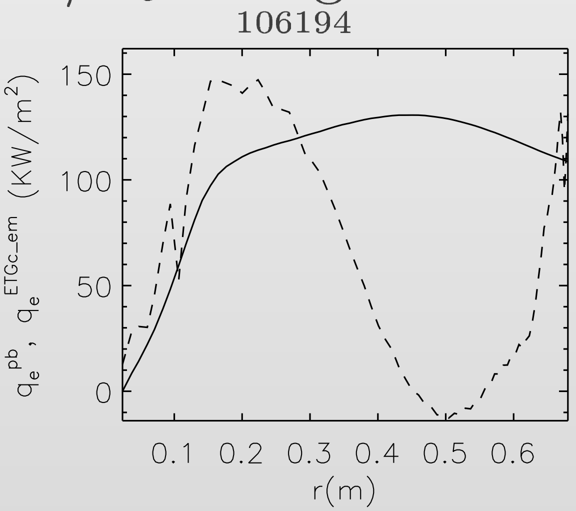
Generally, the heat flux is defined by

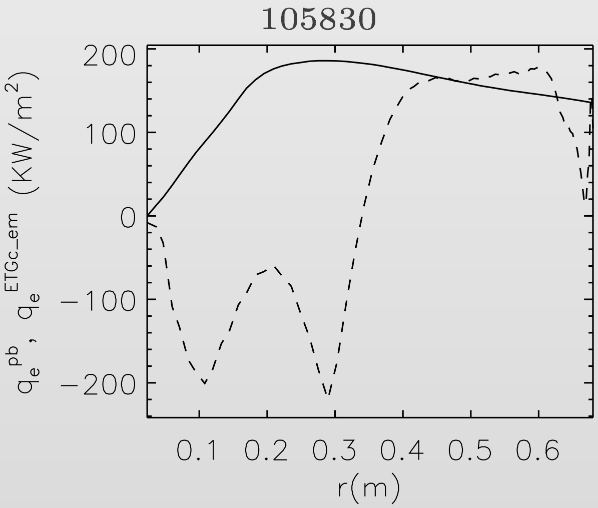
$$q_e = -n_e \chi_e [(\boldsymbol{\nabla} T_e) - (\boldsymbol{\nabla} T_e)_c] \tag{7}$$

where (from Horton et. al. NF 2005)

$$\begin{aligned} R/L_c &= 5(\pm 1) + 10(\pm 2)|s|/q \quad \mathrm{(TH)} \\ R/L_c &= 1.9(|s|/q)(1 + Z_{\mathrm{eff}} T_e/T_i) \quad \mathrm{(EX - ToreSupra)} \end{aligned}$$

Both R/L_cs disagree with power balance heat flux.

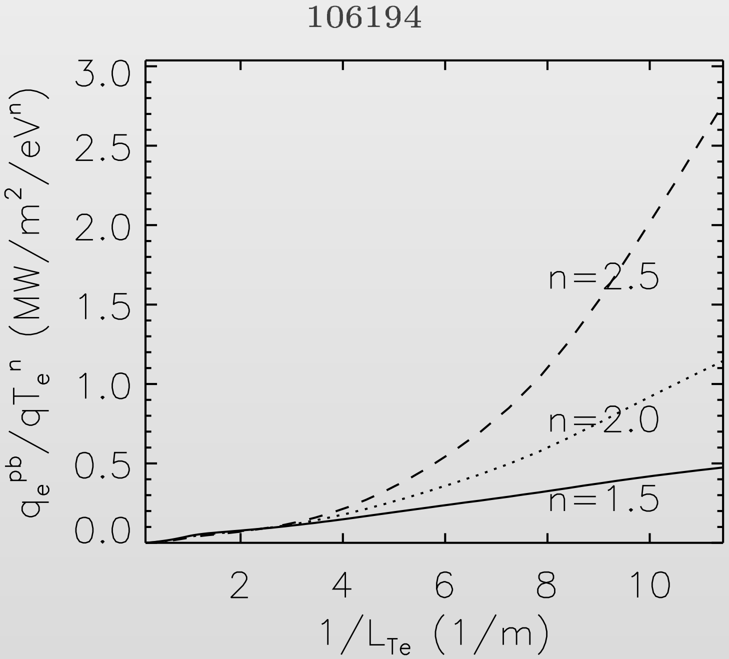




Temperature Dependence

The scaling law shows that heat flux is proportional to

- ETG EM $\sim T_e^{3/2}$
- Bohm $\sim T_e^2$
- gyro-Bohm $\sim T_e^{5/2}$
- ETG ES $\sim T_e^{5/2}$



