Integrated Simulation Code for Burning Plasma Analysis

T.Ozeki, N.Aiba, N.Hayashi, T.Takizuka, M.Sugihara[2], N.Oyama

JAERI、ITER-IT[2]

IEA Large Tokamak Workshop on

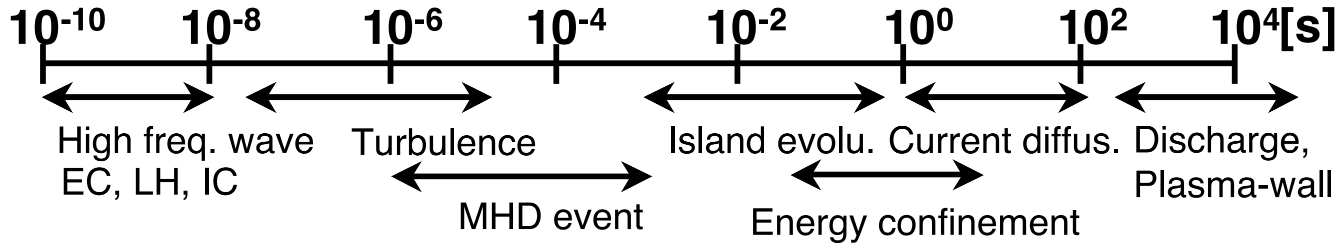
Burning Plasma Physics and Simulation, W60

Tarragona, Spain, 4 - 5 July 2005

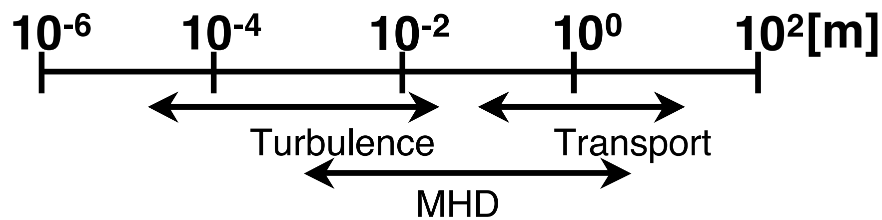
Background

Issues on simulation/evaluation of burning plasma

- **Burning plasma has very wide scales**
  - **Timescales**



  - **Spatial scales**



- **Complex physics: How is the integrated property?**
  - **Turbulence, Transport, MHD, Wave-particle interaction, Plasma-wall interaction, Atomic and molecular physics**

Background

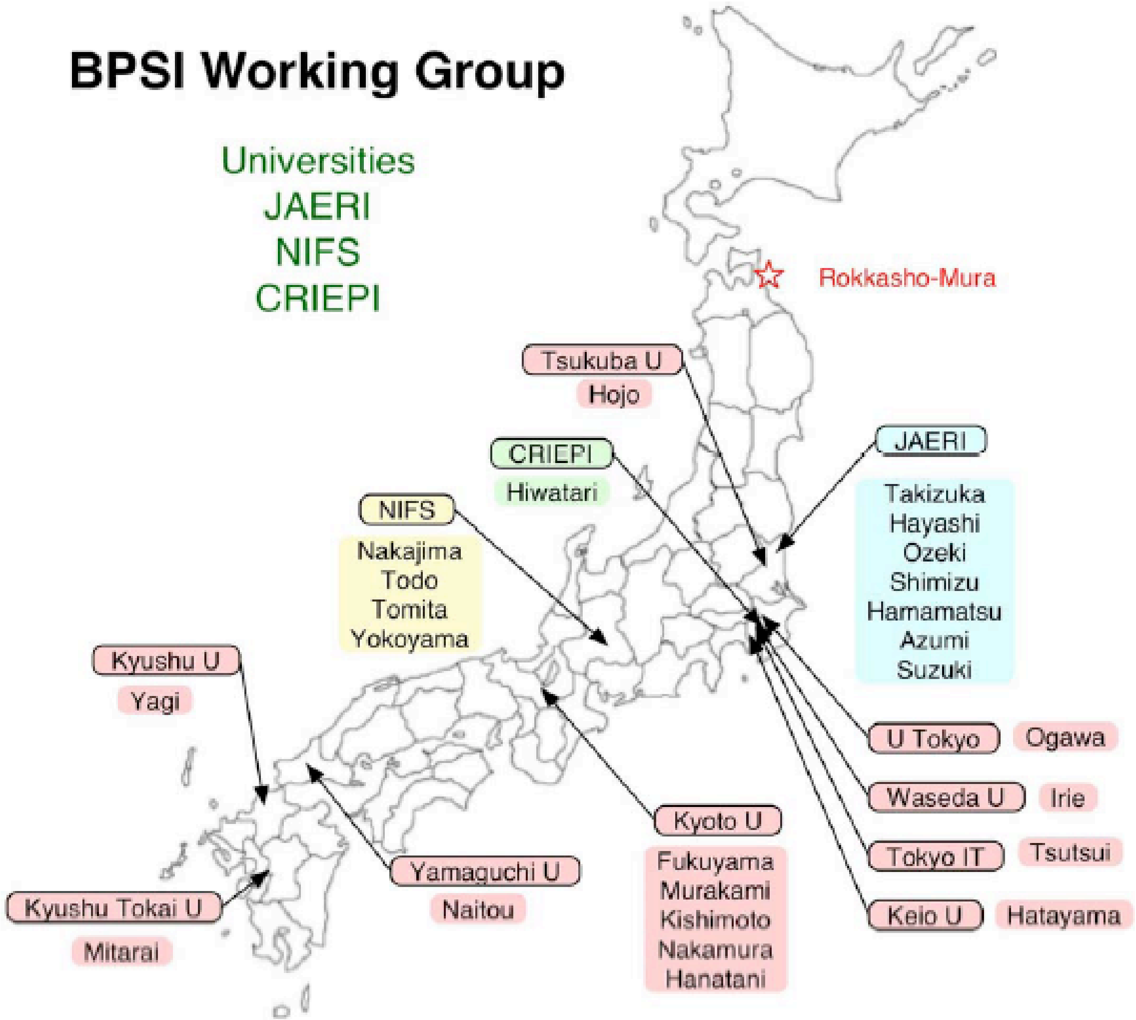
- Controllability of complex plasmas: How do we control the burning plasma and achieve the high performance?
  - High confinement, High beta, High bootstrap, High radiation, Suppression of impurity
  - Controllability of autonomous and burning plasmas
    - Strong coupling of pressure and current profiles: α-heating dominant, bootstrap current dominant

