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Kyoto Terrsa
2006/03/07

Present Status and Future of Simulation Research on Burning Plasmas

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- Introduction
- BPSI/TASK
- Simulation of burning plasmas
- Summary

Burning Plasma Research

How to create burning plasmas?

good confinement

sufficient stability

efficient heating

What is new in burning plasmas?

highly autonomous

energetic particles

high heat flux

How to control burning plasmas?

burning control

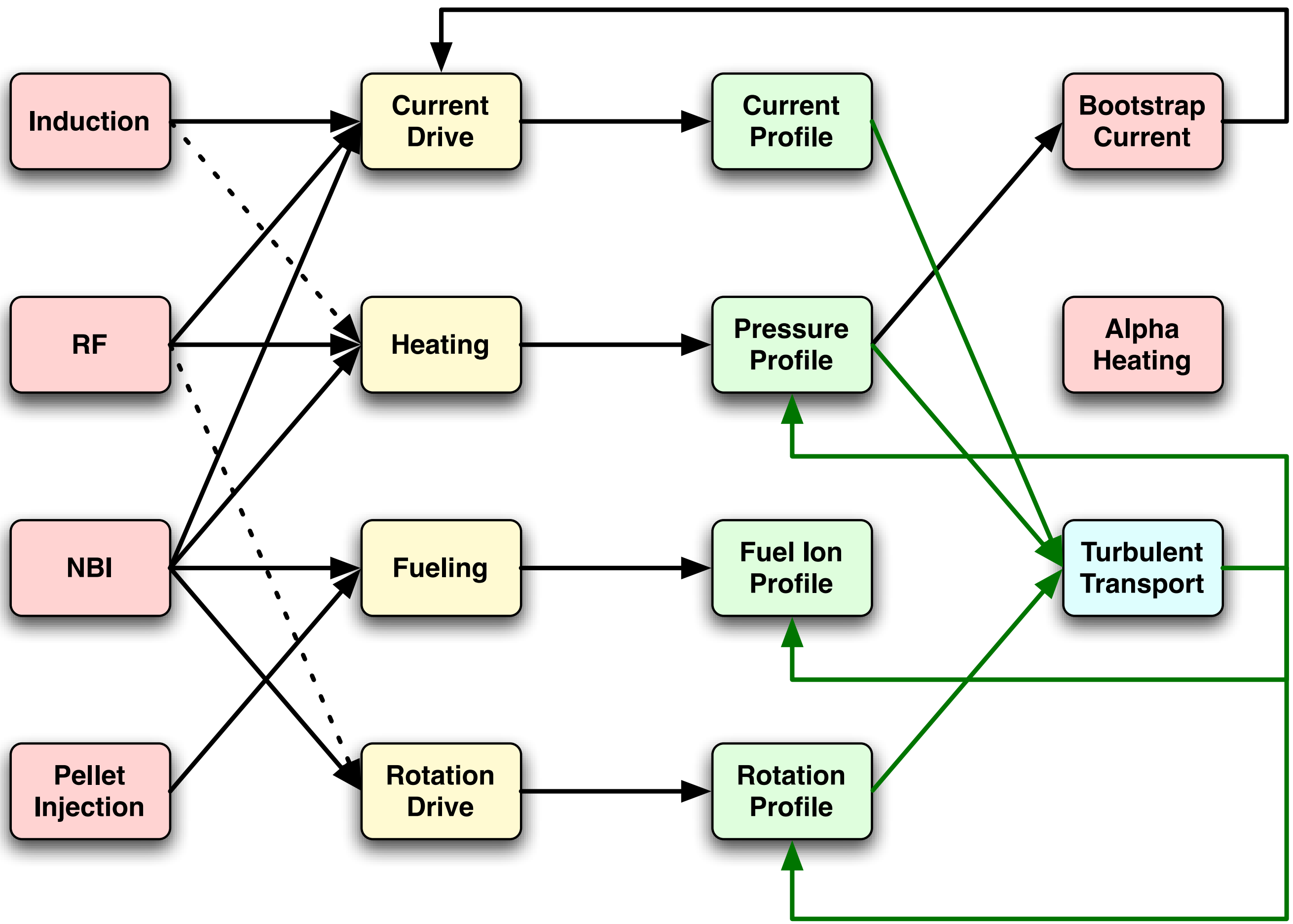
stability control

ELM control

What is new in burning plasmas?

Highly autonomous

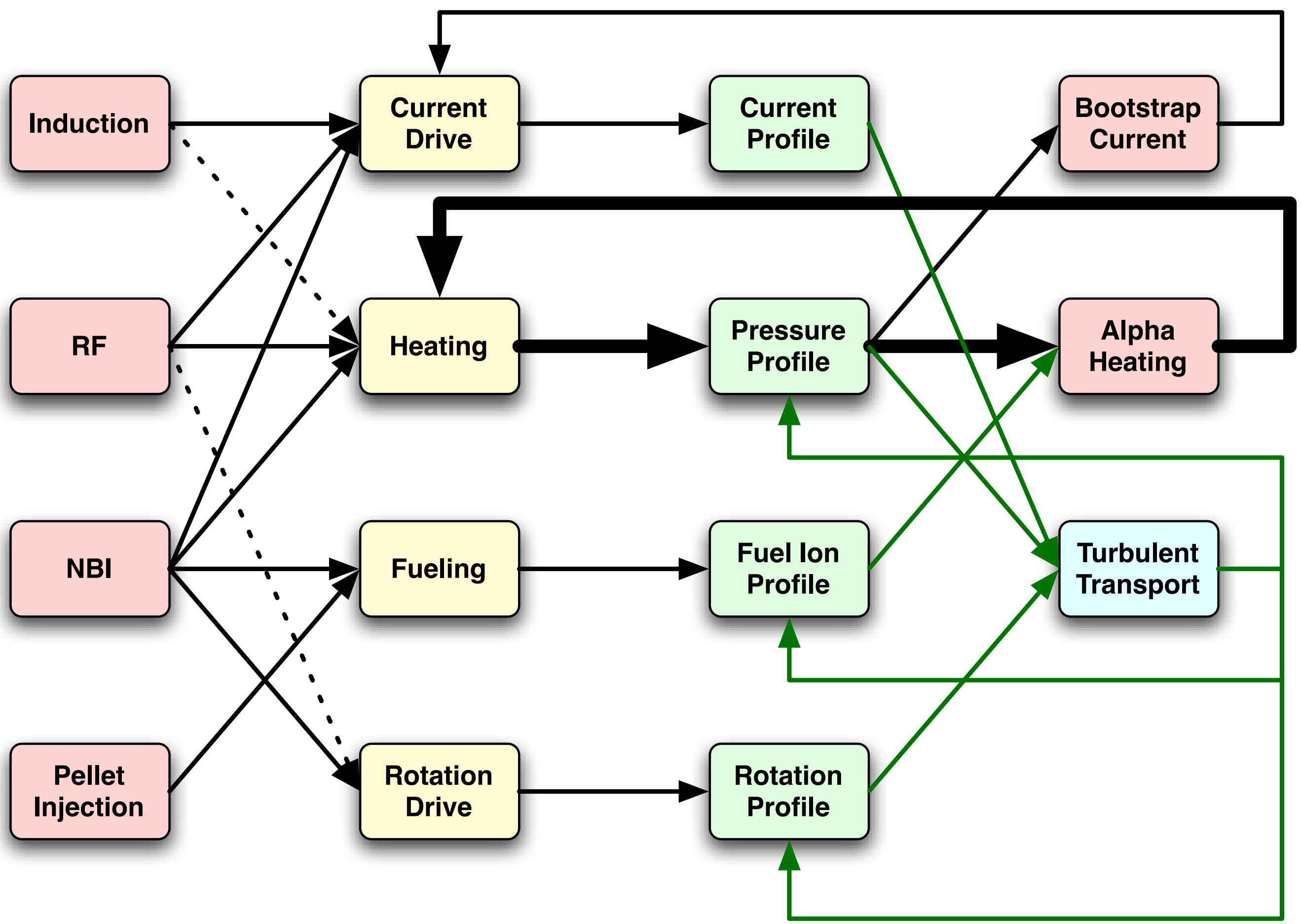
Present Plasma



What is new in burning plasmas?

