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東京タワーホール船堀

シンポジウム「トーラスプラズマにおける高エネルギー粒子の物理課題」

TASKコードによるアルヴェン固有モード解析と核燃焼プラズマの統合シミュレーション

Integrated Simulation of Alfvén Eigenmode in Burning Plasma by TASK Code

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- はじめに
- TASK コードによるアルヴェン固有モード解析
- 核燃焼プラズマにおけるアルヴェン固有モード解析
- ITER実験の前に取り組む課題
- まとめ

Motivation

- **Stability of Alfvén eigenmode is sensitive to**
  - **Destabilization mechanisms**:
    — Spatial and velocity distribution of energetic particles
  - **Stabilization mechanisms**:
    — Mode structure (q profile)
    — Distribution of bulk particles
- **Integrated analysis is required for consistent analysis**:
  - Coupling with transport analysis
  - Interaction with velocity distribution
  - Finite orbit size effects

TASK Code

- **T**ransport **A**nalysing **S**ystem for Tokama**K**
- **Features**
  - **A Core of Integrated Modeling Code in BPSI**
    - — Modular Structure
    - — Reference Data Interface
  - **Various Heating and Current Drive Scheme**
    - — EC, LH, IC, AW, (NB)
  - **High Portability**
    - — Most of Library Routines Included (except LAPACK and MPI)
  - **Development using CVS** (Concurrent Version System)
    - — Open Source (Pre-release: http://bpsi.nucleng.kyoto-u.ac.jp/task/)
  - **Parallel Processing using MPI Library**
  - **Extension to Toroidal Helical Plasmas**

Modules of TASK

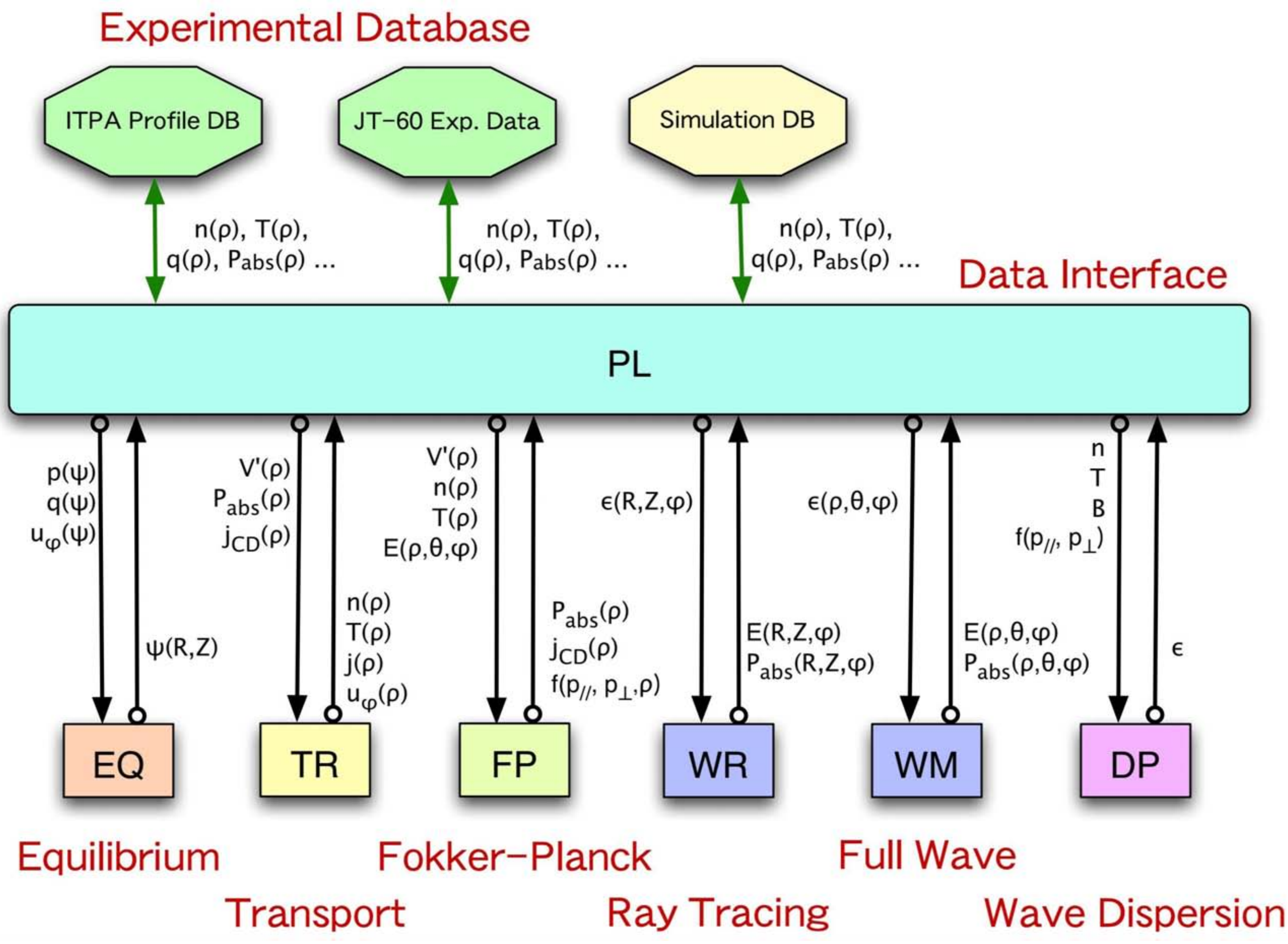
EQ	**2D Equilibrium**	Fixed boundary, Toroidal rotation
TR	**1D Transport**	Diffusive Transport, Transport models
WR	**3D Geometr. Optics**	EC, LH: Ray tracing, Beam tracing
WM	**3D Full Wave**	IC, AW: Antenna excitation, Eigen mode
FP	**3D Fokker-Planck**	Relativistic, Bounce-averaged
DP	**Wave Dispersion**	Local dielectric tensor, Arbitrary $f(\boldsymbol{v})$
PL	**Data Interface**	Data conversion, Profile database
LIB	**Libraries**	

Associated Libraries

GSAF	2D Graphic library for X Window and EPS
GSGL	3D Graphic library using OpenGL

All developed in Kyoto U

Modular Structure of TASK



Full wave analysis: TASK/WM

- **magnetic surface coordinate**: (ψ, θ, φ)
- Boundary-value problem of **Maxwell's equation**

