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Nonlocal Plasma Response to Edge Cooling in tokamak plasmas

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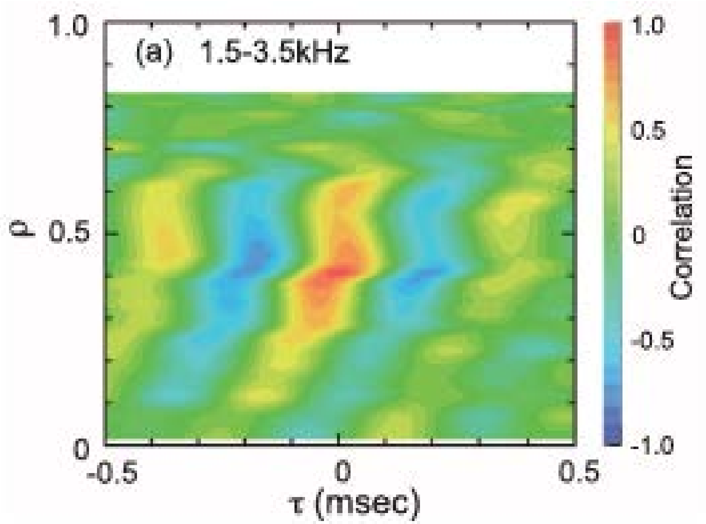
Background

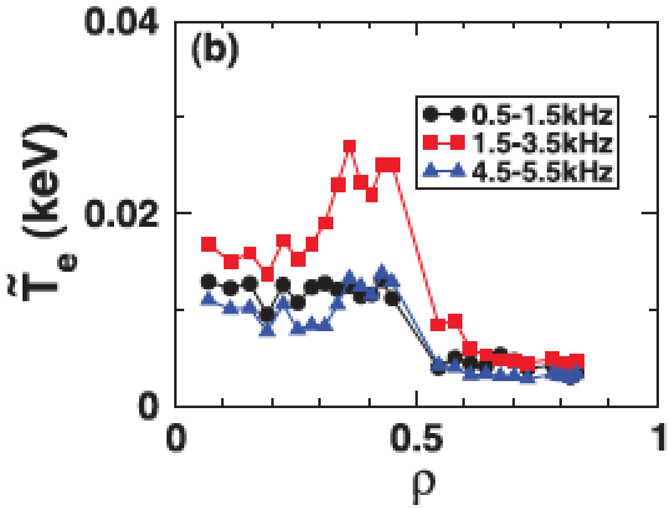
- Transient transport events are observed in toroidally magnetic confinement devices, which cannot be explained by the conventional local transport model.
  [see review by Callen-Kissick PPCF 1997]
  - e.g. edge cooling causes a rapid transient increase of electron temperature at center which occurs before any fluctuation from edge reaches.
- In addition to experimental works, the nonlocal transport was investigated theoretically by the one dimensional integral heat flux model [Iwasaki+ JPSJ 1999].
- More recent experiment indicates that a long-range fluctuation plays a role for the nonlocal transport [Inagaki+ PRL 2011].
- Compared to experimental and model works, turbulence simulation works have been few. Recently, a nonlocal plasma response/transport has been observed in 4-field reduced MHD (RMHD) simulations [Yagi+ CPP 2014, Yagi+ PFR 2014].

Non-local Transport

Experiment

U. Stroth et al., Plasma Phys. Control. Fusion **38** (1996) 1087.
S. Inagaki et al., “Observation of Long-Distance Radial Correlation in Toroidal Plasma Turbulence”, Phys. Rev. Lett. **107** (2011) 1115001.





Mode with long radial correlation in ECH applied phase

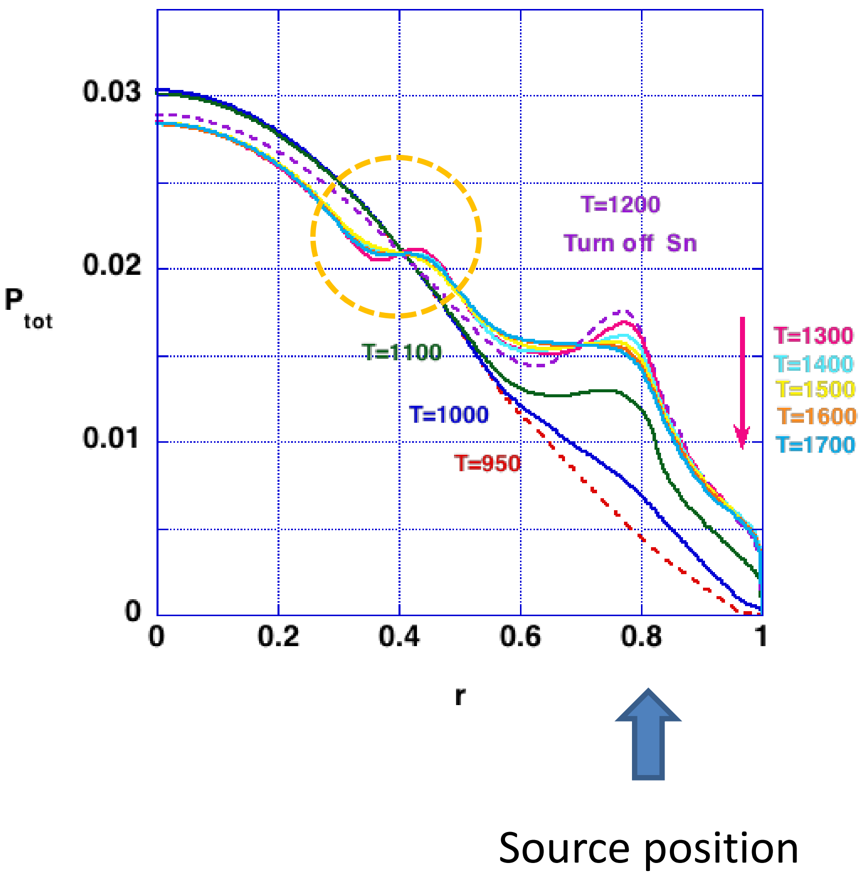
Theory

T. Iwasaki, S.-I. Itoh, et al., “Non-local Model Analysis of Heat Pulse Propagation and Simulation Of Experiments in W7-AS”, J. Phys. Soc. Jpn. **68** (1999) 478.

$$q(r,t)=-\int_0^a dr' K_l(r,r') n_e \chi_e(T(r',t),\nabla T(r',t))\nabla T(r',t)$$

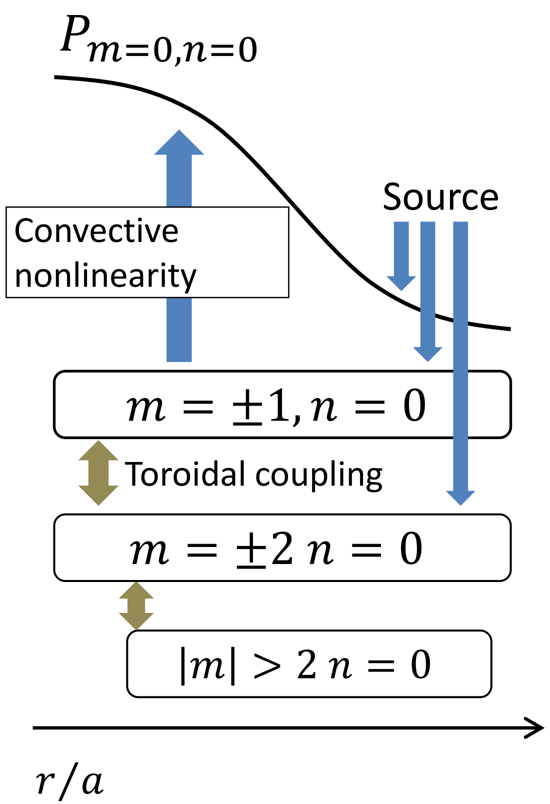
G. Dif-Pradalier, P. H. Diamond, et al., Phys. Rev. E **82** (2010) 025401.