To solve these issues:

- It is not realistic to simulate the whole burning plasma based on the first principle at the present.
- Modeling and integration of the model are a useful method for the complex burning plasma. JAERI is planning to make the integrated code for the burning plasma analysis.

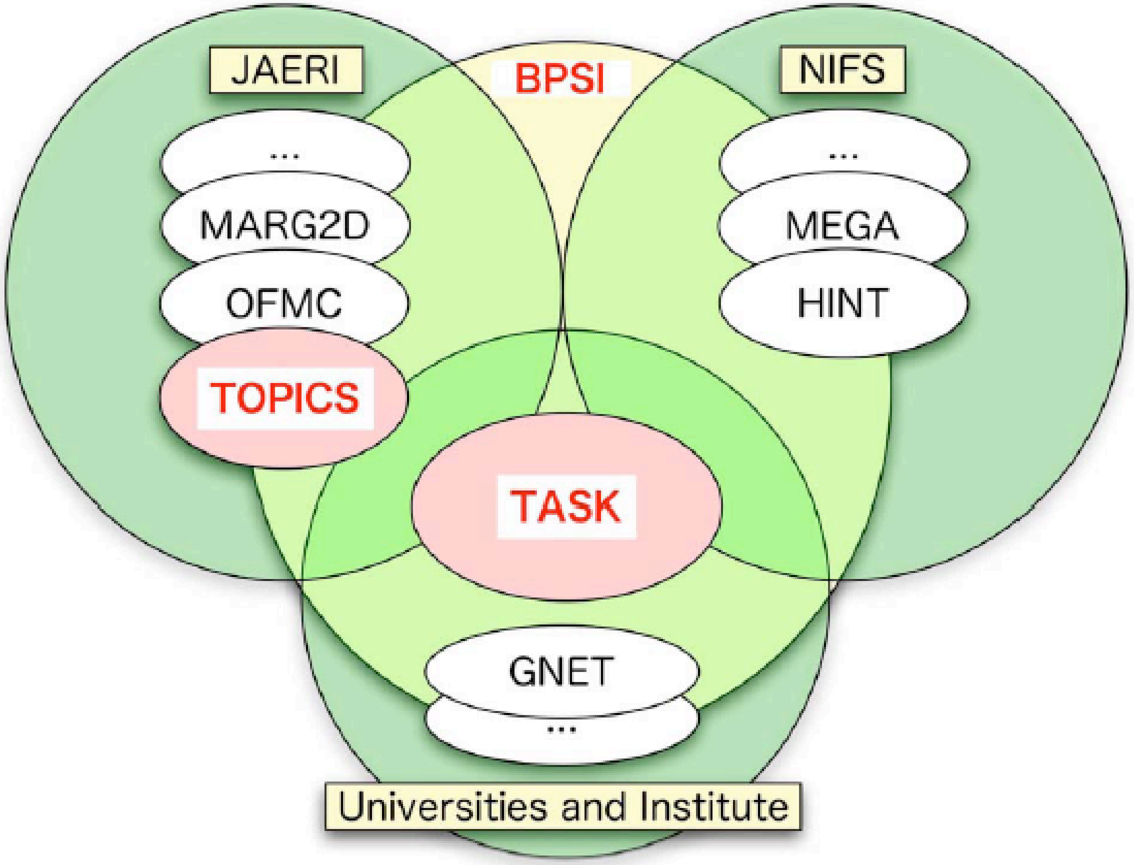
BPSI: Burning Plasma Simulation Initiative

Research Collaboration among Universities, NIFS and JAERI



Structure of BPSI

TASK: Core code of BPSI for ITER, JT-60, LHD, and small machines
TOPICS: Transport Analysis and Predictive Simulation for JT-60



Burning Plasma Simulation Code Cluster in JAERI

Transport code TOPICS

Tokamak Production and Interpretation Code
Time dependent/Steary state analyses
1D transport and 2D equilibrium Matrix Inversion Method for NeoClassical Trans.