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

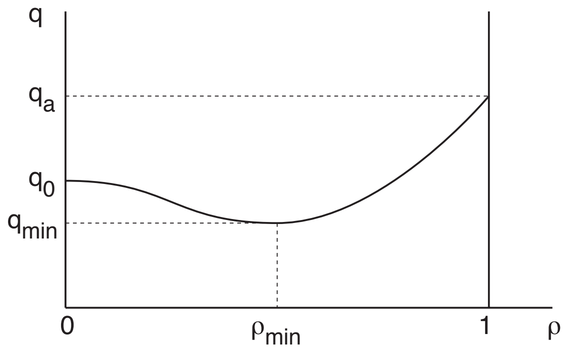
- Kinetic **dielectric tensor**: $\overleftrightarrow{\epsilon}$
  - **Wave-particle resonance**: $Z[(\omega - n\omega_{\mathrm{c}})/k_{\|}v_{\mathrm{th}}]$
  - **Fast ion: Drift-kinetic**

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

- Poloidal and toroidal **mode expansion**
  - **Accurate estimation of $k_{\|}$**
- Eigenmode analysis: **Complex eigen frequency** which maximize wave amplitude for fixed excitation proportional to electron density

Analysis of TAE in Reversed Shear Configuration

Assumed q profile



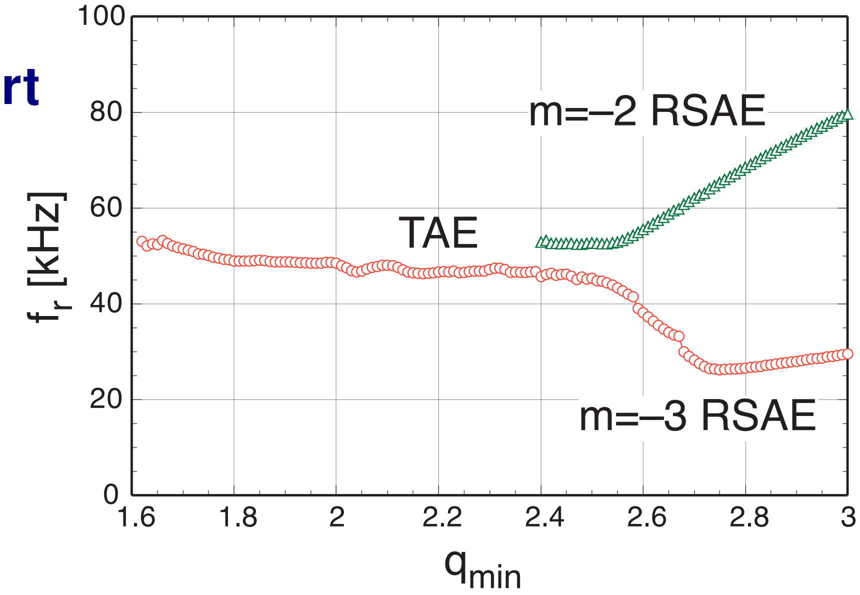
Plasma Parameters

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

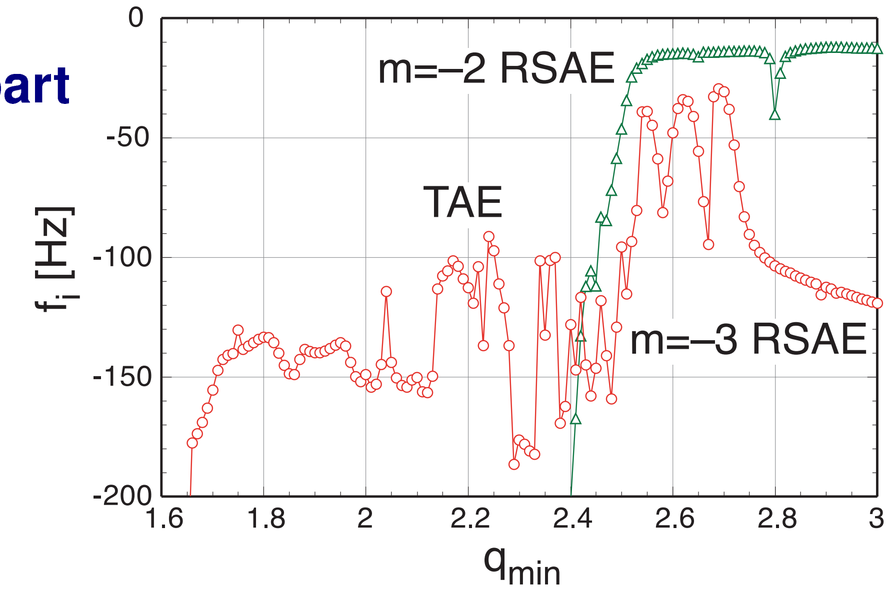
Flat density profile

$q_{\min}$ Dependence of Eigenmode Frequency

Real part



Imag part



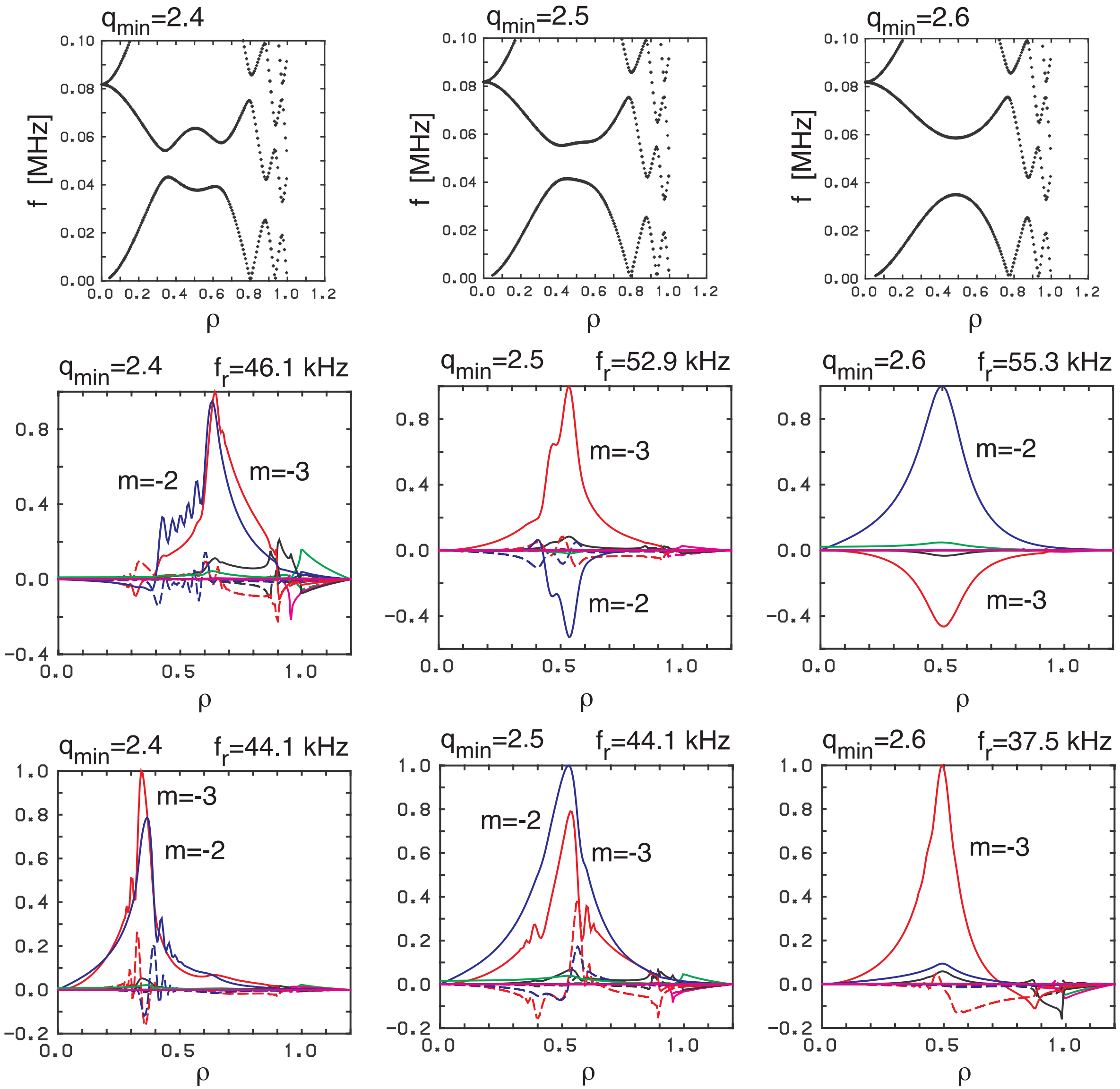
Eigenmode Structure

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

Alfvén resonance

Higher freq.

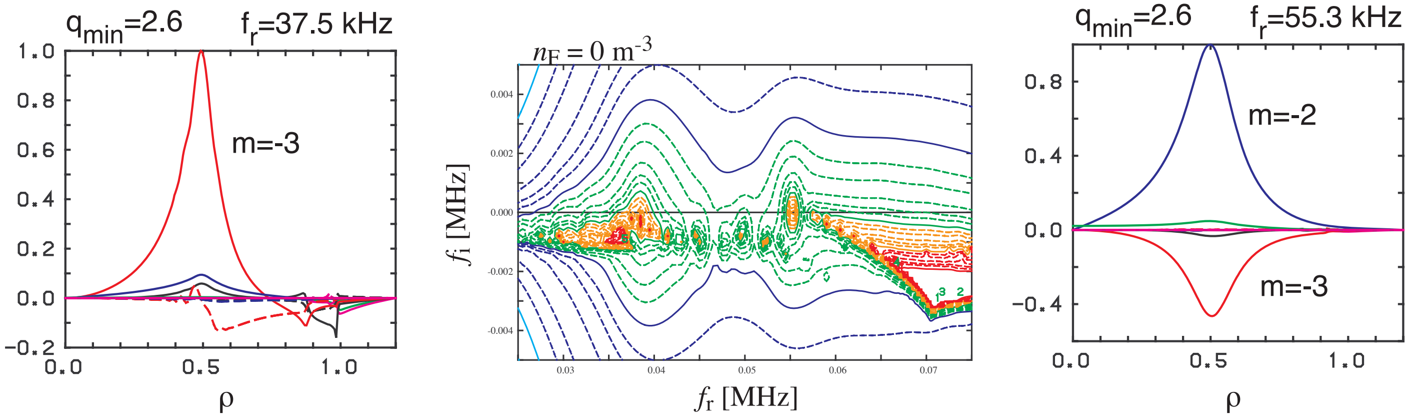
Lower freq.



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

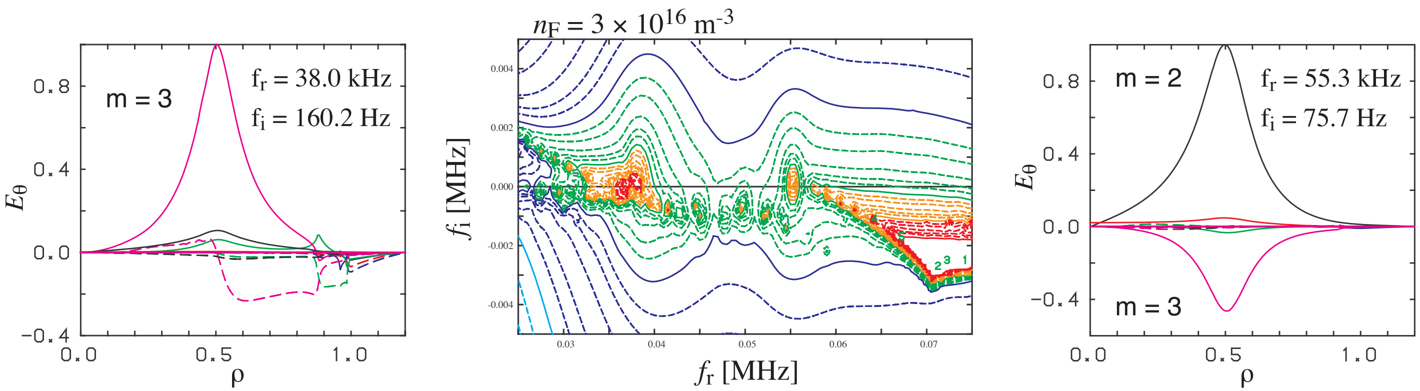
Excitation by Energetic Particles ($q_{\min} = 2.6$)