Highly autonomous

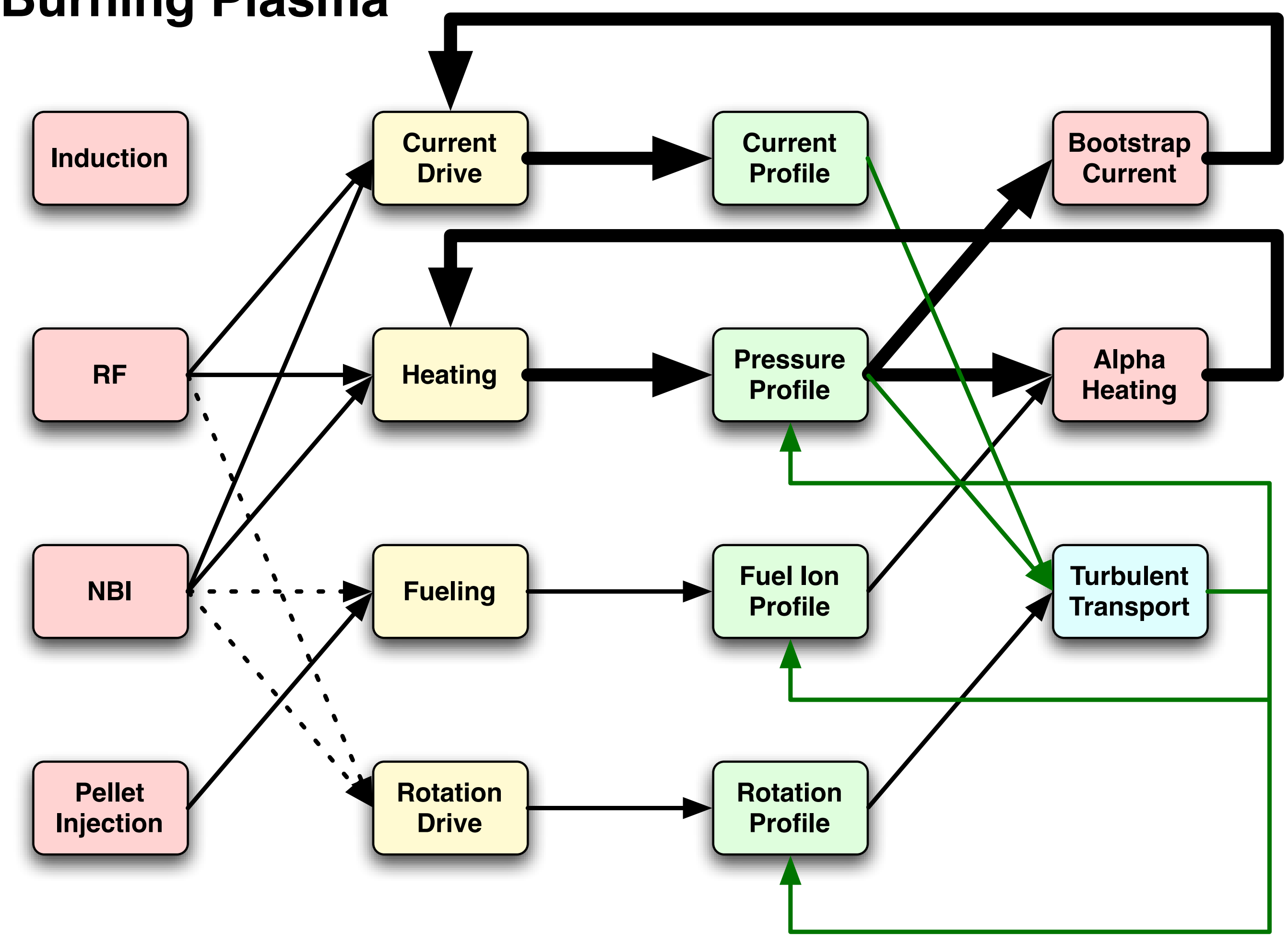
Burning Plasma



What is new in burning plasmas?

Highly autonomous

Steady-State Burning Plasma



What is new in burning plasmas?

Energetic Particles

Particle phenomena

Plasma heating

Orbit loss

Collective phenomena

Alfvén eigenmode

Channeling

High Heat Flux

SOL and divertor plasma

Plasma-wall interaction

Role of Simulation in Burning Plasmas

First principle simulation

- Turbulence — gyrokinetic simulation
- Global instability — extended MHD

Component simulation

- Transport phenomena (core, SOL, diverter)
- MHD phenomena (RWM, NTM, Sawtooth, ELM, ...)
- Wave-particle interaction (EC, LH, IC, AE)

Integrated simulation

- Integration of various physical phenomena

Integrated Burning Plasma Simulation

- **Why needed?**
  - To predict the behavior of burning plasmas
  - To develop reliable and efficient schemes to control them
- **What is needed?**
  - **Simulation describing a burning plasma:**
    - — **Whole plasma** (core & edge & divertor & wall-plasma)
    - — **Whole discharge**
      (startup & sustainment & transients events & termination)
    - — **Reasonable accuracy** (comparison with experiments)
    - — **Reasonable computer resources** (still limited)
- **How can we do?**
  - Gradual increase of understanding and accuracy
  - Organized development of simulation system

