Simulation Study on Transient Plasma Response for Peripheral Density Source

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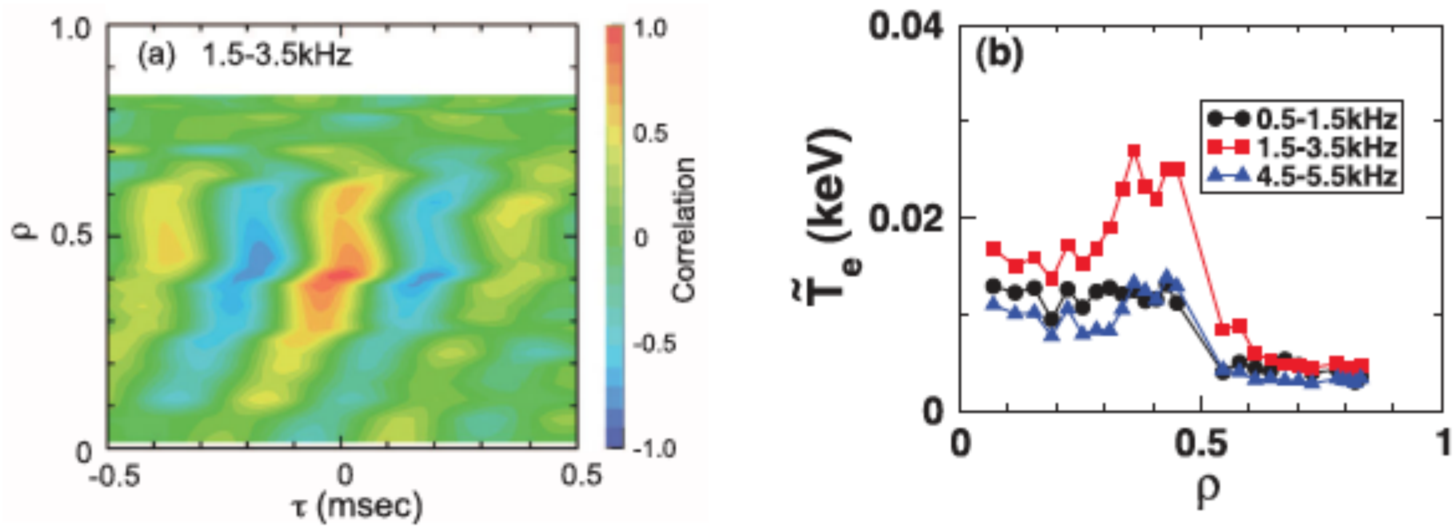
Non-local Transport

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.

Objective

So far, 1 D model for avalanche or turbulent spreading is proposed to explain the non-local transport.

On the other hand, fluctuation with long radial correlation is found in ECH applied phase in LHD, which implies such mode may play a role for non-local transport.

In this study, transient plasma response is investigated, switching on/off particle source in plasma peripheral region to identify the player for non-local transport.

Simulation Model

4-field reduced MHD model(vorticity equation, Ohm's law, parallel momentum balance , density(pressure) evolution

Normalization: poloidal Alfven time and minor radius

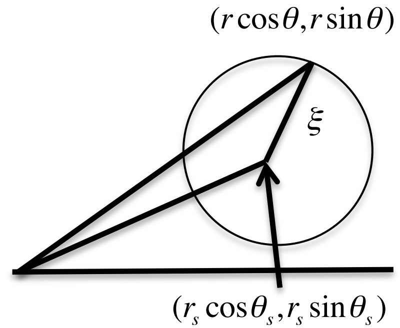
Density evolution

$$\frac{\partial p}{\partial t}+[\phi,p]=\beta[r\cos\theta,\phi-\delta_e p]+\beta(\delta\nabla_{//}j-\nabla_{//}v)+D\nabla_\perp^2 p+S_p$$

$$j=-\nabla_\perp^2 A,\ \delta=c/(a\omega_{pi}),\ \delta_e=1/(1+\tau)\delta,\ \tau=T_i/T_e$$