- **Current Drive** — ECCD/ECH (Ray tracing, Relativistic F-P), NBCD(1 or 2D F-P)
- **Impurity Transport** — 1D transport for each impurities,Radiation: IMPACT
- **Edge Pedestal**
- **Divertor** — Perp. and para. transport in SOL and Divertor, Neutral particles, Impurity transport on SOL/Div. : SOLDOR, NEUT2D, IMPMC
- **MHD** — Tearing/NTM, High-n ballooning, Low-n: ERATO-J, Low and Mid.-n MARG2D
- **High Energy Behaviour** — Transport by α-driven instability:OFMC

MHD Stability and Modeling

MHD Behavior	Stability	Modeling
Sawtooth	Ideal/Resistive m/n=1/1 mode	Kadomtsev, Porcelli Model
Island Evolution	Tearing/NTM	Modified Rutherford Eq.
Beta Limits/ Disruption	low n kink high n ballooning	ERATO-J Ballooing Eq.
ELM	Medium n modes high n ballooning	MARG2D Ballooning Eq.
High energy particles induced instability	TAE/EAE/EPM... Particles loss	Under consideration

Simulation model of ELM

1.5D Transport code: TOPICS

1D transport equations : $$\frac{\partial}{\partial t}\left(\frac{3}{2}n_j T_j\right) = \frac{\partial}{V'\partial\rho}\left(V'\left\langle\left|\nabla\rho\right|^2\right\rangle n_j \chi_j \frac{\partial T_j}{\partial\rho}\right) + P_j \quad (j = e,i)$$

1D current diffusion equation : $$\frac{\partial}{\partial t}\left(\rho\frac{\partial\Psi}{\partial\Phi}\right) = \frac{\partial}{\partial\rho}\left\{D\frac{\partial}{\partial\rho}\left(E\frac{\partial\Psi}{\partial\Phi}\right) - S(j_{BS})\right\}$$

Impurity : C^{6+}, $T_{imp}=T_i$, assumed profile Z_{eff}

$$V' = \frac{dV}{d\rho}$$

2D MHD equilibrium : Grad-Shafranov equation

$$\rho = (\Phi(\rho)/\Phi(1))^{0.5}$$

2DEquilibrium data

ELM model : enhance the transport

Eigenvalue and eigenfunction

Finite n mode by MARG2D, High n ballooning

Model of transport: Neoclassical in peripheral region (ρ>0.9) and anomalous in inside region (ρ<0.9)

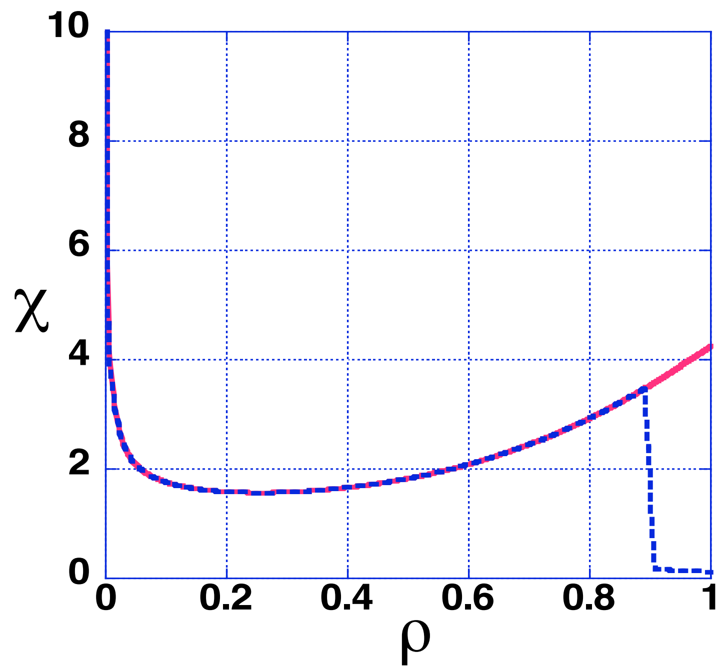
Diffusivities in the transport eqs. :

$$\chi_{i,e} = \chi_{neo,i} + \chi_{ano,i,e}$$

Neoclassical transport :

Diffusivity and bootstrap current : Matrix inversion method for Hirshman & Sigmar Formula (M.Kikuchi, et al., Nucl. Fusion 30(1990)343.)

Neoclassical resistivity : Hirshman & Hawryluk model (Nucl. Fusion 17(1977)611.)



