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Integrated Simulation of Tokamak Plasmas by TASK Code System

A. Fukuyama, M. Honda, S. Nishina and T. Akutsu
Department of Nuclear Engineering,
Kyoto University, Kyoto 606-8501, Japan

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Motivation and Status

- **Predictive Simulation of Tokamak Plasma**
  - **Integrated code with modular structure**
  - **Various heating and current drive schemes**
  - **Portability and compactness**
  - **Future extension for helical system**
  - **Parallel processing using MPI library**
- **Status**
  - **Most of modules work for given spatial profiles.**
  - **Transport module is under reorganization.**
  - **Results of integrated simulation will be available soon.**
  - **Subjects of this presentation**: Results of modules
    - **Transport simulation of current hole formation**: TR
    - **Beam tracing analysis of ECCD**: EQ+WR+DP+FP
    - **Linear stability of Alfvén eigenmodes**: EQ+DP+WM

TASK code system

- **T**ransport **A**nalyzing **S**ystem for tokama**K**
- **Integrated Code**

TASK/ EQ	**Fixed boundary equilibrium**	toroidal rotation
PL	**Profile data interface**	Exp. data, ITPA Profile DB
TR	**Diffusive radial transport**	n_s, $u_{s\phi}$, T_s, B_θ, E_ϕ
DP	**Wave dispersion relation**	various velocity distributions
WR	**Ray and beam tracing**	EC, LH
WM	**3D full wave analysis**	IC, AW, eigenmodes
FP	**Velocity distribution analysis**	3D, relativistic, bounce averaged
EX	**Free boundary equilibrium**	Start up, Shut down
TX	**Fluid-like transport analysis**	n, $\boldsymbol{u}$, T, $\boldsymbol{E}$, $\boldsymbol{B}$, including SOL

Interaction between TASK modules

- **Output\Input variables**

	EQ	PL	TR	DP	WR	WM	FP
EQ	—	$\psi(R,Z)$					
PL	$p, j, u_\phi(\psi)$	—	metric	$n, T, u_\parallel, \boldsymbol{B}(\boldsymbol{r})$		metric	metric
TR		$n, T, j, u_\phi, \psi(\rho)$	—				
DP				—	$\overleftrightarrow{\epsilon}$	$\overleftrightarrow{\epsilon}$	
WR			$P_{\rm abs}(\rho)$		—		$\tilde{\boldsymbol{E}}, \tilde{\boldsymbol{B}}(\boldsymbol{r})$
WM			$P_{\rm abs}(\rho)$			—	$\tilde{\boldsymbol{E}}, \tilde{\boldsymbol{B}}(\boldsymbol{r})$
FP			$P_{\rm abs}, j_{\rm CD}(\rho)$	$f(v_\parallel, v_\perp, \rho)$			—

- **Modules with 3D configuration for helical system**: WM, WR
- **Modules with MPI parallelization for computer cluster**: WM, FP

TASK/TR

- **Diffusive Transport Simulation**
  - **Variables**:

Density	n_s for s = D, T, He, Impurity
Rotation	u_s for s = D, T, He, Impurity
Temperature	T_s for s = Electron, D, T, He, Impurity
Energy density	W_s for s = Alpha, Beam ion
Neutral density	$n_{\mathrm{f}s}$ (fast) , $n_{\mathrm{s}s}$ (slow) for s = D, T
Poloidal flux	Ψ

  - **Diffusion equation**
  - **Transport coefficients**

    Neoclassical model

    Turbulent transport models (CDBM, . . .)
  - **Source**:

    Ionization

    Collisional momentum and energy transfer

    RF heating and current drive

    Fusion reaction

CDBM Turbulence Model

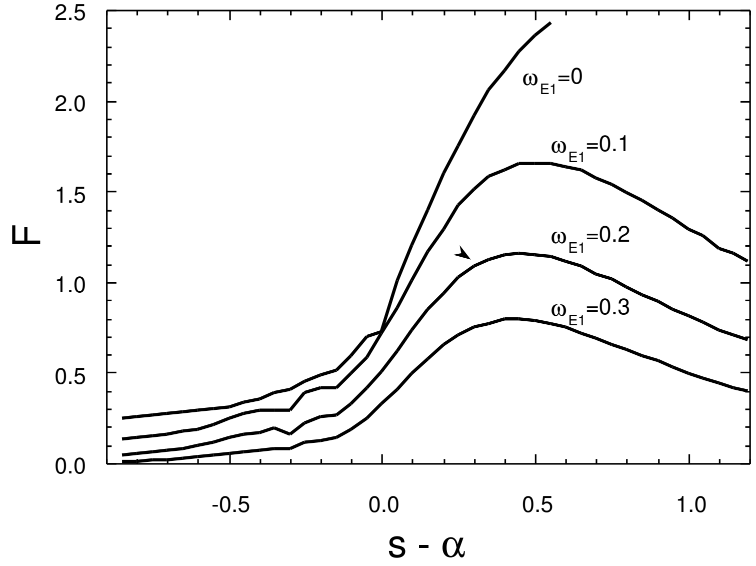
- **Marginal Stability Condition** $(\gamma = 0)$

$$\chi_{\rm TB} = F(s, \alpha, \kappa, \omega_{\rm E1})\, \alpha^{3/2} \frac{c^2}{\omega_{\rm pe}^2} \frac{v_{\rm A}}{qR}$$

Magnetic shear	$s \equiv \dfrac{r}{q} \dfrac{{\rm d}q}{{\rm d}r}$
Pressure gradient	$\alpha \equiv -q^2 R \dfrac{{\rm d}\beta}{{\rm d}r}$
Magnetic curvature	$\kappa \equiv -\dfrac{r}{R}\left(1 - \dfrac{1}{q^2}\right)$
$E \times B$ **rotation shear**	$\omega_{\rm E1} \equiv \dfrac{r^2}{s v_{\rm A}} \dfrac{\rm d}{{\rm d}r} \dfrac{E}{rB}$

- **Weak and negative magnetic shear, Shafranov shift and $E \times B$ rotation shear reduce thermal diffusivity.**