$$D=10^{-6} \longrightarrow \tau_{coll}\approx 10^6\tau_{pA}$$

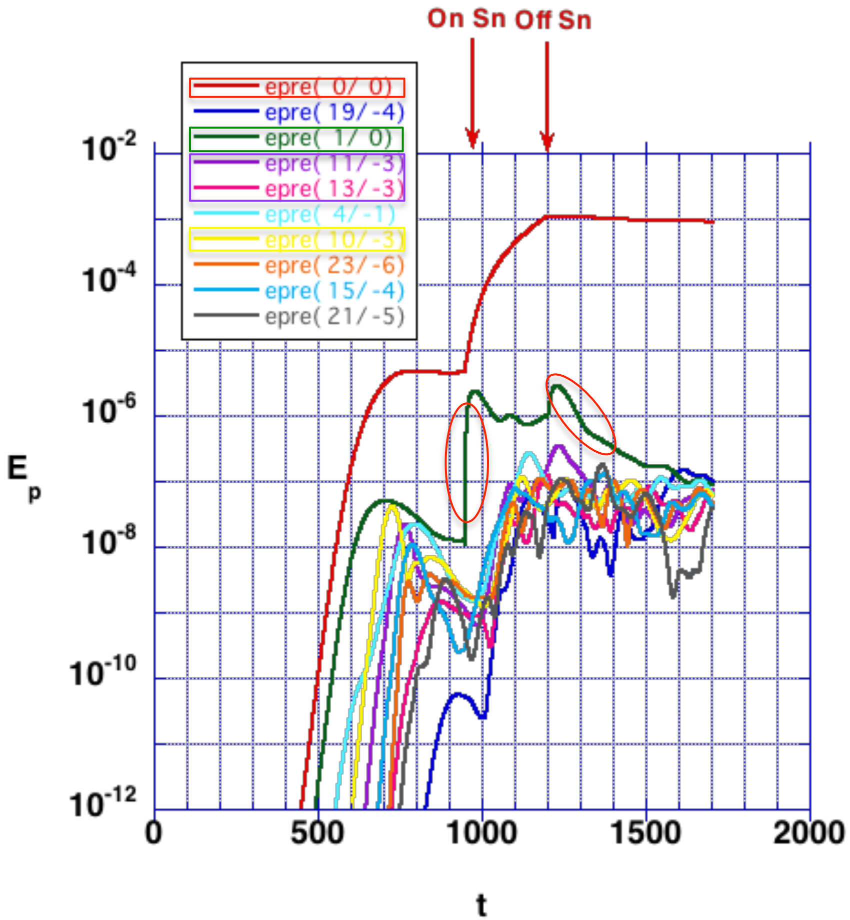
Source term $\exp(-\xi^2/(2\Delta^2))$ $r_s=0.8,\ \theta_s=0,\ \Delta=0.1$