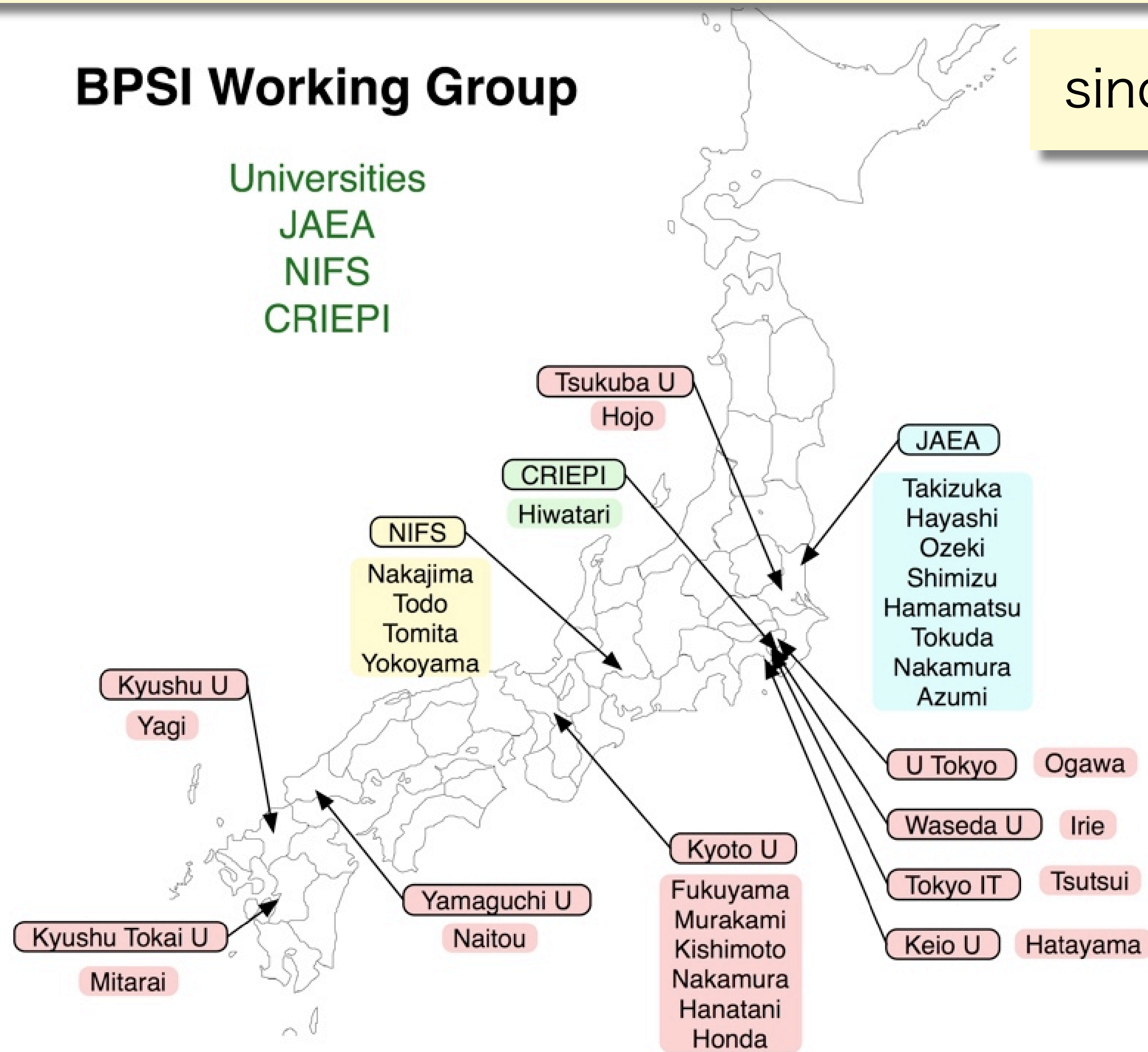
BPSI: Burning Plasma Simulation Initiative

Research Collaboration among Universities, NIFS and JAEA

since 2003

BPSI Working Group

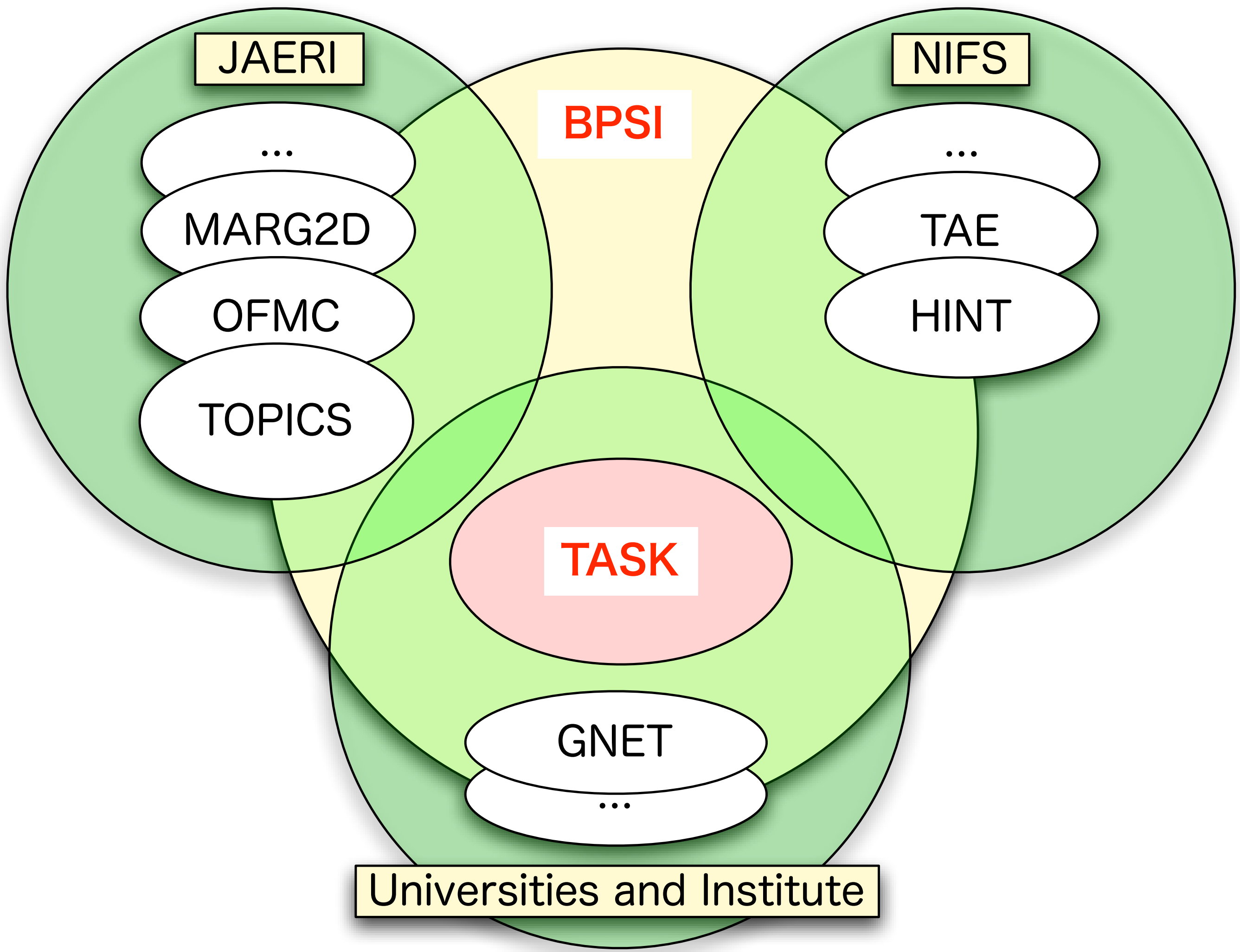
Universities
JAEA
NIFS
CRIEPI



Targets of BPSI

- **Framework** for collaboration of various plasma simulation codes
  - **Common interface** for data transfer
  - **Reference core code**, TASK
  - **Helical configuration** included
- **New Physics** in interactions of phenomena with different time and space scales (e.g.)
  - **Transport during and after a transient MHD events**
  - **Transport in the presence of magnetic islands**
  - **Core-SOL interface**
- **Advanced technique** of computer science
  - **Parallel computing**: PC cluster, Massively Parallel, Vector-Parallel
  - **Distributed computing**: GRID computing, Globus, ITBL
  - **Visualization**: Parallel visualization, VisiGRID

TASK: as a core code of BPSI



TASK code

- **Transport Analysing System for TokamaK**
- **Features**
  - **A Core of Integrated Modelling 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)
    - — Own Graphic Libraries (gsaf, gsgl)
  - **Development using CVS** (Concurrent Version System)
    - — Open Source (by the end of 2004)
  - **Parallel Processing using MPI Library**
  - **Extension to Toroidal Helical Plasmas**

