US-Japan JIFT Workshop on
Integrated Modeling
PPPL, 2004/09/21

Status of the TASK project and BPSI in Japan

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Contents

- BPSI: Burning Plasma Simulation Initiative
- TASK: Core Code for Integrated Modeling
- Summary

Background

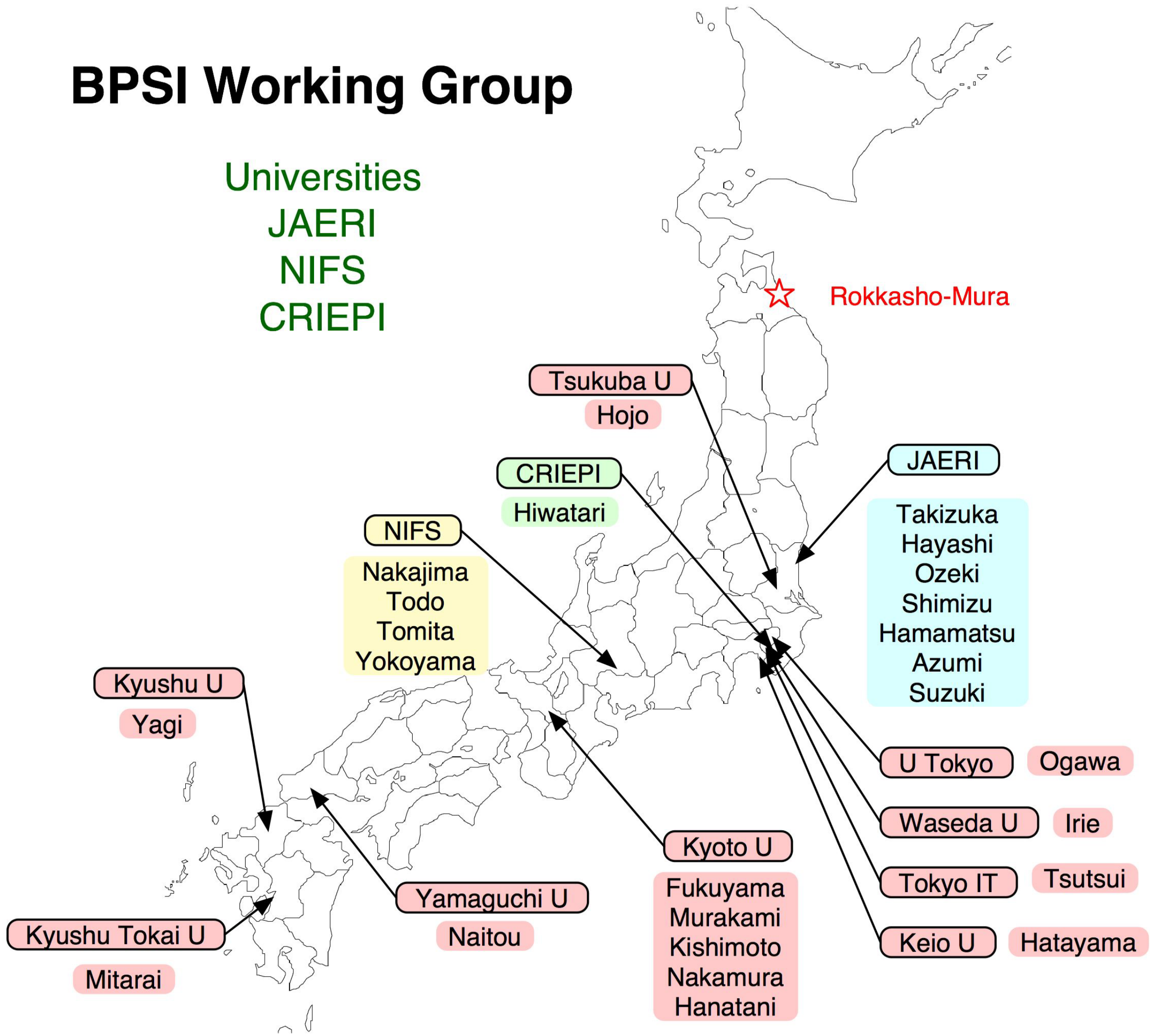
- **Experiments**: **Significant Progress in Diagnostics**
  - High resolution in space and time
  - Electromagnetic field in plasmas
  - ITER burning plasma: more than 10 years from now
- **Theory**: **Better Understanding in Nonlinear Physics**
  - Structure formation, zonal flow, . . .
- **Simulation**: **Detailed Simulation of Individual Phenomenon**
  - Exponential growth of computation resources and network speed
  - Progress in computation technique
  - Lack of methodology to describe a entire picture of plasmas

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

BPSI: Research Collaboration among Universities, NIFS and JAERI



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

Activities of BPSI

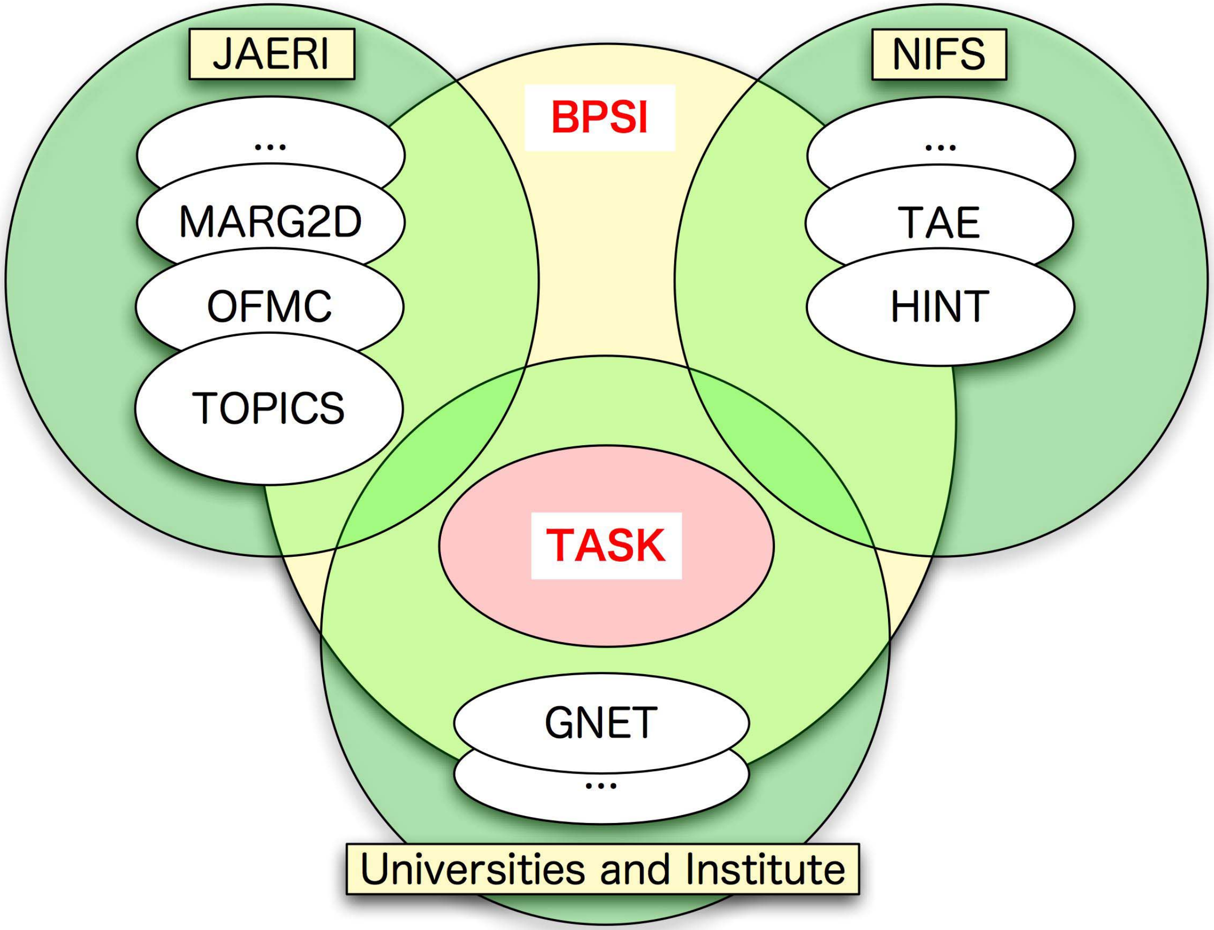
- **Meetings**

2002 Aug	Preparatory discussion	(NIFS)
2002	Small topical meetings	(Kyoto U)
2003 Aug	1st BPSI meeting	(Kyoto U)
2003 Dec	US-Japan workshop	(Kyoto U)
2004 Mar	2nd BPSI meeting	(Kyushu U)
2004 Aug	3rd BPSI meeting	(Kyushu U)
2004 Sep	US-Japan workshop	(PPPL)
2005 Apr	4th BPSI meeting during ITPA(?)	(Kyoto U)