- Without EP



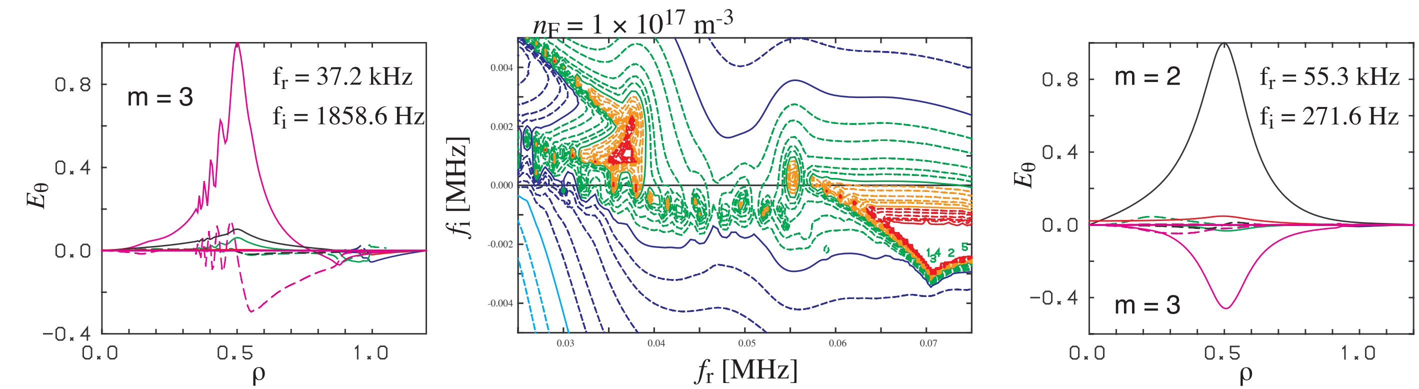
- With EP

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



- With EP

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

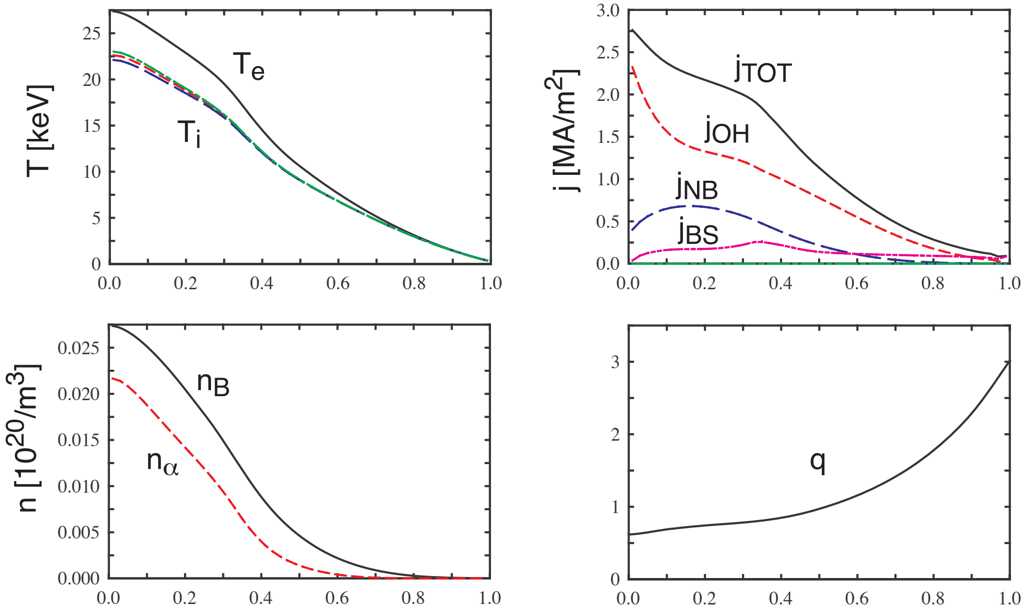


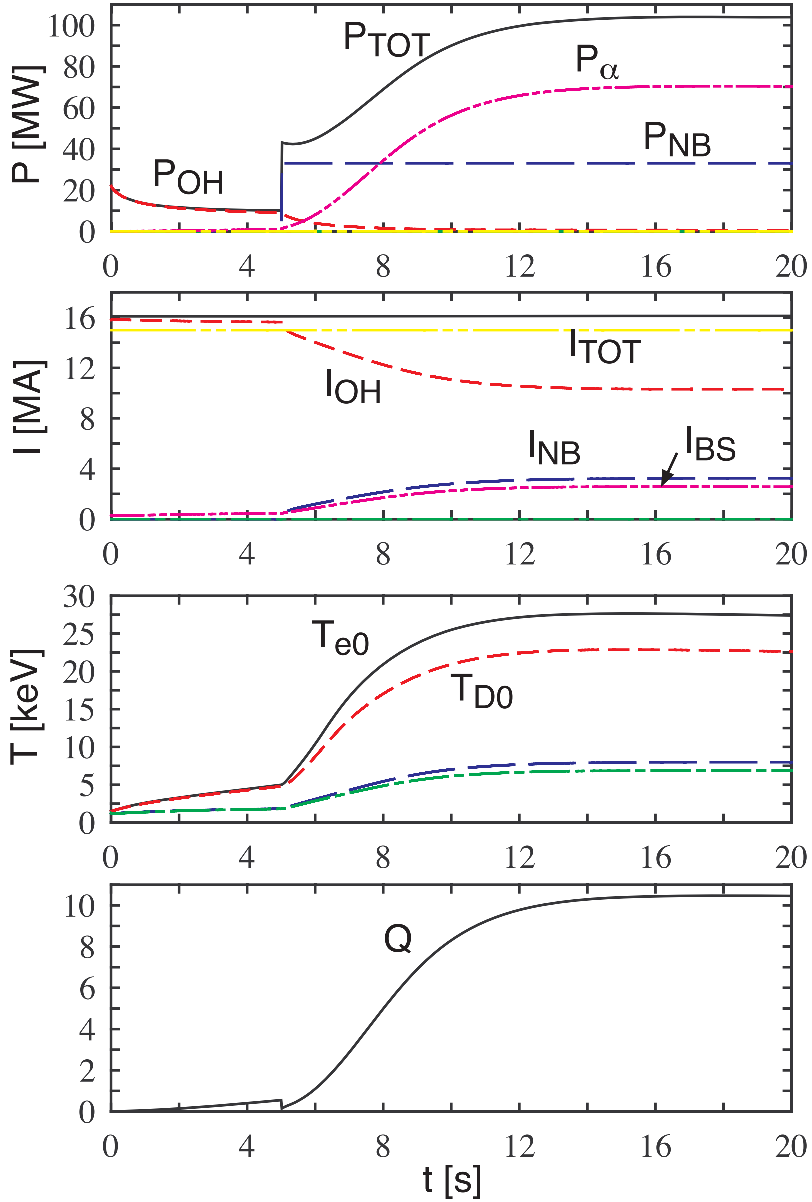
Integrated Analysis of AE in ITER Plasma

