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Recent Progress in Integrated Modeling of Tokamak Plasmas

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Outline

- Integrated Simulation of Tokamak Plasmas
- Integrated Tokamak Modeling Code TASK
- Self-Consistent Analysis of RF Heating and Current Drive
- Transport Simulation (Diffusive and Dynamic)
- Alfv’en Eigenmode Excited by Energetic Ions
- Summary

Integrated Simulation of Tokamak Plasmas

- **Why needed?**
  - To predict the behavior of burning plasmas in tokamaks
  - To develop reliable and efficient schemes to control them

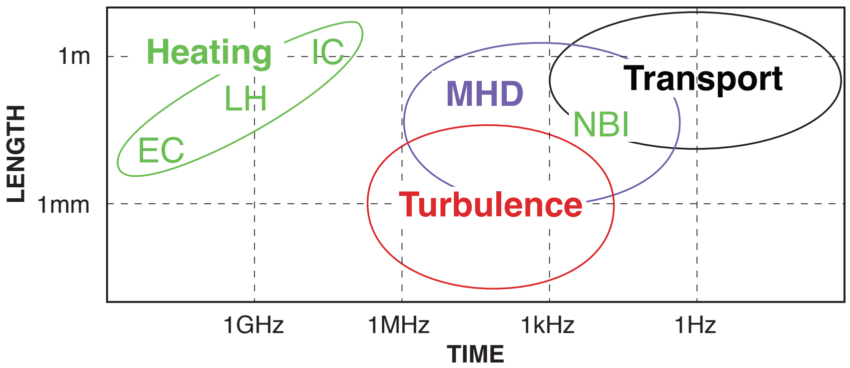
- **What is needed?**
  - **Simulation describing:**
    - — **Whole plasma** (core & edge & divertor & wall-plasma)
    - — **Whole discharge**
      (startup & sustainment & transients events & termination)
    - — **Reasonable accuracy** (validation by experiments)
    - — **Reasonable computer resources** (still limited)

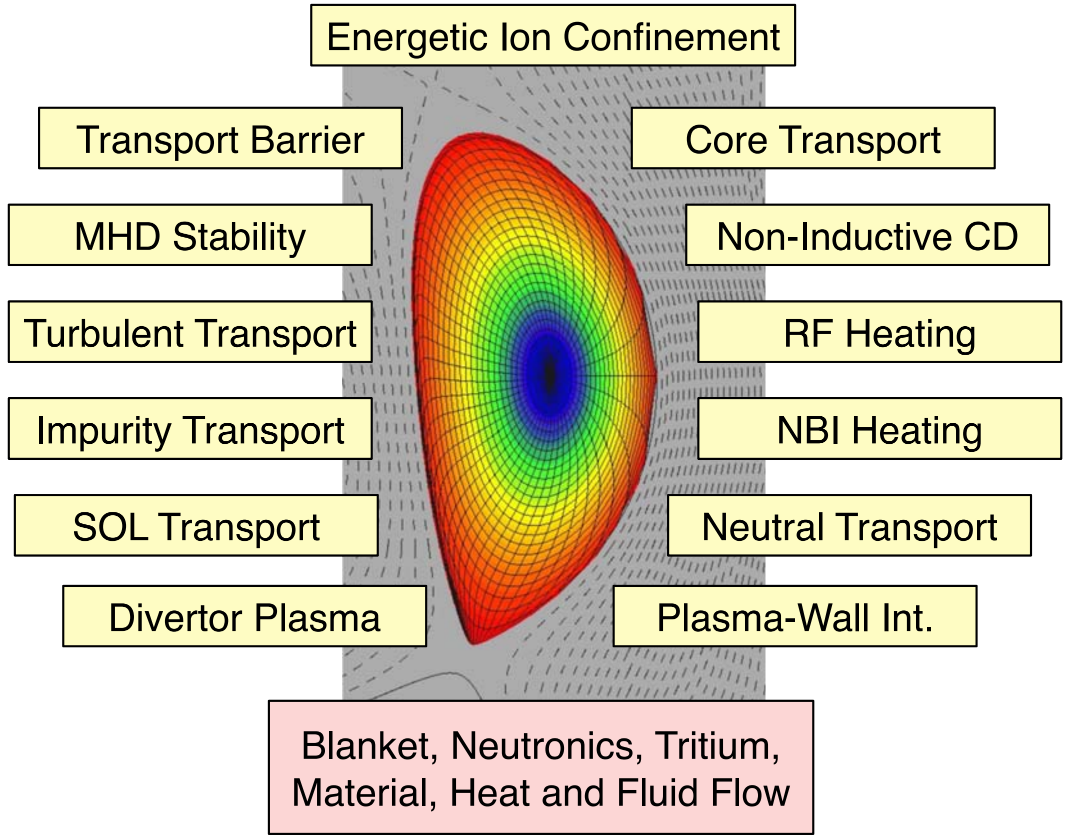
- **How can we do?**
  - Gradual increase of understanding and accuracy
  - Organized development of simulation system