Nonlocal transport in 4-field RMHD simulations



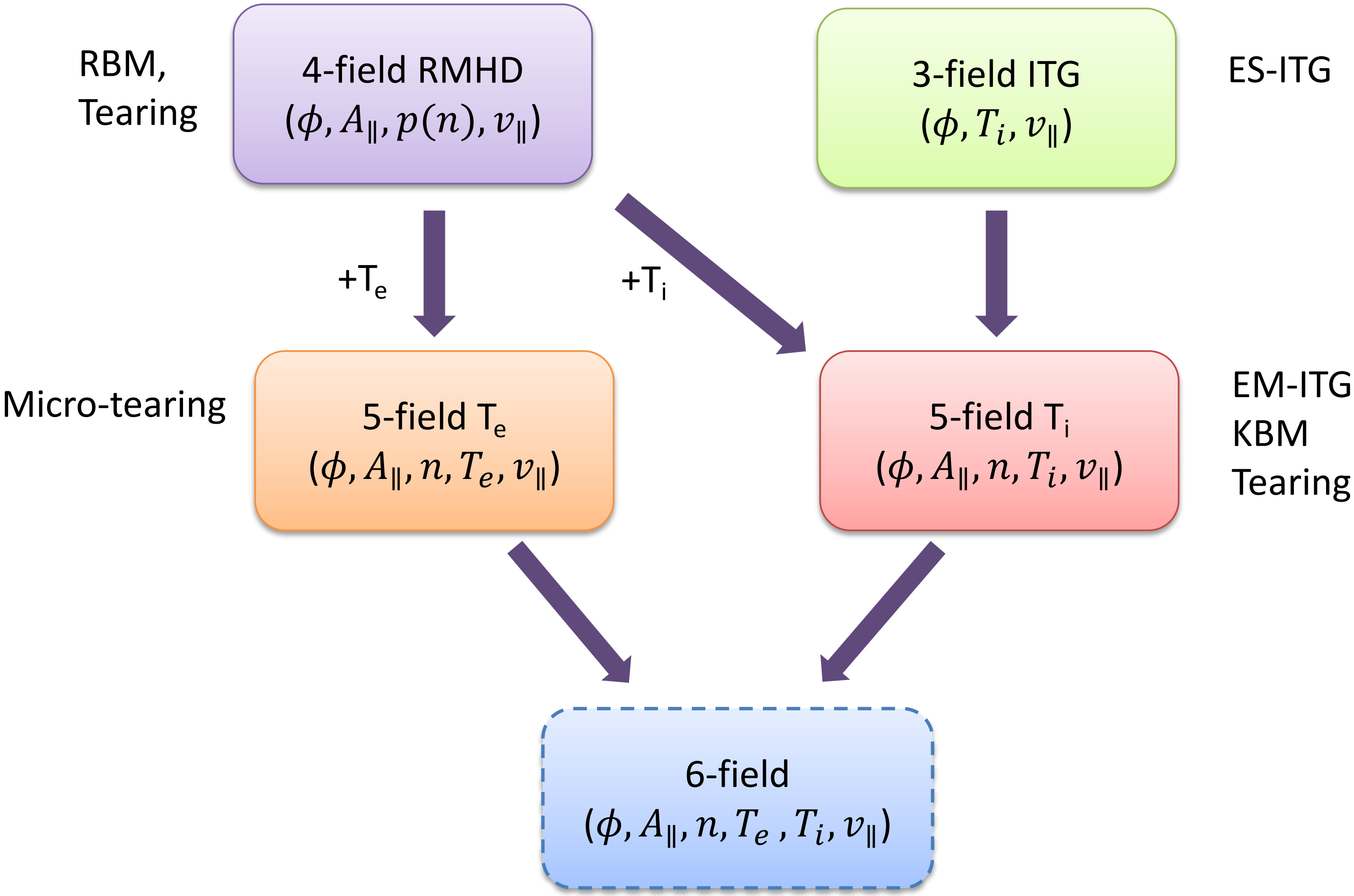
- Transient density source corresponding to pellet injection at tokamak edge in low field side is applied after nonlinear saturation of resistive ballooning modes is attained.
- After the source is terminated (t=1200), reversal of pressure gradient is observed around r=0.4 far from the source position (r=0.8), while edge pressure decreases.
- Time scale of the nonlocal transport is $\sim 100\ R/v_A$.

$P_{m=\pm 1,n=0}$ are essential for the nonlocal transport in 4-field RMHD simulations



- Both nonlinear and toroidal couplings between axisymmetric Fourier modes are responsible for the nonlocal transport.
- Temperature dynamics is not included in 4-field RMHD.
- We perform nonlinear simulations by global codes with temperature dynamics.

Simulation models



3-field ITG and 5-field(Ti) simulations

- 4-filed RMHD cannot treat ion temperature gradient (ITG) driven turbulence which is important in the tokamak core region.
- $(m, n) = (\pm 1{,}0)$ pressure perturbations essential for the nonlocal transport in 4-field RMHD may be affected by the ITG turbulence (ex. GAM oscillations).
- Density source is implemented as a sink in the Ti equation in 3-field simulation. Both density source and Ti sink are applied in 5-field (Ti) simulation.
- Nonlocal transport of a kind found in 4-field RMHD is not observed in 3-field/5-field(Ti) ITG simulations

5-field(Ti) Landau-fluid model [Miyato 03]

Normalization: ion thermal time a/v_{ti} and minor radius a

Continuity equation

$$\frac{dn}{dt} = a\frac{dn_{eq}}{dr}\nabla_\theta\phi - n_{eq}\nabla_{\|}v + \nabla_{\|}j + \omega_d(n_{eq}\phi - p_e) + S_n$$

Vorticity equation

$$\frac{d}{dt}\nabla_\perp^2\phi = -T_{eq}\frac{a}{n_{eq}}\frac{dn_{eq}}{dr}(1+\eta_i)\nabla_\theta\nabla_\perp^2\phi + \frac{1}{n_{eq}}\nabla_{\|}j - \omega_d\left(T_i + \frac{T_{eq}}{n_{eq}}n + \frac{p_e}{n_{eq}}\right)$$

Equation of parallel motion

$$\frac{dv}{dt} = -\nabla_{\|}T_i - (1+\tau)\frac{T_{eq}}{n_{eq}}\nabla_{\|}n - \beta T_{eq}\frac{a}{n_{eq}}\frac{dn_{eq}}{dr}(1+\eta_i+\tau)\nabla_\theta A$$

Ohm's law

$$\beta\frac{\partial A}{\partial t} = -\nabla_{\|}\phi + \tau\frac{T_{eq}}{n_{eq}}\nabla_{\|}n + \beta\tau T_{eq}\frac{a}{n_{eq}}\frac{dn_{eq}}{dr}\nabla_\theta A + \sqrt{\frac{\pi}{2}\tau\frac{m_e}{m_i}}|\nabla_{\|}|\left(v - \frac{j}{n_{eq}}\right) - \eta j$$

Ion temperature

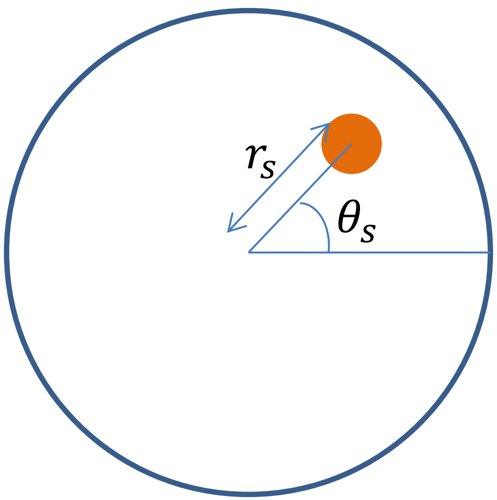
$$\frac{dT_i}{dt} = T_{eq}\frac{a}{n_{eq}}\frac{dn_{eq}}{dr}\eta_i\nabla_\theta\phi - \frac{2}{3}T_{eq}\nabla_{\|}v - \frac{2}{3}\sqrt{\frac{8T_{eq}}{\pi}}|\nabla_{\|}|T_i + T_{eq}\omega_d\left(\frac{2}{3}\phi + \frac{7}{3}T_i + \frac{2}{3}\frac{T_{eq}}{n_{eq}}n\right) + S_T$$