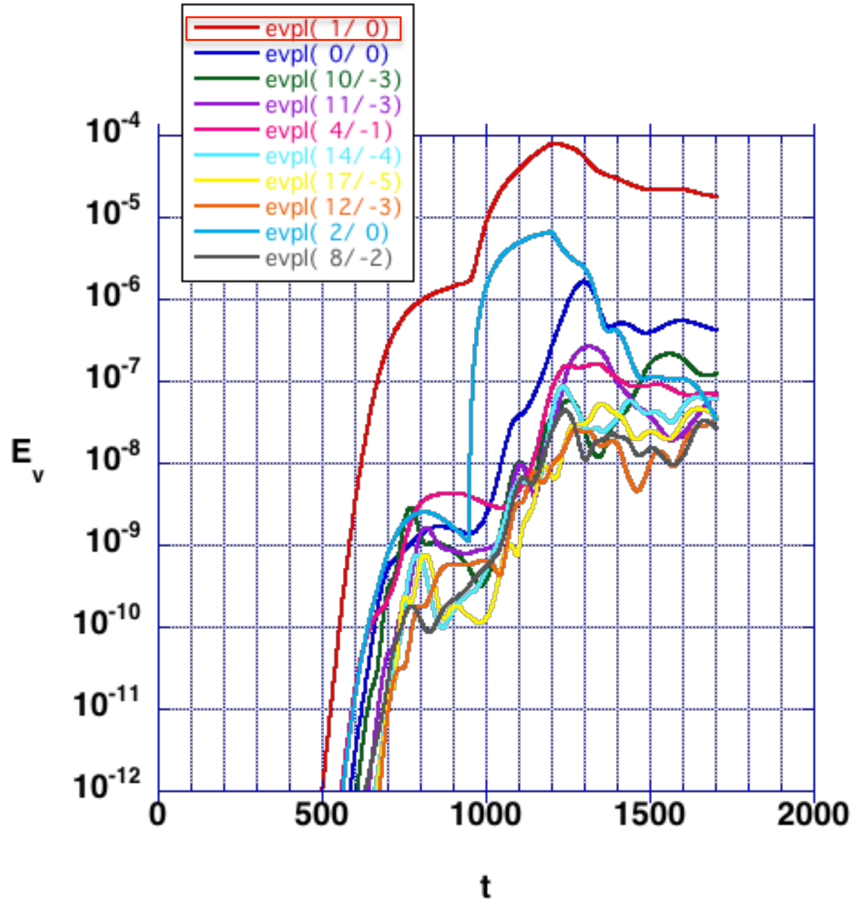


$$\xi^2=(r\cos\theta-r_s\cos\theta_s)^2+(r\sin\theta-r_s\sin\theta_s)^2$$

$$S_p=S_{AMP}\exp(-(r^2+r_s^2-2rr_s\cos\theta)/(2\Delta^2))$$

Time evolution of internal energy





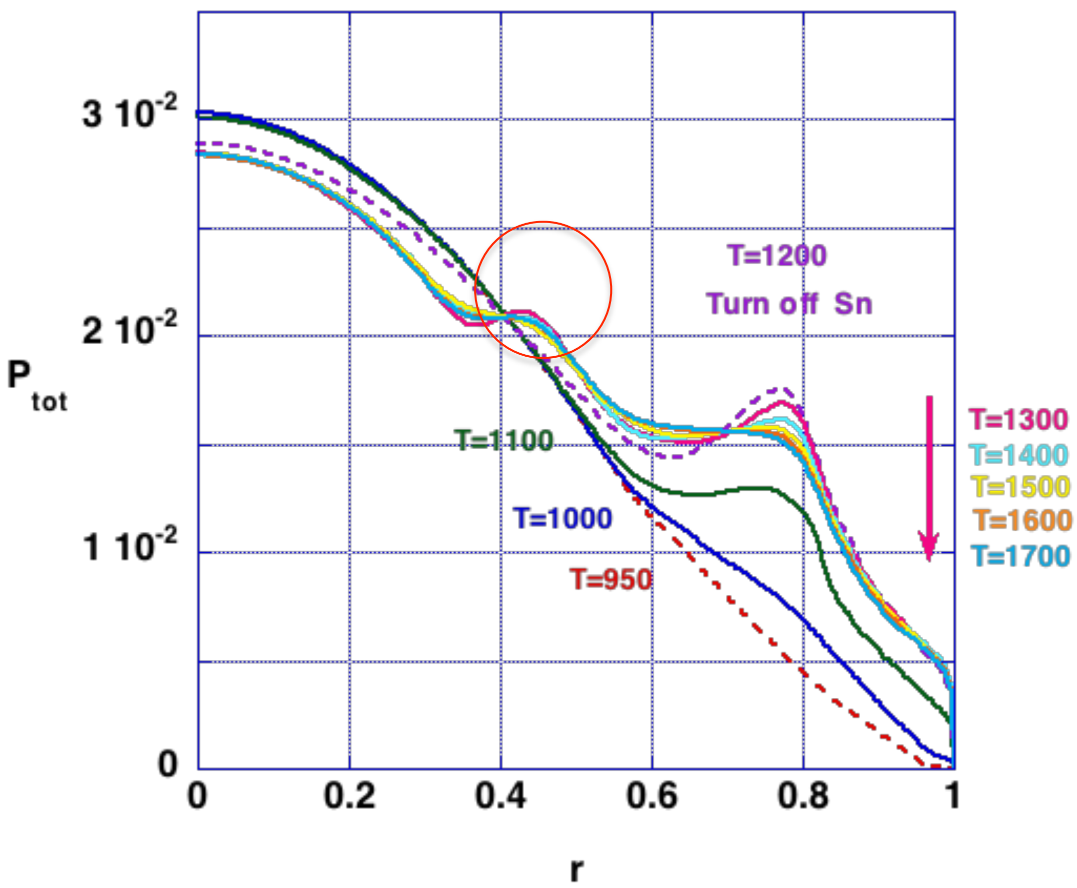
$p_{0,0}$, $p_{1,0}$ are excited after switching on source