- **Support** from various resources
  - Grant-in-Aid from JSPS (M. Yagi, Kyushu U)
  - Part of Grant-in-Aid from MEXT (S.-I. Itoh, Kyushu U)
  - Research collaboration of RIAM, Kyushu U (M. Yagi, Kyushu U)
  - Research collaboration of NIFS (Y. Nakamura Kyoto U)
  - Research collaboration of JAERI (A. Fukuyama, Kyoto U)
  - US-Japan JIFT Workshop from JSPS (A. Fukuyama, Kyoto U)
  - **Only for meeting support at present**

BPSI and TASK

TASK: Core code of BPSI for ITER, JT-60, LHD, and small machines



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

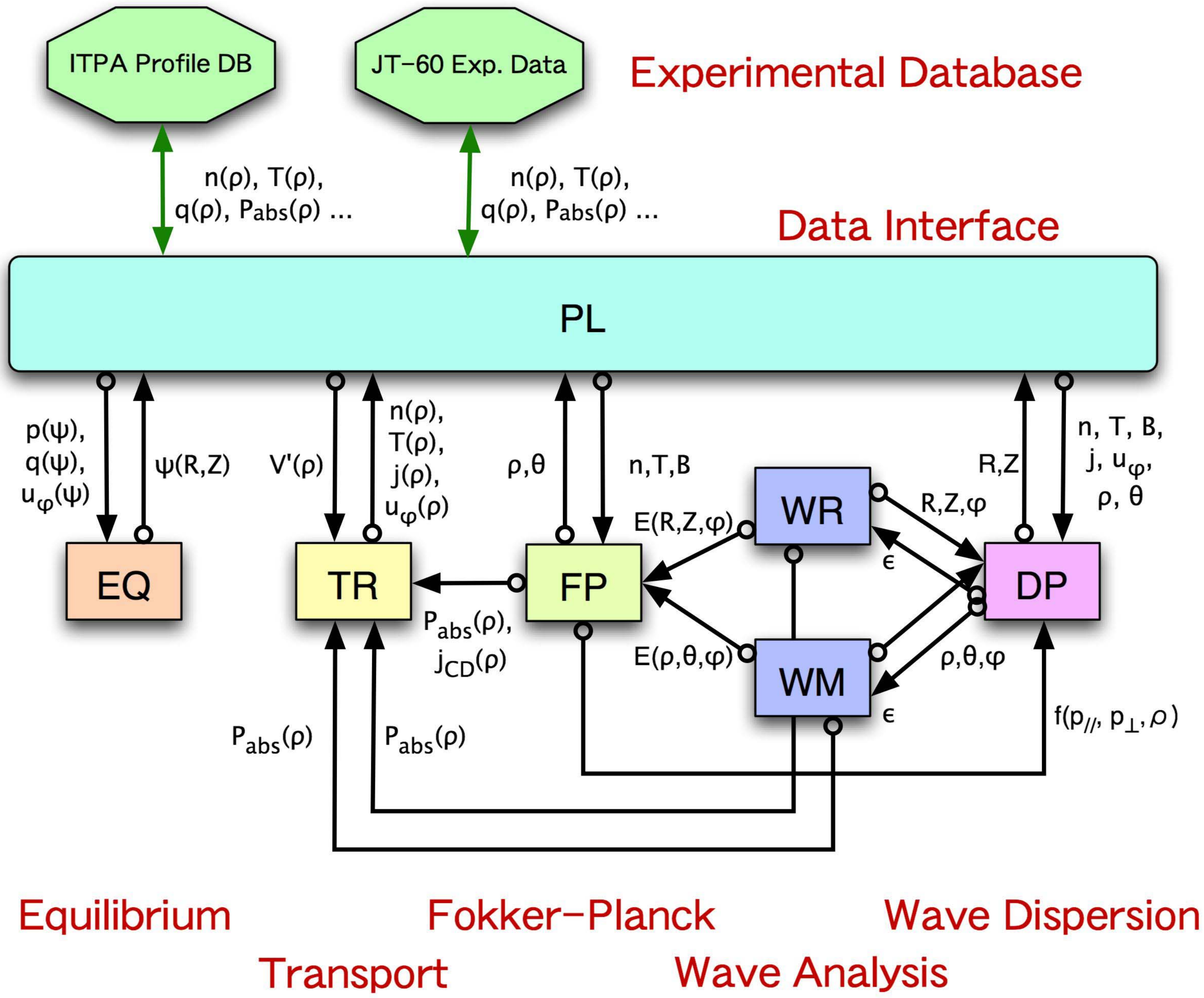
EQ	**2D Equilibrium**	Fixed boundary, Toroidal rotation
TR	**1D Transport**	Diffusive Transport, Transport models
WR	**3D Geometr. Optics**	EC, LH: Ray tracing, Beam tracing
WM	**3D Full Wave**	IC, AW: Antenna excitation, Eigen mode
FP	**3D Fokker-Planck**	Relativistic, Bounce-averaged
DP	**Wave Dispersion**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