Source/sink model

Cylindrical source/sink

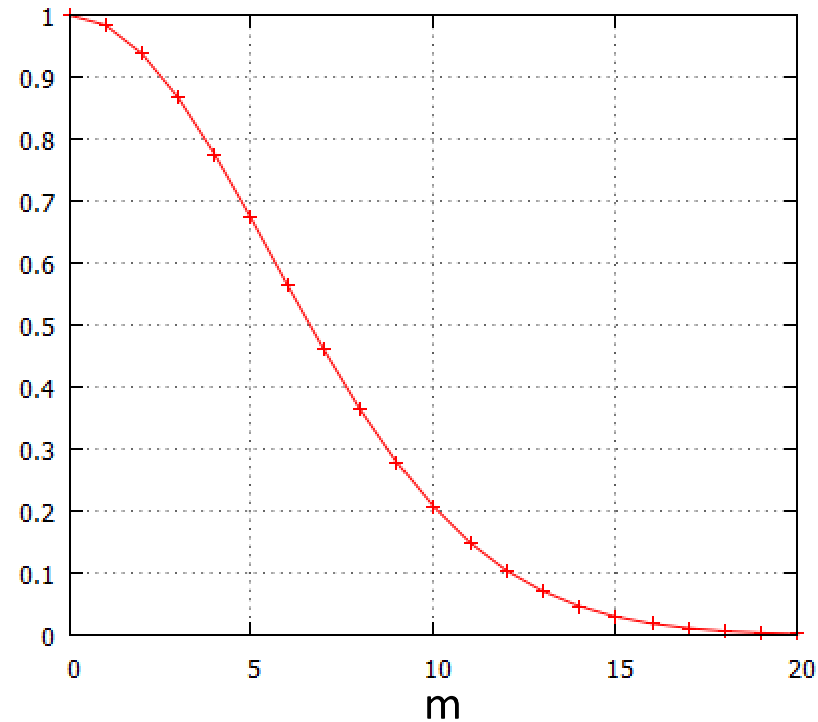
$$S = S_{\mathrm{AMP}}\exp\left(-\frac{r^2 + r_s^2 - 2rr_s\cos\theta\cos\theta_s - 2rr_s\sin\theta\sin\theta_s}{2\Delta^2}\right)$$

Localize in poloidal plane



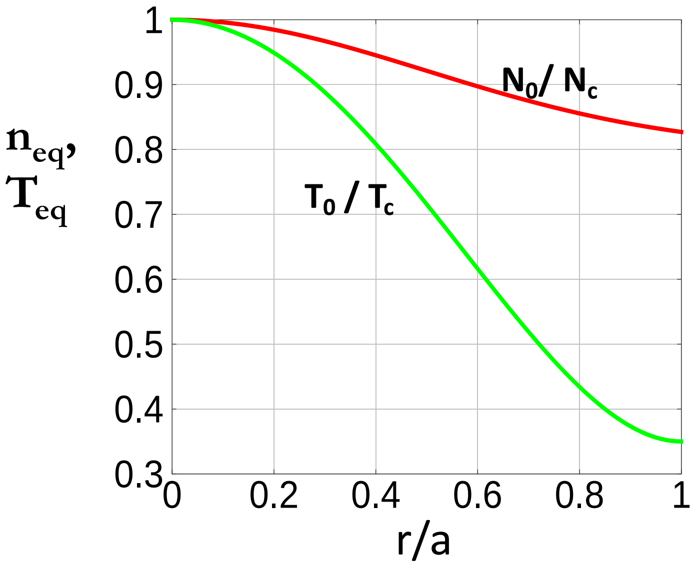
$r_s = 0.8, \theta_s = 0, \Delta = 0.1$
corresponding to edge source/sink in low field side

Poloidal Fourier spectra



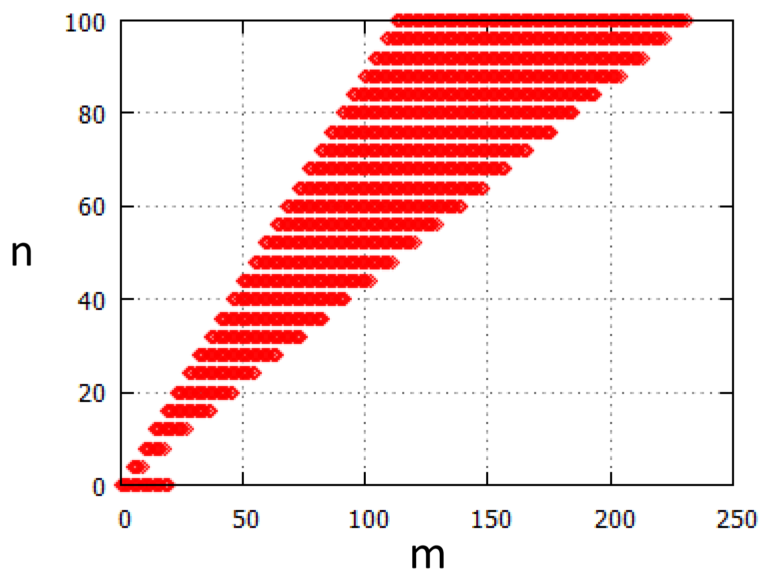
Parameters in Landau-fluid simulation

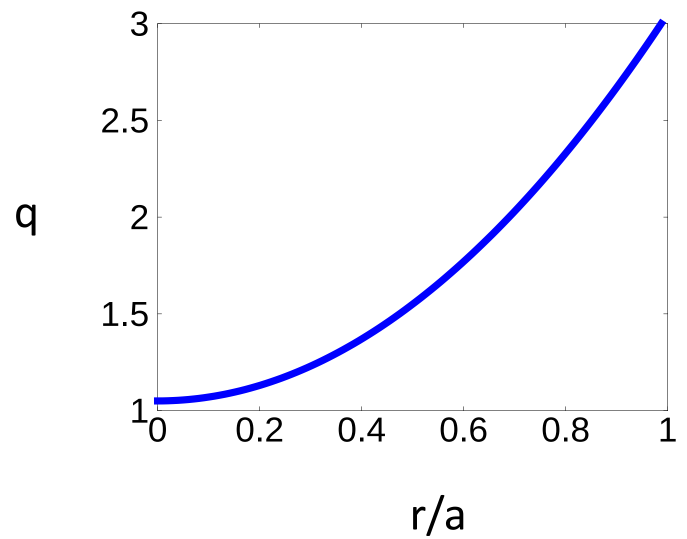
$\rho_i/a = 0.005$
$R/a = 4, \qquad \tau = T_e/T_i = 1$
$n_{eq} = 0.8 + 0.2\exp[-2(r/a)^2]$
$T_{eq} = 0.35 + 0.65[1-(r/a)^2]^2$
$q = 1.05 + 2(r/a)^2$