$p_{1,0}$ is damped after switching off source

$$p_{1,0} \longrightarrow v_{1,0}$$

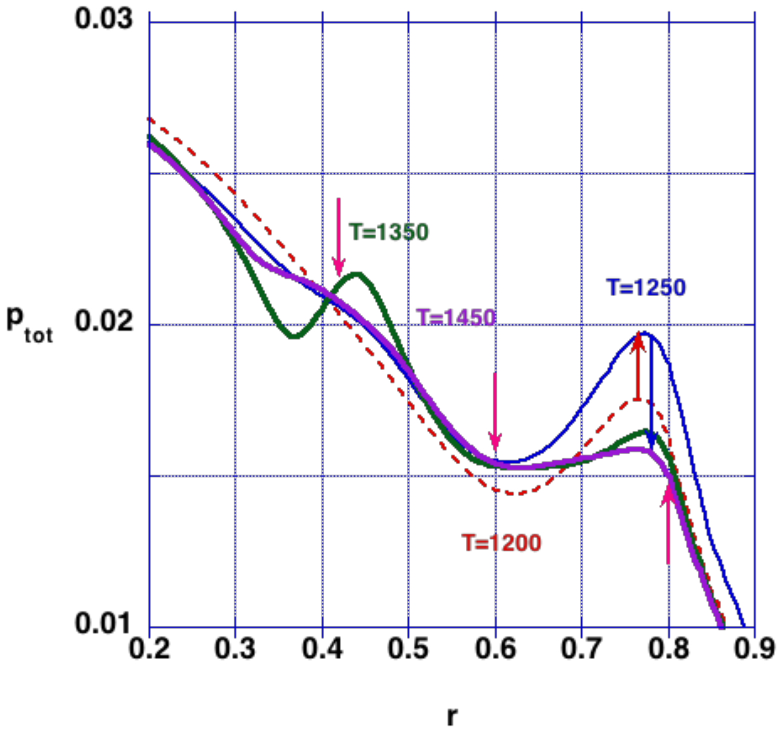
Time evolution of flux averaged total density profile