ETG Model

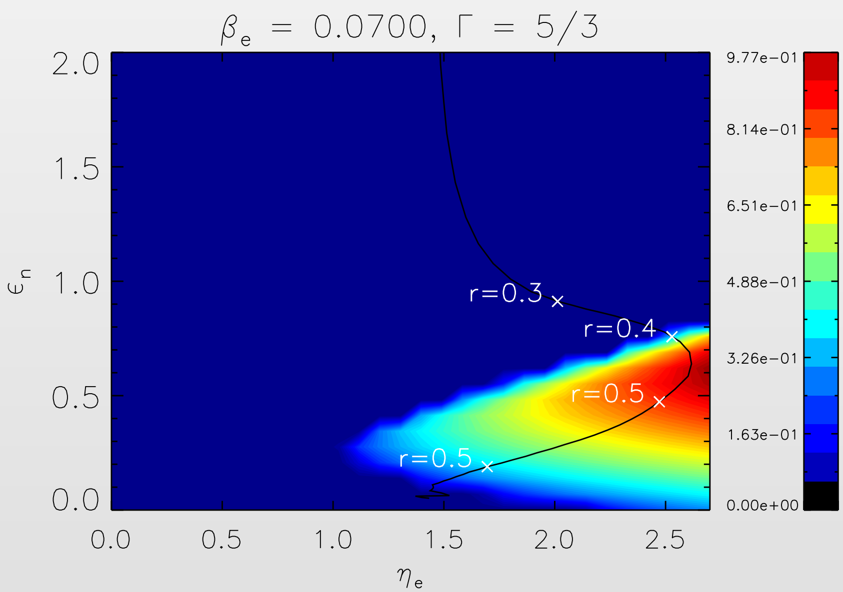
The non-dimensional ETG three-field model is derived by Horton (NF, 2005) in the locally toroidal geometry,

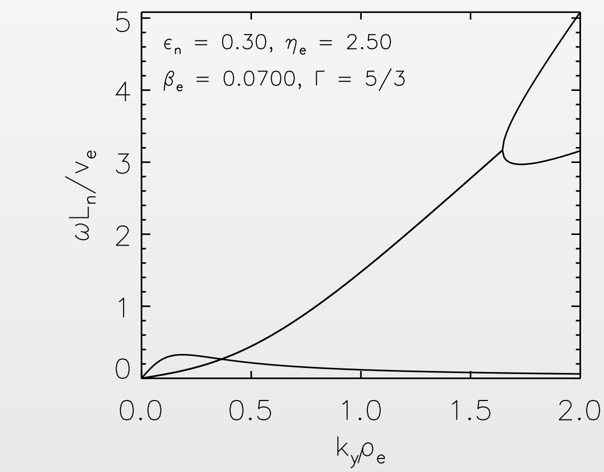
$$
\begin{aligned}
(1-\nabla_\perp^2)\frac{\partial\hat{\phi}}{\partial t} &= \left[1-2\epsilon_n+(1+\eta_e)\nabla_\perp^2\right]\frac{\partial\hat{\phi}}{\partial y}+2\epsilon_n\frac{\partial\delta\hat{T}_e}{\partial y} \\
&\quad+\left[\hat{\phi},\nabla^2\hat{\phi}\right]+\partial_\parallel^{nl}\nabla_\perp^2\hat{A}-\mu\nabla^4\hat{\phi} \\
\left(\nabla^2-\frac{\beta}{2}\right)\frac{\partial\hat{A}}{\partial t} &= \frac{\beta}{2}(1+\eta_e)\frac{\partial\hat{A}}{\partial y}+2\partial_\parallel^{nl}\hat{\phi}-\partial_\parallel^{nl}\delta\hat{T}_e-\left[\hat{\phi},\nabla^2\hat{A}\right]-\frac{\eta}{\mu_0}\nabla^2\hat{A} \\
\frac{\partial\delta\hat{T}_e}{\partial t} &= S_{\mathrm{rf}}(r)-s_{\mathrm{edge}}(r)-\left[\eta_e-4\epsilon_n(\Gamma-1)\right]\frac{\partial\hat{\phi}}{\partial y}-2\epsilon_n(2\Gamma-1)\frac{\partial\delta\hat{T}_e}{\partial y} \\
&\quad-(\Gamma-1)\partial_\parallel^{nl}\nabla^2\hat{A}-\left[\hat{\phi},\delta\hat{T}_e\right]+\chi_\perp\nabla_\perp^2\delta\hat{T}_e+\chi_\parallel\left(\partial_\parallel^{nl}\right)^2\delta\hat{T}_e
\end{aligned}
$$