Radial grid number: 512

Fourier modes ($\Delta n = 4$) $\qquad e^{i(m\theta - n\zeta)}$

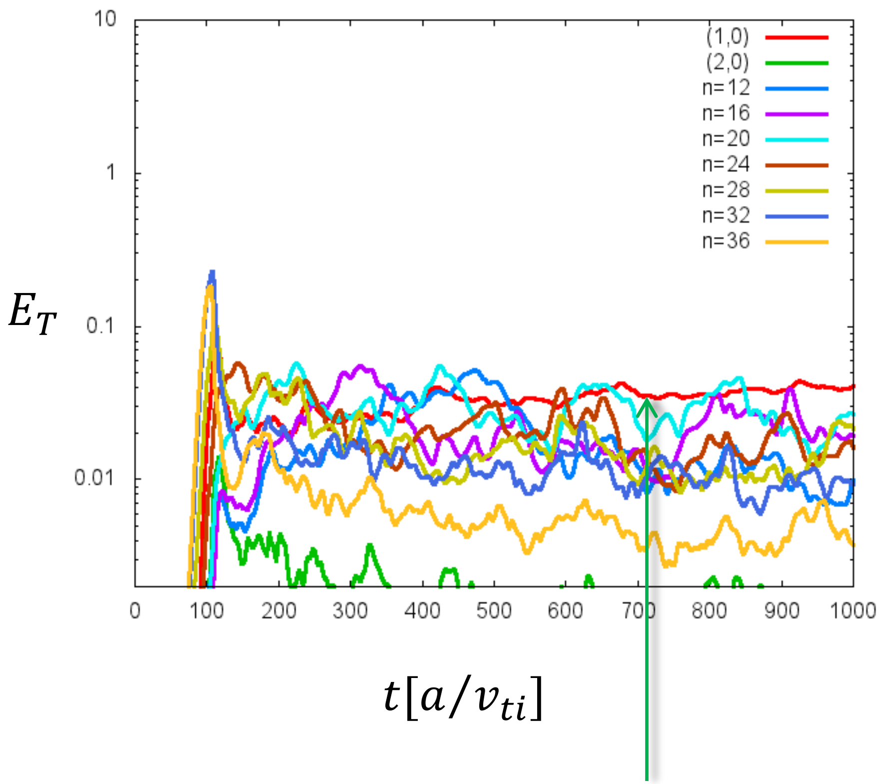




3-field ITG turbulence simulation results

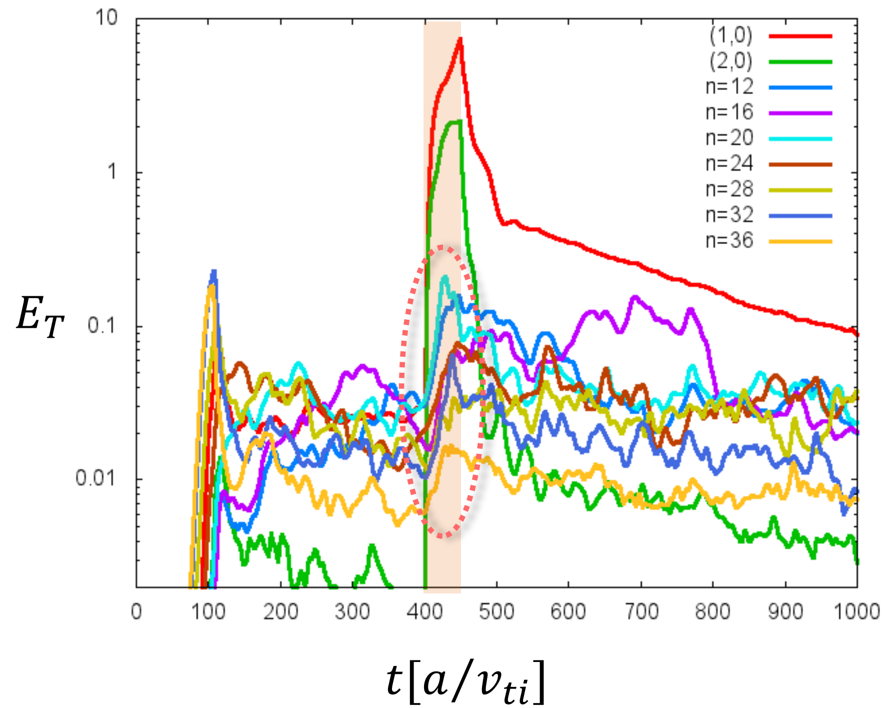
Ion temperature fluctuation energy

No sink



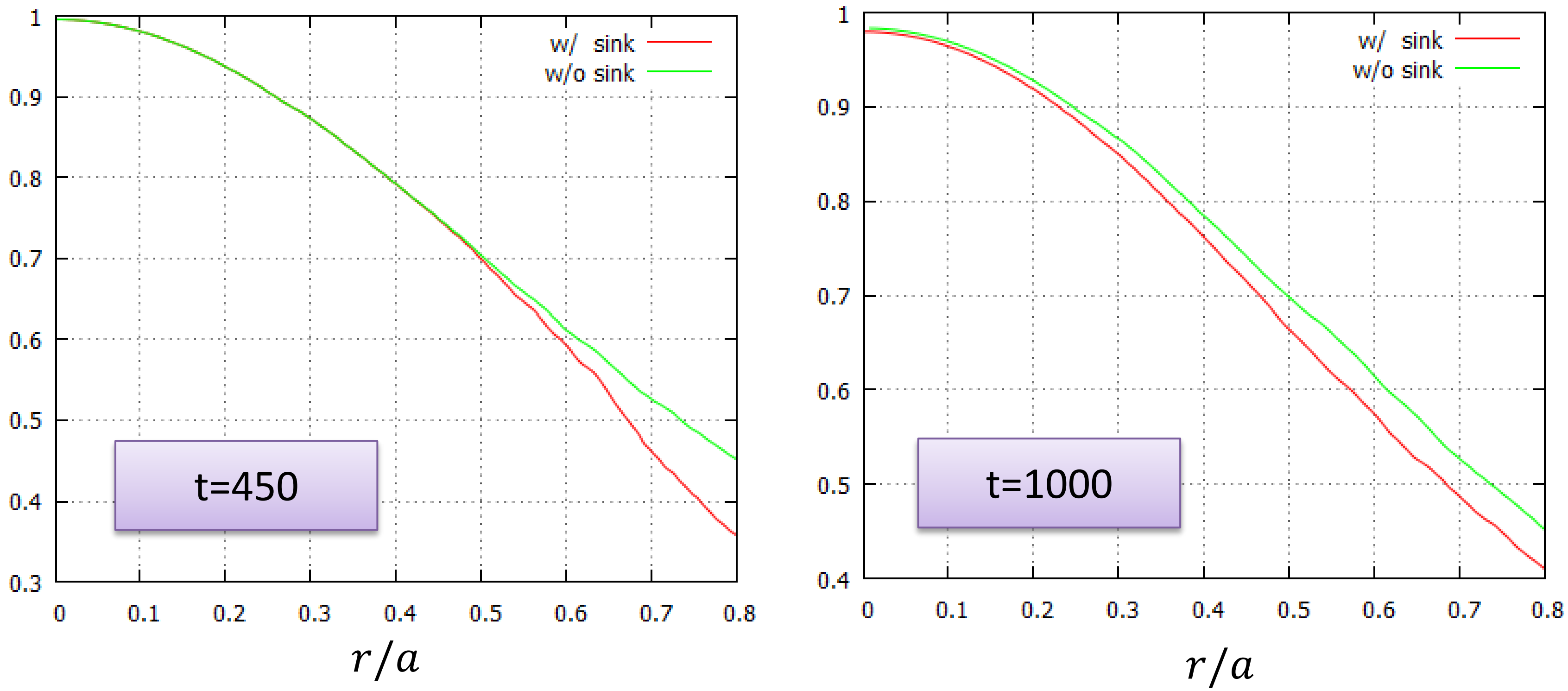
The (1,0) fluctuation is not small.

Cold sink $400 \leqq t \leqq 450$



The (m,0) fluctuations increase due to sink, and $n \neq 0$ modes increase also.

Nonlocal transport of a kind found in 4-field RMHD is not observed in 3-field ITG simulations

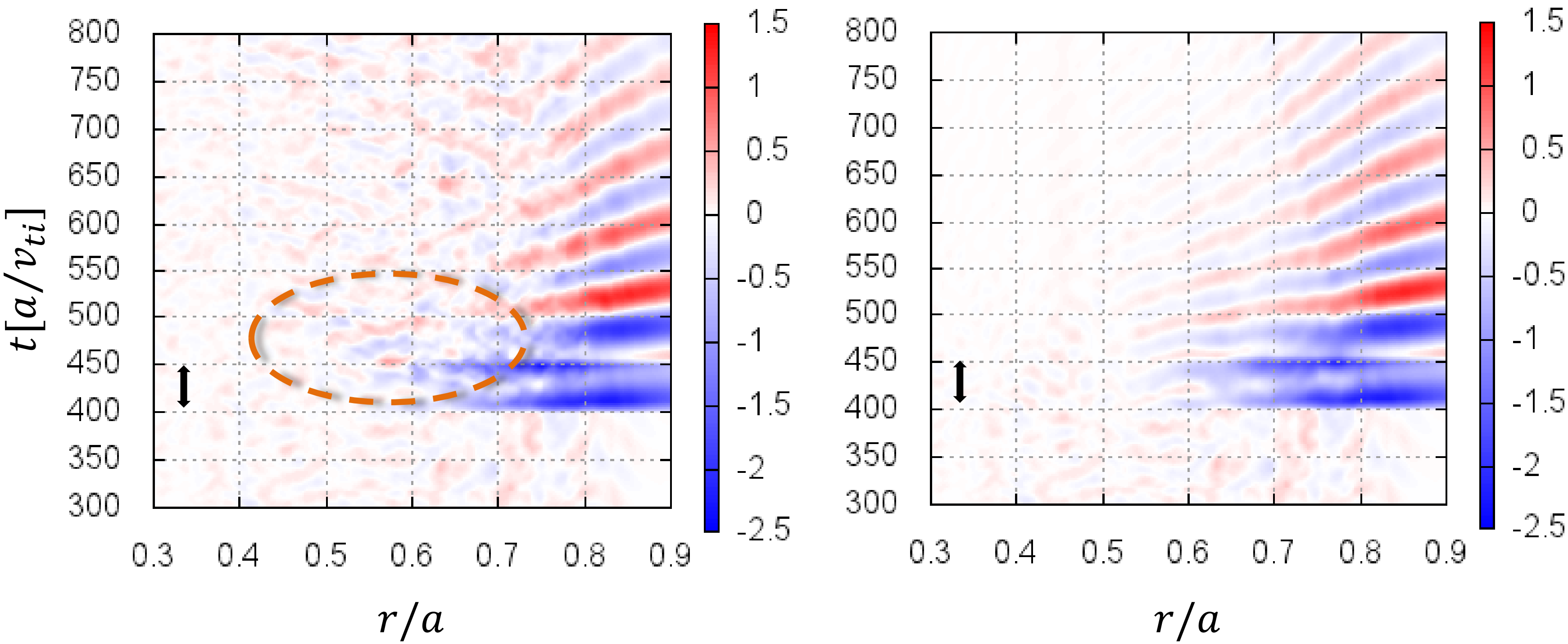


- Further heat transport occurs after sink is terminated, because turbulence activity is still strong.
- Profile change is small in no sink case.