$$P_{tot}(r) \equiv P_{eq}(r) + \tilde{P}_{0,0}(r)$$

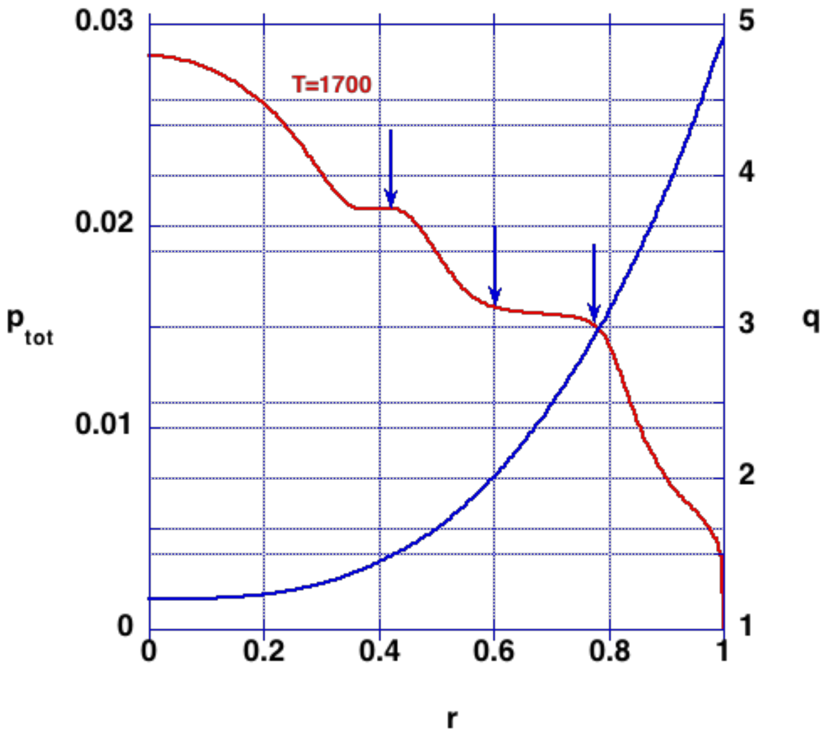


Time evolution of flux averaged total density evolution

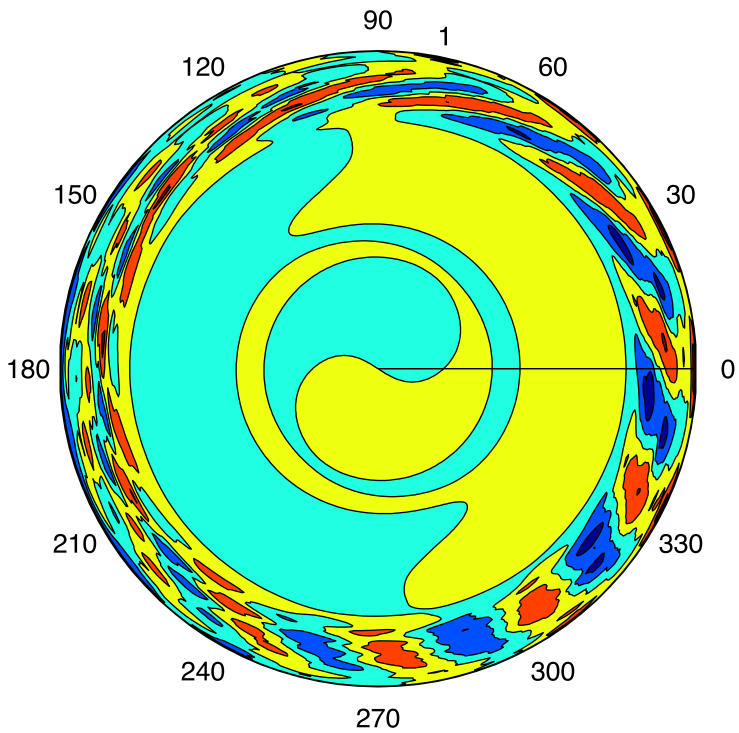
Extended view



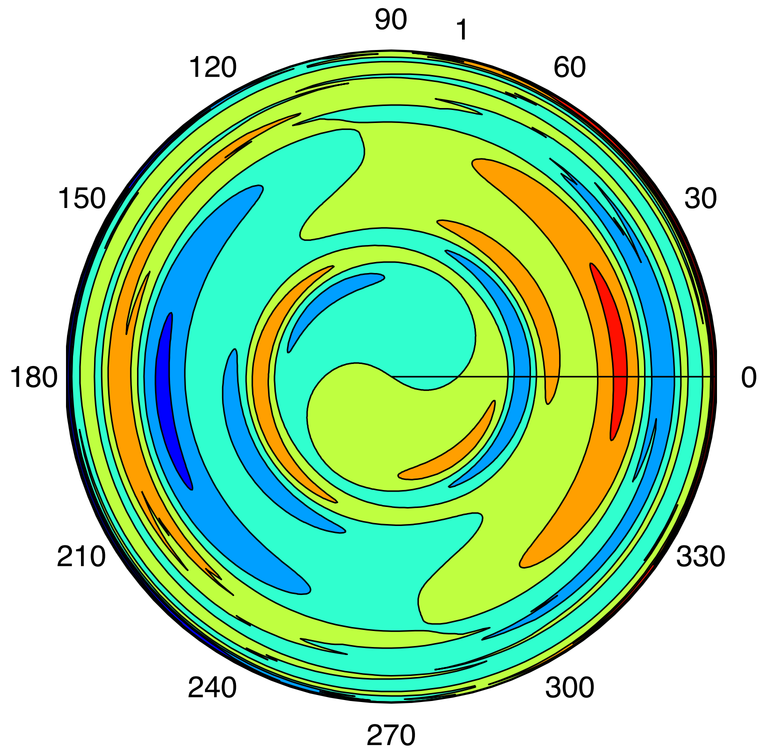
Rational surface



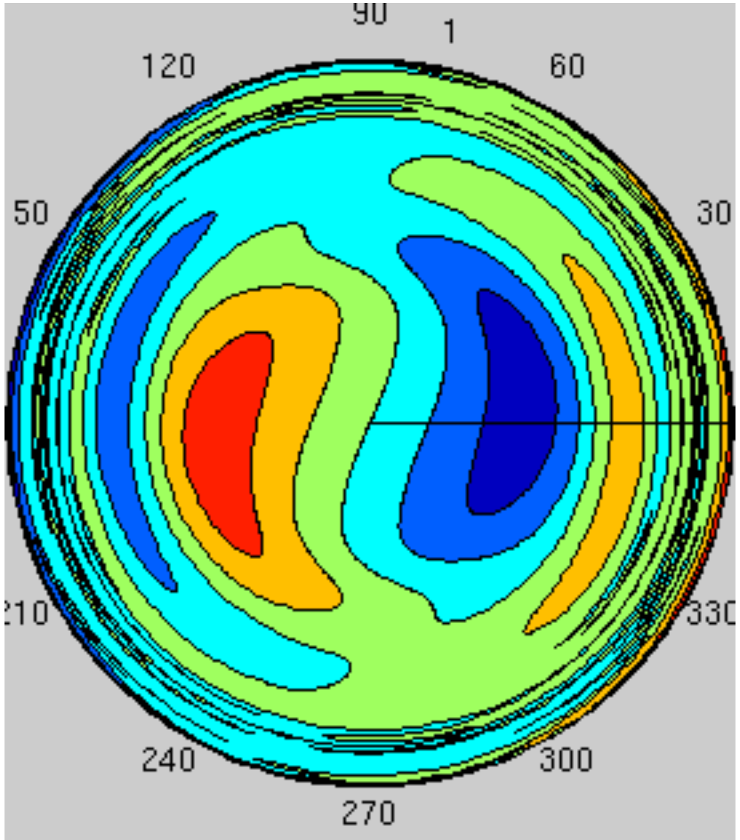
Contour of density fluctuation at T=1350