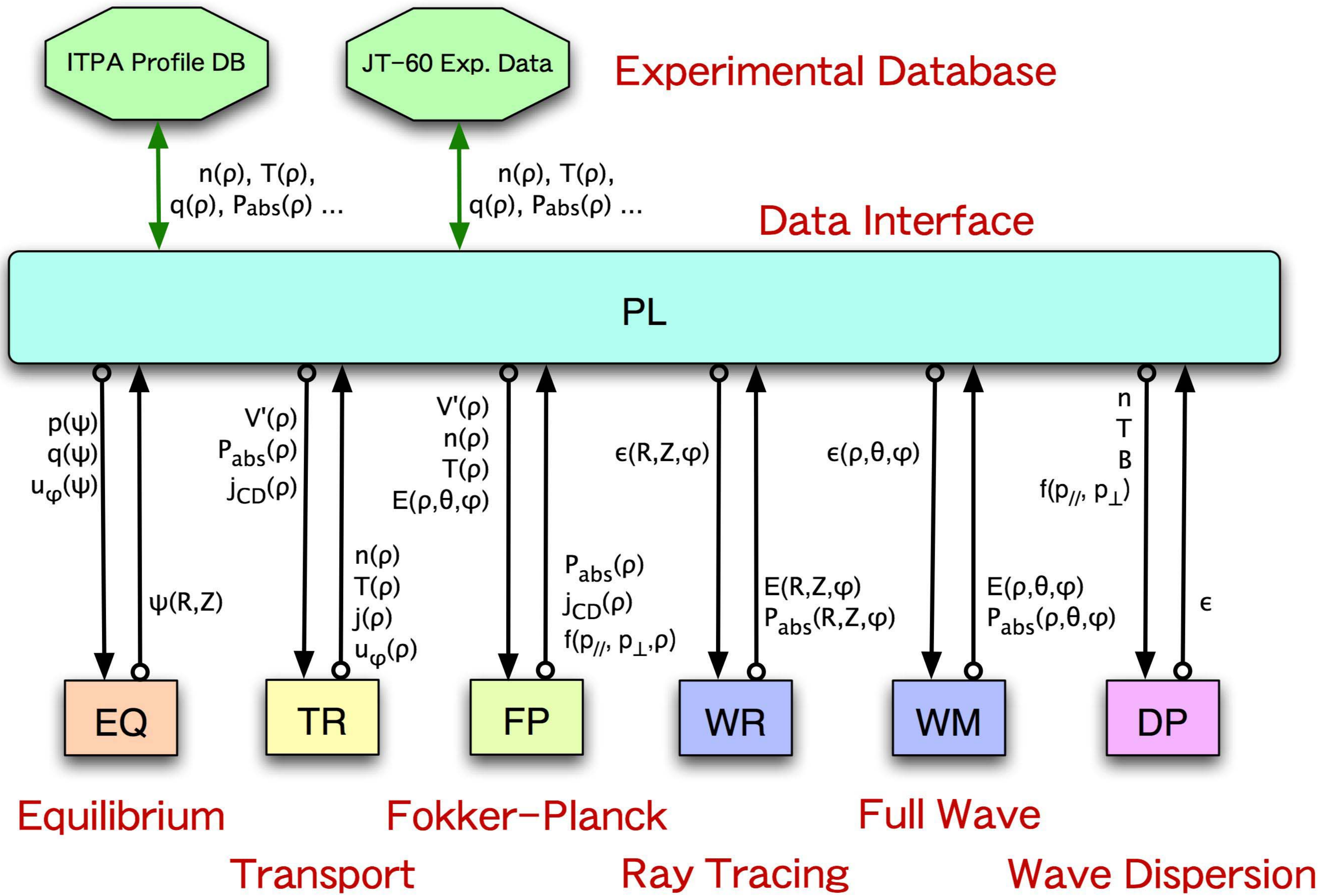
Present Structure of TASK



Under Development

- **New Modules**
  - **EX**: 2D equilibrium with free boundary
  - **TX**: Transport analysis based on flux-averaged fluid equation
  - **WA**: Global linear stability analysis
  - **WI**: Integro-differential wave analysis (FLR, $\boldsymbol{k} \cdot \nabla B \neq 0$)
- **Extension to 3D Helical System**
  - **3D Data Structure**
  - **3D Equilibrium**: VMEC, HINT
  - **Wave Analysis**: Already 3D
  - **Transport Analysis**: New transport model
- **New Modular Structure**

New Modular Structure of TASK



ECCD analysis : TASK/WR/FP/DP

Geometrical Optics: TASK/WR

- **Ray Tracing Method**:
  - Plane wave: beam size $d \gg$ Wave length λ
  - **6 Ordinary Differential Equations** for r_α, k_α,
- **Beam Tracing Method**
  - Analysis of wave propagation with finite beam size
  - **Beam shape** : Gaussian beam
  - **18 Ordinary Differential Equations** for r_α, k_α, $s_{\alpha\beta}$ and $\phi_{\alpha\beta}$

— **Curvature radius**: $R_\alpha = 1/\lambda s_{\alpha\alpha}$,

— **Beam radius**: $d_\alpha = \sqrt{2/\phi_{\alpha\alpha}}$

Fokker-Planck Analysis : TASK/FP

- **Fokker-Planck equation**
  for **velocity distribution function** $f(p_{||}, p_\perp, \psi, t)$

$$\frac{\partial f}{\partial t} = E(f) + C(f) + Q(f) + L(f)$$

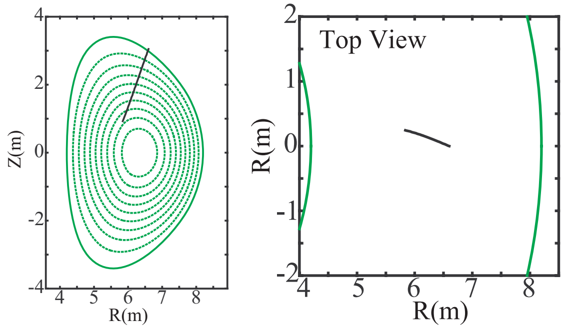
  - $E(f)$: Acceleration term due to DC electric field
  - $C(f)$: Coulomb collision term
  - $Q(f)$: Quasi-linear term due to wave-particle resonance
  - $L(f)$: Spatial diffusion term
- **Bounce-averaged**: Trapped particle effect, zero banana width
- **Relativistic**: momentum $\boldsymbol{p}$, weakly relativistic collision term
- **Nonlinear collision**: momentum or energy conservation
- **Three-dimensional**: spatial diffusion (neoclassical, turbulent)

Wave Dispersion Analysis : TASK/DP

- **Various Models of Dispersion Tensor $\overleftrightarrow{\epsilon}(\omega, \boldsymbol{k}; \boldsymbol{r})$:**
  - Resistive MHD model
  - Collisional cold plasma model
  - Collisional warm plasma model
  - Kinetic plasma model (Maxwellian, non-relativistic)
  - Kinetic plasma model (Arbitrary $f(\boldsymbol{v})$, relativistic)
  - Gyro-kinetic plasma model (Maxwellian, non-relativistic)
  - Gyro-kinetic plasma model (Arbitrary $f(\boldsymbol{v})$, non-relativistic)
- **Arbitrary $f(\boldsymbol{v})$:**
  - Relativistic Maxwellian
  - Output of TASK/FP

Analysis of ECCD by TASK Code

Poloidal angle	70°
Toroidal angle	20°
Initial beam radius	0.05 m
Initial beam curvature	2 m

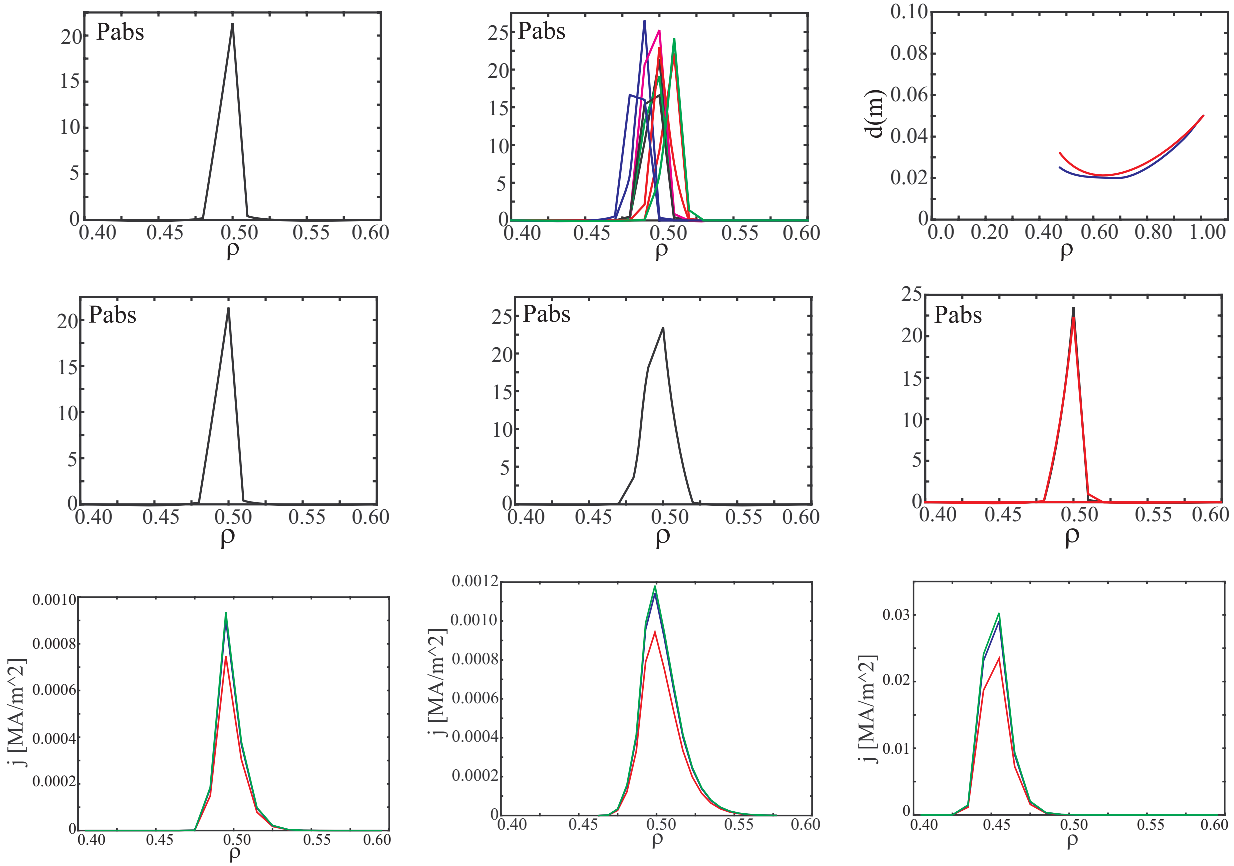


One Ray | **Multi Rays** | **Beam Tracing**

Ray/Beam Profile

P_{abs} **Profile**

j_{CD} **Profile**



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**

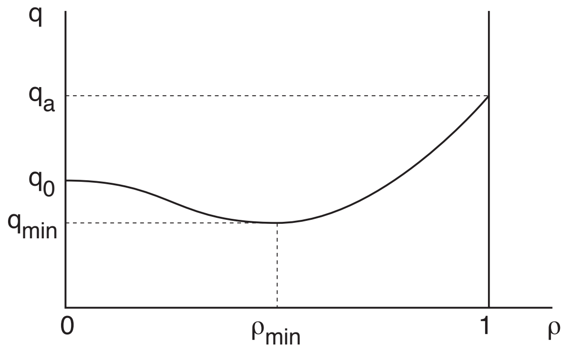
$$\left[\frac{\partial}{\partial t} + v_{\|}\nabla_{\|} + (\boldsymbol{v}_{\mathrm{d}} + \boldsymbol{v}_{\mathrm{E}}) \cdot \nabla + \frac{e_\alpha}{m_\alpha}(v_{\|}E_{\|} + \boldsymbol{v}_{\mathrm{d}} \cdot \boldsymbol{E})\frac{\partial}{\partial \varepsilon}\right] f_\alpha = 0$$