Effects of turbulence on $\cos\theta$ component of pressure perturbations

Miyato PFR 2014

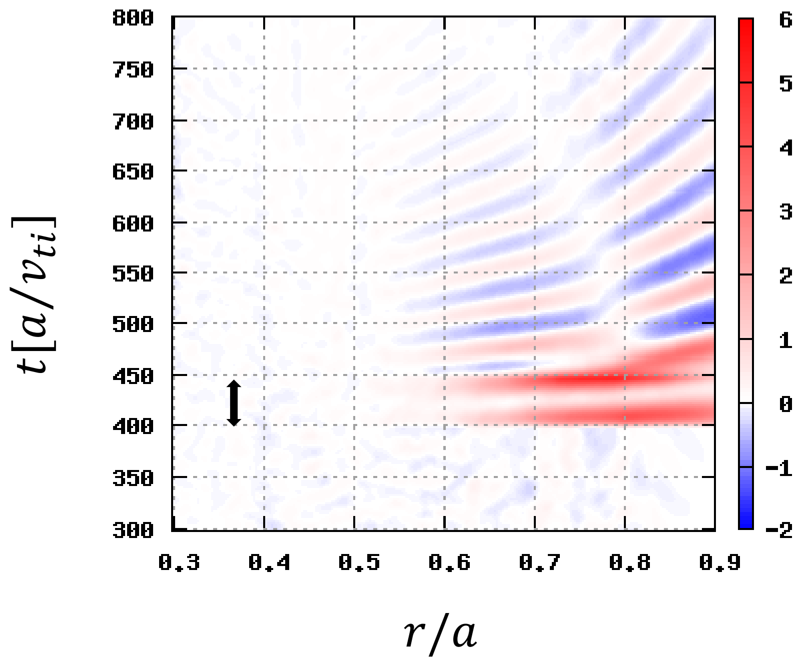
Nonlinear couplings : OFF



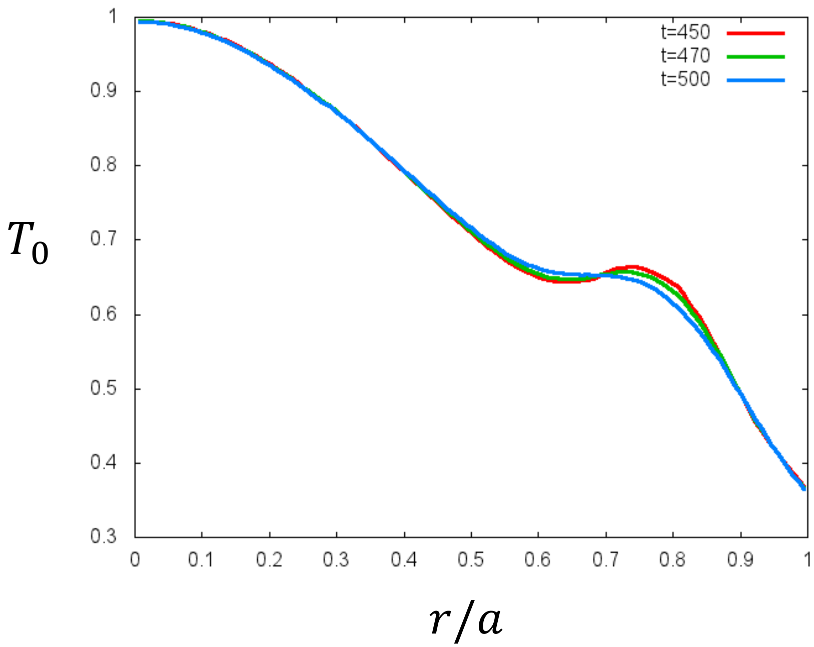
- ITG turbulence is destabilized by the transient sink.
- The $\cos\theta$ component of $P_{m=\pm1,n=0}$ input by sink is stirred by ITG turbulence and its radial wavelength is considerably shortened.
- As a result the component cannot connect core and edge regions.

3-field simulation: heating case

Cosθ component



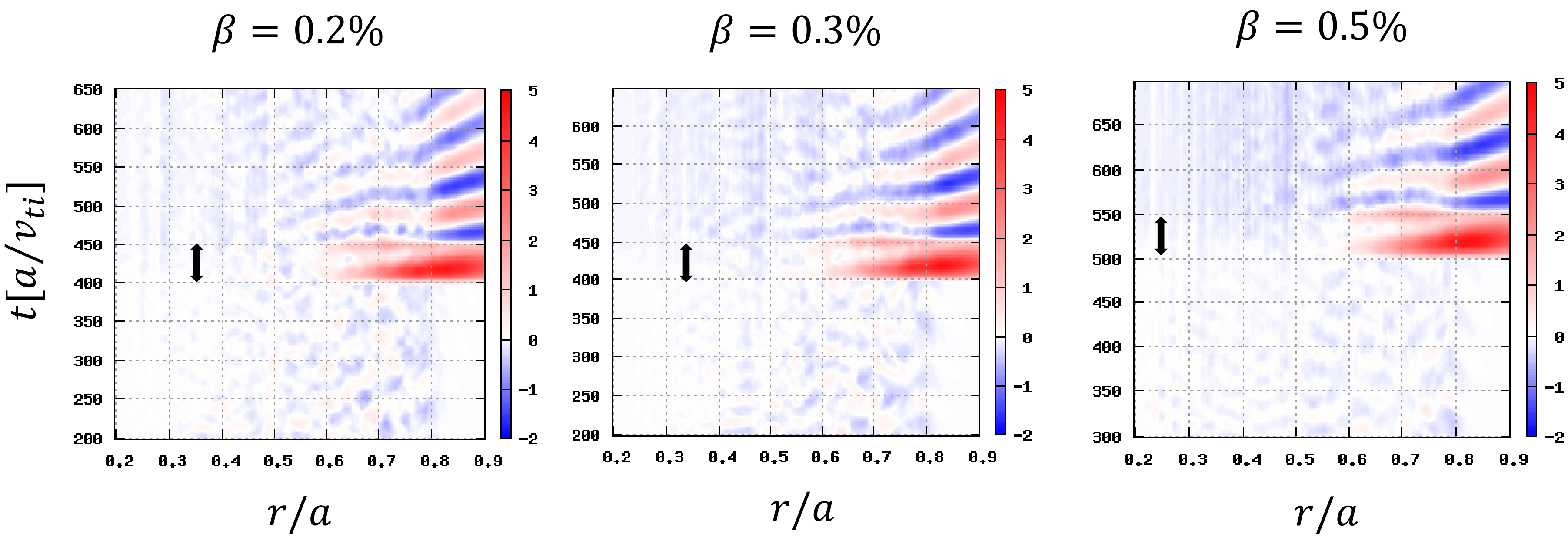
Ti profile change



- ITG turbulence is suppressed in the region where Ti gradient is small. As a result, the cos θ component is not dissipated there.
- Rapid change of Ti profile is observed in the region where ITG turbulence is not active.
- However, ITG turbulence exists in the inner core region where the cos θ component is dissipated, no rapid Ti profile change there.