$s - \alpha$ dependence of $F(s, \alpha, \kappa, \omega_{\rm E1})$

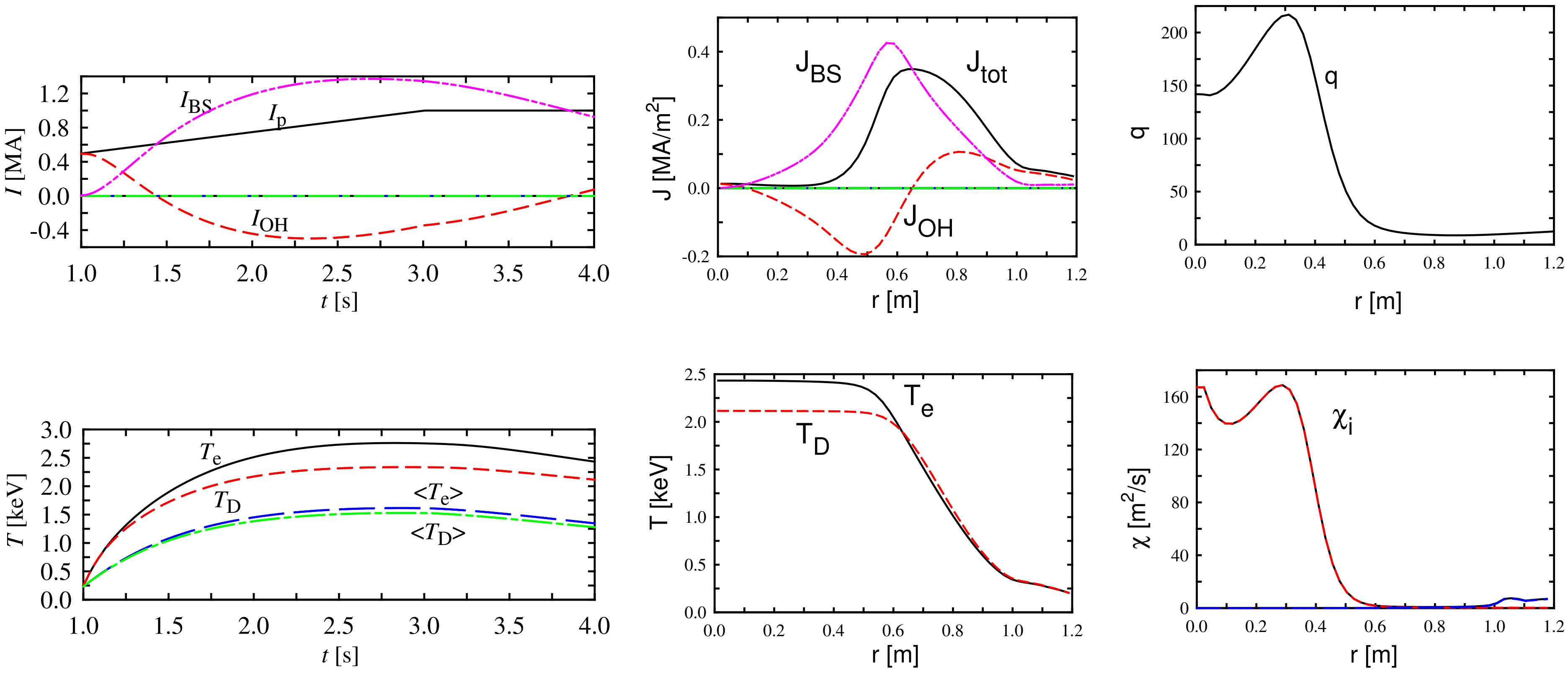


Fitting Formula

$$F = \begin{cases} \dfrac{1}{1 + G_1 \omega_{\rm E1}^2} \dfrac{1}{\sqrt{2(1-2s')(1-2s'+3s'^2)}} & \text{for} \quad s' = s - \alpha < 0 \\[2ex] \dfrac{1}{1 + G_1 \omega_{\rm E1}^2} \dfrac{1 + 9\sqrt{2} s'^{5/2}}{\sqrt{2}(1 - 2s' + 3s'^2 + 2s'^3)} & \text{for} \quad s' = s - \alpha > 0 \end{cases}$$

Simulation of Current Hole

- Current ramp up: $I_\mathrm{p} = 0.5 \longrightarrow 1.0\,\mathrm{MA}$
- Moderate heating: $P_\mathrm{H} = 5\,\mathrm{MW}$
- **Current hole** is formed.
- The formation is sensitive to the edge temperature.



TASK/DP

- **Various Models of Dielectric Tensor**: (**available**, **underway**)
  - **Resistive MHD plasma model**
  - **Cold plasma model with collision**
  - **Warm plasma model with collision**
  - **Kinetic plasma model (Maxwellian)**
  - **Kinetic plasma model (Relativistic Maxwellian)**
  - **Kinetic plasma model (Numerical, Relativistic/Non-Rel.)**
  - **Gyrokinetic plasma model (Maxwellian)**
  - **Gyrokinetic plasma model (Numerical, Relativistic/Non-Rel.)**
- **for**
  - **given** n, $u_\parallel$, T, B, $\nabla_\perp p$, $\nabla_\perp B$
  - **given** n, $u_\parallel$, T, B, $\nabla_\perp n$, $\nabla_\perp T$, $\nabla_\perp B$, $E_\perp$

TASK/WR

- **Ray Tracing** (Geometrical Optics)
  - Wave length $\lambda \ll$ Characteristic scale length L of the medium
  - Plane wave: Beam size d is sufficiently large
    — **Fresnel condition**: $L \ll d^2/\lambda$
  - Beam : Diffraction effect determines the beam size d

- **Beam Tracing**
  - Propagation of beam with finite size
    — Spatial evolution of beam size
  - References

    — G. V. Pereverzev, in *Reviews of Plasma Physics*, Vol. 19, p. 1.
    — A. G. Peeters, Phys. Plasmas **3** (1996) 4386.
    — G. V. Pereverzev, Phys. Plasmas **4** (1998) 3529.