Anomalous transport :

Empirical transport model

$$\chi_{ano} = \chi_0 (1 + 2\rho^3)\left(1 + \sqrt{P_{NB}}\right)$$

$$\chi_{ano,i} = 2\chi_{ano,e}$$

χ_0 **: constant (=0.18[m²/s])**

P_{NB} **:NBI power**

Density profile $$n_e = n_0\left[0.7\left(1 - \rho^2\right)^{0.5} + 0.3\right] \quad n_0 = 0.33 \times 10^{20}[m^{-3}]$$

MARG2D: low-n and high-n mode stability code [S.Tokuda, Phys. Plasmas 6 (8) 1999]

- **MARG2D solves the 2D Newcomb equation**

$$N\xi := -\frac{d}{dr}\left(L\frac{d\xi}{dr}\right) - \frac{d}{dr}(M^t\xi) + M\frac{d\xi}{dr} + K\xi = 0$$

associated with eigenvalue problem

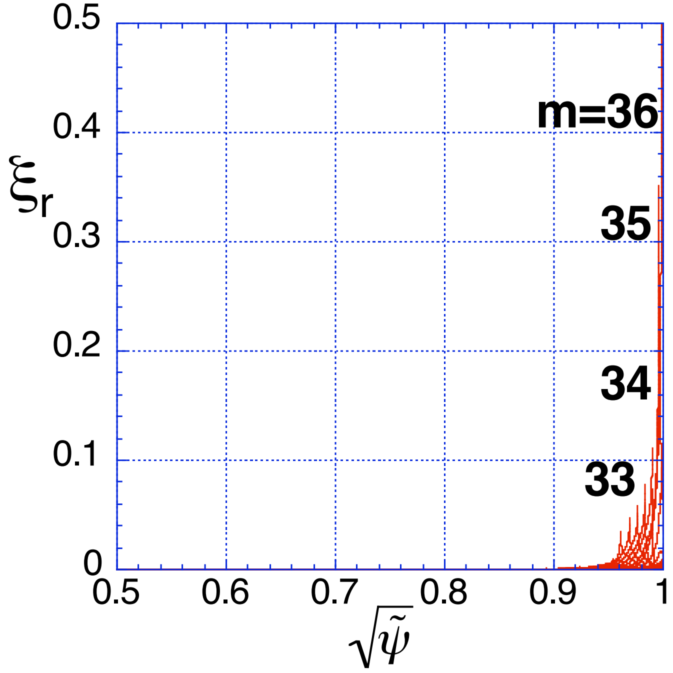
$$N\xi = -\lambda R\xi$$

$$R: \text{diagonal matrix with } R_{m,m} \propto (n/m - 1/q)^2$$

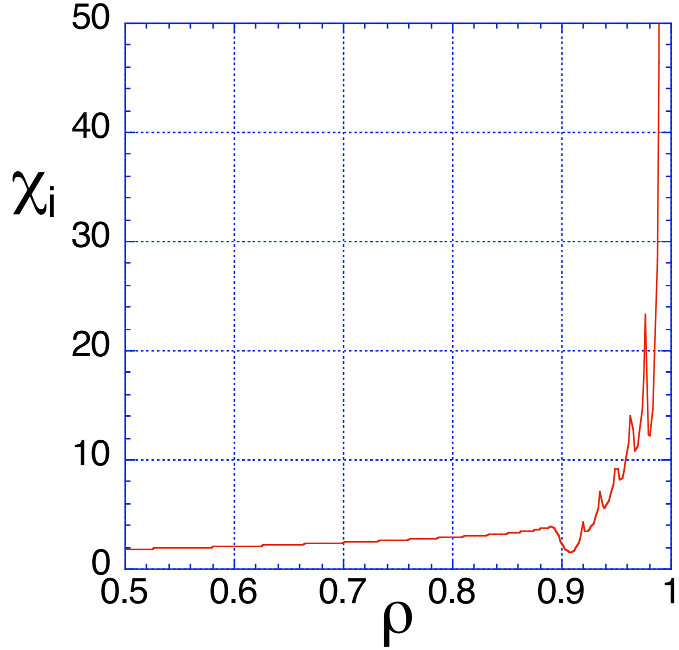
- **Properties of the code**
  - **This method can avoid problems due to the continuum spectrum.**
  - **Applicable for high n modes stabilities (more than n=50)**
  - **Very short calculation time (~85sec for n=40, NR=2800, NV=280,m=90 by Origin 3800,128cpu)**
  - **Results of the stability of n=1 agree with those of ERATO-J**

ELM Model

- **The stability is examined in each iteration step of TOPICS.**
  - **When the plasma is unstable, the thermal diffusivity increases according to the eigen-function.**
  - **When the mode becomes stable, χ_{ELM}=0.**