5-field (Ti) simulation with various beta values

Cosθ component of density perturbation

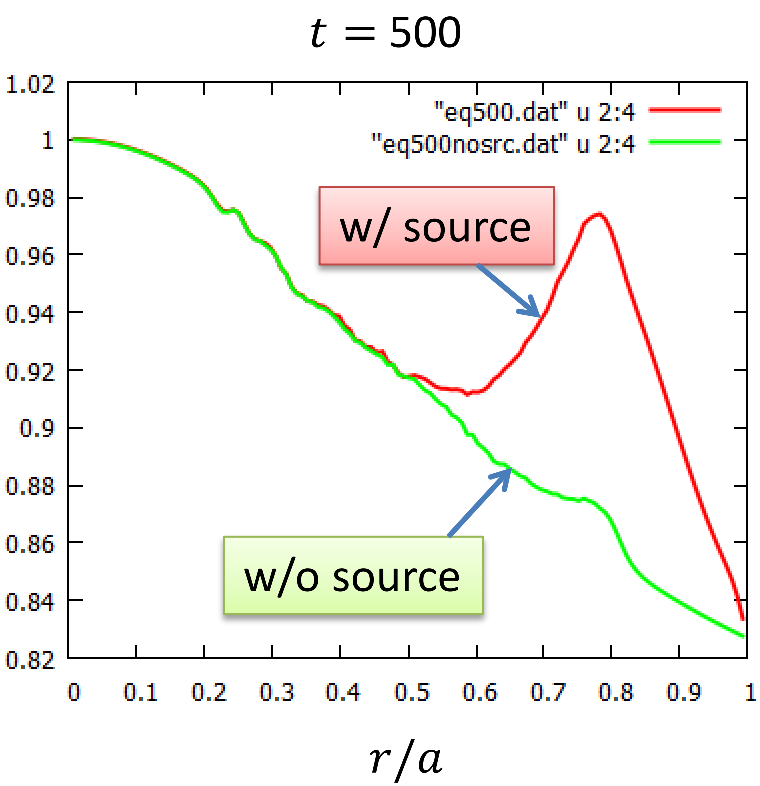


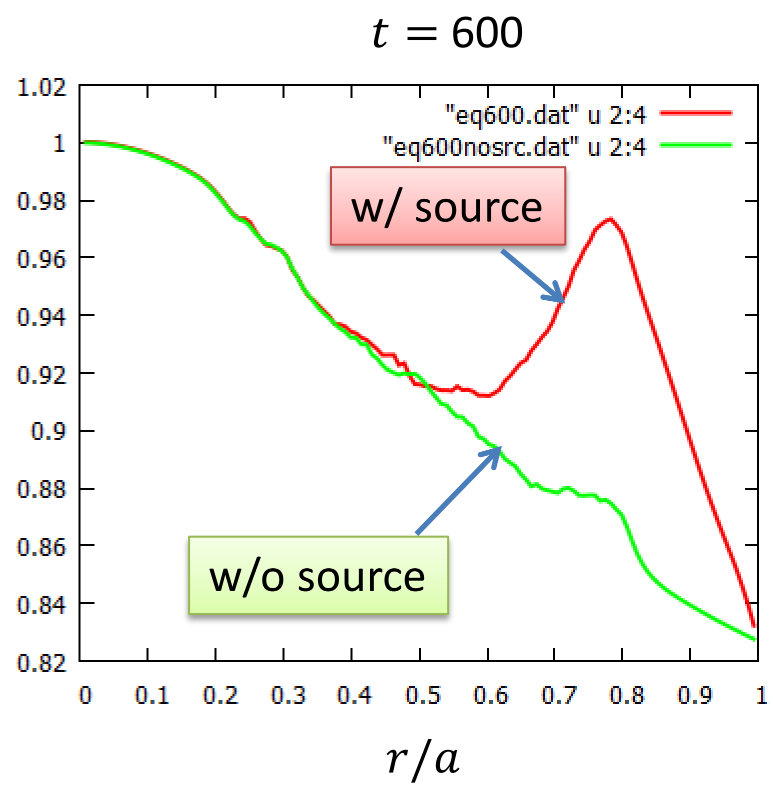
- Increase of beta stabilize ITG turbulence.

Weak dissipation of $\cos\theta$ component of density perturbation for r/a>0.5.

No density profile change in inner core

$$\beta = 0.2\%$$





5-field(Te) RMHD simulations

- Electron temperature (Te) equation is added. Source and sink terms are introduced into density and Te equations, respectively.
- Cold ions (Ti=0) are assumed and (m, n)=(2, 1) tearing mode is dominant instability. (RBMs are stabilized.)
- Nonlocal transport appears at r < 0.6 which corresponds to location inside q=2 surface.
- Location of source and sink weekly affects nonlocal response.

Simulation Model

5F RMHD model(vorticity equation, Ohm's law, parallel momentum balance , density evolution, Electron Temperature evolution,

Normalization: poloidal Alfven time and minor radius

$$\frac{\partial}{\partial t}\nabla_\perp^2 F+[F,\nabla_\perp^2 F]-\delta_i\nabla_\perp\cdot[p,\nabla_\perp F]=-\nabla_{//}J-[\Omega,p]+\mu_i\nabla_\perp^4 F$$

$$\frac{\partial}{\partial t}A=-\nabla_{//}(\phi-\delta_e p)+\eta_{//}J+\alpha_T\delta\nabla_{//}T_e$$

$$\frac{\partial}{\partial t}v+[\phi,v]=-\nabla_{//}p+\mu_2\nabla_\perp^2 v$$

$$\frac{dn}{dt}+\beta\frac{dp}{dt}=\beta[\Omega,\phi-\delta p_e]-\beta\nabla_{//}(v+\delta J)+\eta_\perp\beta\nabla_\perp^2 p+S_n$$

$$\frac{3}{2}\frac{dT_e}{dt}-\frac{\beta_e}{\beta}\frac{dn}{dt}=-\alpha_T\delta\beta_e\nabla_{//}J+\varepsilon^2\chi_{e//}\nabla_{//}^2 T_e+\chi_{e\perp}\nabla_\perp^2 T_e-\frac{5}{2}\delta\beta_e[\Omega,T_e]+S_T$$

$$\frac{d}{dt}=\frac{\partial}{\partial t}+[\phi,],\ \nabla_{//}=\nabla_{//}^{(0)}-[A,],\ F=\phi+\delta_i p,\ J=\nabla_\perp^2 A,$$

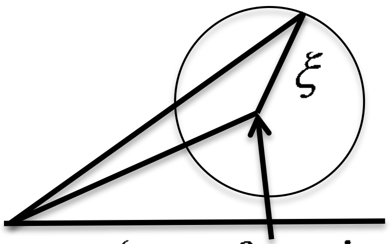
$$\delta_i=\frac{\beta_i}{\beta}\delta,\ \delta_e=\frac{\beta_e}{\beta}\delta,\quad p_i=\frac{\beta_i}{\beta}n,\ p_e=T_e+\frac{\beta_e}{\beta}n$$

Source and Sink Model

Spherical Source

$$S_n = S_{AMP}\exp(-(\xi^2+\zeta^2/\varepsilon^2)/(2\Delta^2))\Theta(T_{tot}(r,\theta,\zeta,t))$$

$$T_{tot}(r,\theta,\zeta,t) = T_{eq}(r) + \tilde{T}(r,\theta,\zeta,t)$$

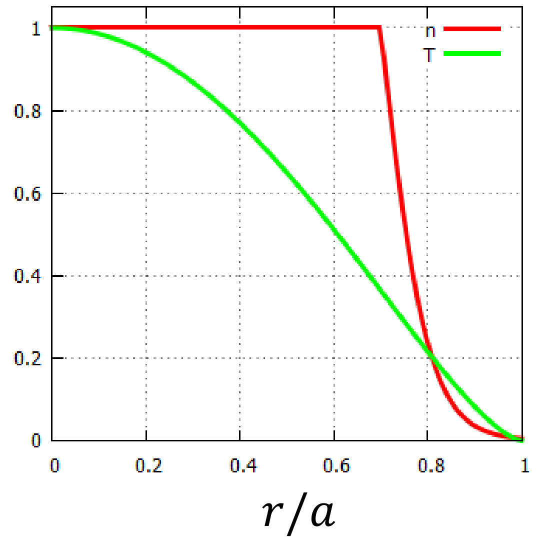


$$\xi^2 = (r\cos\theta - r_s\cos\theta_s)^2 + (r\sin\theta - r_s\sin\theta_s)^2$$

$$\Theta(T) = \begin{cases} 1 & T > T_c \\ 2T/T_c - (T/T_c)^2 & T < T_c \end{cases}$$