(1,0)+(m=10~13/n=-3)



Only (1,0) mode


90
1
120
60
50
30
210
330
240
300
270

Analysis

Direct energy transfer to (0,0) and (1,0) modes from source

rhs1

$$\frac{\partial}{\partial t}\frac{1}{2}\left|p_{0,0}\right|^2 = p_{0,0}NL$$

rhs2

$$+i\hat{\beta}p_{0,0}(k_{-1}F_{-1,0}+k_{+1}F_{+1,0})-i\hat{\beta}p_{0,0}\left(\frac{\partial F_{-1,0}}{\partial r}-\frac{\partial F_{+1,0}}{\partial r}\right)$$

$$+\eta_\perp\hat{\beta}\nabla_\perp^2 p_{0,0}$$ rhs5

rhs1

$$\frac{\partial}{\partial t}\frac{1}{2}\left|p_{1,0}\right|^2 = p_{1,0}^*NL$$

rhs2

$$+i\hat{\beta}p_{1,0}^*(k_2F_{2,0})-i\hat{\beta}p_{1,0}^*\left(\frac{\partial F_{0,0}}{\partial r}-\frac{\partial F_{2,0}}{\partial r}\right)$$

$$-i\hat{\beta}\delta p_{1,0}^*k_{//}J_{1,0}-i\hat{\beta}p_{1,0}^*k_{//}v_{1,0}+\eta_\perp\hat{\beta}p_{1,0}^*\nabla_\perp^2 p_{1,0}$$