Simulation of Tokamak Plasmas

Broad time scale:
100GHz $\sim$ 1000s

Broad Spatial scale:
10 μm $\sim$ 10m

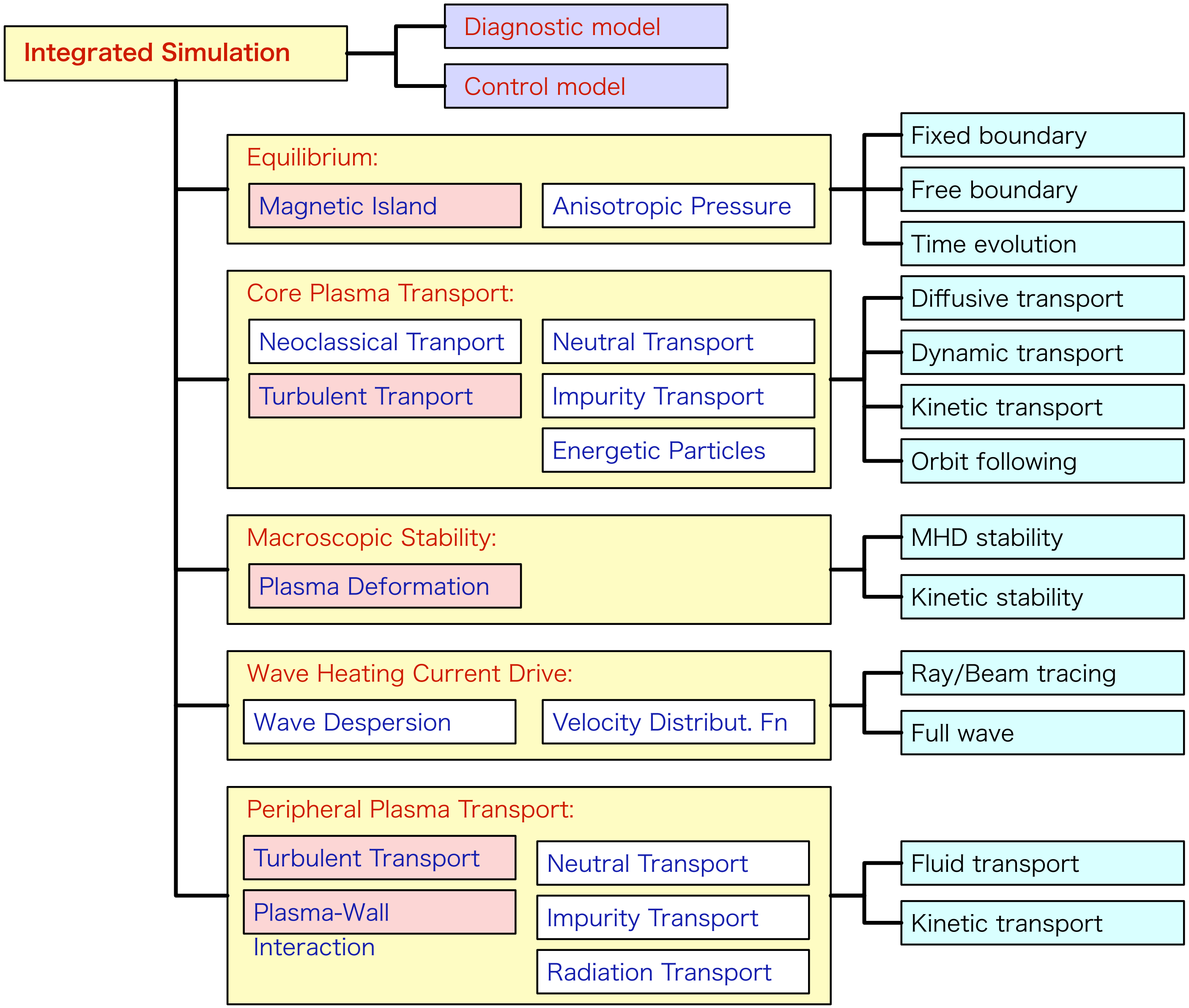




One simulation code never covers all range.

Integrated simulation combining modeling codes interacting each other

Integrated Tokamak Simulation



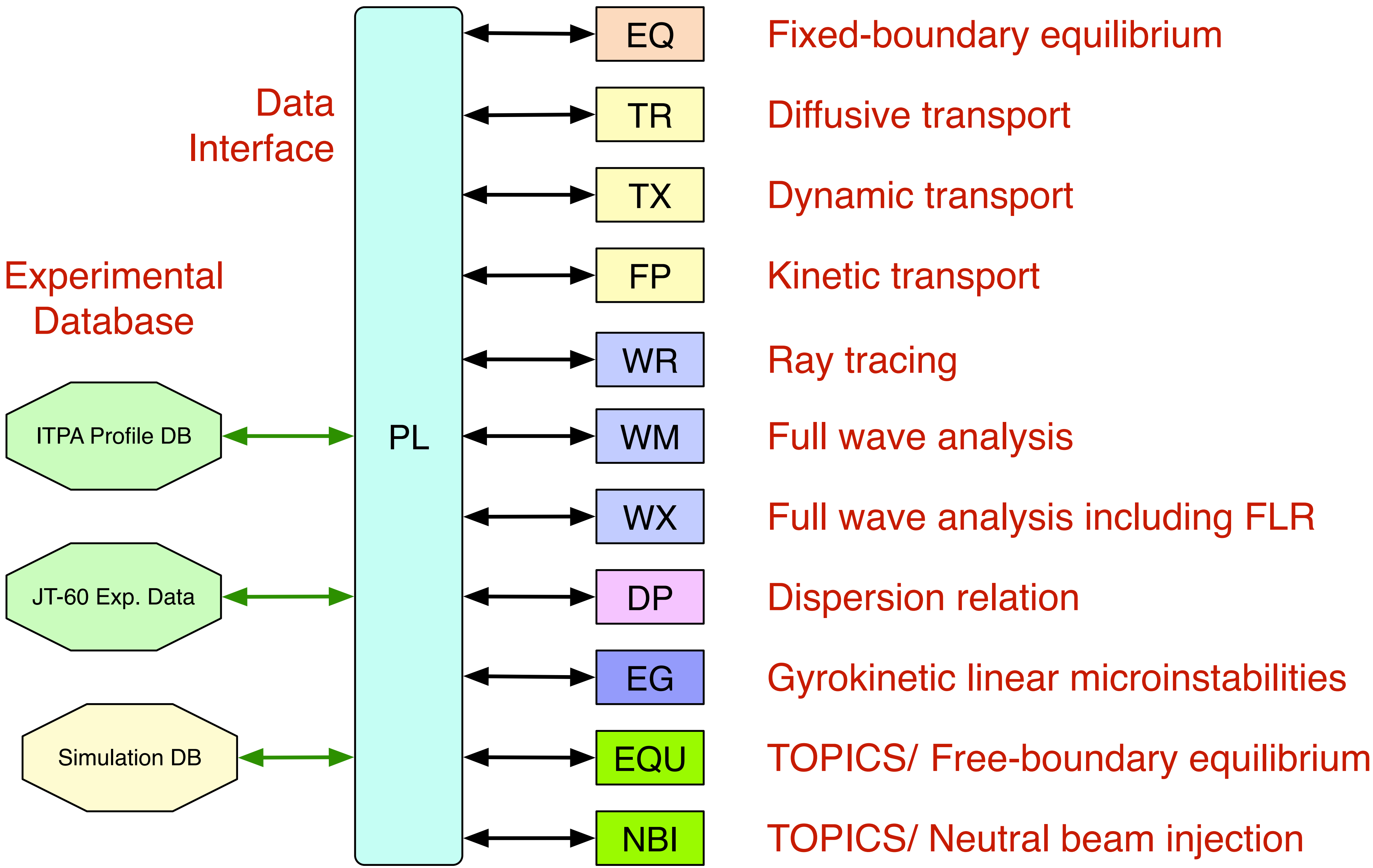
International Activities for Integrated Modeling