Beam Tracing Method

- Beam size perpendicular to the beam direction: first order in δ
- **Beam shape** : Weber function Hermite polynomial: H_n)

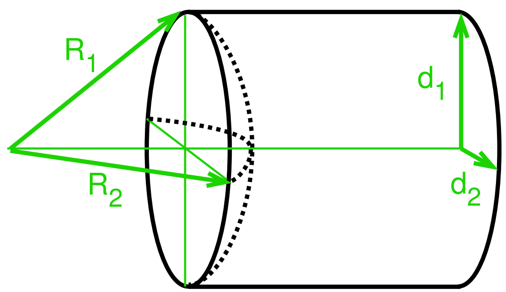
$$\boldsymbol{E}(\boldsymbol{r}) = \mathrm{Re}\left[\sum_{mn} C_{mn}(\delta^2\boldsymbol{r})\boldsymbol{e}e(\delta^2\boldsymbol{r})H_m(\delta\xi_1)H_n(\delta\xi_2)\,\mathrm{e}^{\,\mathrm{i}\,s(\boldsymbol{r})-\phi(\boldsymbol{r})}\right]$$

  - Amplitude : C_{mn}, Polarization : $\boldsymbol{e}e$, Phase : $s(\boldsymbol{r}) + \mathrm{i}\,\phi(\boldsymbol{r})$

$$s(\boldsymbol{r}) = s_0(\tau) + k^0_\alpha(\tau)[r^\alpha - r^\alpha_0(\tau)] + \frac{1}{2}s_{\alpha\beta}[r^\alpha - r^\alpha_0(\tau)][r^\beta - r^\beta_0(\tau)]$$

$$\phi(\tau) = \frac{1}{2}\phi_{\alpha\beta}[r^\alpha - r^\alpha_0(\tau)][r^\beta - r^\beta_0(\tau)]$$

  - Position of beam axis : $\boldsymbol{r}_0$, Wave number on beam axis: $\boldsymbol{k}^0$
  - **Curvature radius** of equi-phase surface: $R_\alpha = \dfrac{1}{\lambda s_{\alpha\alpha}}$
  - **Beam radius**F $d_\alpha = \sqrt{\dfrac{2}{\phi_{\alpha\alpha}}}$



- Gaussian beam : case with $m = 0$, $n = 0$

Beam Propagation Equation

- Solvable condition for Maxwell's equation with beam field

$$\frac{\mathrm{d}r_0^\alpha}{\mathrm{d}\tau} = \frac{\partial K}{\partial k_\alpha}$$

$$\frac{\mathrm{d}k_\alpha^0}{\mathrm{d}\tau} = -\frac{\partial K}{\partial r^\alpha}$$

$$\frac{\mathrm{d}s_{\alpha\beta}}{\mathrm{d}\tau} = -\frac{\partial^2 K}{\partial r^\alpha \partial r^\beta} - \frac{\partial^2 K}{\partial r^\beta \partial k_\gamma} s_{\alpha\gamma} - \frac{\partial^2 K}{\partial r^\alpha \partial k_\gamma} s_{\beta\gamma} - \frac{\partial^2 K}{\partial k^\gamma \partial k^\delta} s_{\alpha\gamma} s_{\beta\delta} + \frac{\partial^2 K}{\partial k^\gamma \partial k^\delta} \phi_{\alpha\gamma}\phi_{\beta\delta}$$

$$\frac{\mathrm{d}\phi_{\alpha\beta}}{\mathrm{d}\tau} = -\left(\frac{\partial^2 K}{\partial r^\alpha \partial k^\gamma} + \frac{\partial^2 K}{\partial k^\gamma \partial k_\delta} s_{\alpha\delta}\right)\phi_{\beta\gamma} - \left(\frac{\partial^2 K}{\partial r^\beta \partial k^\gamma} + \frac{\partial^2 K}{\partial k^\gamma \partial k_\delta} s_{\beta\delta}\right)\phi_{\alpha\gamma}$$

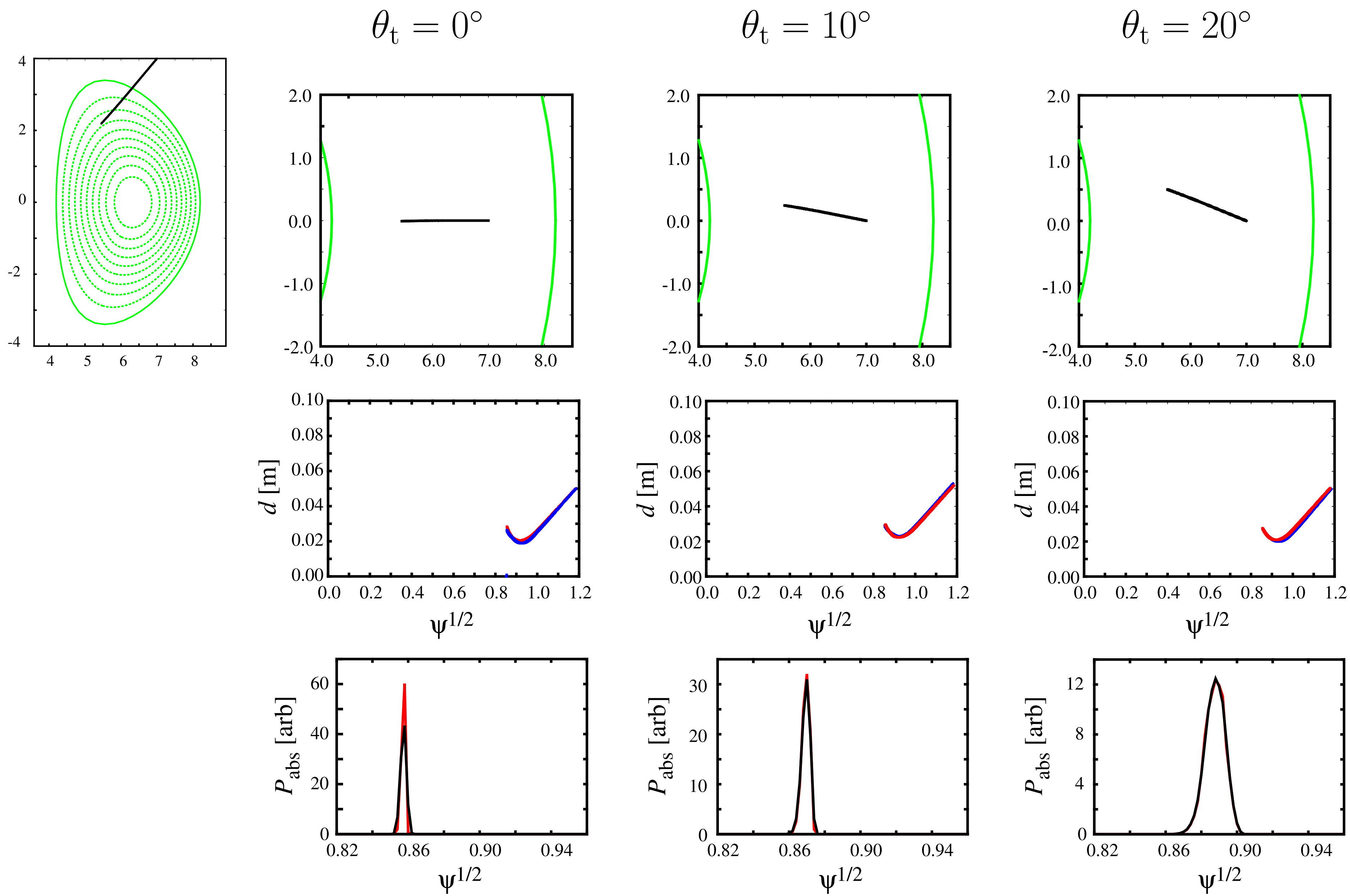
- By integrating this set of 18 ordinary differential equations, we obtain trace of the beam axis, wave number on the beam axis, curvature of equi-phase surface, and beam size.