- 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

$q_{\min}$ Dependence of Eigenmode Frequency

Assumed q profile

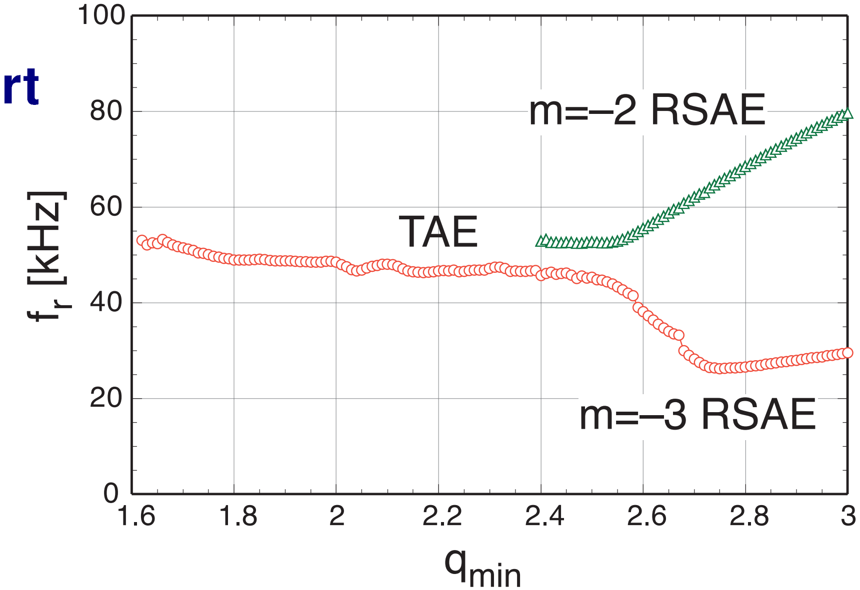


Plasma Parameters

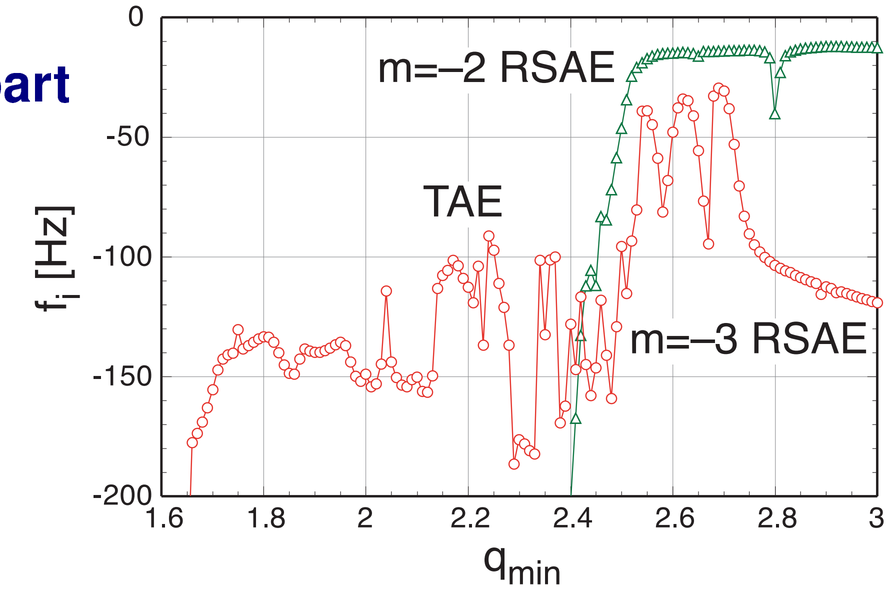
R_0	3 m
a	1 m
B_0	3 T
$n_e(0)$	$10^{20}\,\mathrm{m}^{-3}$
$T(0)$	3 keV
$q(0)$	3
$q(a)$	5
$\rho_{\min}$	0.5
n	1

Flat density profile

Real part



Imag part



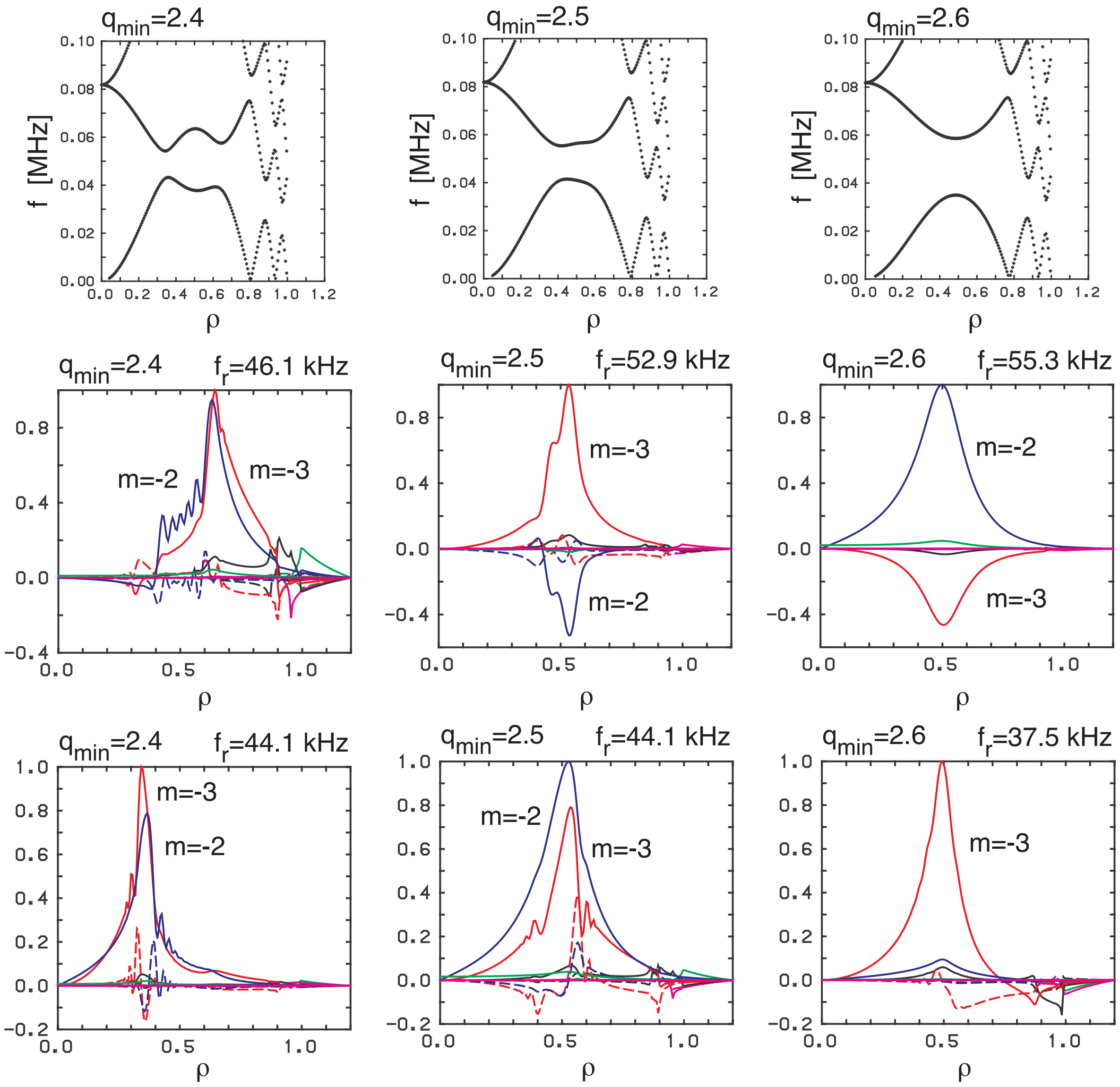
Eigenmode Structure

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

Alfvén resonance

Higher freq.