- **JAPAN**: Burning Plasma Simulation Initiative (BPSI)
  - **TASK**: Kyoto University
  - **TOPICS-IB**: JAEA (Japan Atomic Energy Agency)
- **EU**: Integrated Tokamak Modelling Task Force (ITM-TF) of EFDA
  - **The Code Platform Project** (CPP): Code integration, End user tools
  - **The Data Coordination Project** (DCP): Data structure, Validation
  - **Five Integrated Modelling Projects** (IMPs):
    - Equilibrium, MHD, Transport, Turbulence, Actuators
- **US**: Scientific Discovery through Advanced Computing (SciDAC)
  - **Integrated simulation of magnetic fusion systems**
    - Wave+MHD, Plasma Edge, Turbulence, Extended MHD, Wave-Plasma
- **ITER**: ITPA-CDBM-IMAGE WG: to be started

TASK Code

- **Transport Analysing System for TokamaK**
- **Features**
  - **Core of Integrated Modeling Code in BPSI**
    - **Modular structure**
    - **Reference data interface and standard data set**
    - **Uniform user interface**
  - **Various Heating and Current Drive Scheme**
  - **High Portability**
  - **Development using CVS** (Concurrent Version System)
  - **Open Source**: **http://bpsi.nucleng.kyoto-u.ac.jp/task/**
  - **Parallel Processing using MPI Library**
  - **Extension to Toroidal Helical Plasmas**

Structure of TASK



Interface between Modules: TASK/PL

- **Role of Module Interface**
  - **Data exchange between modules**:
    - — **Standard dataset**: Specify set of data (cf. ITPA profile DB)
    - — **Specification of data exchange interface**: initialize, set, get
  - **Execution control**:
    - — **Specification of execution control interface**: initialize, setup, exec, visualize, terminate
    - — **Uniform user interface**: parameter input, graphic output
- **Role of data exchange interface: TASK/PL**
  - **Keep present status of plasma and device**
  - **Store history of plasma**
  - **Save into file and load from file**
  - **Interface to experimental data base**

Standard Dataset (at present)

Shot data

Machine ID, Shot ID, Model ID

Device data: (Level 1)

RR	R	m	Geometrical major radius
RA	a	m	Geometrical minor radius
RB	b	m	Wall radius
BB	B	T	Vacuum toroidal mag. field
RKAP	κ		Elongation at boundary
RDLT	δ		Triangularity at boundary
RIP	I_p	A	Typical plasma current

Equilibrium data: (Level 1)

PSI2D	$\psi_\mathrm{p}(R,Z)$	Tm^2	2D poloidal magnetic flux
PSIT	$\psi_\mathrm{t}(\rho)$	Tm^2	Toroidal magnetic flux
PSIP	$\psi_\mathrm{p}(\rho)$	Tm^2	Poloidal magnetic flux
ITPSI	$I_\mathrm{t}(\rho)$	Tm	Poloidal current: $2\pi B_\phi R$
IPPSI	$I_\mathrm{p}(\rho)$	Tm	Toroidal current
PPSI	$p(\rho)$	MPa	Plasma pressure
QINV	$1/q(\rho)$		Inverse of safety factor

Metric data

1D: $V'(\rho)$, $\langle\nabla V\rangle(\rho)$, $\cdots$

2D: g_{ij}, $\cdots$

3D: g_{ij}, $\cdots$

Fluid plasma data

NSMAX	s		Number of particle species
PA	A_s		Atomic mass
PZ0	Z_{0s}		Charge number
PZ	Z_s		Charge state number
PN	$n_s(\rho)$	m^3	Number density
PT	$T_s(\rho)$	eV	Temperature
PU	$u_{s\phi}(\rho)$	m/s	Toroidal rotation velocity
QINV	$1/q(\rho)$		Inverse of safety factor

Kinetic plasma data

FP	$f(p,\theta_p,\rho)$		momentum dist. fn at $\theta=0$

Dielectric tensor data

CEPS	$\overleftrightarrow{\epsilon}(\rho,\chi,\zeta)$		Local dielectric tensor

Full wave field data

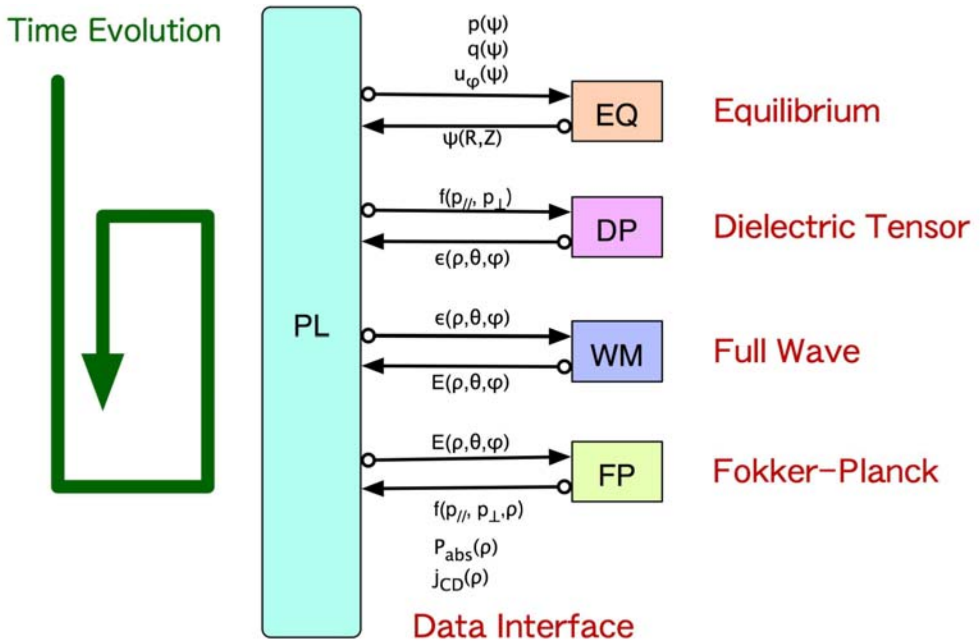
CE	$\boldsymbol{E}(\rho,\chi,\zeta)$	V/m	Complex wave electric field
CB	$\boldsymbol{B}(\rho,\chi,\zeta)$	$\mathrm{Wb/m}^2$	Complex wave magnetic field