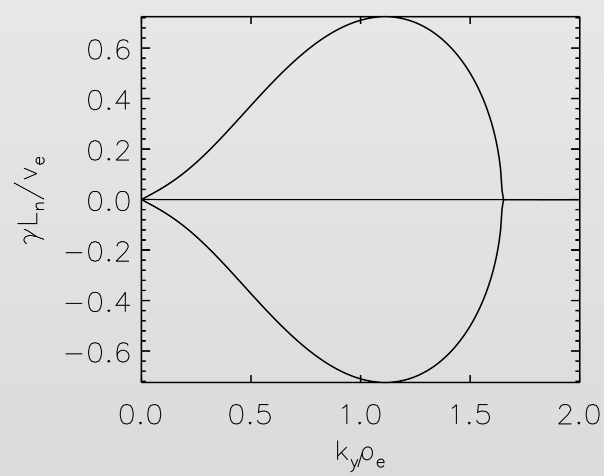
where $T_e/T_i = 1.0$ is assumed and $(x,y)/\rho_e \to (x,y)$, $tv_e/L_n \to t$.

Linear Analysis

$k_y\rho_e \sim 1$ mode has the maximum growth rate even at $\beta_e > \beta_{e,cr}$.
Mainly the electrostatic modes are destabilized.

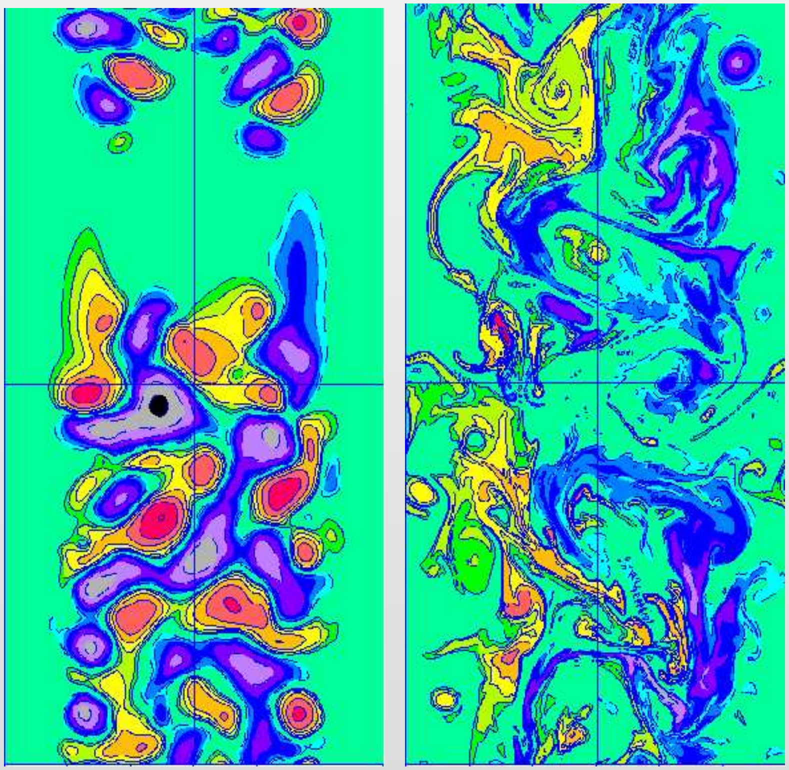






Nonlinear Simulation