Eigen function of unstable mode of n=7

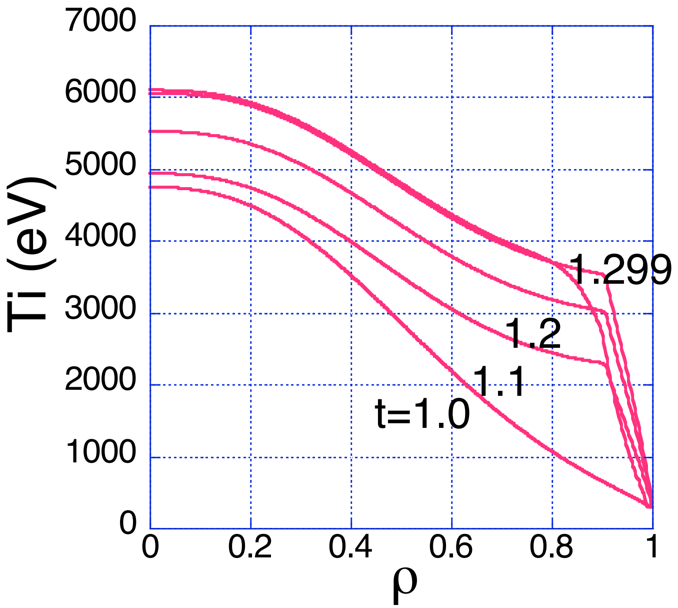


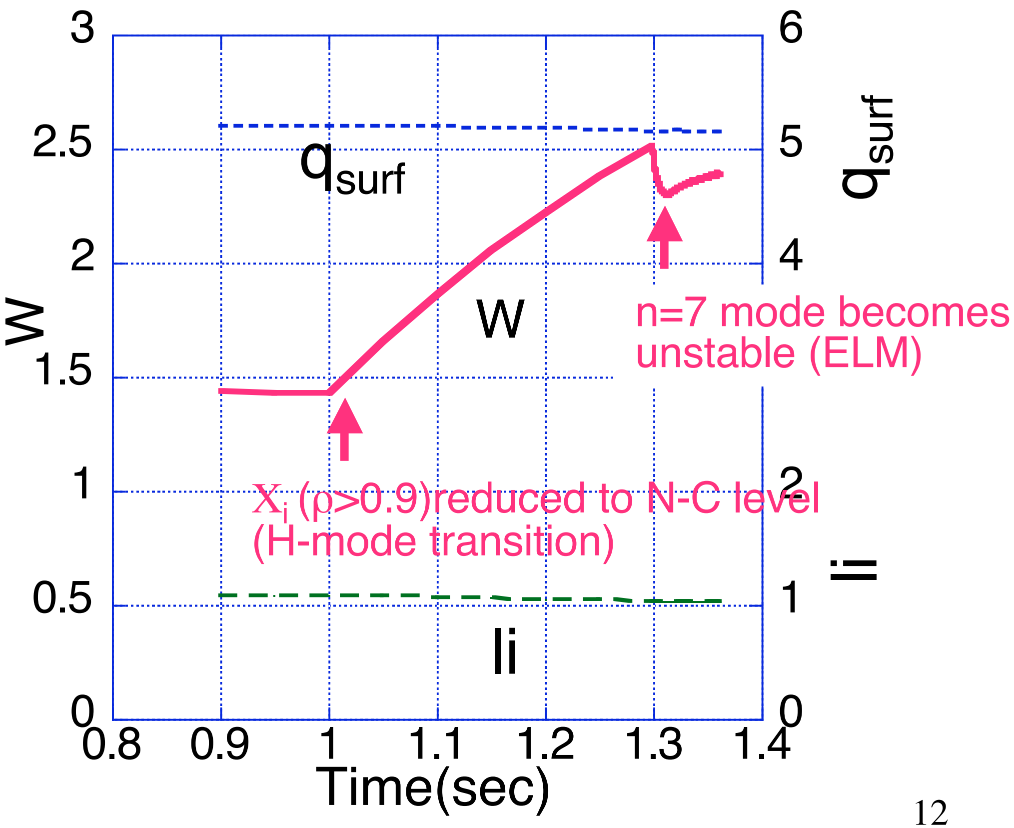
$$\chi_i = \chi_e = \chi_{neo,i} + \chi_{ano} + \chi_{ELM}$$

$$\chi_{ELM} = 1000[m^2/s] \times \bar{f}_{eig}(\rho)^2$$

Results: Simulation of ELM

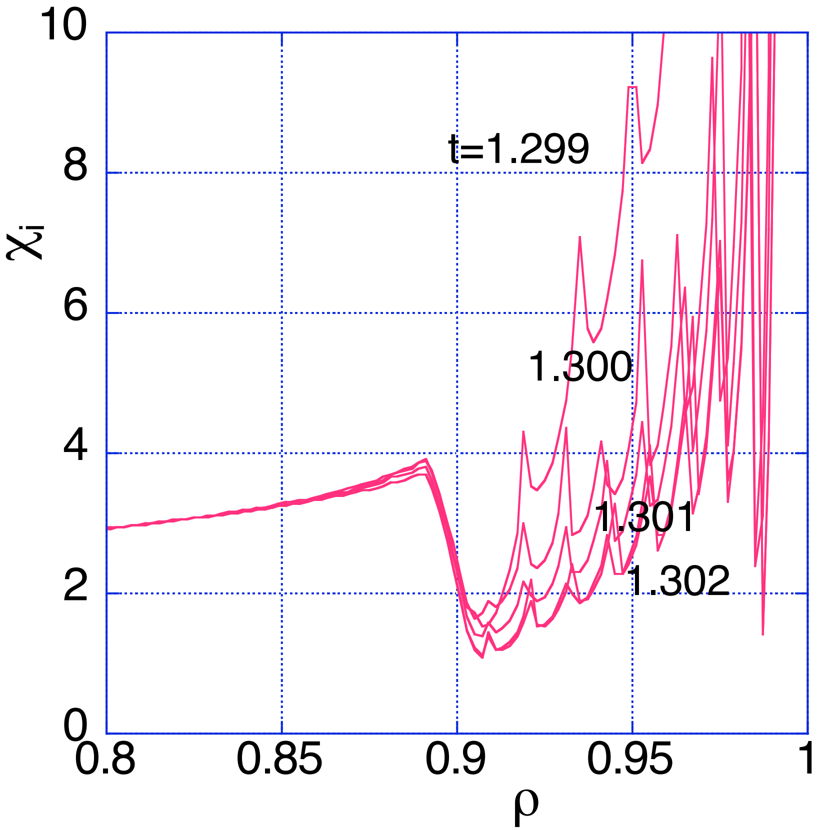
- **Parameters**
  - **R_{maj}=3.4m, a=0.9m, Ip=1.5MA, Bt=3.5T, κ~1.5, δ~0.2**
  - **Ti_{edge}=300eV , ne_{edge}=1x10^{19}1/m^3, Z_{eff}=2.8-2.3**
  - **β_N~0.5-0.8, $P_{NB(perp)}$=8MW,**
  - **n=1-10 modes**