Ray/Beam tracing field data

RRAY	$R(\ell)$	m	R of ray at length ℓ
ZRAY	$Z(\ell)$	m	Z of ray at length ℓ
PRAY	$\phi(\ell)$	rad	ϕ of ray at length ℓ
CERAY	$\boldsymbol{E}(\ell)$	V/m	Wave electric field at length ℓ
PWRAY	$\boldsymbol{P}(\ell)$	W	Wave power at length ℓ
DRAY	$\boldsymbol{d}(\ell)$	m	Beam radius at length ℓ
VRAY	$\boldsymbol{v}(\ell)$	1/m	Beam curvature at length ℓ

Self-Consistent Wave Analysis with Modified $f(v)$

- **Modification of velocity distribution from Maxwellian**
  - Absorption of ICRF waves in the presence of energetic ions
- **Self-consistent wave analysis including modification of $f(v)$**

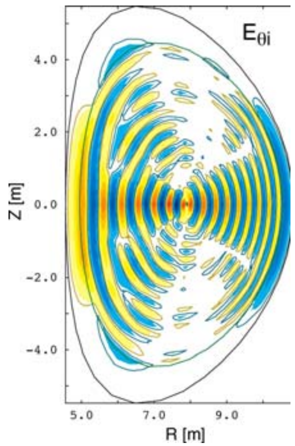


DP	Dielectric tensor for arbitrary $f(v)$	$\overleftrightarrow{\epsilon}(\omega, \boldsymbol{k}; \boldsymbol{r})$
WM	Full wave analysis with the dielectric tensor	$\boldsymbol{E}(\boldsymbol{r})$
FP	Fokker-Plank analysis with the wave field	$f(\boldsymbol{v})$
loop	Self-consistent iterative analysis	

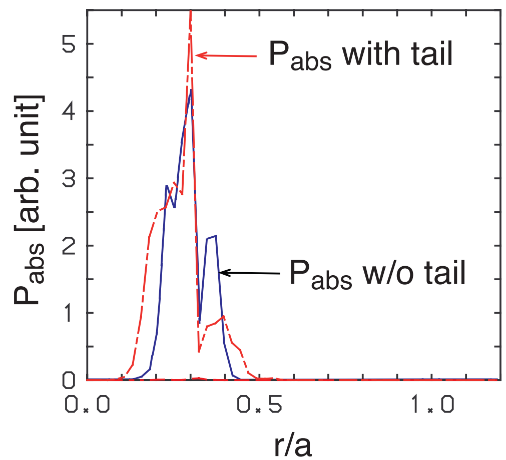
Self-Consistent Analysis of ICRF Minority Heating

- **Energetic ion tail formation**
  - **Broadening of power deposition profile**

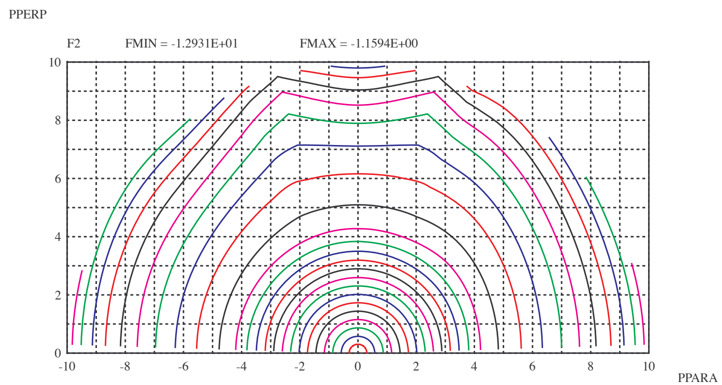
Wave Structure



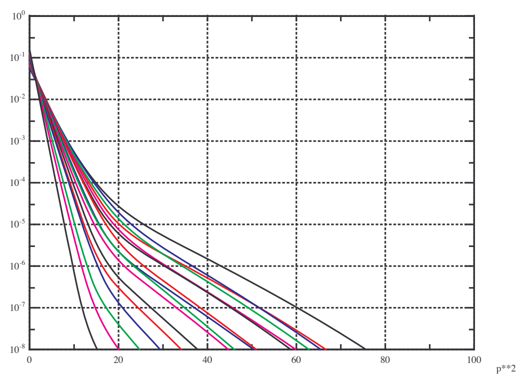
Power deposition



Momentum Distribution



Tail Formation



Level of Transport Simulation

- **Diffusive transport equation**: **TASK/TR**
  - Diffusion equation for plasma density
  - Flux-Gradient relation
  - Conventional transport analysis
- **Dynamical transport equation: TASK/TX**:
  - Continuity equation and equation of motion for plasma density
  - Flux-averaged fluid equation
  - Plasma rotation and transient phenomena
- **Kinetic transport equation: TASK/FP**:
  - Gyrokinetic equation for momentum distribution function
  - Bounce-averaged Fokker-Plank equation
  - Modification of momentum distribution

Diffusive Transport Analysis: TASK/TR

- **Transport Equation Based on Gradient-Flux Relation**
  - **Multi thermal species**: e.g. Electron, D, T, He
    — Density, thermal energy, (toroidal rotation)
  - **Two beam components**: Beam ion, Energetic α
    — Density, toroidal rotation
  - **Neutral**: Two component (cold and hot), Diffusion equation
  - **Impurity**: Thermal species or fixed profile
- **Transport Model**
  - **Neoclassical**: Wilson, Hinton & Hazeltine, Sauter, NCLASS
  - **Turbulent**: CDBM (current diffusive ballooning mode), GLF23 (V1.61), IFS/PPPL, Weiland
- **Interface to Experimental Data**
  - UFILE (ITPA profile DB)