- Equation for the wave amplitude C_{mn}

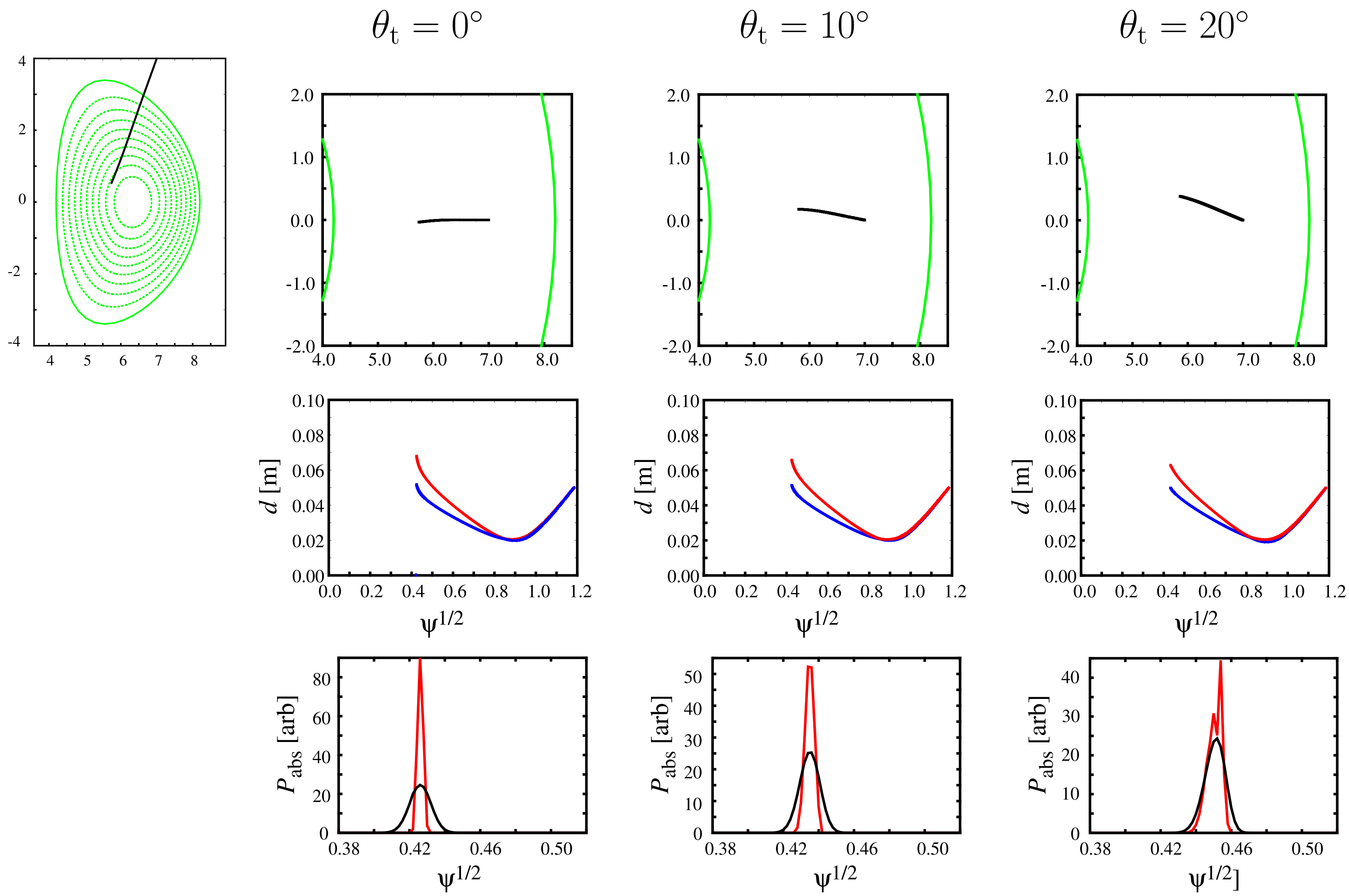
$$\boldsymbol{\nabla} \cdot \left(\boldsymbol{v}_{\mathrm{g}0} |C_{mn}|^2\right) = -2\left(\gamma |C_{mn}|^2\right)$$

Group velocity: $\boldsymbol{v}_{\mathrm{g}0}$, Damping rate: $\gamma \equiv (\boldsymbol{e}^* \cdot \overleftrightarrow{\epsilon}_{\mathrm{A}} \cdot \boldsymbol{e})/(\partial K/\partial \omega)$

Beam Tracing in ITER-FEAT Plasma: $R_c = 2\,\mathrm{m}$, $d_{ini} = 0.05\,\mathrm{m}$



