Advance in integrated modelling towards prediction and control of JT-60SA plasmas

N. Hayashi, M. Honda, J. Shiraishi, Y. Miyata, T. Wakatsuki, K. Hoshino, M. Toma, T. Suzuki, H. Urano, K. Shimizu, K. Hamamatsu, S. Ide and JT-60SA Team

Japan Atomic Energy Agency, Japan

1. Introduction

The project mission of JT-60SA [1] is to contribute to early realization of fusion energy by supporting the exploitation of ITER and by complementing ITER in resolving key physics and engineering issues for DEMO reactors. The device aims to achieve high-beta and high-bootstrap-fraction plasmas, in which the linkage between many physics factors is strong, resulting in complicated behavior of self-regulating plasmas. This self-regulation is expected to be strong in ITER and DEMO burning plasmas. In order to predict, control such plasmas, and to develop operation scenarios, we are developing codes/models which can describe each of both physics and engineering factors, and integrating them to one code suite TOPICS, as shown in Fig.1. It had been formally referred to as TOPICS-IB [2]. Now it is simply referred to as TOPICS, since the core transport module which was called TOPICS has now evolved integrating the other functions and modules so as to represent the suite.

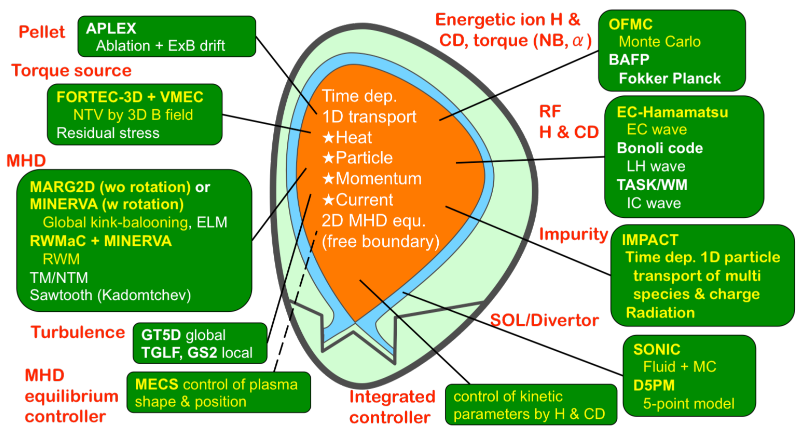

Fig.1 Schematic view of integrated code TOPICS and its modules where yellow denotes codes/models used in this paper.

2. Physics modelling

To study RWM in high-beta plasmas, TOPICS is coupled with a stability code MINERVA/RWMaC, in which the kinetic-MHD model is extended to include the toroidal rotation effect self-consistently. The energy exchange between MHD modes and particle's motion is generalized to yield three additional terms, representing Coriolis, centrifugal and rotation shear effects, compared with the conventional model. Figure 2 shows a stability diagram in a plane of rotation shear and rotation for a JT-60U experiment analyzed by MINERVA / RWMaC. For the rotation Ω=30-40 krad/s, increased rotation shear leads to the RWM

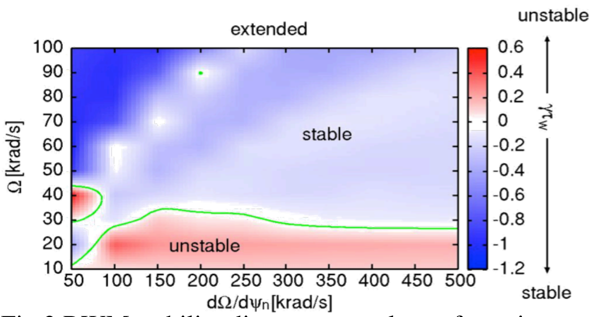

Fig.2 RWM stability diagram on a plane of rotation shear $d\Omega/d\psi_n$ and rotation Ω, where ψ_n is normalized poloidal flux, for a JT-60U experiment.

stabilization and this tendency is consistent with experiment. While the conventional model shows that the rotation shear destabilizes RWM and unstable regions appear for faster rotation Ω>60 krad/s, the extended model removes the unstable regions and enlarge the stable region [3]. Simulations of MINERVA/RWMaC and TOPICS with the MHD equilibrium variation by the centrifugal force, which largely affects the RWM stability, realizes self-consistent analyses of RWM stability on the plasma evolution.