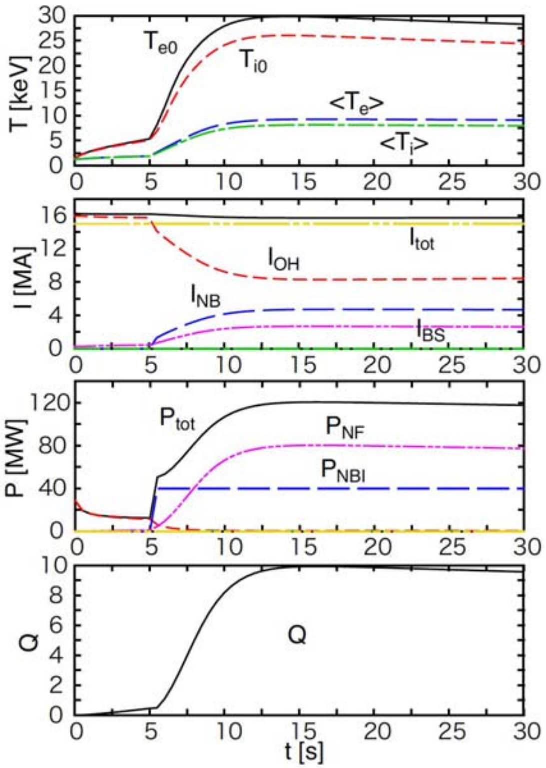
Heat Transport Simulation of ITER Scenarios

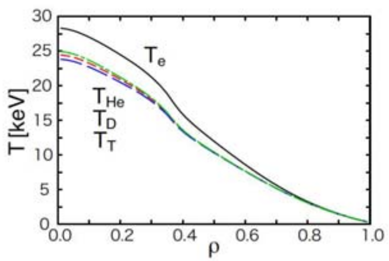
High Performance Scenario

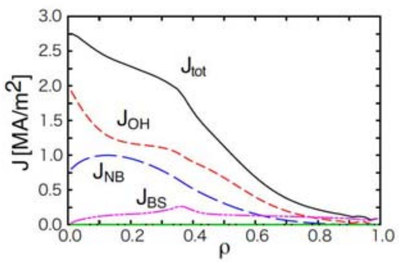
CDBM05

$\beta_N = 1.88$

$\tau_E = 3.0$ s





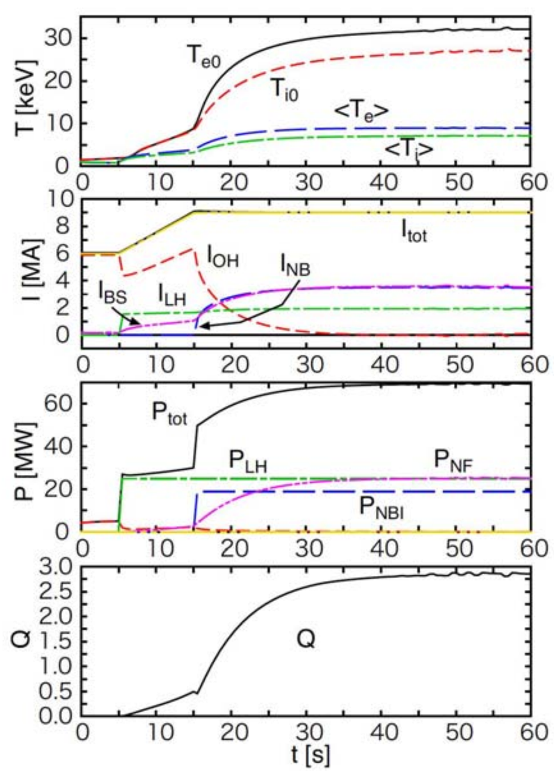


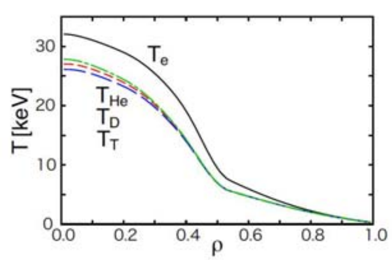
Steady State Scenario

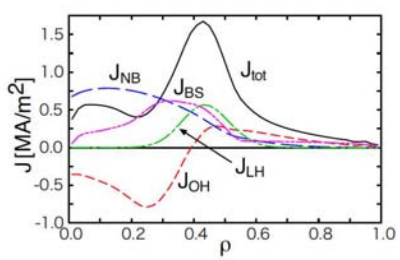
CDBM05

$\beta_N = 1.8$

$\tau_E = 3.1$ s







1D Dynamic Transport Code: TASK/TX

- **Dynamic Transport Equations** (TASK/TX)

  M. Honda and A. Fukuyama, submitted to JCP

  - **A set of flux-surface averaged equations**
  - **Two fluid equations for electrons and ions**
    - Continuity equations
    - Equations of motion (radial, poloidal and toroidal)
    - Energy transport equations
  - **Maxwell's equations**
  - **Slowing-down equations for beam ion component**
  - **Diffusion equations for two-group neutrals**

Transport Model

- **Neoclassical transport**
  - Parallel viscous force due to a poloidal plasma rotation

$$F_{s\theta}^{\mathrm{NC}} \equiv -n_s m_s \nu_{\mathrm{NC}s} u_{s\theta} = -\frac{\langle B^2 \rangle \hat{\mu}_{11}^{si}}{n_s m_s B_\theta^2} n_s m_s u_{s\theta}$$

  $\hat{\mu}_{11}^{si}$: viscosity coefficient from the NCLASS module
  - **Diffusion, resistivity, Ware pinch and bootstrap current**
- **Turbulent diffusion**
  - Poloidal momentum exchange between electrons and ions
  - Intrinsic ambipolar flux (electron particle flux = ion particle flux)