- **Combined Analysis**
  - **Equilibrium**: TASK/EQ
  - **Transport**: TASK/TR
    - — Turbulent transport model: CDBM
    - — Neoclassical transport model: NCLASS (**Houlberg**)
    - — Heating and current profile: given profile
  - **Full wave analysis**: TASK/WM
- **Stability analysis**
  - Standard H-mode operation: $I_\mathrm{p} = 15\,\mathrm{MA}$, $Q \sim 10$
  - Hybrid operation: $I_\mathrm{p} = 12\,\mathrm{MA}$, flat q profile above 1
  - Steady-state operation: $I_\mathrm{p} = 9\,\mathrm{MA}$, reversed shear

Standard H-mode Operation

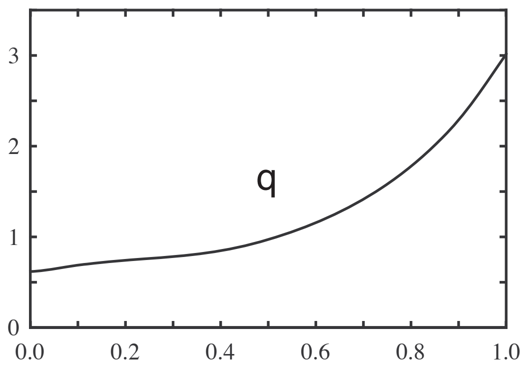
- $I_p = 15\,\mathrm{MA}$
- $P_{NB} = 33\,\mathrm{MW}$
- $\beta_N = 1.3$



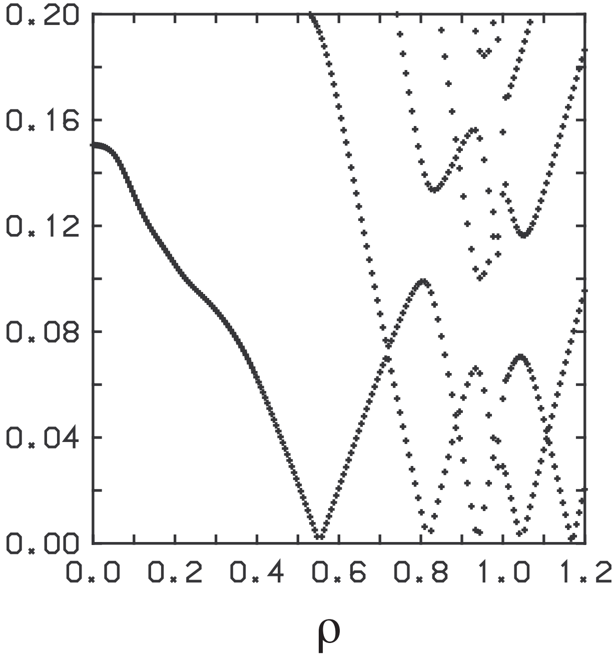


AE in Standard H-mode Operation

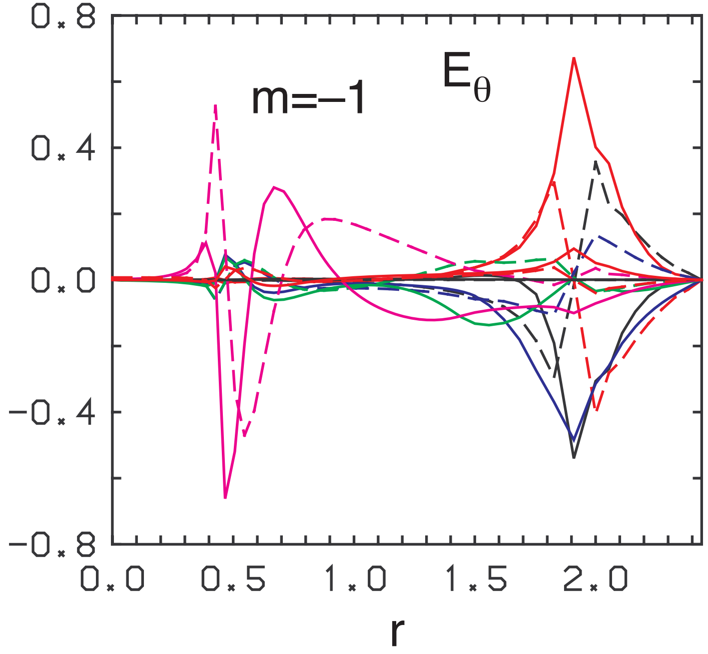
q profile



Alfvén Continuum



Mode structure ($n = 1$)