rhs3 rhs4 rhs5

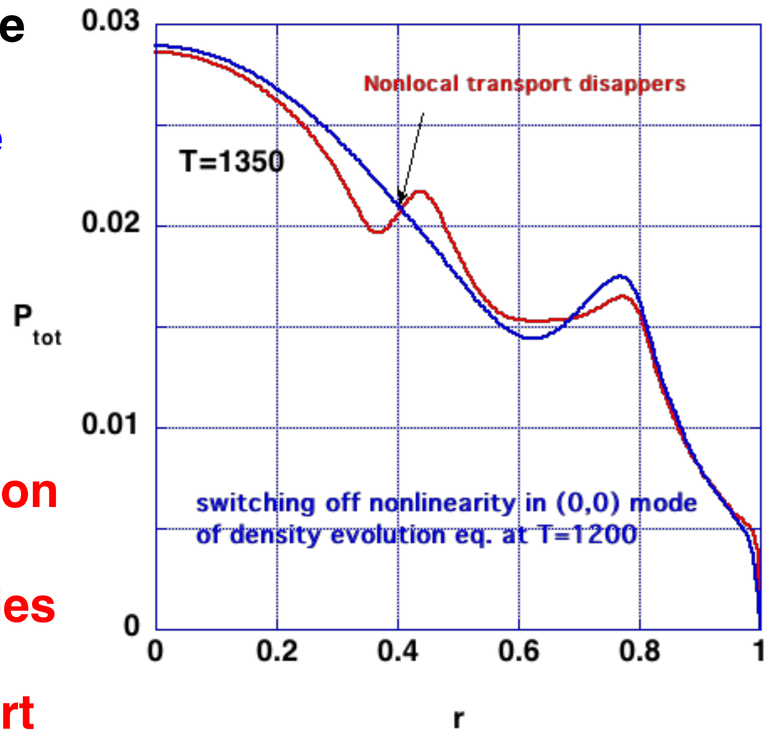
Switch off source

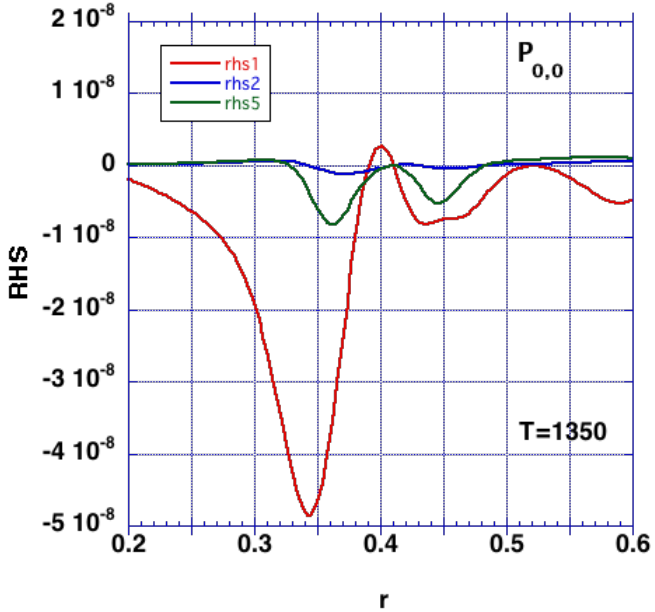
Spiral structure by (1,0) mode

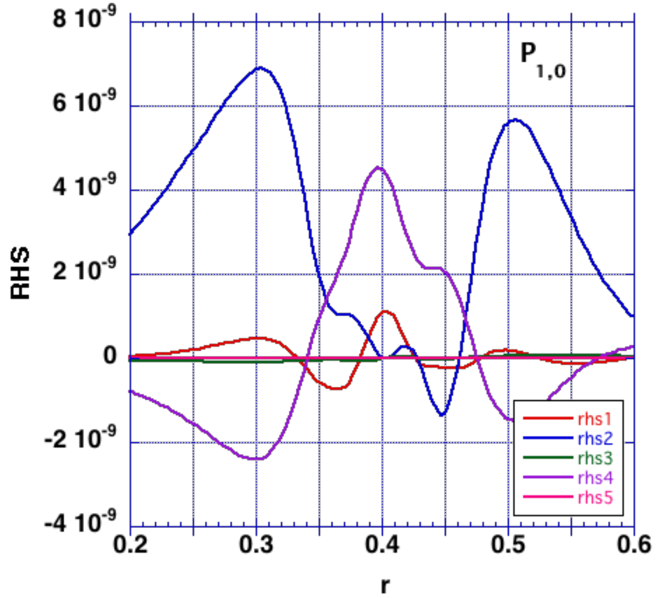
↓

Nonlinear interaction between (0,0) and (1,0) modes

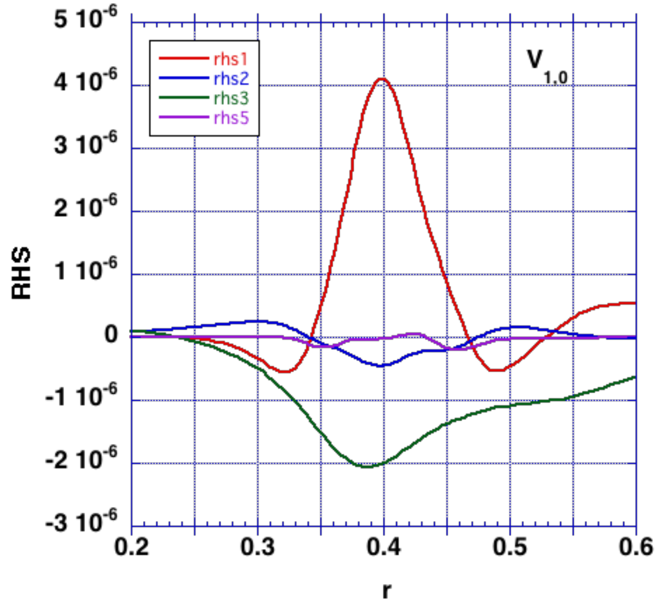
Non-local transport







Non-local transport is produced by convective nonlinearity in $P_{0,0}$



$P_{1,0}$ is driven by toroidal coupling and compressibility which is coupled with $V_{1,0}$

$V_{1,0}$ is driven by convective nonlinearity and compressibility which is coupled with $A_{1,0}$

Summary

Nonlinear simulation is performed using 4F MHD model with peripheral source

After switching off source term, non-local transport appears near q=3/2 surface

(1,0) mode plays a role in non-local transport in this simulation

(1) Energy is directly transferred to $P_{0,0}$ and $P_{1,0}$ modes when source is switched on
(2) Spiral structure is formed by $P_{1,0}$ mode when source is switched off
(3) $P_{1,0}$ interacts with $P_{0,0}$ mode via convective nonlinearity, which produces non-local transport near q=3/2 surface

2D structure (convective cell mode) is essential to produce non-local transport in this simulation