Beam Tracing in ITER-FEAT Plasma: $R_c = 2\,\mathrm{m}$, $d_{ini} = 0.05\,\mathrm{m}$

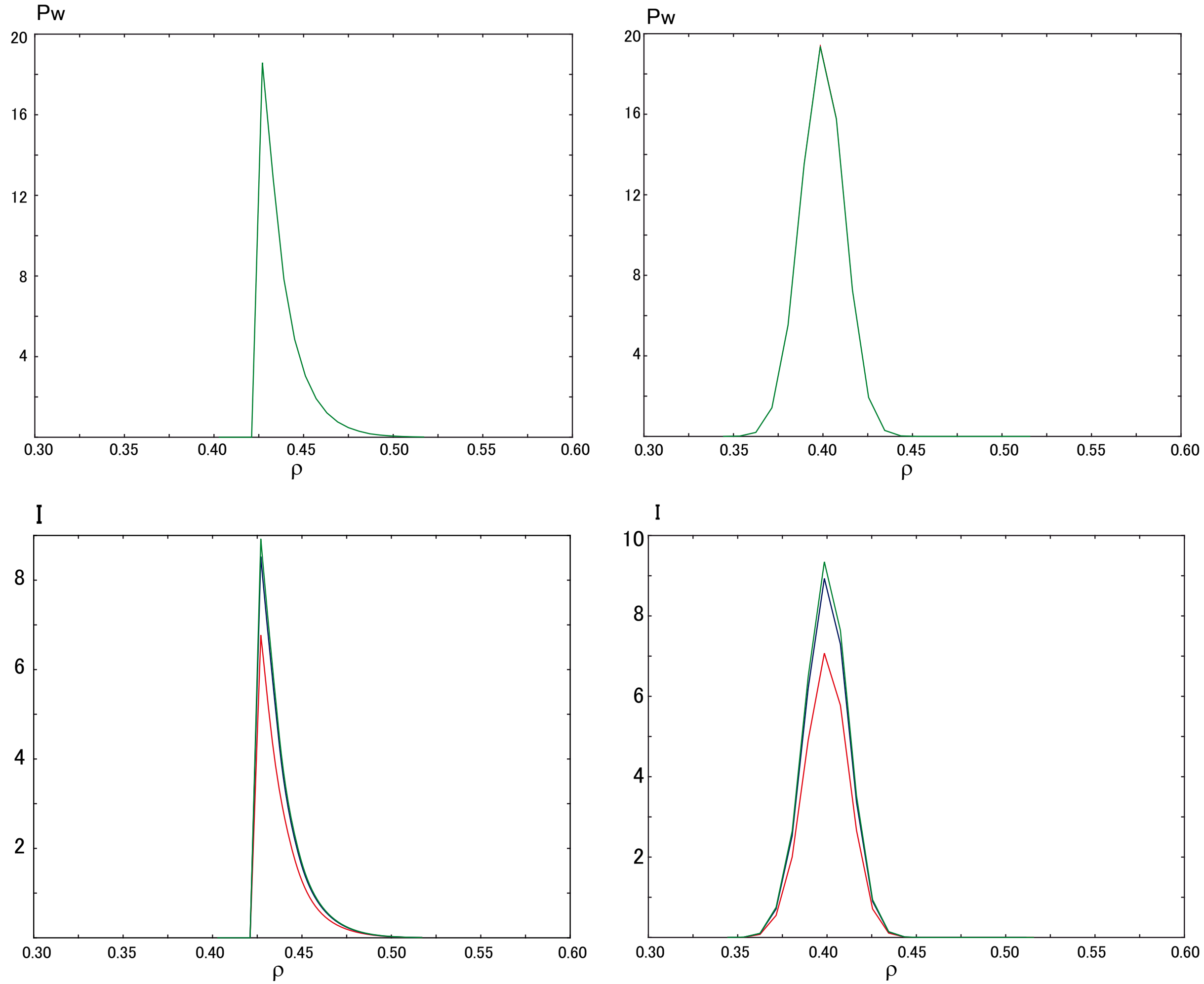


ECCD Driven Current Profile

Single-Ray Tracing　　Beam Tracing

Power deposition

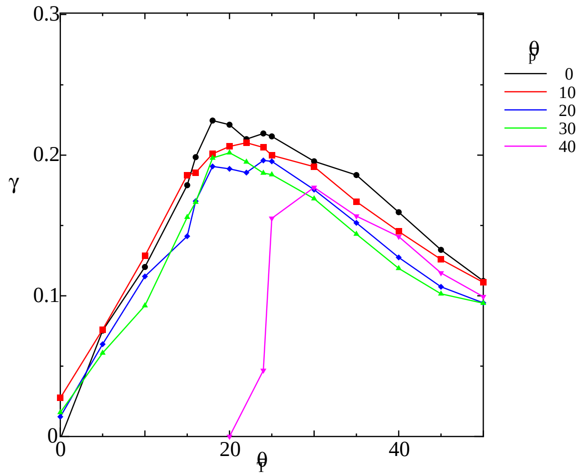
Driven current density

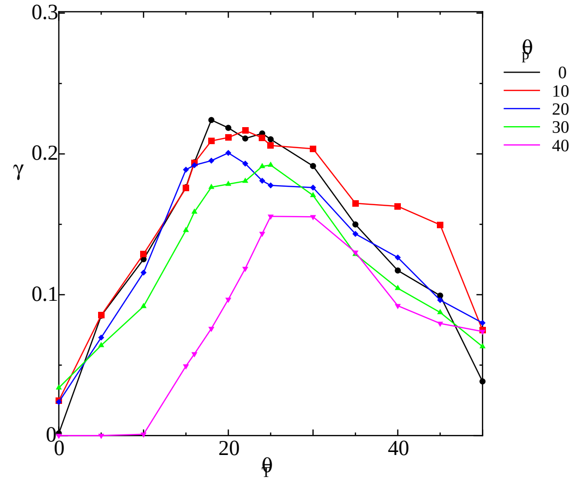


Current Drive Efficiency (Preliminary)