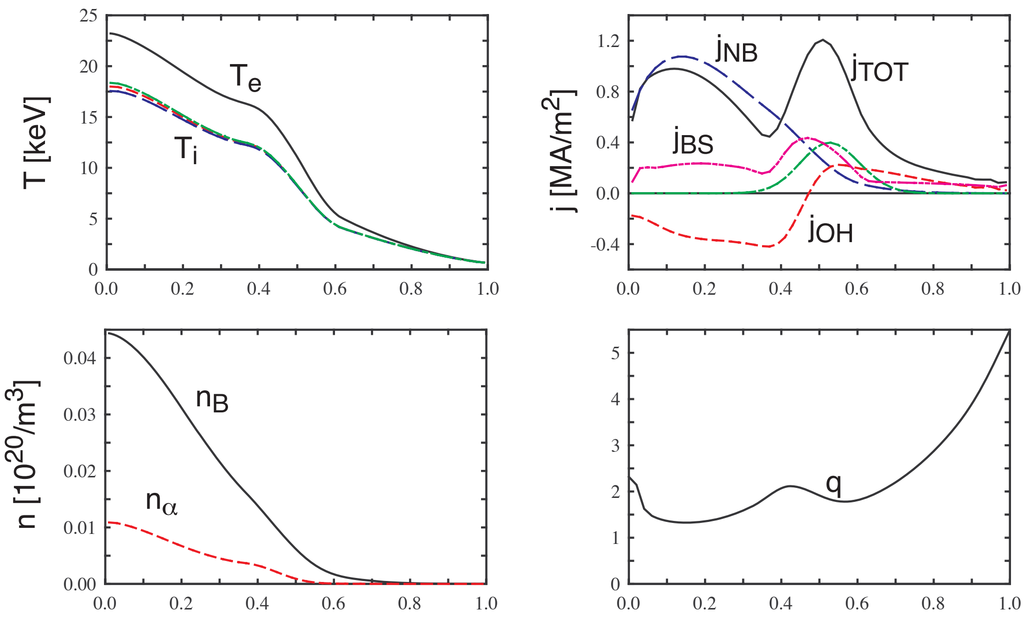
$f_r = 95.95\,\mathrm{kHz}$

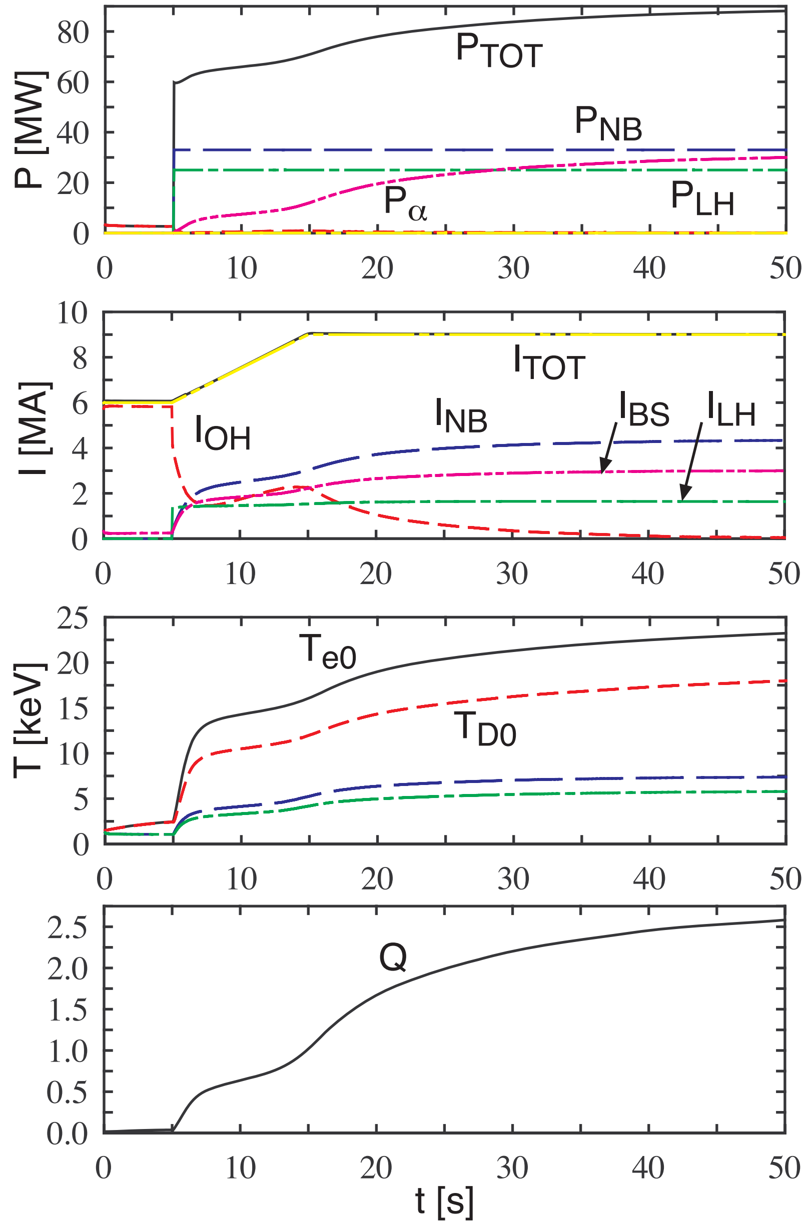
$f_i = -1.95\,\mathrm{kHz}$

Stabilization due to $q = 1$

Steady-State Operation

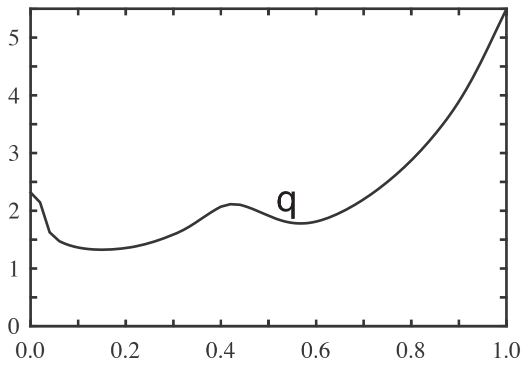
- $I_p = 6 \rightarrow 9\,\mathrm{MA}$
- $P_{NB} = 33\,\mathrm{MW}$
- $P_{LH} = 20\,\mathrm{MW}$
- $Q = 10.4$
- $\beta_N = 1.8$



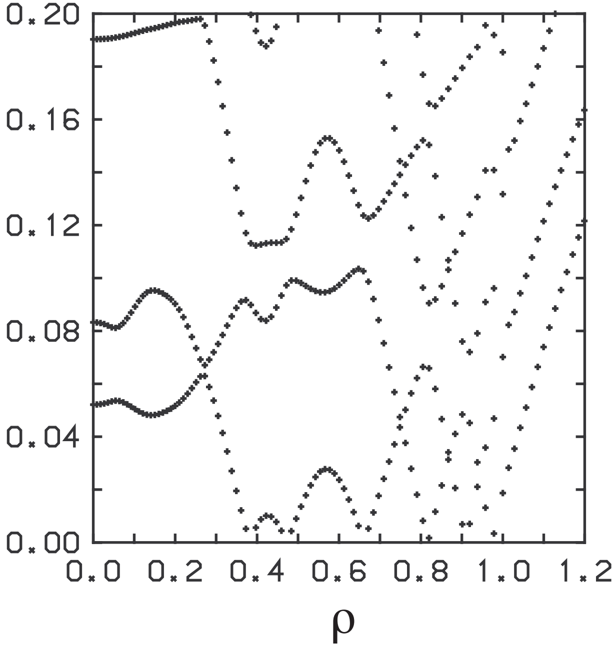


AE in Steady-State Operation

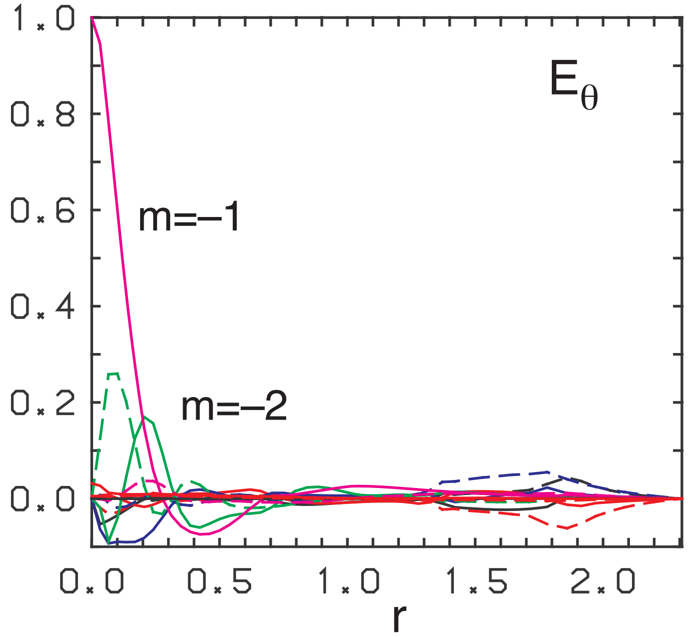
q profile



Alfvén Continuum



Mode structure ($n = 1$)