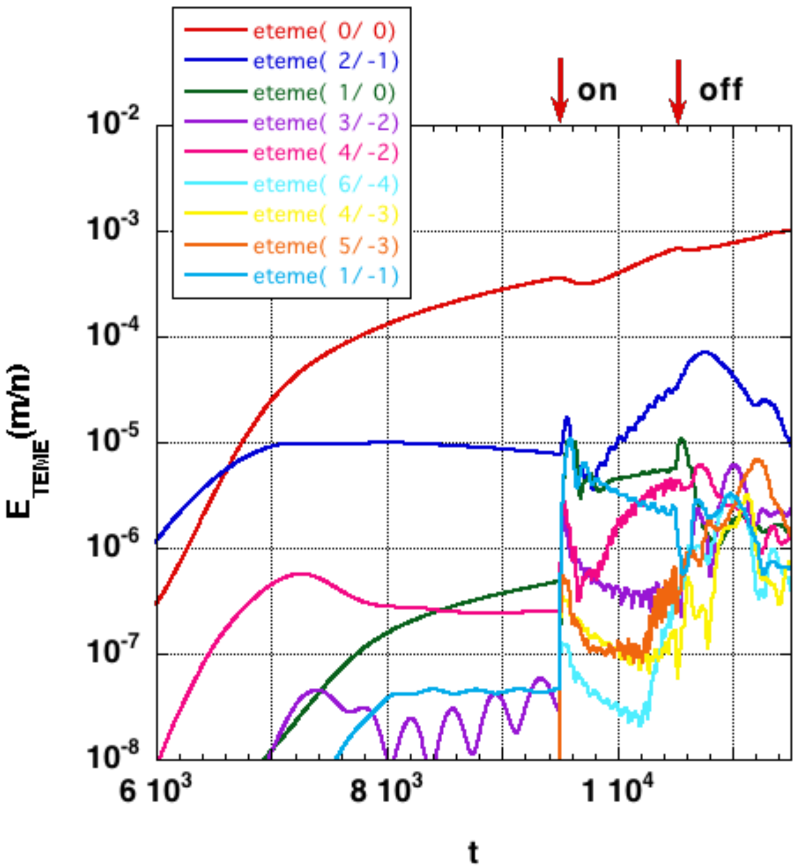
$S_T = -S_n$ **Sink**

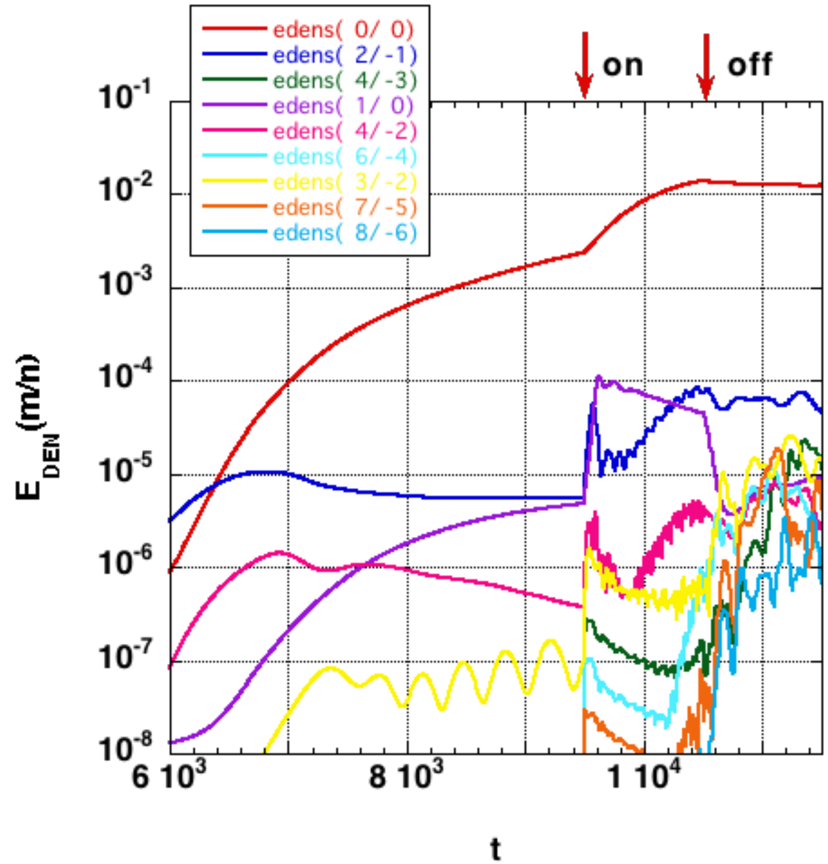
Initial profiles



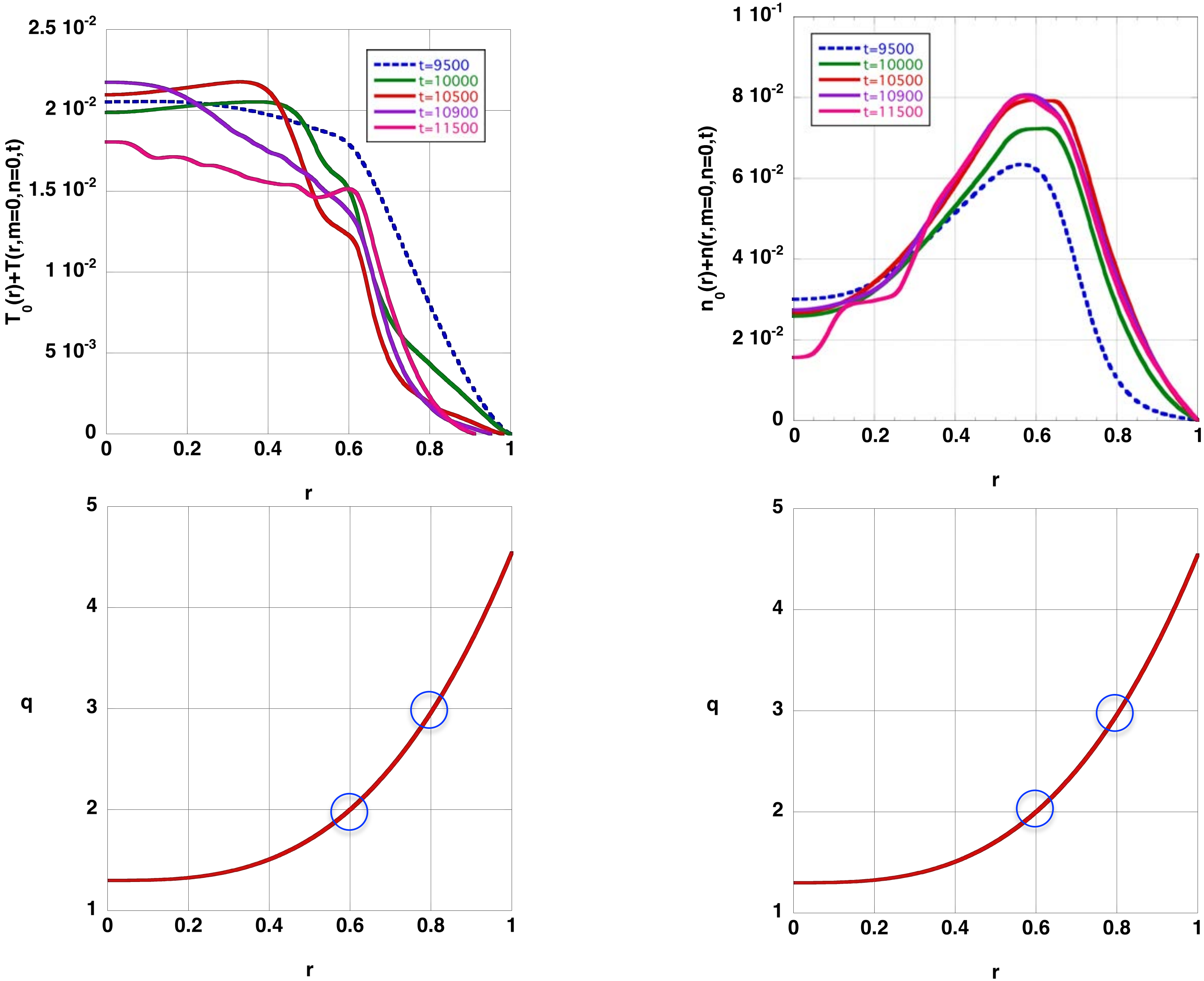
$$r_s = 0.8,\ \theta_s = 0,\ \Delta = 0.1,\ S_{AMP} = 0.5,\ T_c = 0.005$$