Future work

Investigate non-local transport for spherical source

Investigate cold pulse propagation introducing electron temperature fluctuation

Model Equation

$$\frac{dU}{dt} = -\nabla_{//} J - [r\cos\theta, p] + \mu \nabla_{\perp}^{2} U$$

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

$$\frac{dv}{dt} = -\boxed{\nabla_{//} p} + 4\mu \nabla_{\perp}^{2} v$$

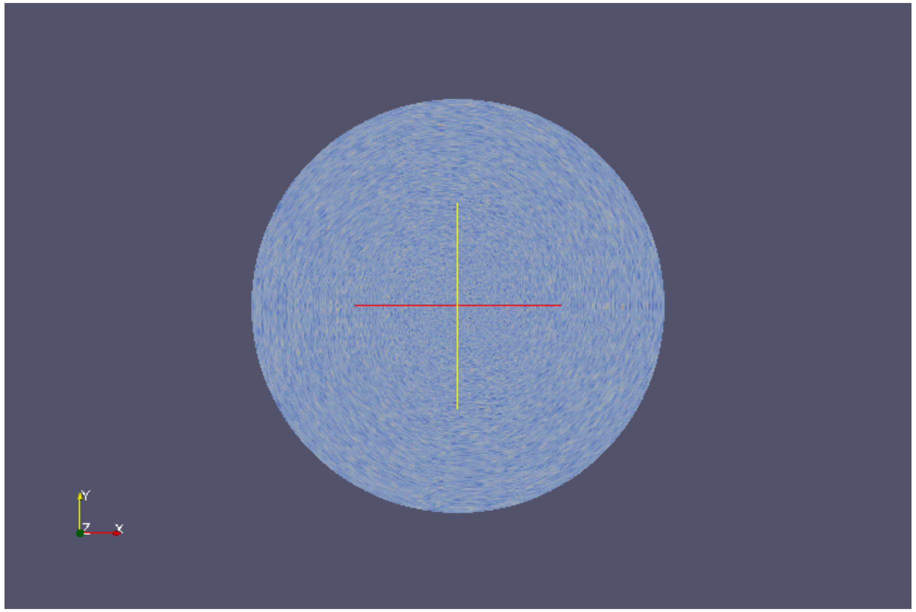
$$\frac{dp}{dt} = \hat{\beta}[r\cos\theta, \phi \boxed{- \delta_e p}] - \hat{\beta}\boxed{\nabla_{//}(v} + \delta J) + \eta_{\perp}\hat{\beta}\nabla_{\perp}^{2} p + S$$

$$\begin{tikzcd}
p_{0,0} \arrow[r, leftrightarrow, "S"] & p_{1,0} \arrow[d, leftrightarrow] \\
& v_{1,0}
\end{tikzcd}$$

$$\frac{d}{dt} = \frac{\partial}{\partial t} + [\phi,],\ U = \nabla_{\perp}^{2}\phi,\ J = \nabla_{\perp}^{2} A$$

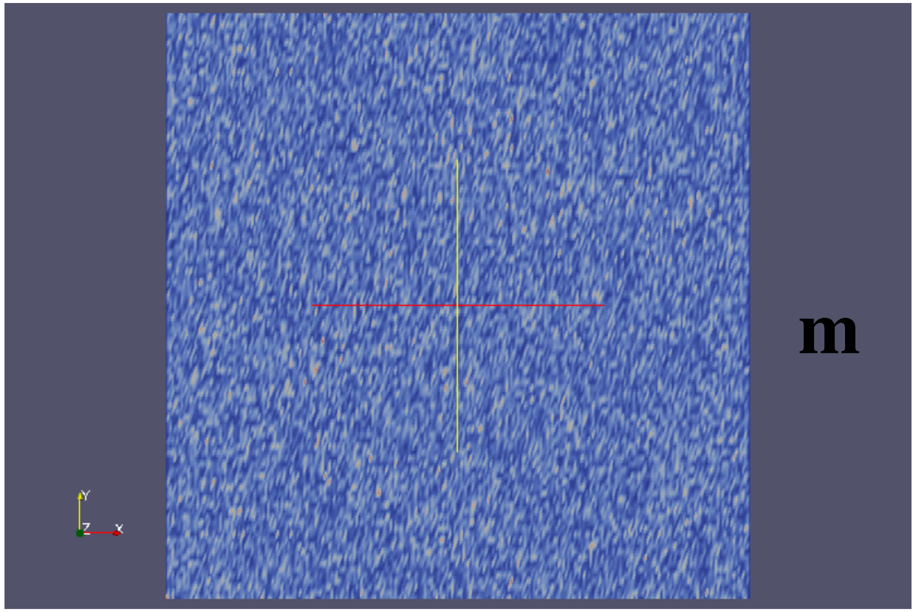
$$\nabla_{//} = \nabla_{//}^{(0)} - [A,],\ \delta = c/(a\omega_{pi}),\ \delta_e = \delta\tau/(1+\tau),\ \tau = T_e/T_i,\ \hat{\beta} = \beta/(1+\beta)$$

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



WO (0,0) mode

$\tilde{p}(r,m,z=0)$



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