To study the toroidal rotation driven by various torques, TOPICS is coupled with an orbit-following code OFMC for NB induced collisional and jxB torques, with a 3D MHD equilibrium code VMEC and a δf drift-kinetic code FORTEC-3D for a NTV torque, and with a toroidal momentum boundary model based on a zero gradient of radial electric field at the separatrix observed in JT-60U experiments. Analyses for JT-60U experiments show including NTV improves the reproducibility of toroidal rotation, and the boundary model in conjunction with a SOL/divertor model D5PM predicts well the toroidal rotation at the boundary. This integrated model is applied to predict the toroidal rotation in a hydrogen L-mode plasma in ITER. Figure 3 shows profiles of torques and toroidal rotation. Since the minimum toroidal field (TF) ripple created by 18 TF coils and ferritic steel tiles is considered here, the NTV torque is small compared to NB ones and the core rotation of ~2% of Alfven speed is predicted. However, NB ports and the tritium blanket module can enhance the TF ripple and thus NTV [4].

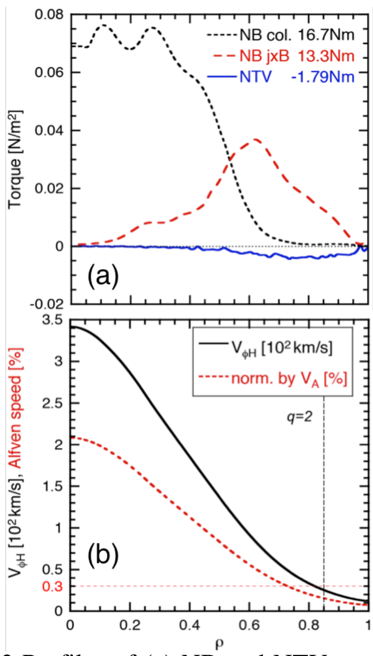

Fig.3 Profiles of (a) NB and NTV torques, and (b) toroidal rotation for a ITER hydrogen L-mode plasma.

We develop a core impurity transport code IMPACT, integrate it with TOPICS and study the core accumulation of impurity seeded to reduce the divertor heat load below a preferable level. For a JT-60SA steady-state (SS) scenario, an integrated divertor code SONIC showed that the low divertor heat load (< 10 MW/m^2) with low SOL density (< 1.5×10^{19} m^{-3}), which is required for the scenario, was achieved by Ar gas puffing of 0.86 Pa m^3/s to the divertor region [5]. The Ar inflow to the core is evaluated from the SONIC result

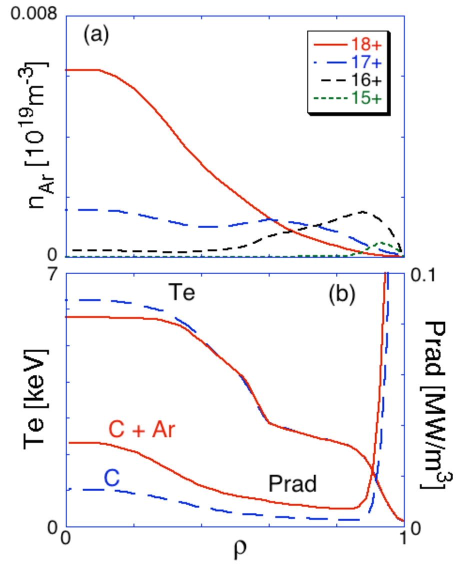

Fig.4 Profiles of (a) Ar density with charge states 15-18+, (b) electron temperature and radiation without/with Ar (intrinsic C exists in both cases) for a JT-60SA SS scenario.

and is assumed to be injected as MC neutrals in IMPACT, the neoclassical transport is calculated by NCLASS, and anomalous diffusivities are set to the neoclassical level to consider the maximum accumulation. Figure 4 shows simulation results of IMPACT and TOPICS where the same amount of intrinsic C exists in both cases without and with Ar. Ar with charge states 15-18+ are accumulated in the core and the radiation increases slightly (+ 1.5 MW). The Ar accumulation is so mild that the plasma performance can be recovered by additional heating within the machine capability.