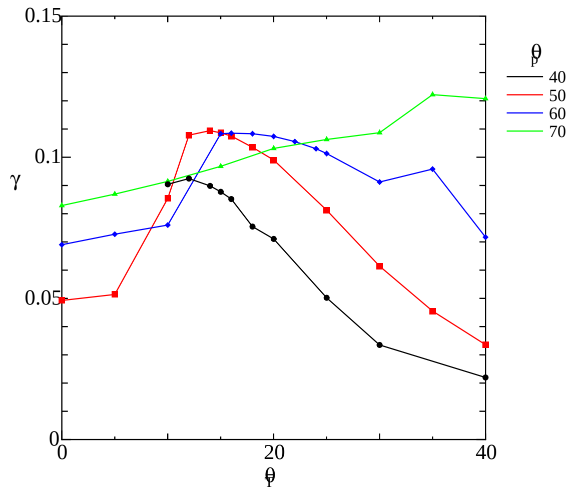
Single-Ray Tracing | Beam Tracing

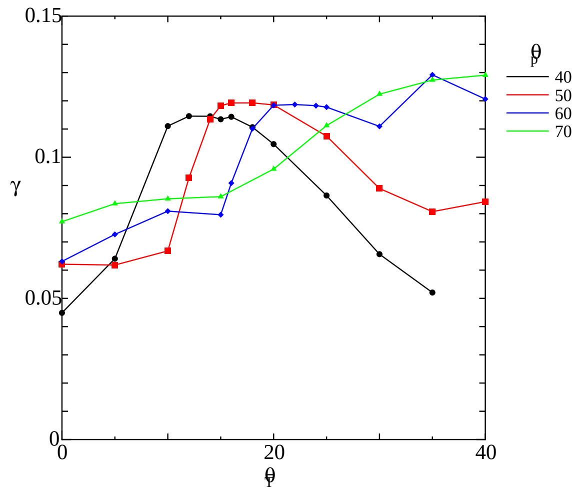
Horizontal port





Upper port





- Multiple-ray tracing is underway.

TASK/WM

- **Magnetic flux coordinates**: (ψ, θ, φ)
  - **Non-orthogonal system**
- **Maxwell's equation** for stationary wave electric field $\boldsymbol{E}$

$$\boldsymbol{\nabla} \times \boldsymbol{\nabla} \times \boldsymbol{E} = \frac{\omega^2}{c^2} \overleftrightarrow{\epsilon} \cdot \boldsymbol{E} + \mathrm{i}\,\omega\mu_0\, \boldsymbol{j}_{\mathrm{ext}}$$

  - $\overleftrightarrow{\epsilon}$ **: Dielectric tensor with kinetic effects**: $Z[(\omega - n\omega_{\mathrm{c}})/k_{\parallel}]$
- **Fourier expansion** in poloidal and toroidal directions
  - **Exact parallel wave number**: $k_{\parallel}^{m,n} = (mB^{\theta} + nB^{\varphi})/B$
- **Destabilization by energetic ions** include in $\overleftrightarrow{\epsilon}$
  - **Drift kinetic equation**

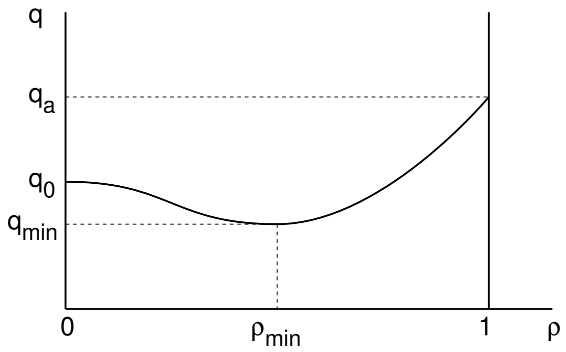
$$\left[\frac{\partial}{\partial t} + v_{\parallel}\nabla_{\parallel} + (\boldsymbol{v}_{\mathrm{d}} + \boldsymbol{v}_{\mathrm{E}}) \cdot \boldsymbol{\nabla} + \frac{e_{\alpha}}{m_{\alpha}}(v_{\parallel}E_{\parallel} + \boldsymbol{v}_{\mathrm{d}} \cdot \boldsymbol{E})\frac{\partial}{\partial \varepsilon}\right] f_{\alpha} = 0$$

- **Eigenvalue problem** for complex wave frequency
  - **Maximize wave amplitude** for finite excitation proportional to nne