Modules of TASK code

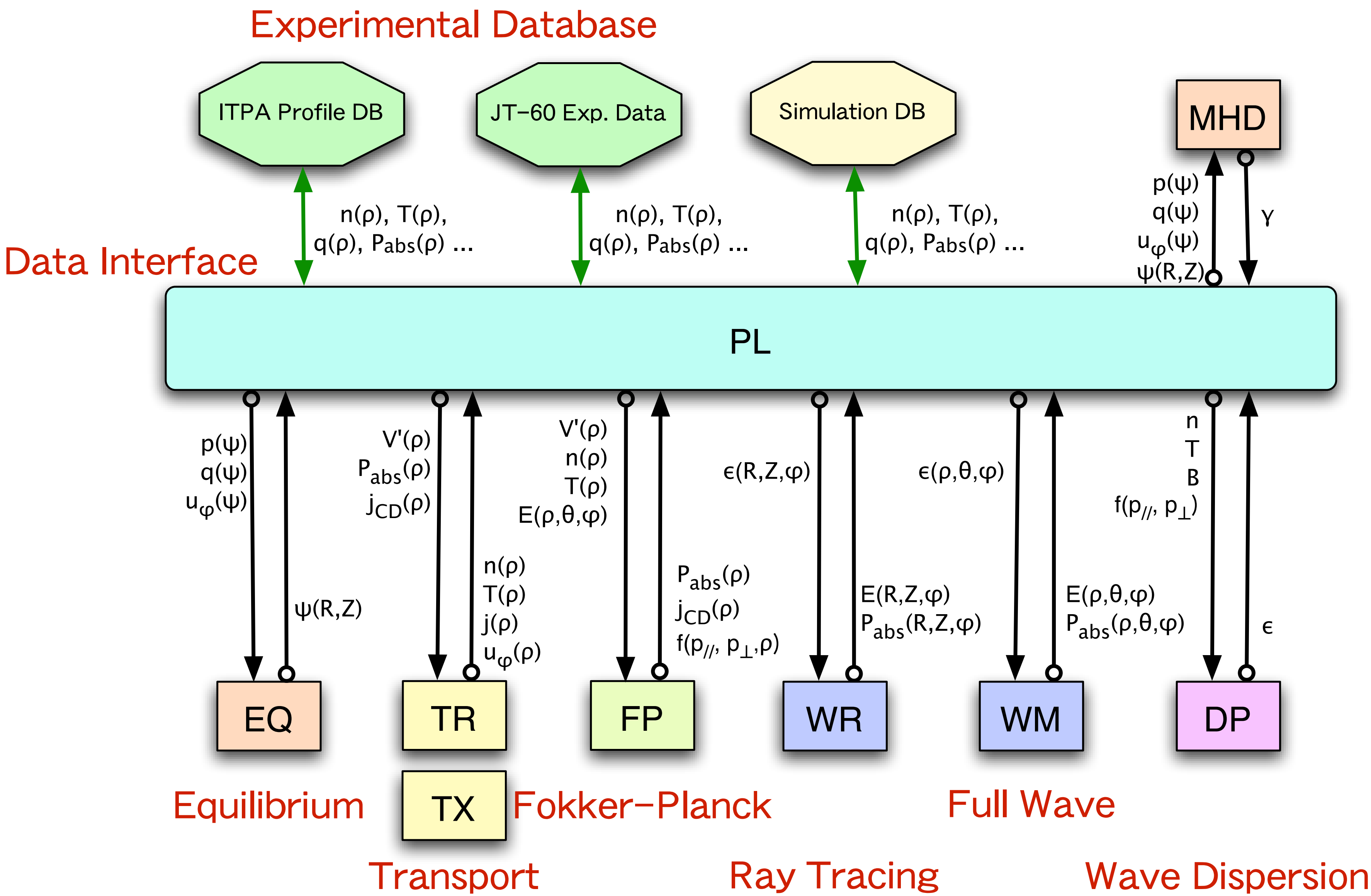
EQ	**2D Equilibrium**	Fixed boundary, Toroidal rotation
TR	**1D Transport**	Diffusive Transport, Transport models
WR	**3D Geometr. Optics**	EC, LH: Ray tracing, Beam tracing
WM	**3D Full Wave**	IC, AW: Antenna excitation, Eigen mode
FP	**3D Fokker-Planck**	Relativistic, Bounce-averaged
DP	**Wave Dispersion**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



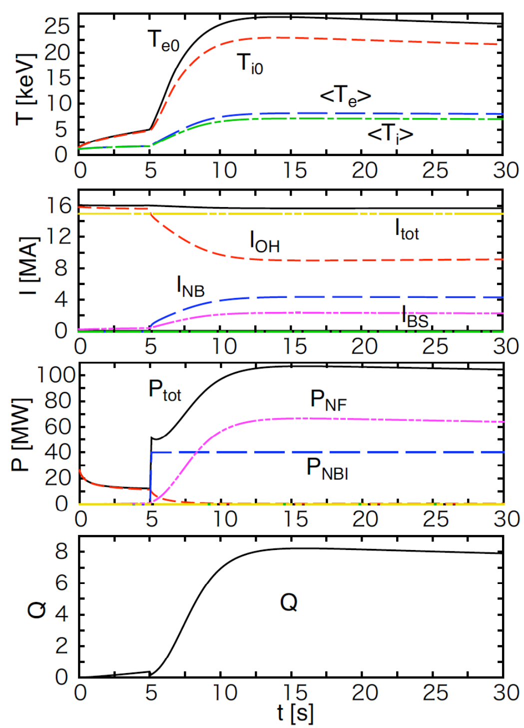
Transport Simulation of ITER

- Large plasma current: $I_p = 15$ MA, On-axis heating: $P_{NB} = 40$ MW
- Positive shear profile, Relatively large f_{OH}