$$f_r = 109.10\,\text{kHz}$$

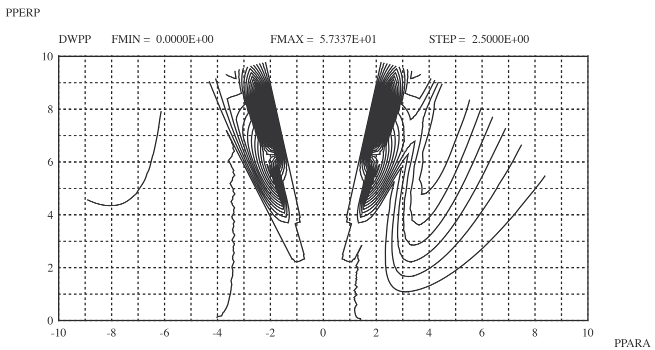
$$f_i = 0.77\,\text{kHz}$$

Unstable core localized mode

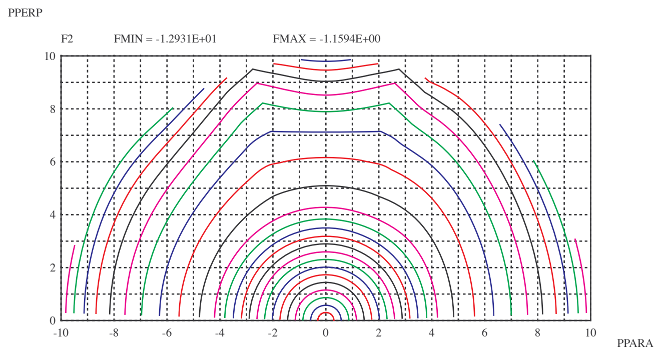
Self-Consistent Full Wave Analysis

- **Deviation of velocity distribution from Maxwellian affects**
  - Absorption of ICRF waves in the presence of energetic ions
  - Stability of modes driven by velocity anisotropy
  - Growth rate of Alfvén eigenmode
- **Systematic analyses including the modification of velocity distribution by TASK code is under way.**
  - **Full wave analysis with arbitrary velocity distribution**
  - **Bounce averaged Fokker-Plank analysis**

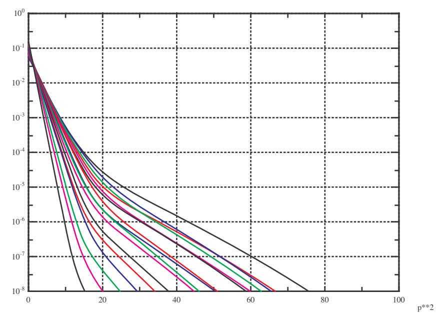
Quasi-linear Diffusion



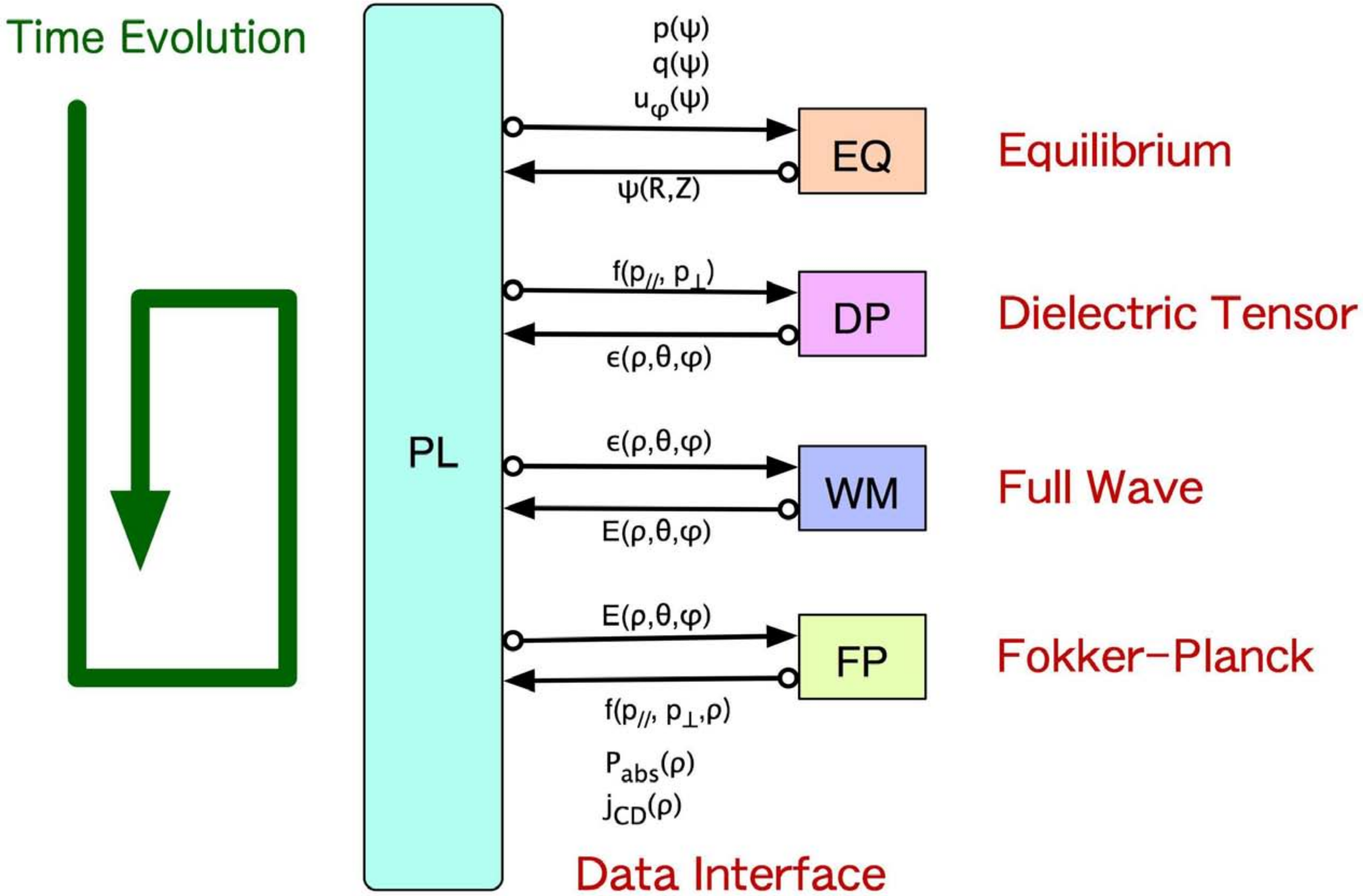
Momentum Distribution



Tail Formation



Procedure of Self-consistent Full Wave Analysis



Integro-Differential Full Wave Analysis

- **Purpose**
  - **FLR effects**
    - — **Existence of energetic particles**
    - — **Cyclotron higher harmonics**
  - **Inhomogeneous k along k**
    - — Landau damping in inhomogeneous plasmas
    - — Cyclotron resonance along the field line