Analysis of TAE in Reversed Shear Configuration

$q_{\rm min}$ Dependence of Eigenmode Frequency

Assumed q profile

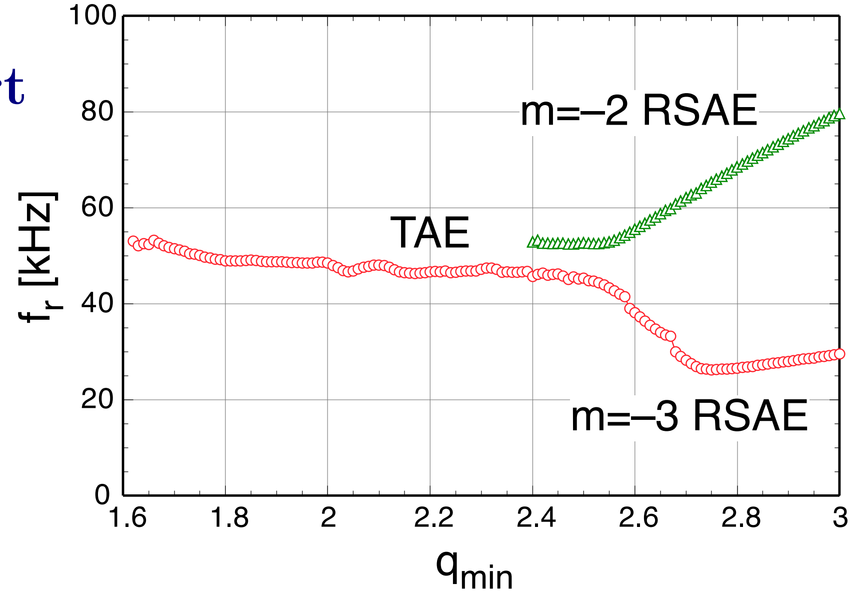


Plasma Parameters

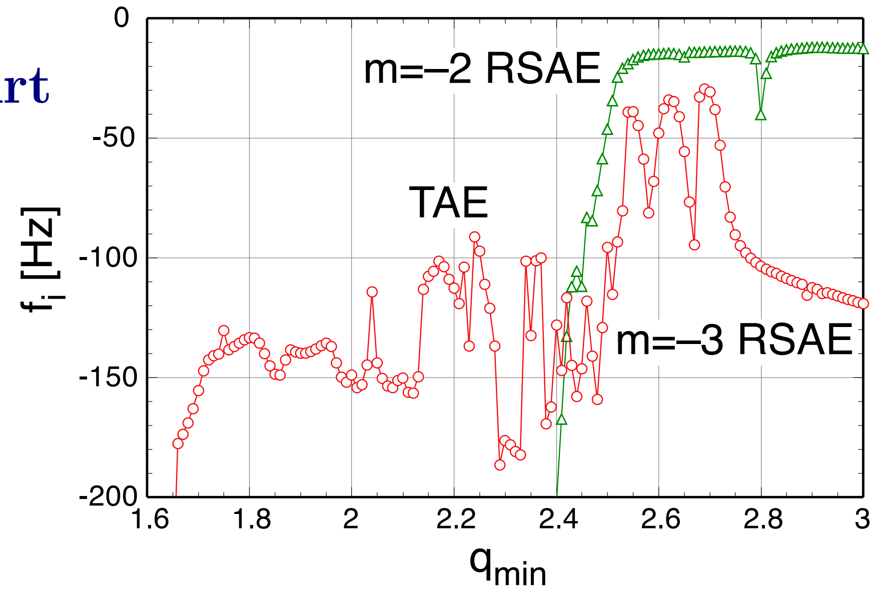
R_0	$3\,\mathrm{m}$
a	$1\,\mathrm{m}$
B_0	$3\,\mathrm{T}$
$n_e(0)$	$10^{20}\,\mathrm{m}^{-3}$
$T(0)$	$3\,\mathrm{keV}$
$q(0)$	3
$q(a)$	5
$\rho_{\rm min}$	0.5
n	1

Flat density profile

Real part



Imag part



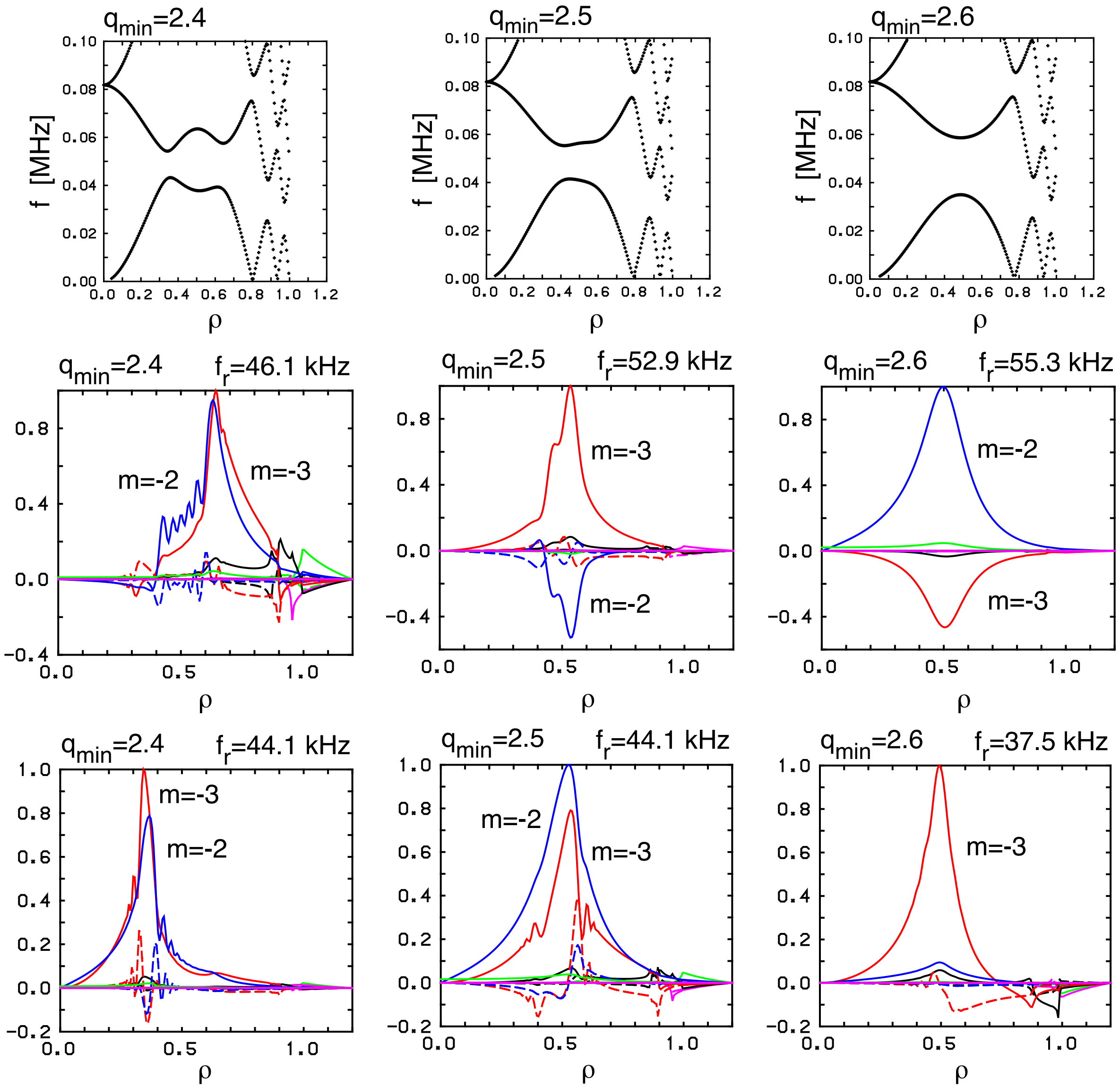
Eigenmode Structure

$q_{\min} = 2.4$ $q_{\min} = 2.5$ $q_{\min} = 2.6$

Alfvén resonance

Higher freq.