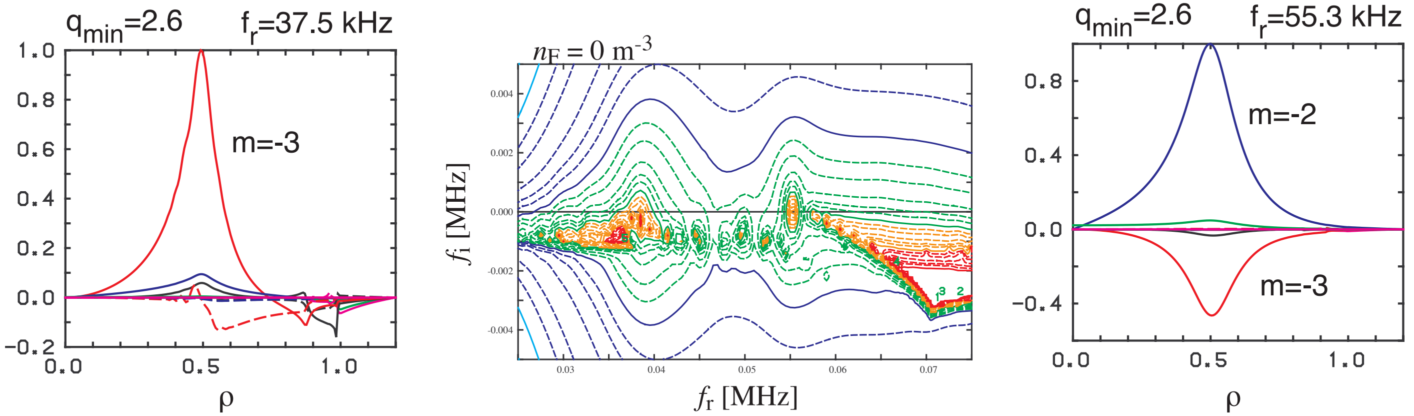
Lower freq.



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

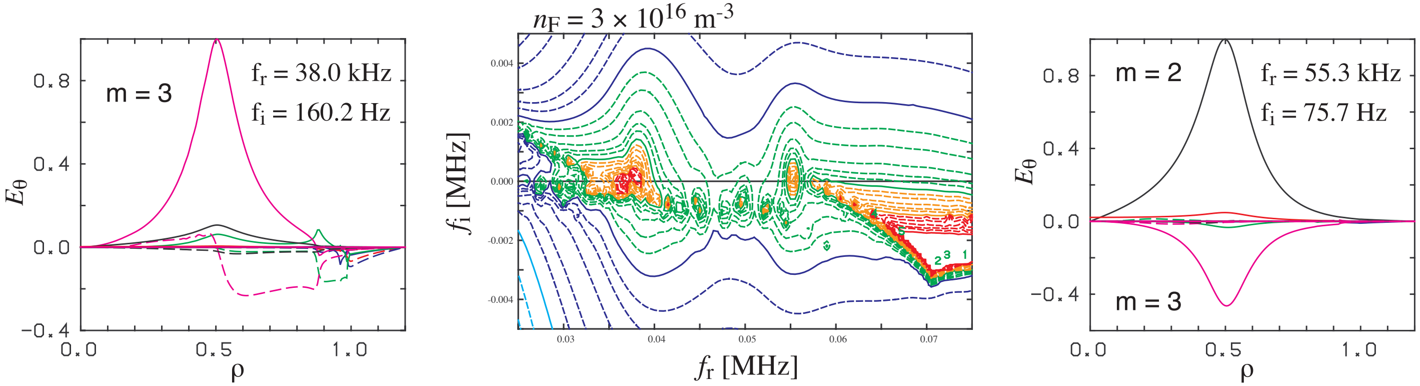
Excitation by Energetic Particles (q_{min} = 2.6)

- Without EP



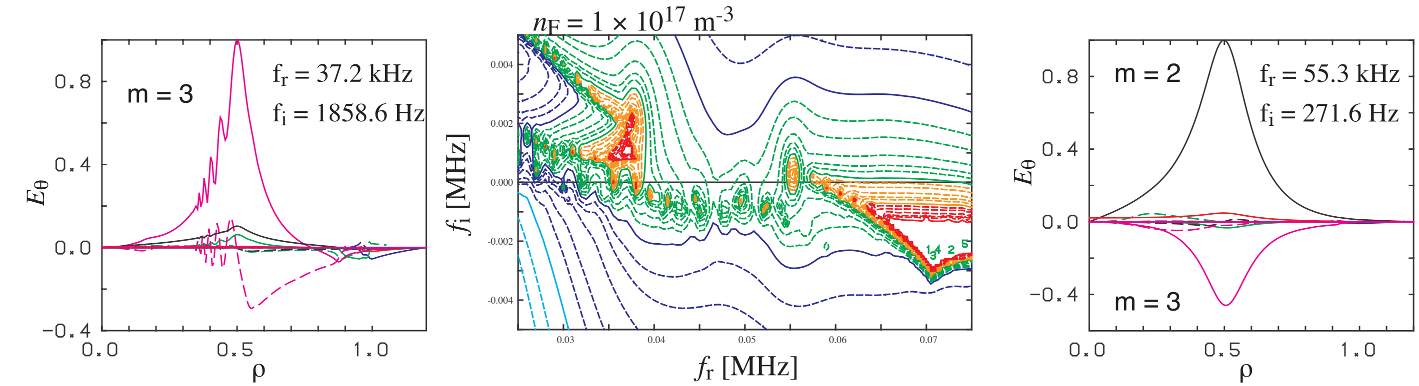
- With EP

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



- With EP

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



Transport Analysis

- **Level of Analysis**:
  - **TASK/TR**: Diffusive transport equation:
    — Flux-Gradient relation
    — Conventional transport analysis
  - **TASK/TX**: Dynamical transport equation:
    — Flux-averaged fluid equation
    — Plasma rotation and transient phenomena
  - **TASK/FP**: Kinetic transport equation:
    — 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)

CDBM Turbulence Model

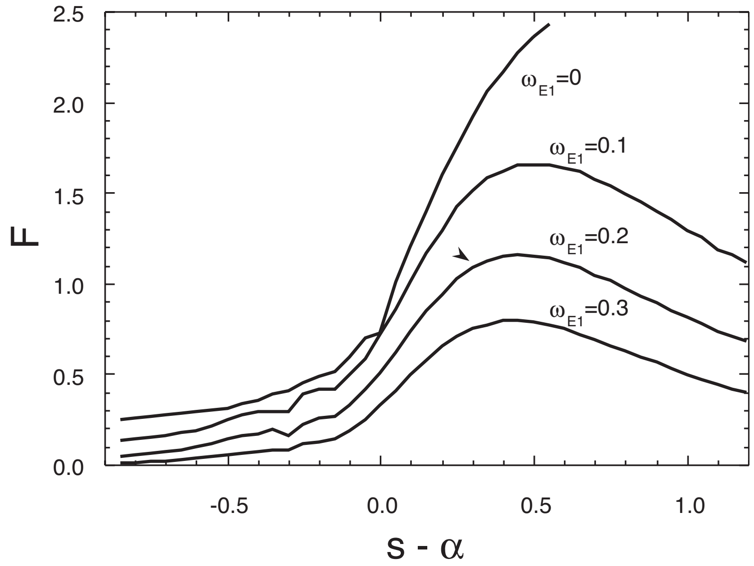
- **Marginal Stability Condition** ($\gamma = 0$)