CDBM

$\beta_N = 1.49$

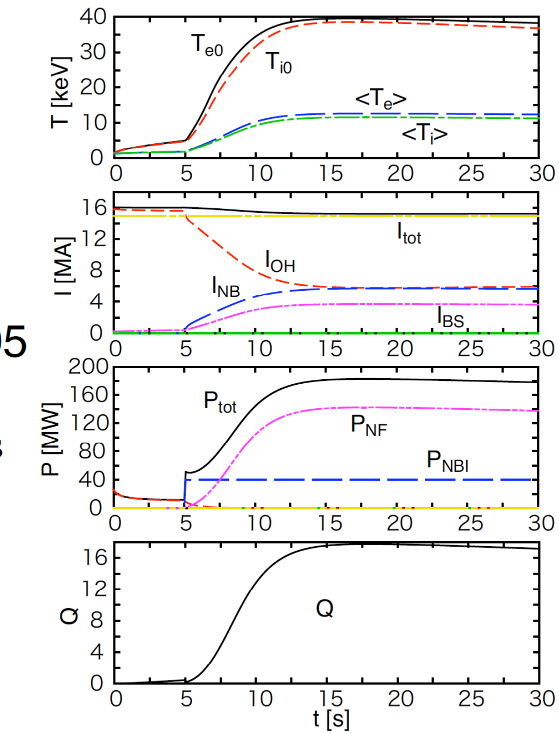
$\tau_E = 3.0$ s

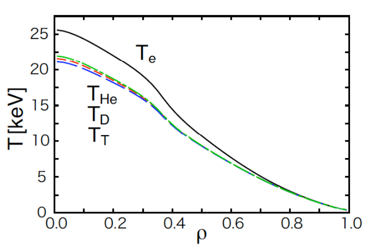


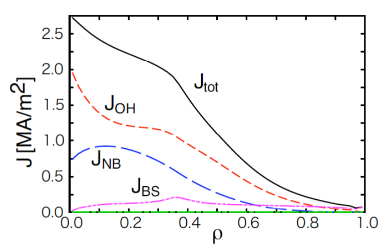
CDBM05

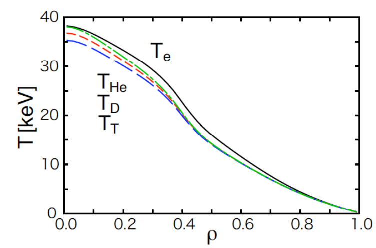
$\beta_N = 2.63$

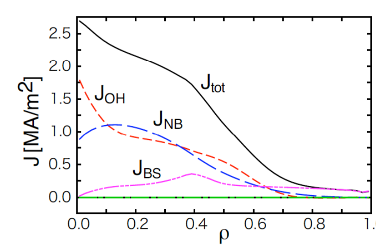
$\tau_E = 3.1$ s











Turbulence transport models

Linear + $\gamma_L/k_\perp^2$

Multi Mode Model

Weiland model

Linear + Zonal Flow

Gyrokinetic models

Fluid models

Linear+ZF+NL Sim

GLF23 (ITG,TEM)

Self-sustained Turbulence

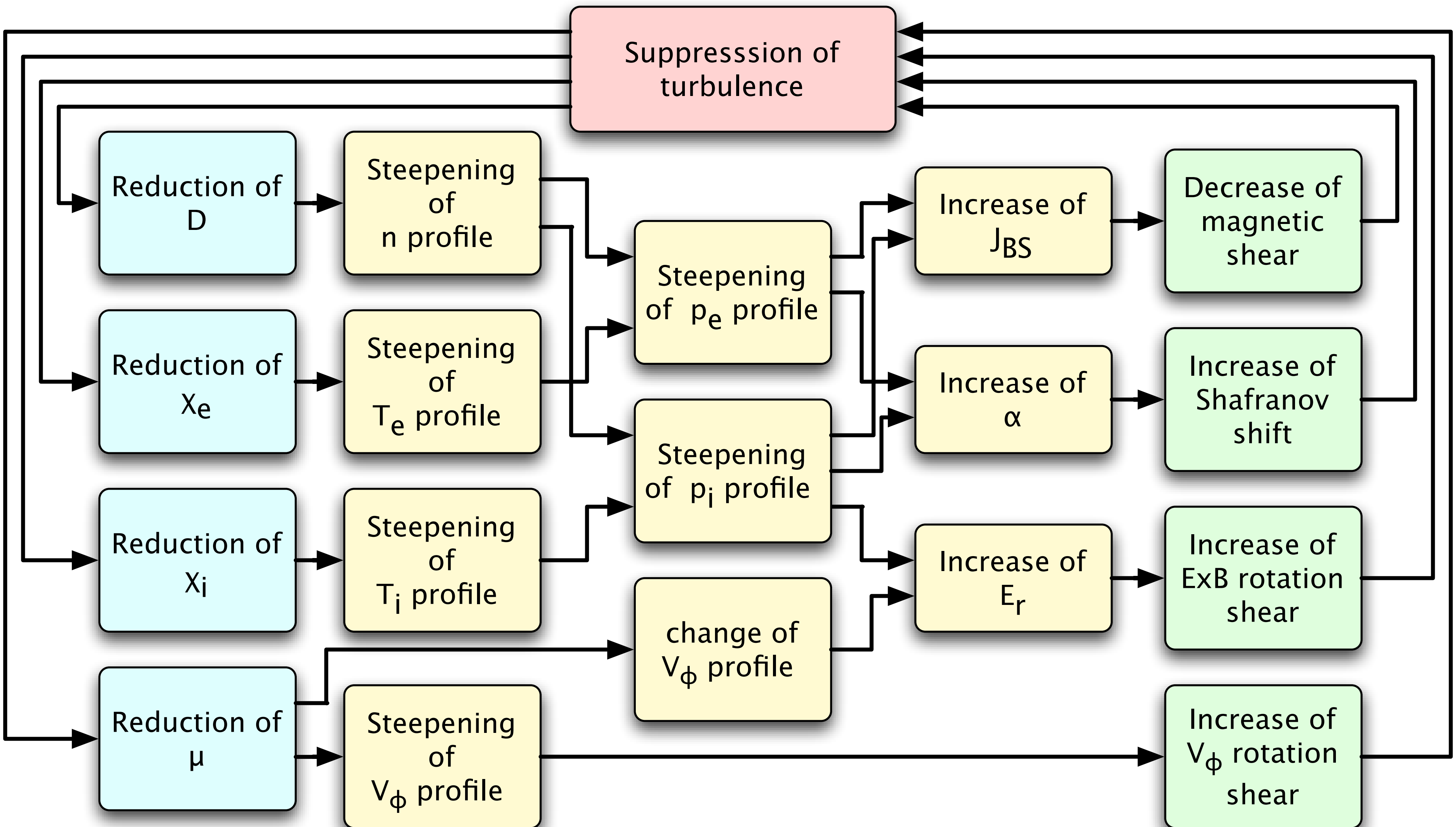
CDBM

Gyrokinetic simulation

Particle simulation

Vlasov simulation

Improved Confinement



CDBM05 Transport Model

- **Thermal Diffusivity** (Marginal: $\gamma = 0$)

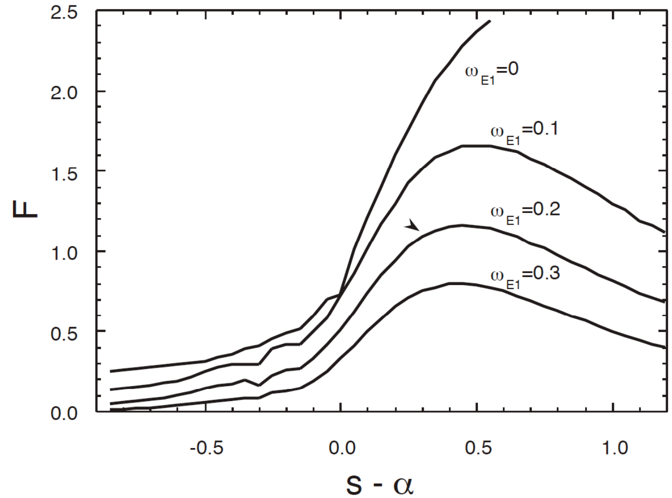
$$\chi_{\rm TB} = F(s, \alpha, \kappa, \omega_{\rm E1})\, \alpha^{3/2} \frac{c^2}{\omega_{\rm pe}^2} \frac{v_{\rm A}}{qR}$$

Magnetic shear	$s \equiv \dfrac{r}{q} \dfrac{\mathrm{d}q}{\mathrm{d}r}$
Pressure gradient	$\alpha \equiv -q^2 R \dfrac{\mathrm{d}\beta}{\mathrm{d}r}$
Elongation	$\kappa \equiv b/a$
$E \times B$ **rotation shear**	$\omega_{\rm E1} \equiv \dfrac{r^2}{s v_{\rm A}} \dfrac{\mathrm{d}}{\mathrm{d}r} \dfrac{E}{rB}$

- **Weak and negative magnetic shear, Shafranov shift, elongation, and $E \times B$ rotation shear**

reduce thermal diffusivity.