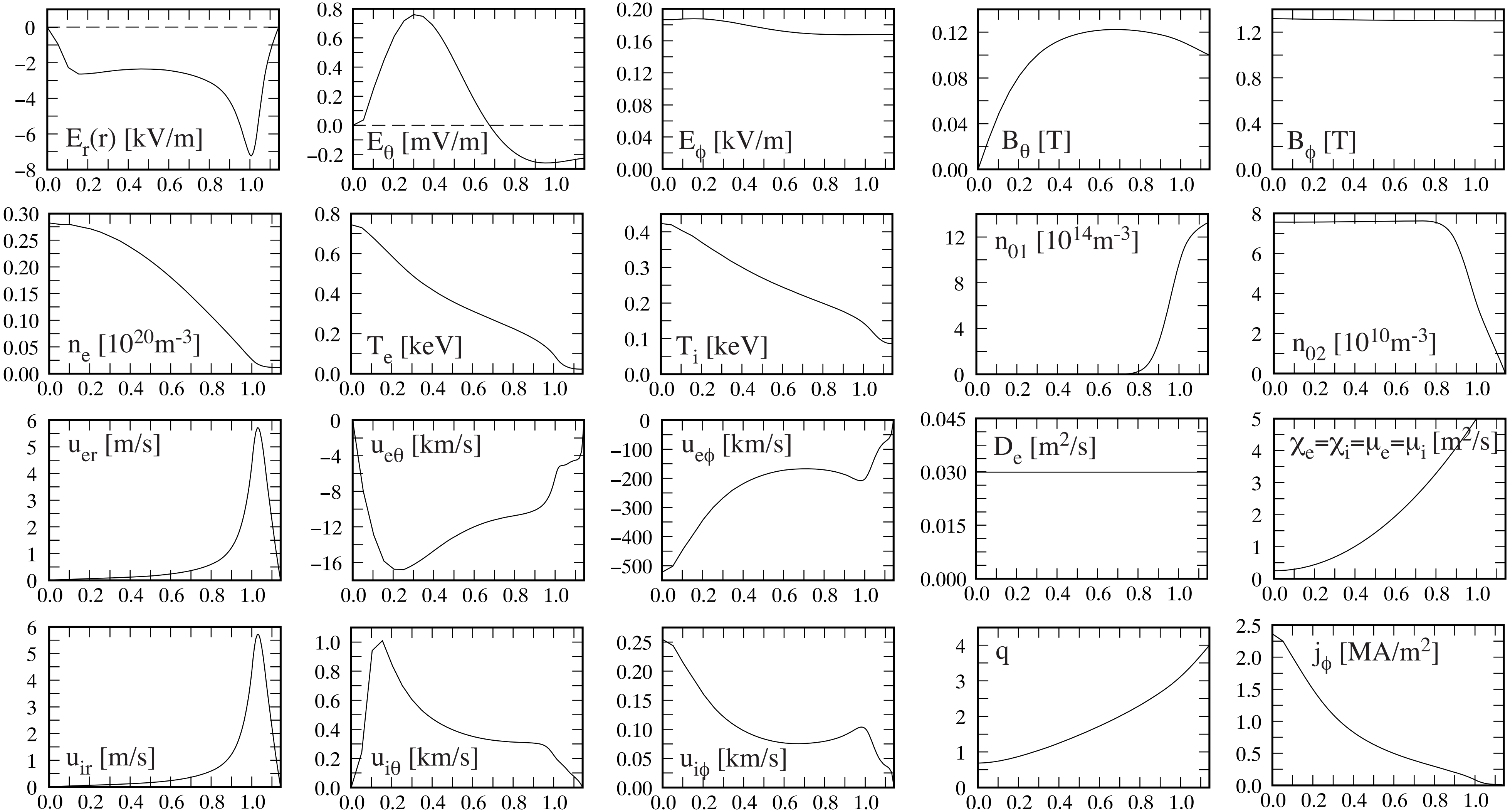
$$F_{\mathrm{e}\theta}^{\mathrm{W}} = -F_{\mathrm{i}\theta}^{\mathrm{W}} = -\frac{e^2 B_\phi^2 D_{\mathrm{e}}}{T_{\mathrm{e}}} n_{\mathrm{e}} \left(u_{\mathrm{e}\theta} - \frac{B_\theta}{B_\phi} u_{\mathrm{e}\phi} \right)$$

- **Perpendicular viscosity**: **Non-ambipolar particle flux**

Typical Ohmic Plasma Profiles at t = 50 ms

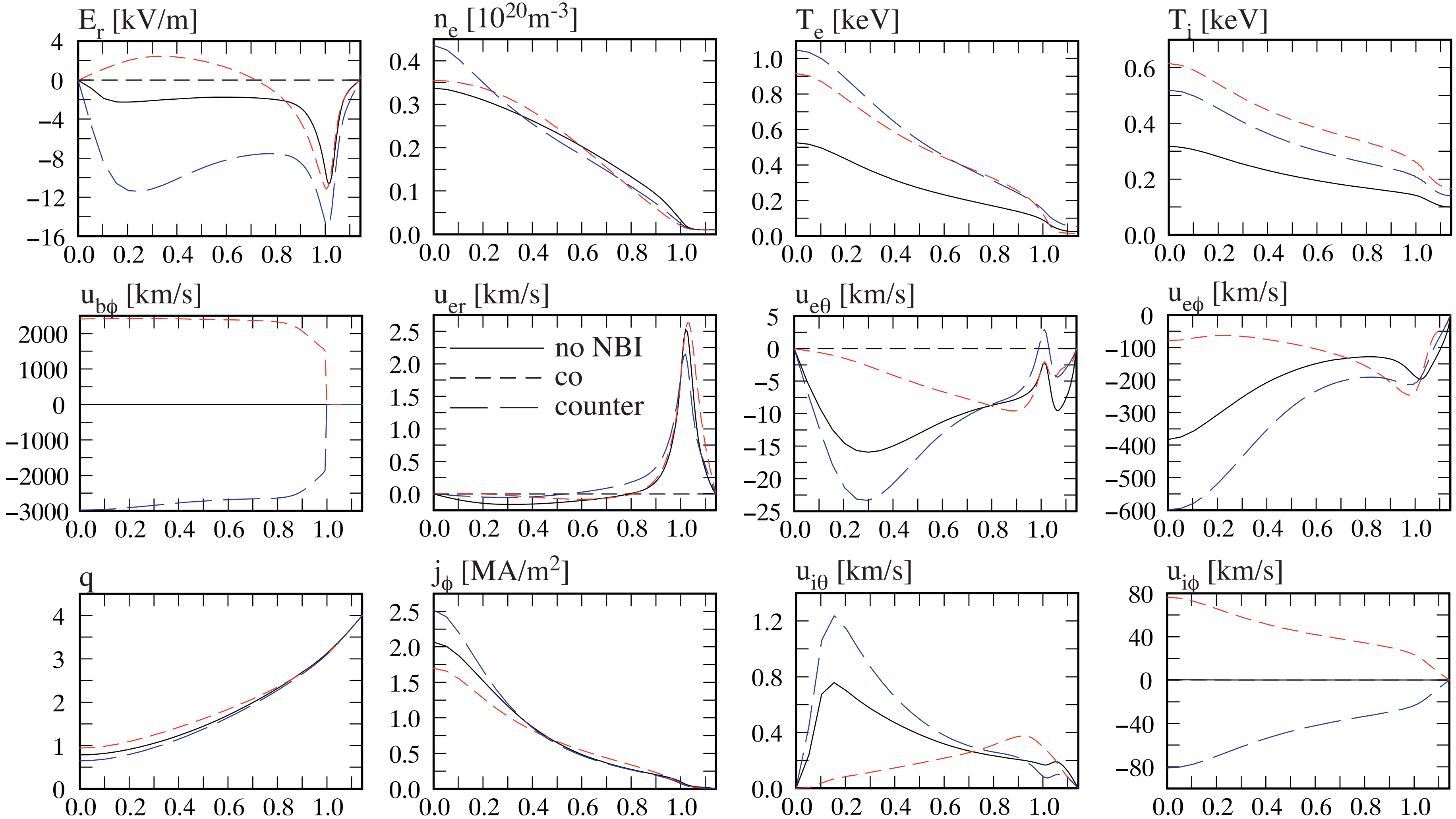
- **JFT-2M like plasma** composed of electron and hydrogen