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

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.**

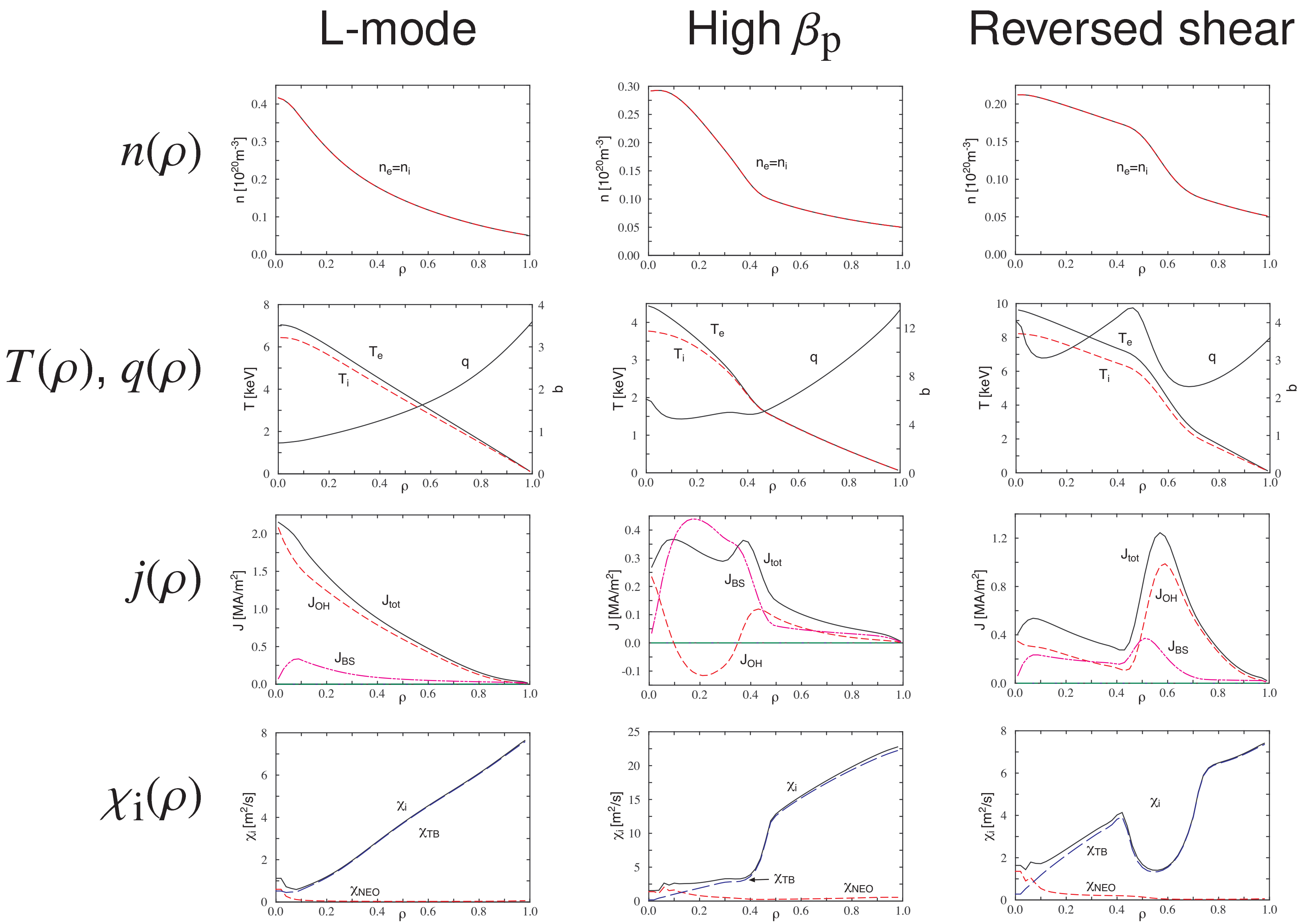
$s - \alpha$ dependence of $F(s,\alpha,\kappa,\omega_{\rm E1})$



Fitting Formula

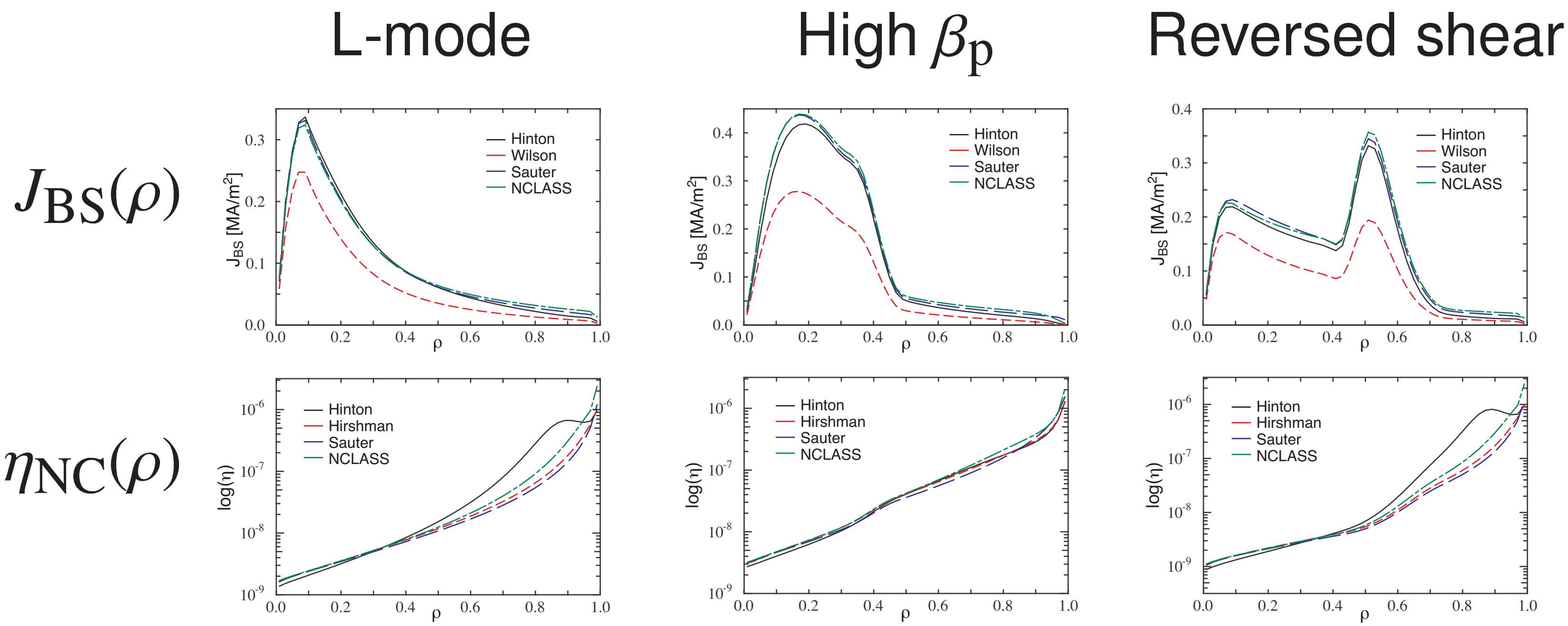
$$F = \begin{cases} \dfrac{1}{1+G_1\omega_{\rm E1}^2}\,\dfrac{1}{\sqrt{2(1-2s')(1-2s'+3s'^2)}} & \text{for } s' = s-\alpha < 0 \\[2ex] \dfrac{1}{1+G_1\omega_{\rm E1}^2}\,\dfrac{1+9\sqrt{2}s'^{5/2}}{\sqrt{2}(1-2s'+3s'^2+2s'^3)} & \text{for } s' = s-\alpha > 0 \end{cases}$$

Typical Profile (CDBM+NCLASS)



Neoclassical Transport Model

- **Comparison of Bootstrap Current and Resistivity**
  - **Wilson model**: from “Tokamaks 2nd ed” (Wesson)
  - **Hinton and Hazeltine model**
  - **Sauter model**
  - **NCLASS package**

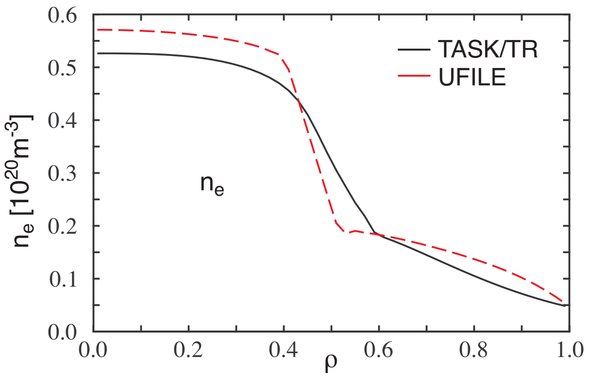


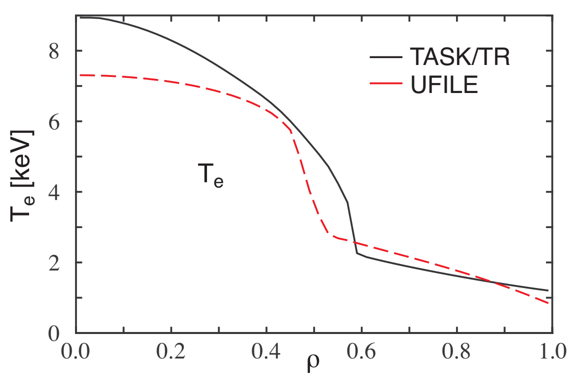
- **Fairly good agreement except Wilson model**