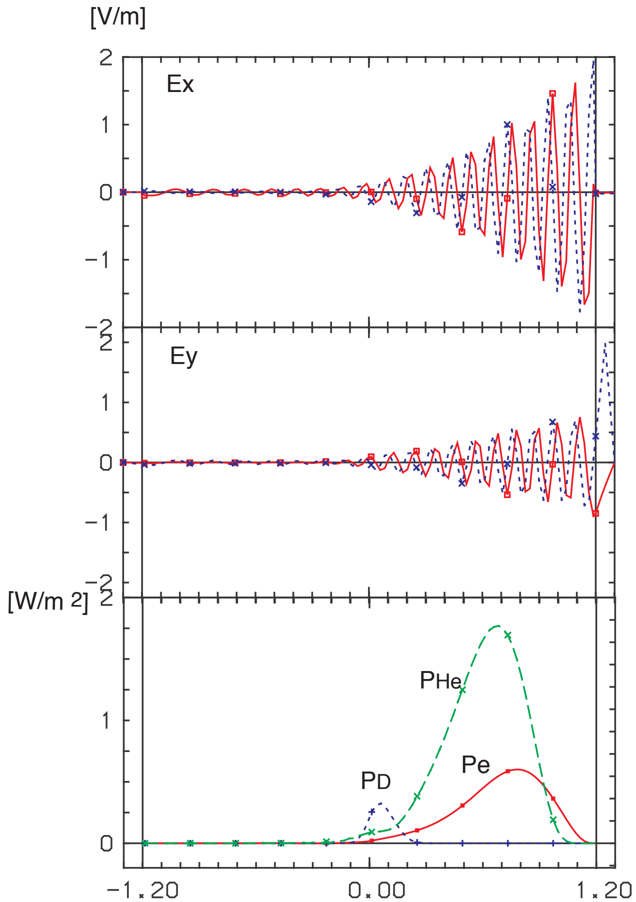
- **Previous analyses: FLR effects**
  - Estimation of $k_\perp$ from fast wave dispersion relation
  - Differential operator up to the second order (**TORIC, old WM, ...**)
  - Spectral expansion in three dimensions (**AORSA**)
  - Integral operator approach (1D)

1D Full Wave Analysis including FLR Effects

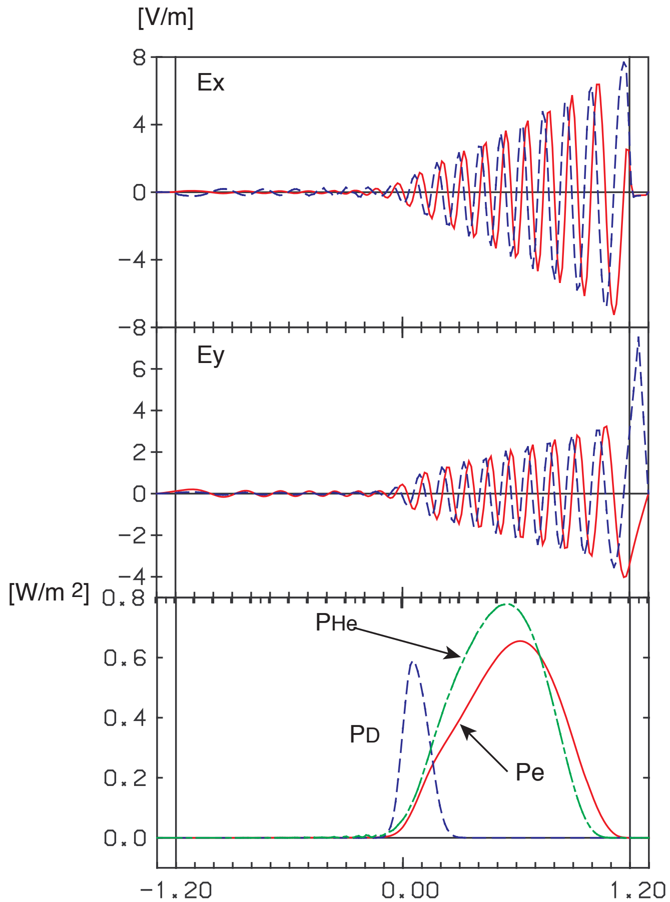
- **Absorption of ICRF wave by α particles:**

  O. Sauter, J. Vaclavik (1992), Y. Uetani, A. Fukuyama (1998)

Differential analysis up to $k_\perp^2 \rho_{\rm H}^2$



Integro-Differential Analysis



Overestimate α absorption

Issues to Be Resolved before ITER Operation

- Systematic stability analyses of AEs in a burning plasma
  - Real geometry including X point and vacuum region
  - Consistent density profile of plasma and energetic ions
  - Consistent velocity distribution of energetic ions
- Coupling with low-frequency drift waves
  - Full gyrokinetic plasma model
  - Integral representation of FLR effects
  - High-n short-wavelength modes
- Interaction with energetic ions
  - Modification of velocity distribution
  - Finite size of drift orbit and orbit loss of energetic ions
- Nonlinear effects

Summary

- One of the targets of the integrated code, TASK, is to consistently analyze the behavior of AE (Alfvén Eigenmodes) driven by energetic particles.

- Coupled with 1-1/2D transport module, TASK/WM was used to study AEs in ITER operation scenarios.

- Self-consistent analysis including modification of $f(v)$
  - Full wave module with arbitrary velocity distribution: OK
  - Fokker-Planck module with full wave electric fields: OK
  - Coupling of the two modules will be completed soon.

- Integro-differential full wave analysis including FLR
  - Formulation was extended to 2D configuration.
  - Implementation is under way.