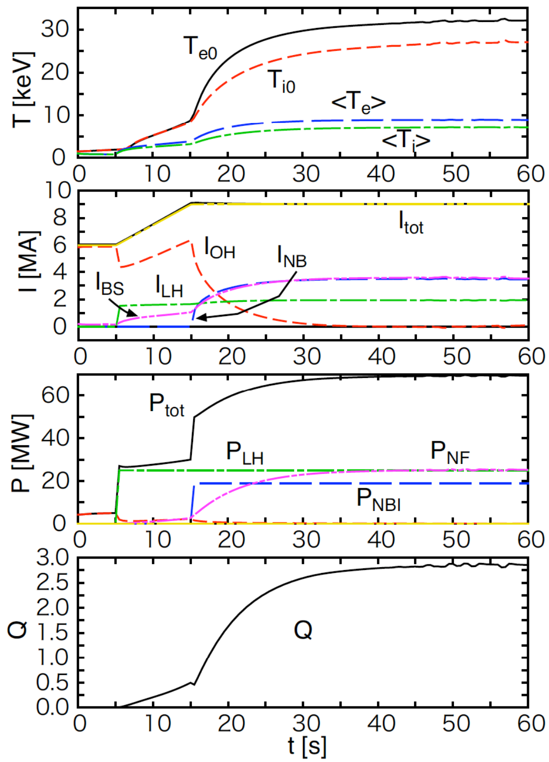
$s - \alpha$ dependence of $F(s, \alpha, \kappa, \omega_{\rm E1})$



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

Quasi steady-state operation of ITER

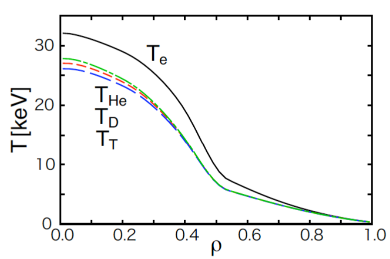
- $I_p = 6 \rightarrow 9$ MA for 10 s $P_{NB} = 19$ MW on-axis, $P_{LH} = 25$ MW off-axis

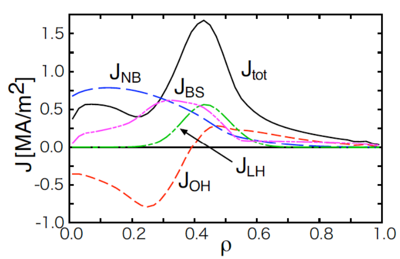


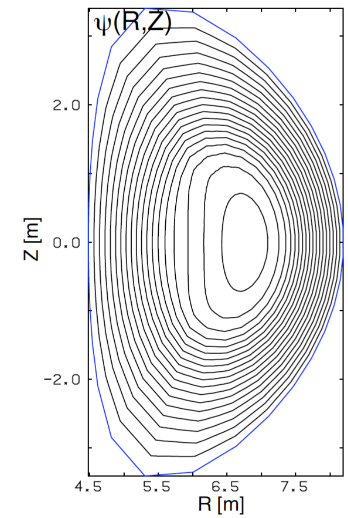
CDBM05

$\beta_N = 1.8$

$\tau_E = 3.1$ s







- $R = 6.34$ m
- $a = 1.859$ m
- $\kappa = 1.857$
- $\delta = 0.434$
- $B_\phi = 5.3$ T
- $I_p = 6$ MA $\rightarrow I_p = 9$ MA
- $n_{e,D,T,He} = 0.6, 0.27, 0.27, 0.03\ m^{-3}$ on-axis
- NBI: same condition except $P_{NB} = 19$ MW
- LHRF
  - Position of deposition: $r = 0.837$ m
  - Width of deposition profile: $r_W = 0.8$ m
  - Tangential radius: $r_T = 6.2$ m
  - Parallel refractive index: $N_{||} = 2.0$
  - Total power: $P_{LH} = 25$MW