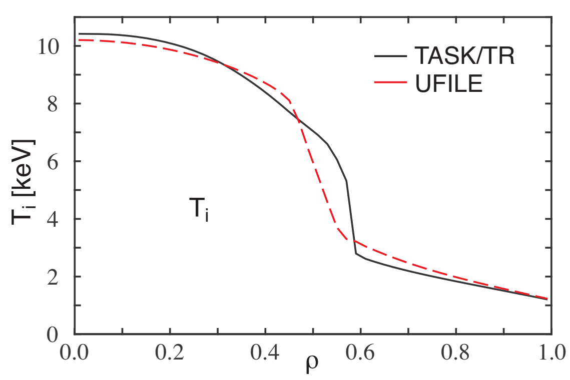
Comparison with JT-60 Experiment

- **Reversed Shear Configuration**
  - **Shot number: 29728**
  - Profiles q, P_e, P_i: given
  - Metric data: given
  - Edge density and temperature: given
  - Transport model: Sauter + CDBM(with $E \times B$ rotation)

$n_\mathrm{e}(\rho)$ $T_\mathrm{e}(\rho)$ $T_\mathrm{i}(\rho)$







Comparison with JET Experiment

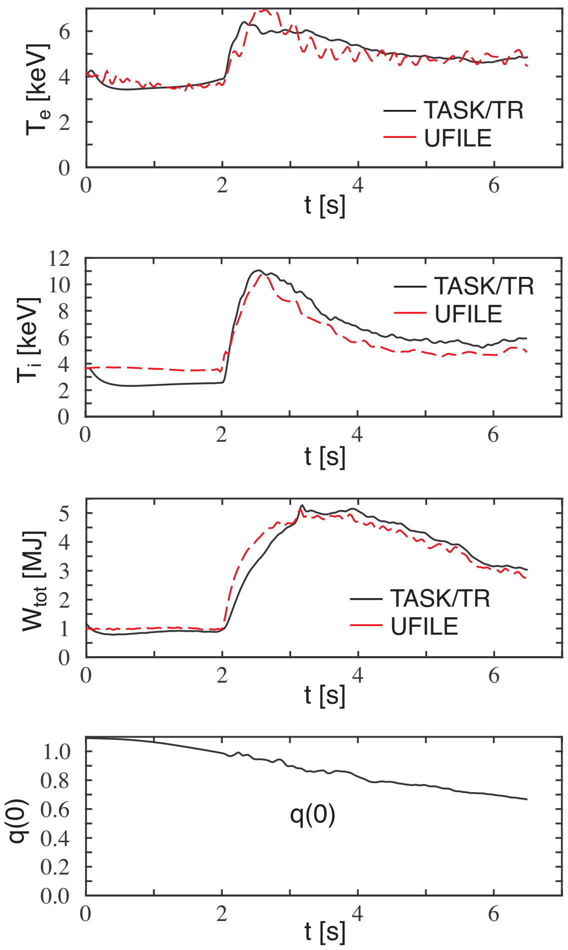
- **Shot number: 19691**

T_{e0}

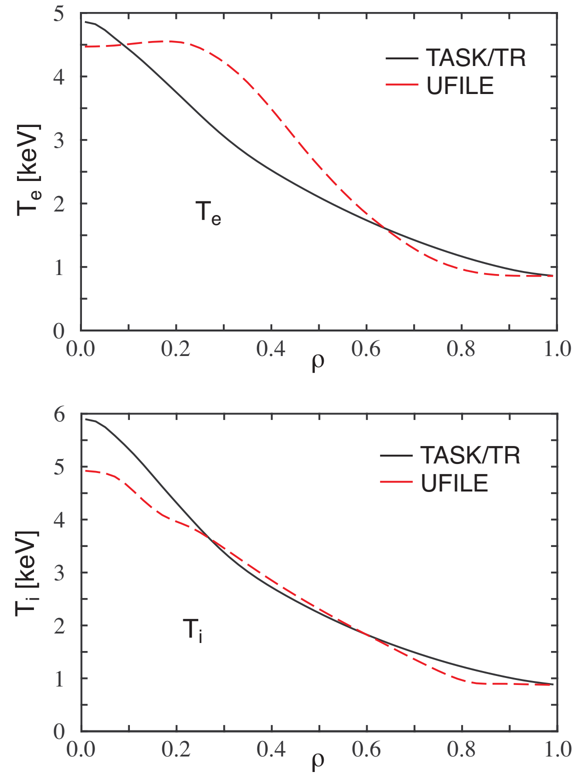
T_{i0}

W_{tot}

q_0



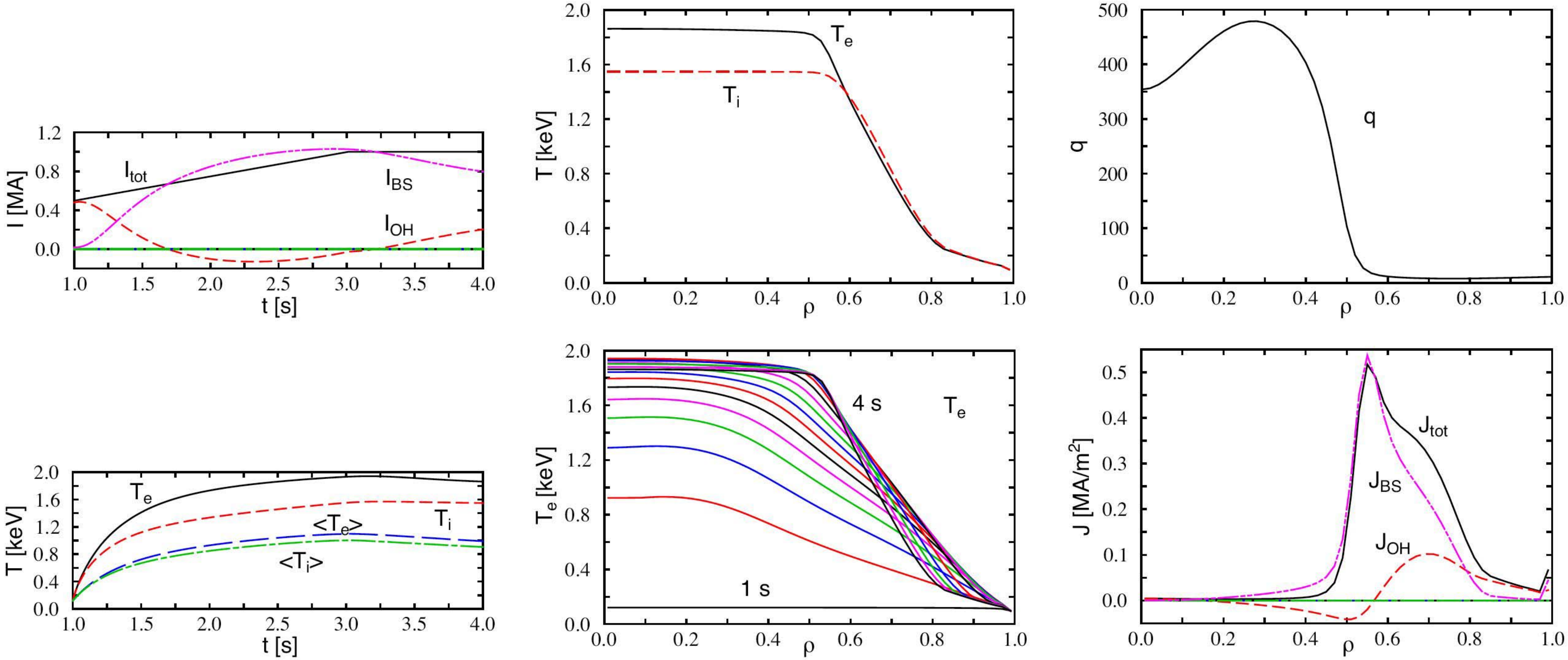
T_e and T_i



- **Sawtooth relaxation slightly improves T_e profile.**

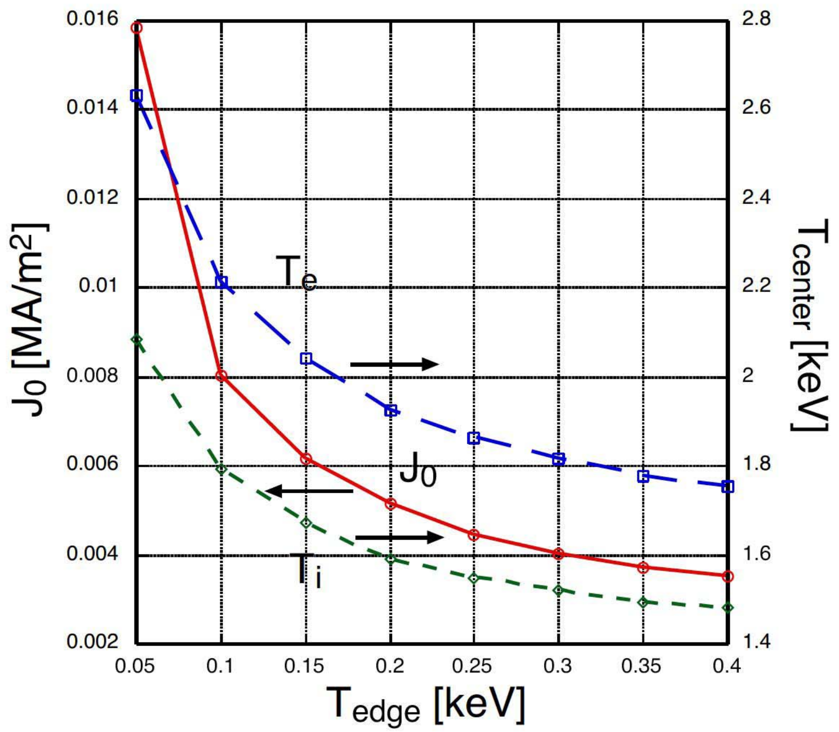
Simulation of Current Hole Formation

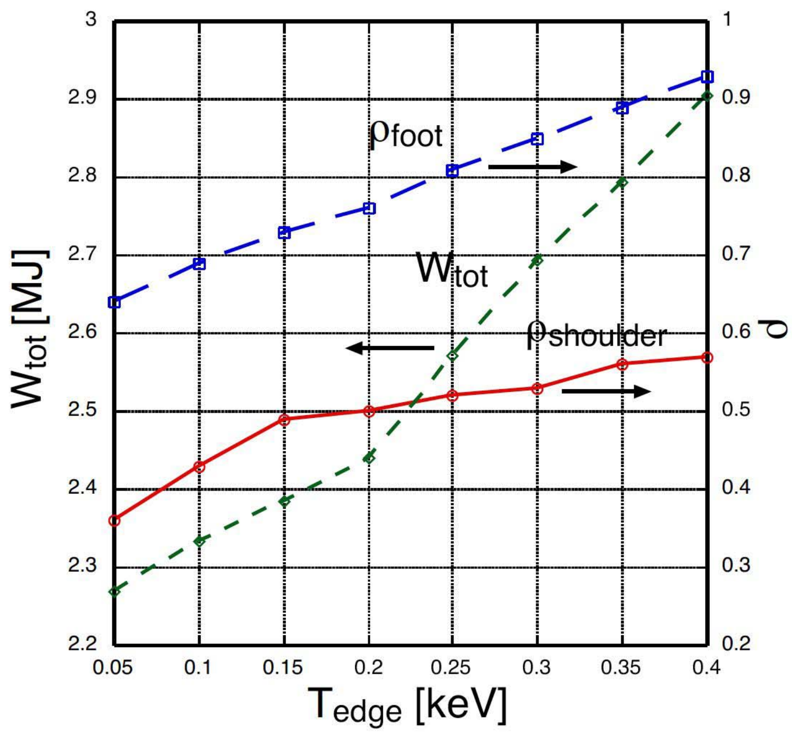
- Current ramp up: $I_{\rm p} = 0.5 \longrightarrow 1.0\,\rm MA$
- Moderate heating: $P_{\rm H} = 6.5\,\rm MW$
- **Current hole** is formed.



Dependence on Edge Temperature (P_{in} = 6.5 MW, r_H = 0.25 m)