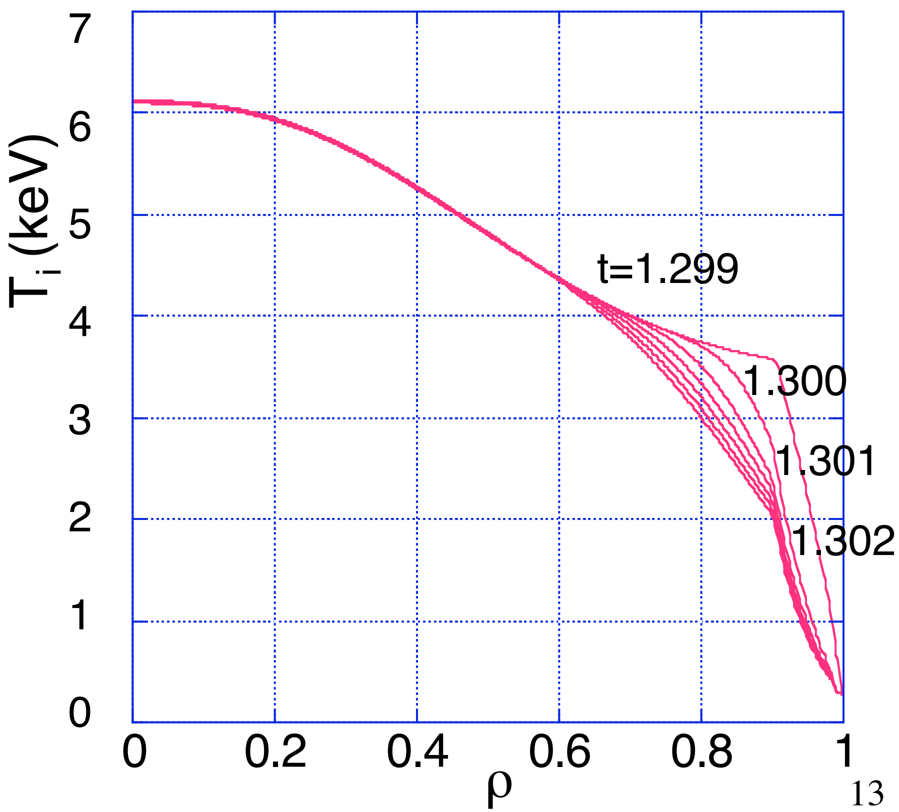




Enhancement of χ_i and degradation of T_i

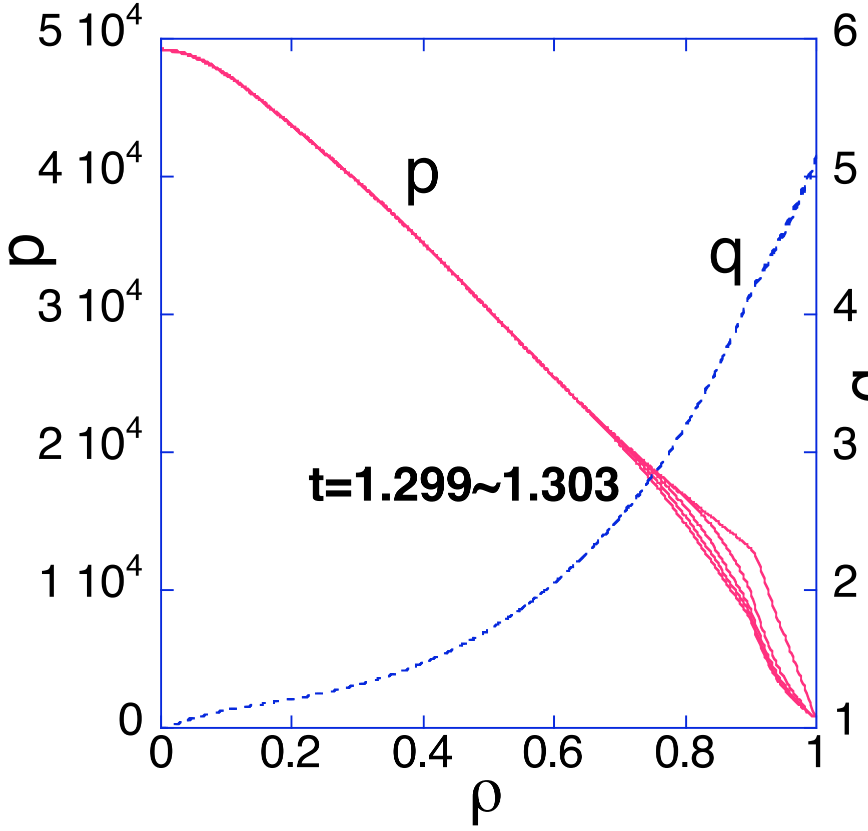
- **n=7 mode becomes unstable at 1.299.**
- **The heat conductivity increases according to the eigen function.**
- **The pedestal of the ion temperature is degraded.**
  - **next, the relaxation of the shoulder appeared.**