Lower freq.



TAEs **Double TAE** **RSAE**

Excitation by Energetic Particles ($q_{\min} = 2.6$)

- Without EP
- With EP

  $3 \times 10^{16}\,\mathrm{m}^{-3}$

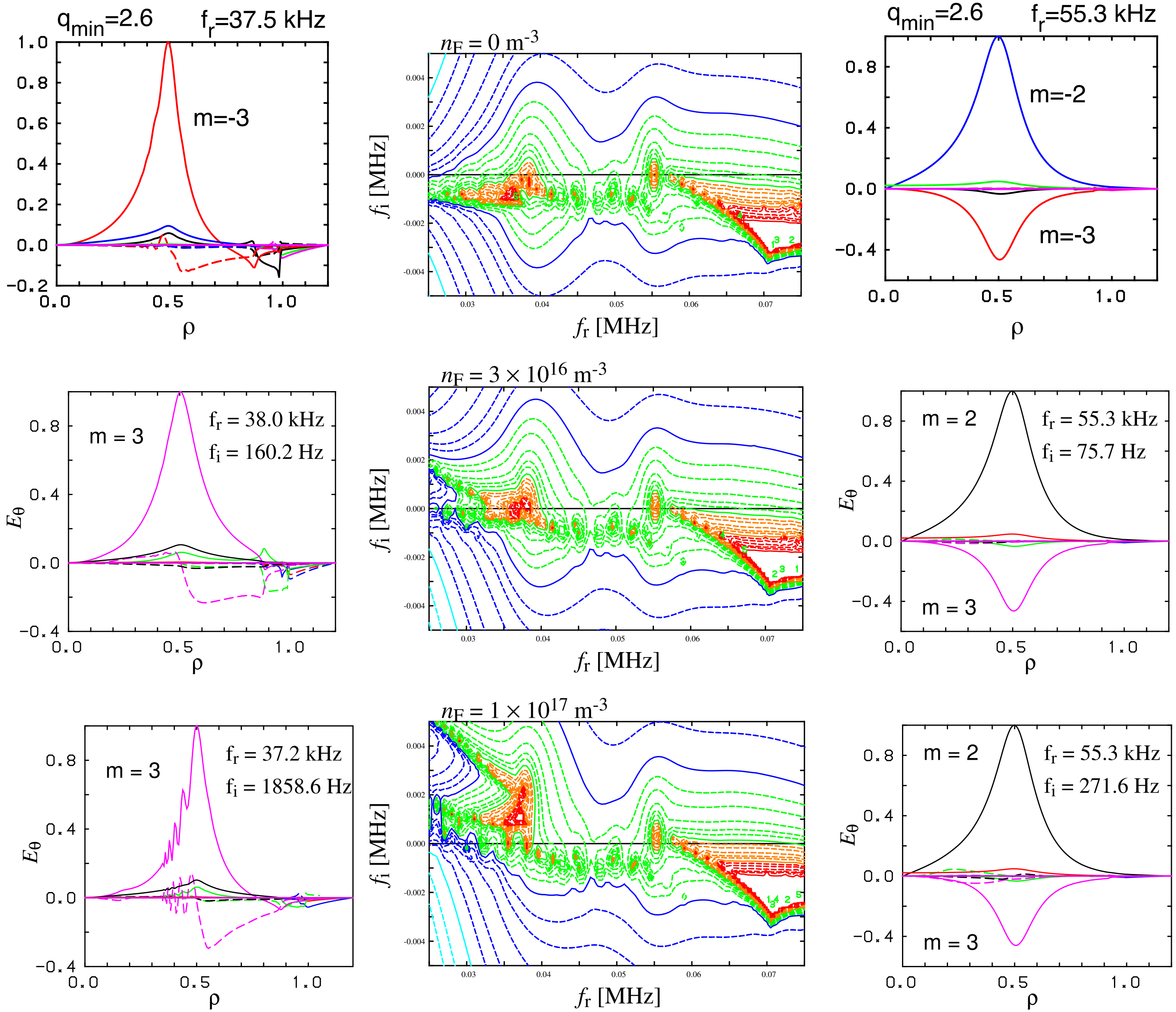
  360 keV

  0.5 m
- With EP

  $1 \times 10^{17}\,\mathrm{m}^{-3}$

  360 keV

  0.5 m



Summary

- Development of TASK code system for integrated simulation of tokamak plasmas in underway.
- New results obtained by the modules:
  - TR: Heat transport simulation using CDBM transport model reproduced the current hole formation. The obtained radial profiles are similar to the experimental ones, though the ITB formation occurs in earlier phase.
  - WR: In order to estimate the driven current profile in ITER, the beam tracing method was applied to the analysis of ECCD. In the case of toroidally oblique injection, the effect of Doppler shift seems dominant for the current width.
  - WM: In the reversed magnetic shear configuration, reversed-shear induced Alfvén eigenmode (RSAE) can be excited by energetic ions. The lower frequency mode (slightly above the lower end of frequency gap) which has a larger damping rate is more easily excited by the energetic beam.
- Near future works:

- **Complete the update to include toroidal rotation in TR module**
- **Test integrated simulation code with experimental observations**

Burning Plasma Simulation Initiative

- **Purpose**:
  - Integrated simulation of burning plasma
  - Interaction between various codes (Universities, NIFS, JAERI)
  - Consistent analysis of phenomena with different time/space scales
- **Activity**: (in consideration)
  - **Level 0**: Development of open-source core code based on TASK
  - **Level 1**: Unified data interface between various codes
    Enhancement and extension of modules
    Parallel processing and grid computing
  - **Level 2**: Innovative model including different time/space scales
  - **Level 3**: Interaction with direct numerical simulation

- **Collaborations:**
  - **Theory group:** New approach
Critical issues
  - **Experimental group:** Experimental data handling
User-oriented interface
  - **Computer science:** New Algorithm
Grid computing
  - **ITPA:** International collaboration
- **Framework:**
  - **Voluntary work** from November 2002
  - **Research collaboration** of NIFS
  - Proposal for **Grant-in-Aid for Scientific Research**