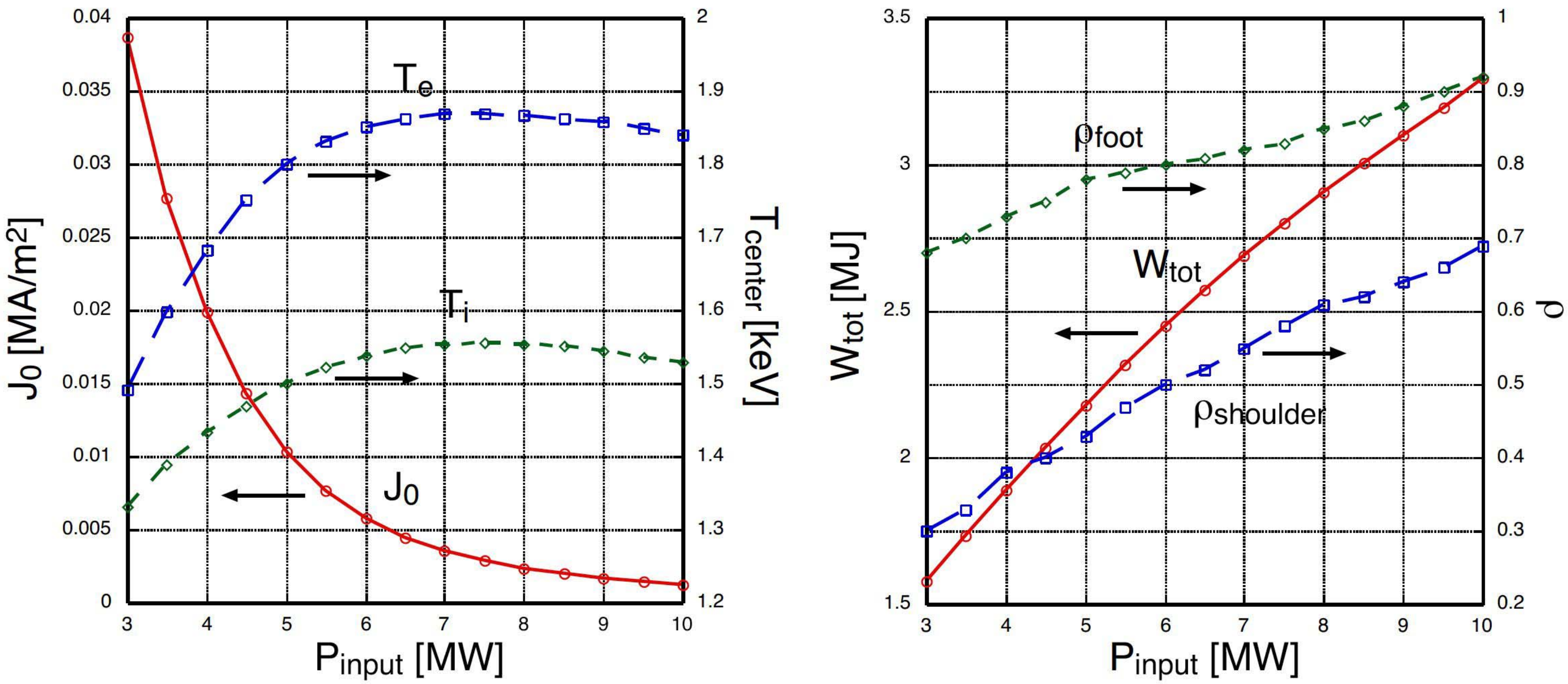
- **Sensitive to the Edge Temperature**
  - Increase of Edge Temperature
  - Slow Penetration of Current
  - Outer ITB Foot





Dependence on Input Power (T_{edge} = 0.25 keV, r_H = 0.25 m)

- Current density on axis decays exponentially, no negative
- Increase of ITB foot leads to decrease of central temperature



Summary

- We have started Burning Plasma Simulation Initiative in Japan, but littl finantial support yet.
- We are developing TASK code as a reference core code for burning plasma simulation based on transport analysis.
- The TASK code is composed of modules: equilibrium, transport, wave analysis, velocity space analysis, and data interface. New moduar structure is under construction.
- Future work
  - Improvement of modules: Full modular structure
  - Standard data interface with other simulation code
  - Systematic comparison with experimental data
  - Development of new modules: WA, TX