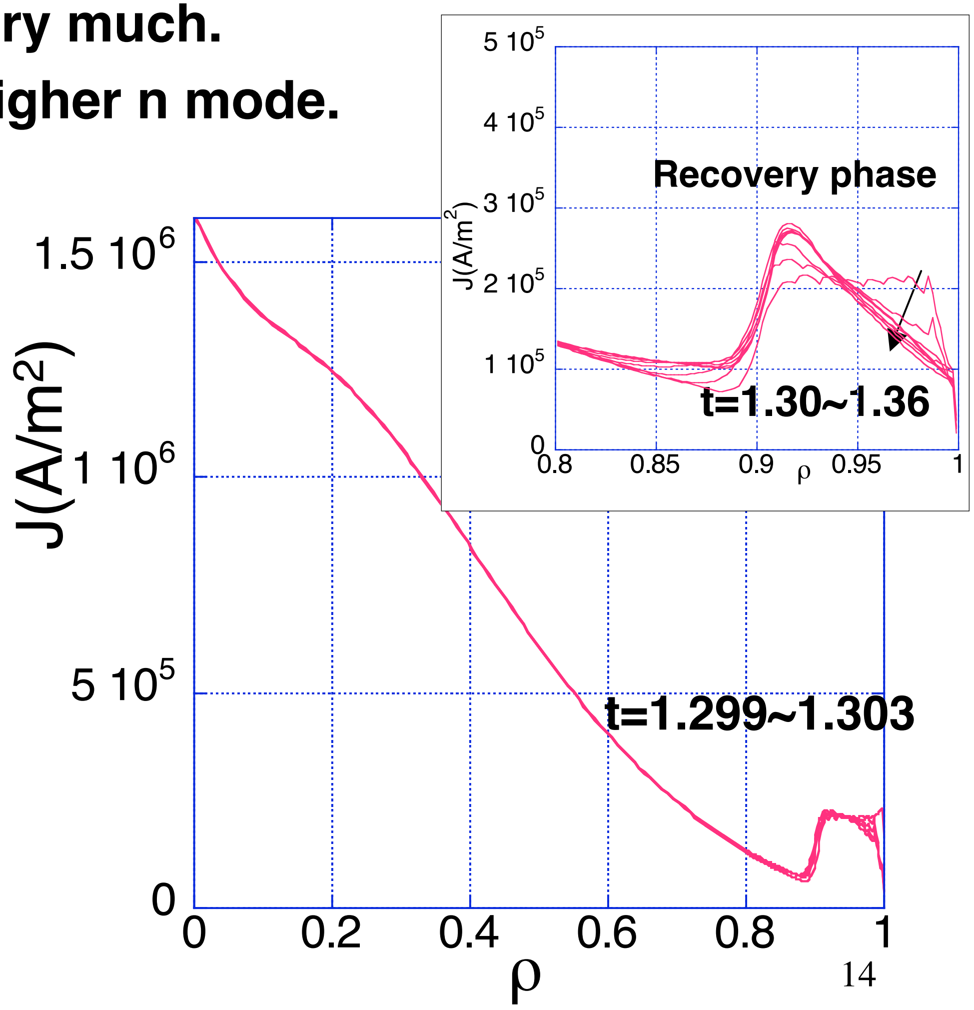




Reduction of p and small change of q

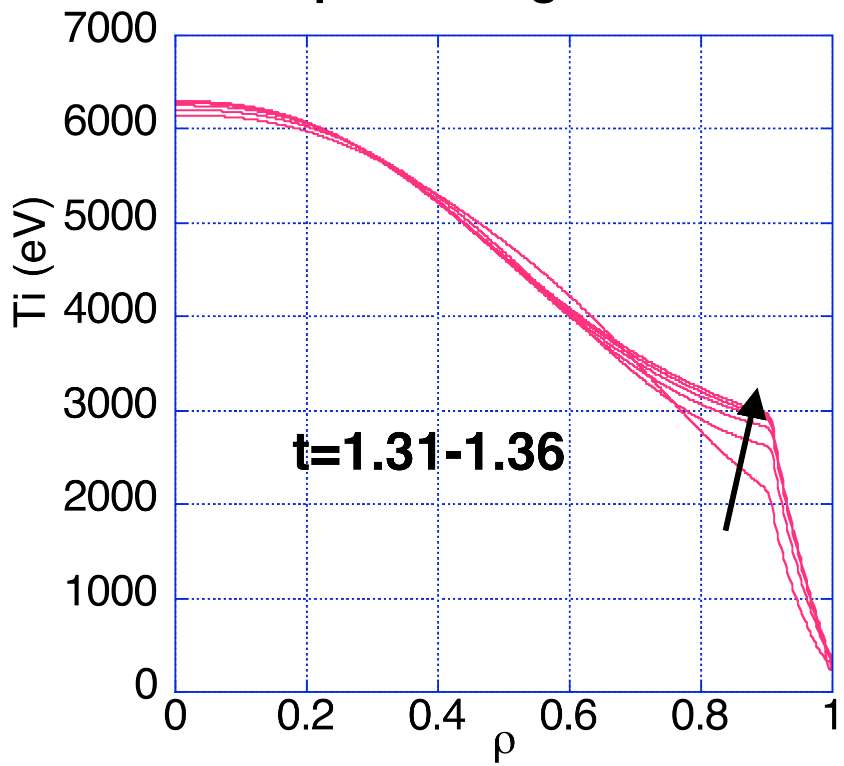
- During the degradation (t=1.299-1.303), the current density profile does not change very much.
- The most unstable mode shift to higher n mode.

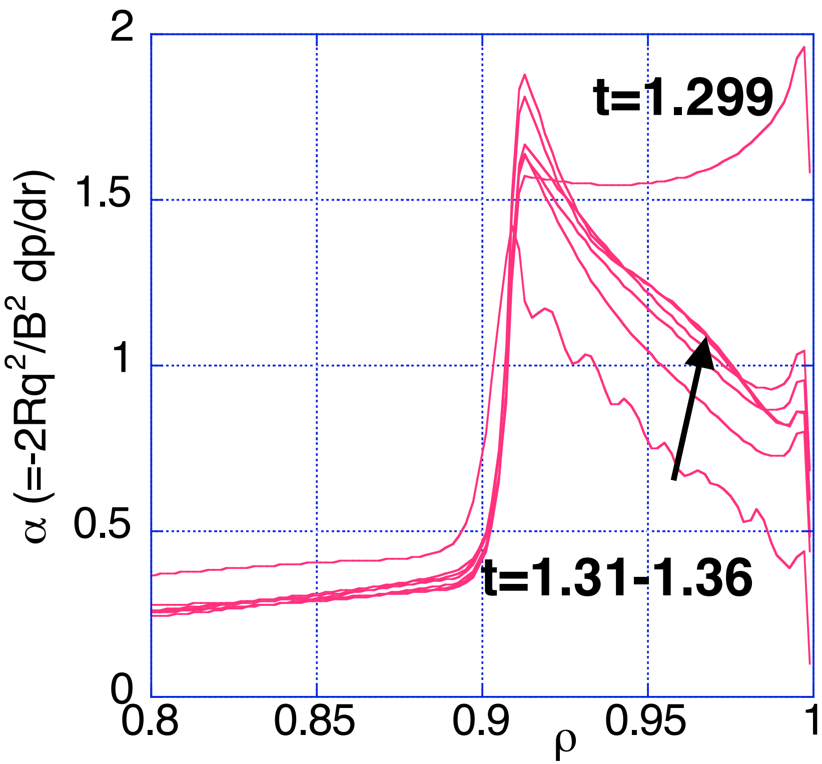




Stabilization of the mode and Recovery of Ti

- **After the short period of the ELM crash,**
  - **the finite-n MHD mode becomes stable**
  - **the evolution of the pedestal restarts.**
  - **the pressure gradient locally increases, but the modes remain stable.**





Computer system and calculation time

PC-Cluster
PAC1
6GFlops

TOPICS
One step
CPU ~9sec

Parallel computer
SGI-VSL3000
6G×64PE=384GFlops

MARG2D
n=1-10 modes
CPU 138sec (64PE)
CPU 242sec (32PE)
(29sec for n=10 only)

One iteration cal.
~210sec(64PE)
~300sec(32PE)

TOPICS:	9s
MARG2D:	138s
Communication:	63s
Total of 64PE:	210s

- Estimated cal. time is 58hour for 100msec simulation for 100μs iteration, using 64PE.

Summary

- Integrated simulation for ELMs is realized by the iterative calculation of MHD stability code MARG2D and the transport code TOPICS.
- Collapse event like ELM is produced.
  - Degradation and evolution of the pedestal structure are reproduced.
- Future work
  - Improvement of the model by the comparison with the experiment: profiles and time-dependent behavior of p and j, MHD and pedestal width etc.
  - Analysis of the mechanism of ELM events
  - Clarify the parameter dependency on ELM and give the guideline of control of ELM

Discussion

- **"where are we, where do we want to go, how do we get there"**
  - **Integrated modeling is a quite realistic simulation; such as real shape, real time scale, and real device parameters.**
  - **Usually the modeling uses some assumptions, then integrated modeling is seems to be the integrated assumption. Keeping the physics is the key point.**
  - **The validation of the model is important; comparison with the experiments.**
  - **Each integrated modeling and simulation should be focused on the issues what we want to know, for example, ELM effects on the burning plasma, … .**
  - **It is important to select the physics issues, the control issues, scenarios…**