Using the pseudospectral method, the set of the electrostatic equations are solved with the source and sink at $x = \pm L_x/4$ for $\epsilon_n = 0.2$ and $\eta_e = 2.0$. The box size is $[120\rho_e.240\rho_e]$.



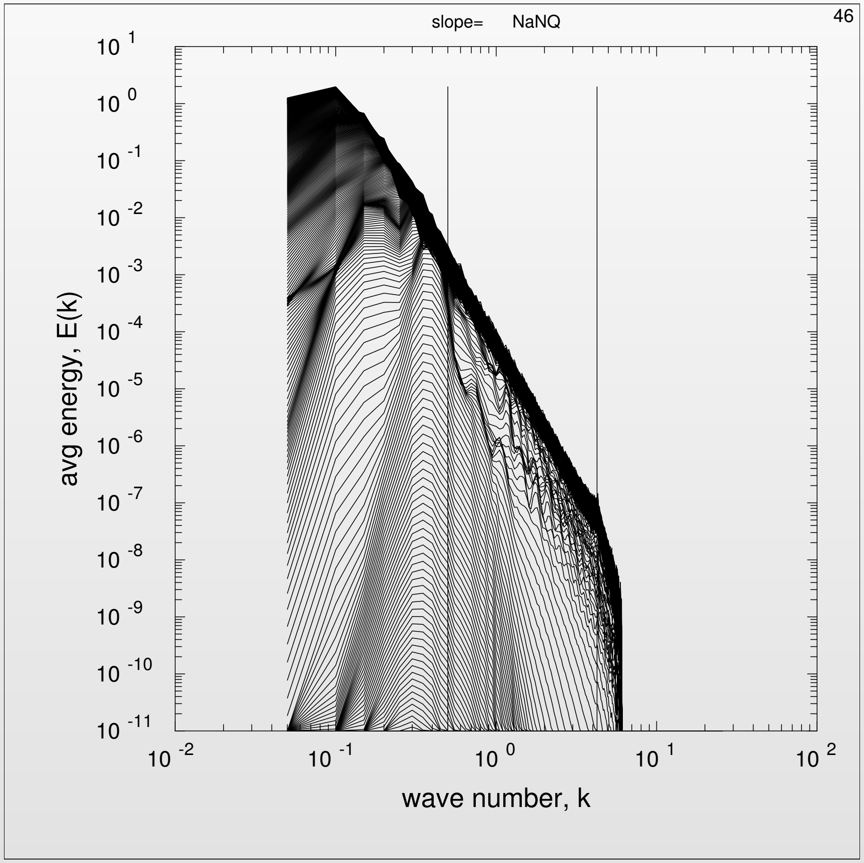
Inverse Cascade

- The most energies are pumped into $k_y \rho_e \sim 0.7$.
- During the turbulence, the energies are transfered to the lower $k_y \rho_e \sim 0.1$.
- The correlation length