$R = 1.3\,\mathrm{m},\ a = 0.35\,\mathrm{m},\ b = 0.4\,\mathrm{m},\ B_{\phi b} = 1.3\,\mathrm{T},\ I_p = 0.2\,\mathrm{MA},\ S_{\mathrm{puff}} = 5.0 \times 10^{18}\,\mathrm{m^{-2}s^{-1}}$



Density Profile Modification due to NBI Injection

- Modification of n and E_r profile depending on the direction of NBI, viz. $u_{i\phi}$
  - Co:Density flattening
  - Counter:Density peaking

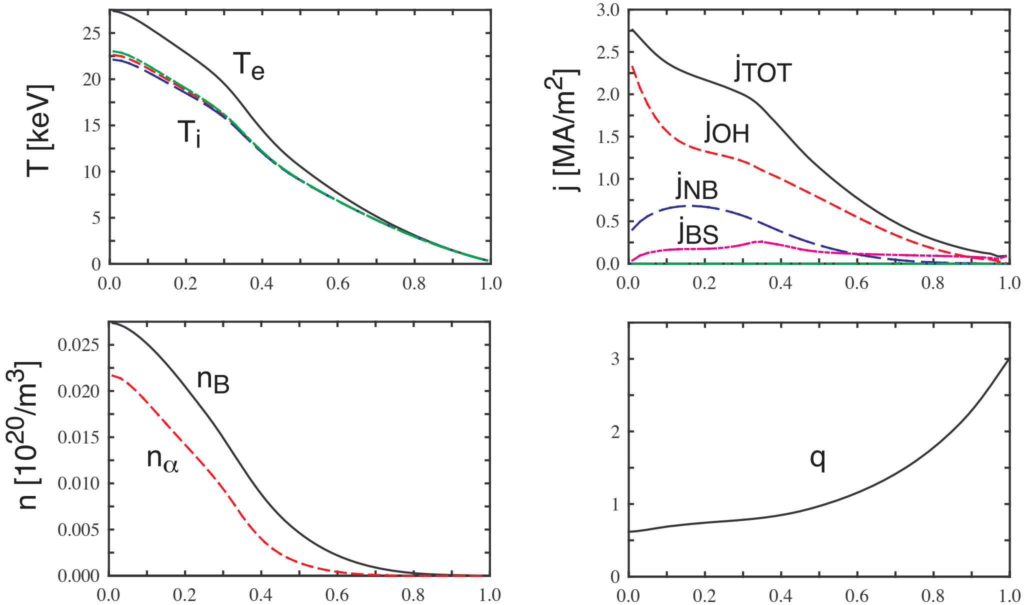


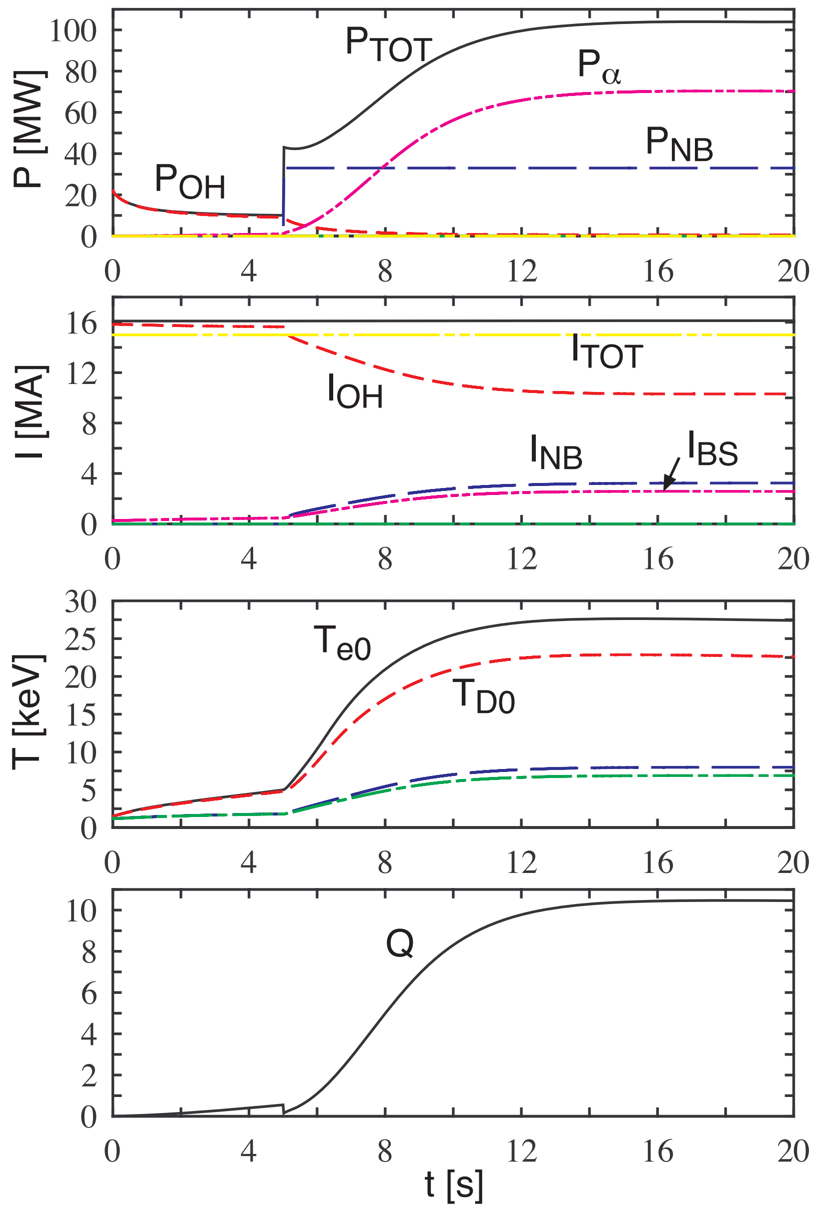
Integrated Analysis of Alfvén Eigen Mode