Time Evolution of Mode Energy



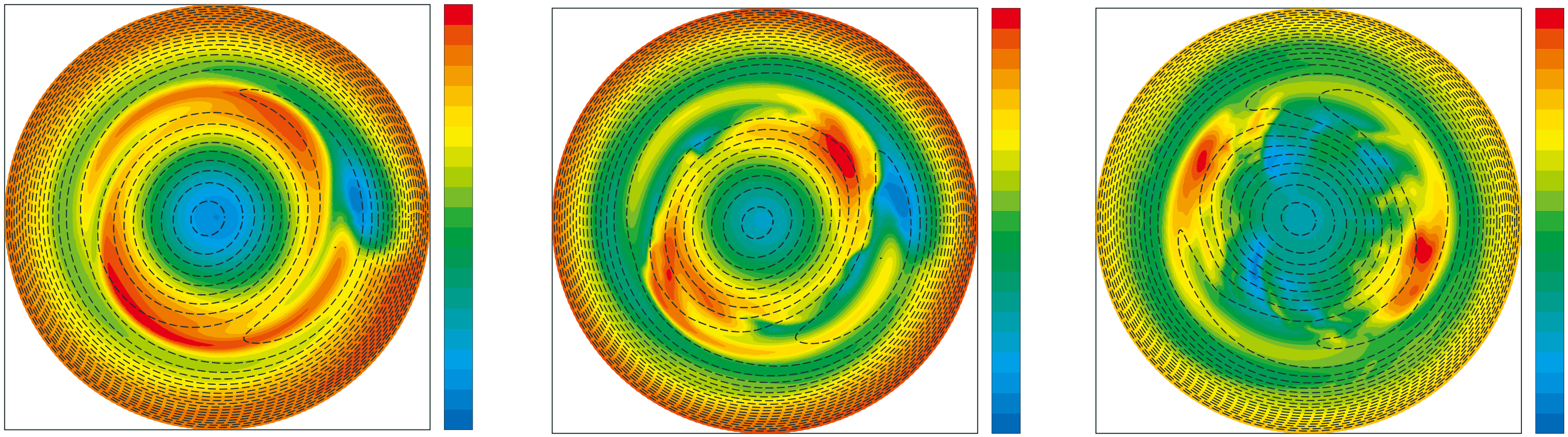


Time Evolution of Profile

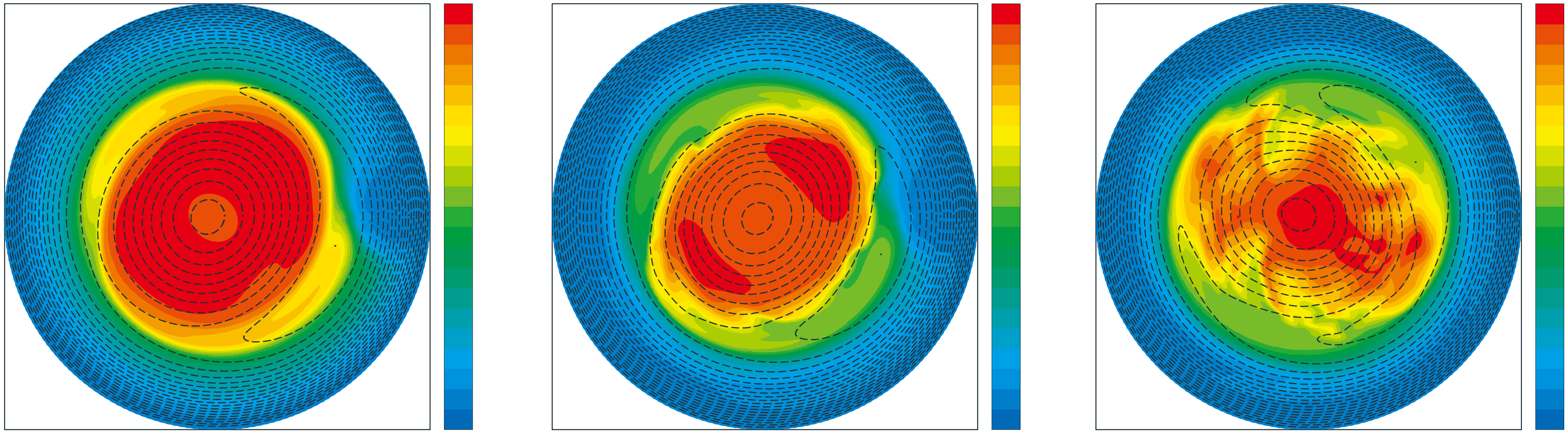


2D Contour Plot of Temperature

$\tilde{T}(r,\theta,z=0)$

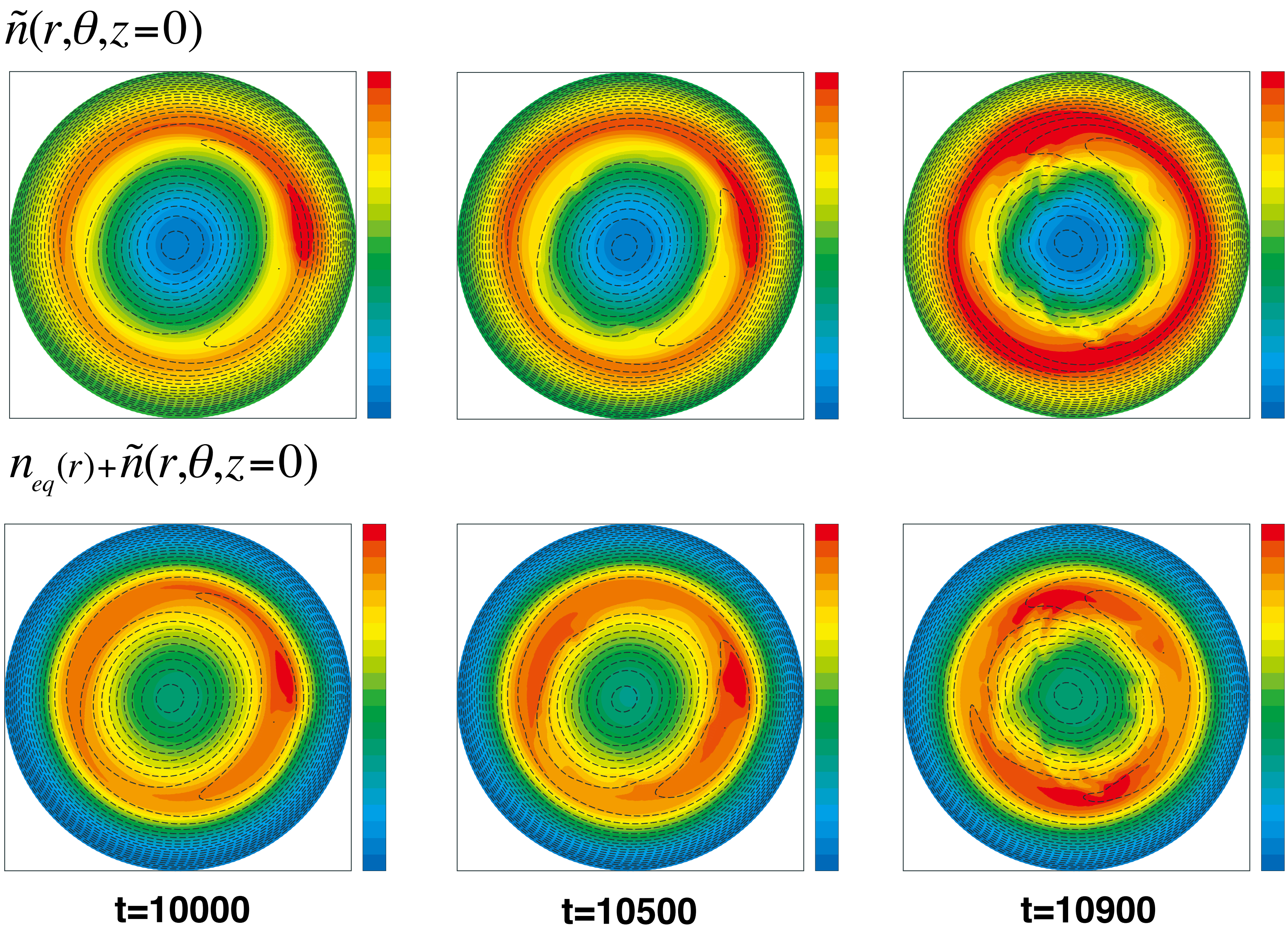


$T_{eq}(r)+\tilde{T}(r,\theta,z=0)$



t=10000 **t=10500** **t=10900**

2D Contour Plot of Density



Summary

Nonlocal transport is investigated in the presence of ITG turbulence using 3-field/5field gryo-fluid model

- ✓ **ITG turbulence triggered by an transient edge sink remains strong for a while (several a/vti) after the sink is terminated.**
- ✓ **The turbulence (n≠0 modes) causes heat transport in a wide radial region.**
- ✓ **The turbulence also excite GAM oscillations of ZFs and the (±1,0) modes are dominated by them.**

Nonlocal response of electron temperature fluctuation is investigated using 5-field RMHD model.

Source and sink terms are introduced into density and electron temperature evolution equations, respectively.

Summary

The simulation result shows that

(i) the mean central electron temperature increases according to the edge cooling,

(ii) the magnetic island located at q=2 rational surface plays an important role as well as non-resonant modes such as 0/0 and 1/0,

(iii) re-distribution of electron temperature occurs after switching off source and sink where meso-scale mode plays a major role.

6-field simulation unifying both 5-field models

$$\frac{3}{2}\frac{dT_e}{dt}-\frac{\beta_e}{\beta}\frac{dn}{dt}=-\alpha_T\delta\beta_e\nabla_{//}J+\varepsilon^2\chi_{e//}\nabla_{//}^2T_e+\chi_{e\perp}\nabla_{\perp}^2T_e-\frac{5}{2}\delta\beta_e[\Omega,T_e]+S_T-\frac{3}{2}\nu_{ei}(T_e-T_i)$$

$$\frac{3}{2}\frac{dT_i}{dt}-\frac{\beta_i}{\beta}\frac{dn}{dt}=\varepsilon^2\chi_{i//}\nabla_{//}^2T_i+\chi_{i\perp}\nabla_{\perp}^2T_i+\frac{5}{2}\delta\beta_i[\Omega,T_i]+\frac{3}{2}\nu_{ei}(T_e-T_i)$$