$$l_c \sim 10.0\rho_e$$

agrees with

$$d_e = \sqrt{\beta_e}\rho_e \sim 5\rho_e \, .$$

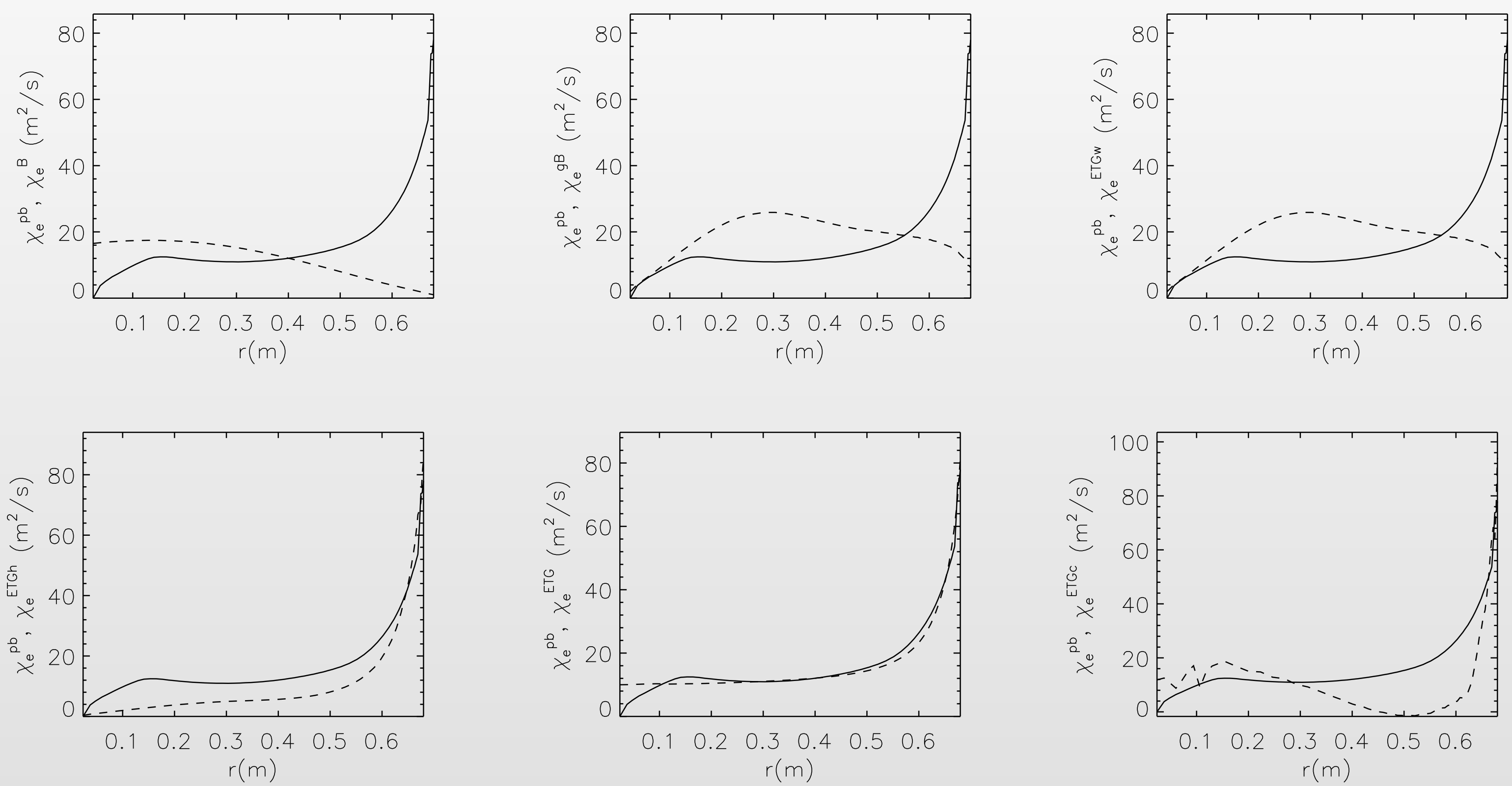


Conclusion

- The electron heat transport in NSTX shot 106194 can be explained by the electromagnetic electron temperature gradient(ETG) mode.
- We couldn't find the evidence of critical temperature gradient.
- The linear analysis indicates that the electromagnetic ETG mode are unstable outside $r = 0.4$ m and the modes with the strongest growth rate are electrostatic.
- The inverse cascade leads the ETG turbulence to the electromagnetic perturbation.
- Now we include microtearing mode with current gradients.

NSTX 106194

Using Least-Square Method, the coefficients are obtained.



NSTX 105830

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