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

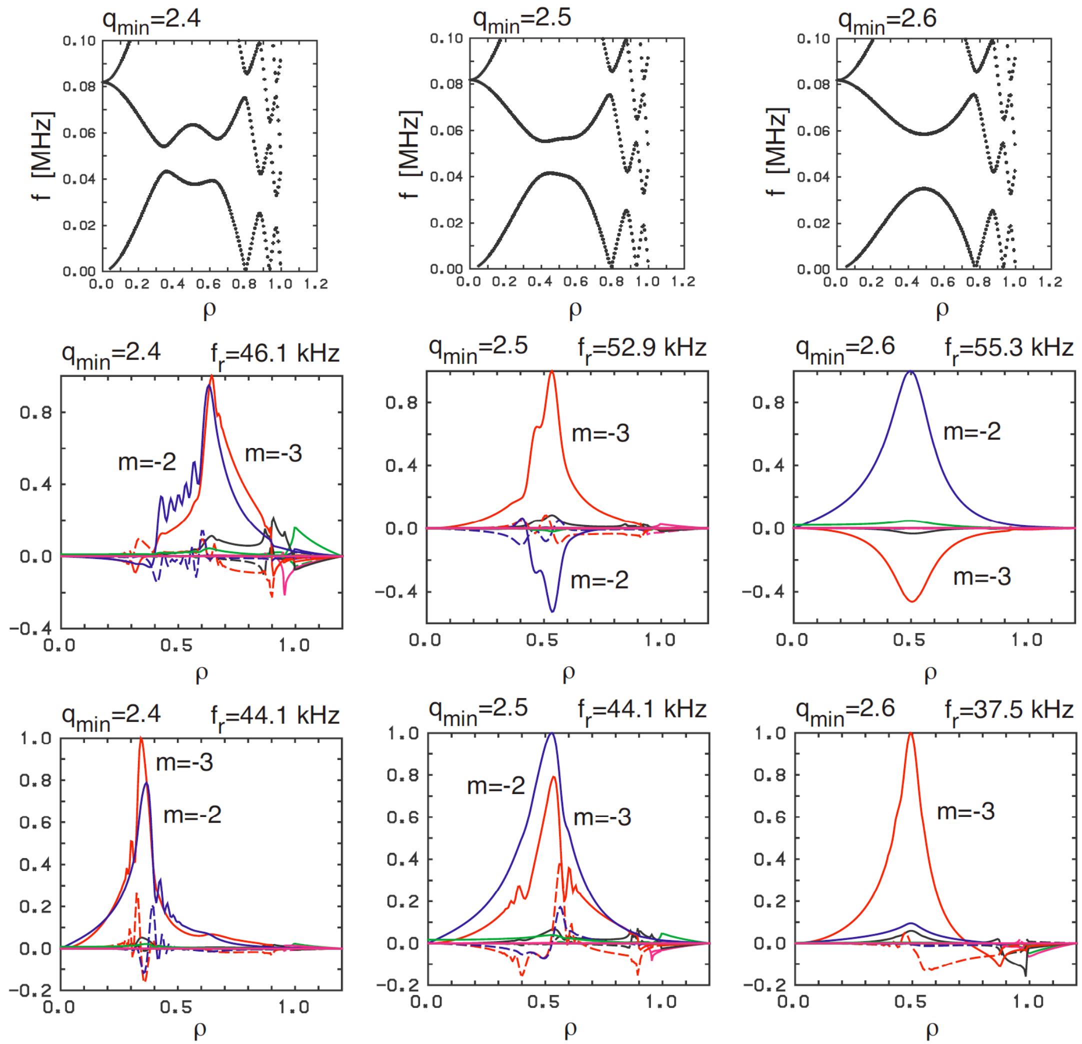
Analysis of Alfvén Eigenmode

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

Alfvén resonance

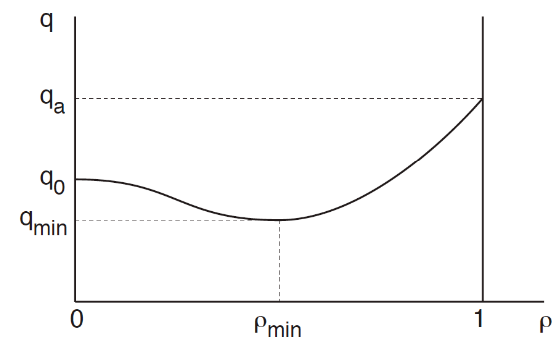
Higher freq.

Lower freq.



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

Assumed q profile



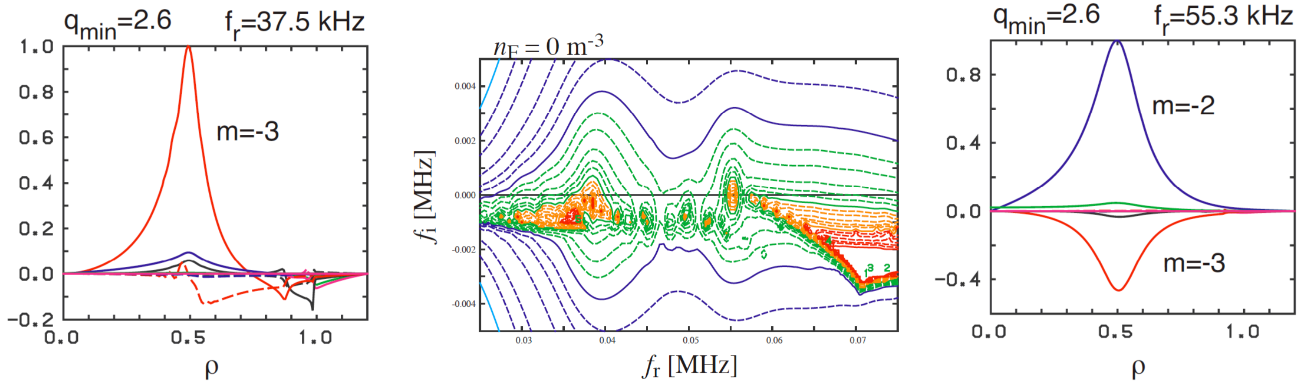
Plasma Parameters

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

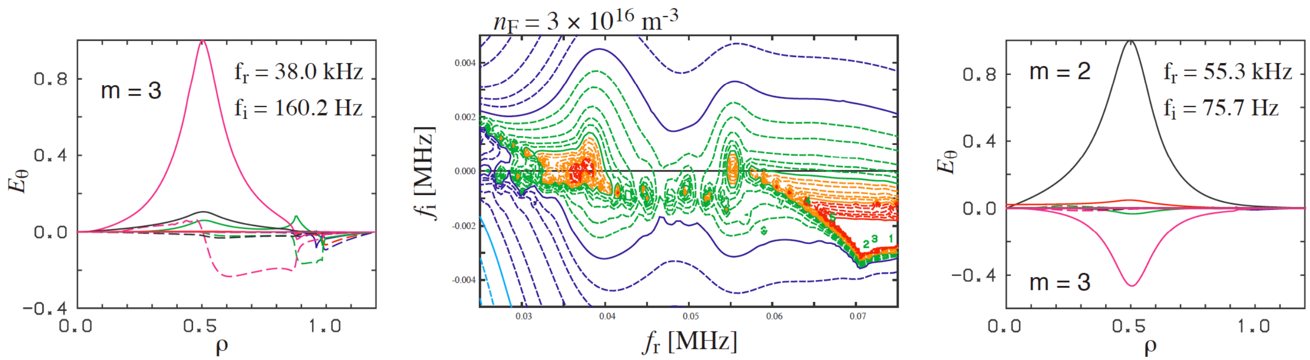
Excitation by Energetic Ions

- Without EP



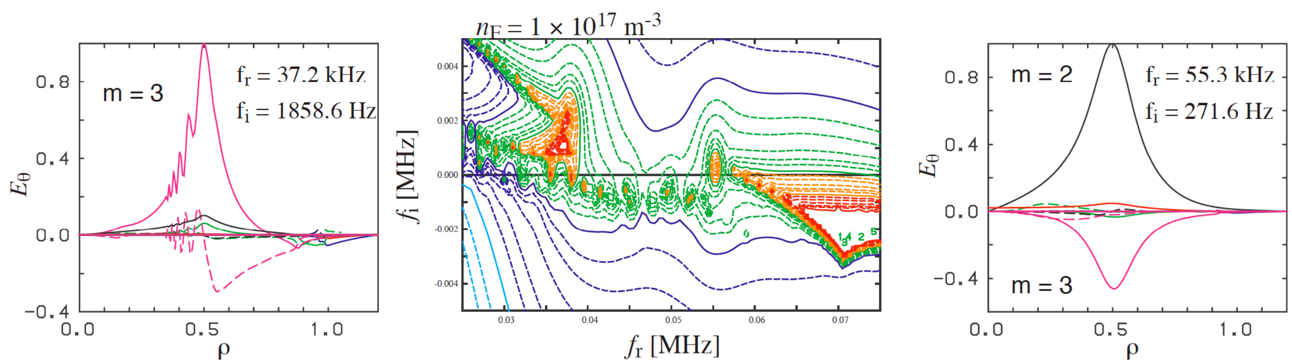
- With EP

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



- With EP

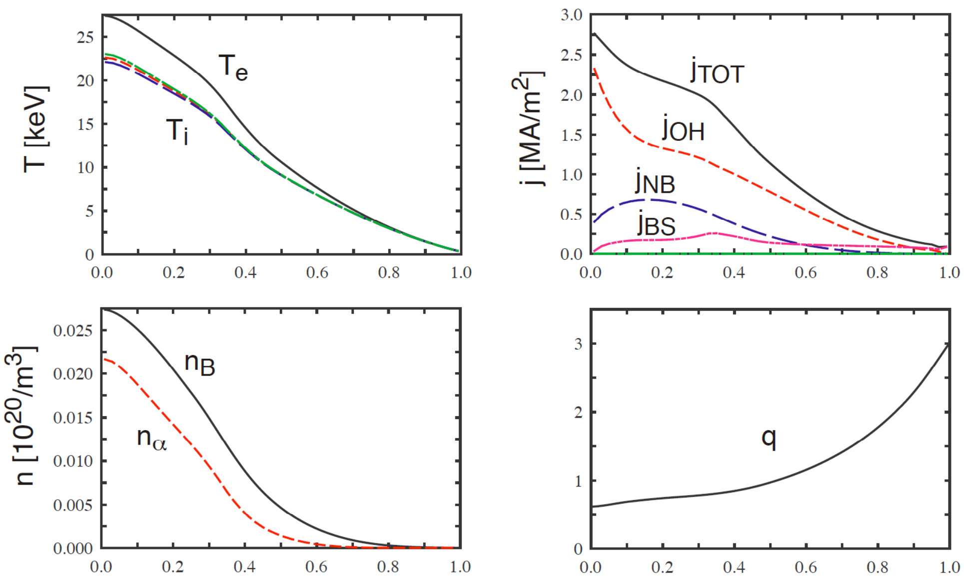
$1 \times 10^{17}\ m^{-3}$
360 keV
0.5 m