- **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
    - Excitation by energetic alpha particles
    - Damping at the Alfvén resonance
- **Stability analysis**
  - High Performance Scenario: $I_\mathrm{p} = 15\,\mathrm{MA}$, $Q \sim 10$

ITER High Performance Scenario

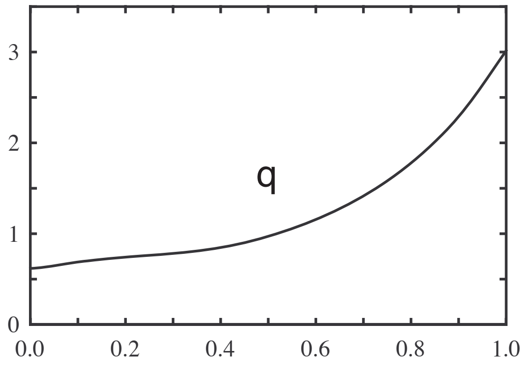
- $I_p = 15\,\mathrm{MA}$
- $P_{NB} = 33\,\mathrm{MW}$
- $\beta_N = 1.3$



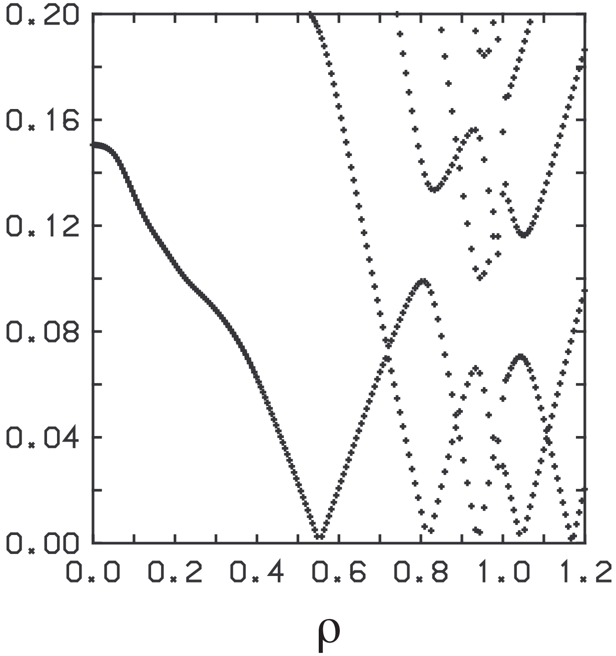


AE in High Performance Scenario

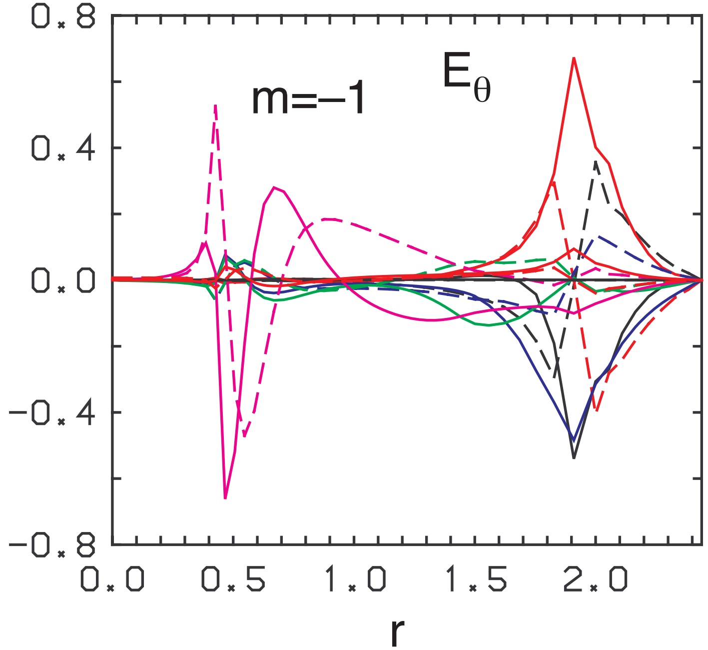
q profile



Alfvén Continuum



Mode structure ($n = 1$)



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

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

Stabilization due to $q = 1$

Road map of TASK code

	Present Status	In 2 years	In 5 years
Equlibrium	Fixed/Free Boundary	Equilibrium Evolution	Start Up Analysis
Core Transport	1D Diffusive TR	Kinetic TR	2D Fluid TR
	1D Dynamic TR		
SOL Transport		2D Fluid TR	Plasma-Wall Interaction
Neutral Tranport	1D Diffusive TR	Orbit Following	
Energetic Ions	Kinetic Evolution	Orbit Following	
Wave Beam	Ray/Beam Tracing	Beam Propagation	
Full Wave	Kinetic ϵ	Gyro Integral ϵ	Orbit Integral ϵ
Stabilities	Sawtooth Osc.	Tearing Mode	Systematic Stability Analysis
	ELM Model	Resistive Wall Mode	
Turbulent Transport	CDBM Model	Linear GK + ZF	Nonlinear ZK + ZF
		Diagnostic Module	
		Control Module	

Summary

- It is necessary to develop **integrated tokamak simulation code** to predict the behavior of burning plasmas in ITER.
- We are developing an integrated code, **TASK**, as a reference core code for BPSI activity in Japan.
- We have shown several examples of **integrated analysis**
  - Self-consistent analysis of ICRF heating
  - Integrated simulation of ITER scenarios
  - Density profile modification due to the NBI injection
  - Analysis of Alfv'en eigenmode in a ITER plasma
- Further continuous development of integrated modeling is needed for **comprehensive ITER simulation**.