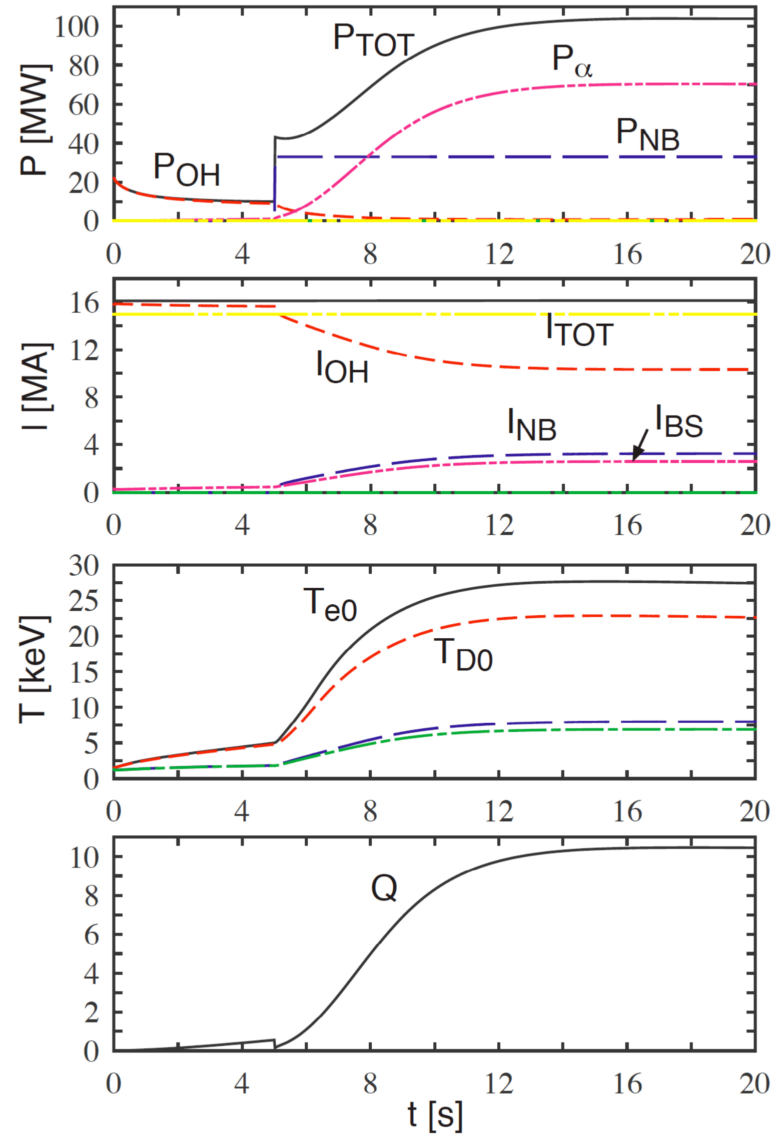


Integrated Analysis of AE in ITER

Standard H-mode Operation

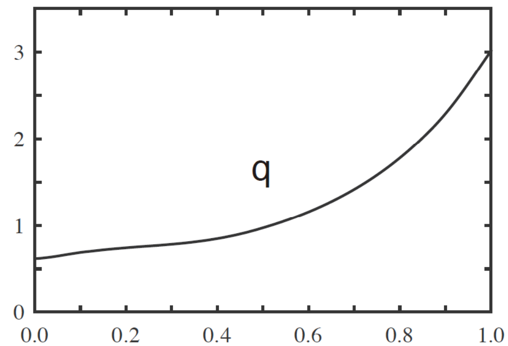
- $I_p = 15\,\mathrm{MA}$
- $P_{NB} = 33\,\mathrm{MW}$
- $\beta_N = 1.3$



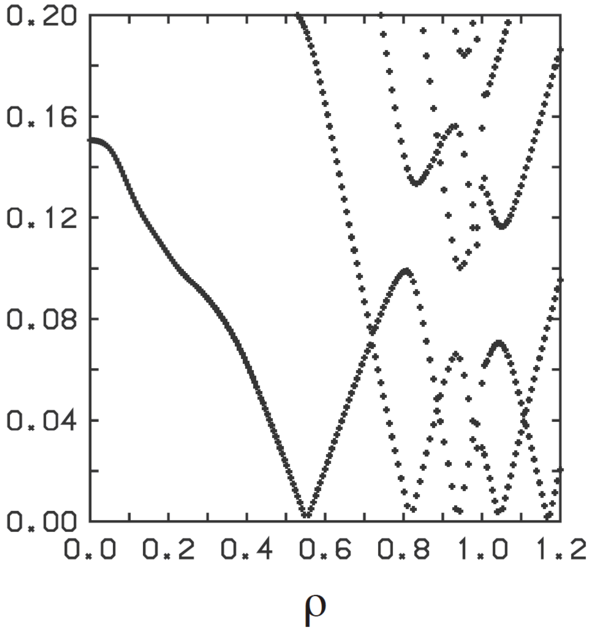


AE in Standard H-mode Operation

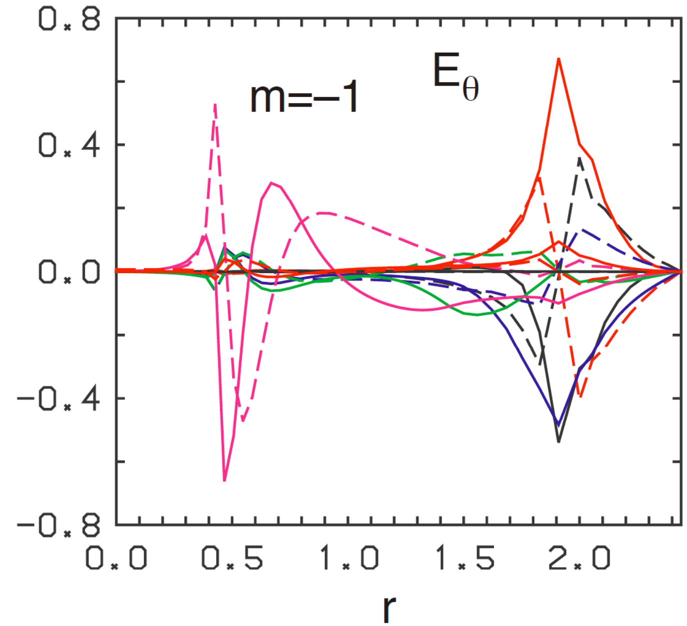
q profile



Alfvén Continuum



Mode structure ($n = 1$)



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

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

Stabilization due to $q = 1$

Summary

- Analyses of burning plasmas require systematically integrated simulations which consist of a number of components describing various phenomena.
- Turbulent transport and nonlinear effects of MHD phenomena require first principle simulations which will clarify the physical mechanisms.
- The activity to develop burning plasma simulations, BPSI in Japan, is in progress based on TASK and TOPICS.