TOPICS is applied to study the reduction of flux consumption of central solenoid (CS) during the current ramp up, which can relax a constrain on DEMO. JT-60SA simulations coupled with an ideal MHD stability code MARG2D show that the plasma current can be ramped-up to reach $\beta_N \geq 3$ with MHD modes stabilized by an ideal wall, and with high bootstrap and NB driven currents, resulting in no additional CS flux consumption [6].

3. Control engineering modelling

In the SS operation, the real-time control of plasma parameters is essential in avoiding MHD activities and sustaining the self-regulating plasma at the high performance within the machine capability. To study the controllability of kinetic parameters and their profiles via external actuators, an integrated real-time controller is developed on the basis of PID control scheme in a matrix form for multi-input and multi-output control, and coupled with TOPICS. Figure 5 shows waveforms of real-time control of β_N and V_{loop} for a JT-60SA SS scenario, where positive-ion-based NB and ECH is used for the β_N control and negative-ion-based NBCD for V_{loop} control. The integrated controller commands NB and EC powers, which are used as inputs of a simple 1D Fokker Planck code for NBH/CD and a EC-hamamatsu code for ECH. By optimizing control gains, β_N follows well its reference raised by 3 steps and V_{loop}~0 is achieved during β_N=4 as its zero reference value. Simultaneous control of β_N and V_{loop} is possible at $\beta_N \geq 4$ in either high (f_{GW}=0.88, Fig.5) or low density (f_{GW}=0.52) [7].

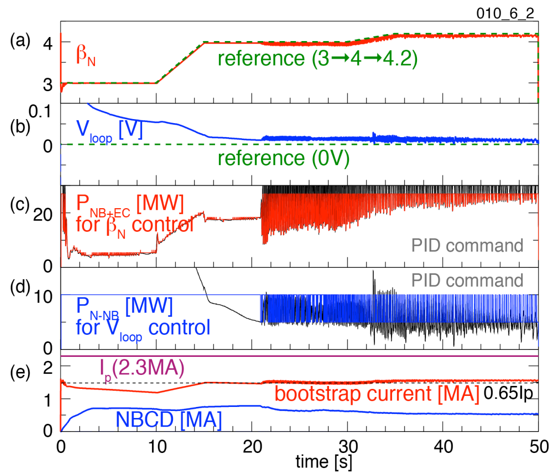

Fig.5 Real-time control of β_N and V_{loop} for a JT-60SA SS scenario. (a) β_N and reference, (b) V_{loop} and reference, (c) P-NB and EC heating power controlling β_N, (d) N-NBCD controlling V_{loop}, (e) plasma current, bootstrap current and NBCD current.

A MHD equilibrium control simulator (MECS) has been developed to study control techniques with the power supply capability of PF coils and the reconstructed plasma boundary by Cauchy condition surface (CCS) method. MECS consists of modules as shown in Fig.6. The isoflux controller modifies coil currents to reduce residuals between the poloidal magnetic flux at LCFS and that at the control points which specify the plasma position and shape, and also between actual and reference values of plasma current. The MHD equilibrium solver predicts the equilibrium for given β_p and l_i at present and this part will be coupled with TOPICS. Figure 7 shows a MECS simulation with and without CCS for a modelled heating phase in JT-60SA. Waveforms with CCS agree well with an ideal case without CCS where the shape is assumed known without diagnostics. This indicates the MHD equilibrium can be feedback controlled on the basis of combination of isoflux scheme and CCS method [8].

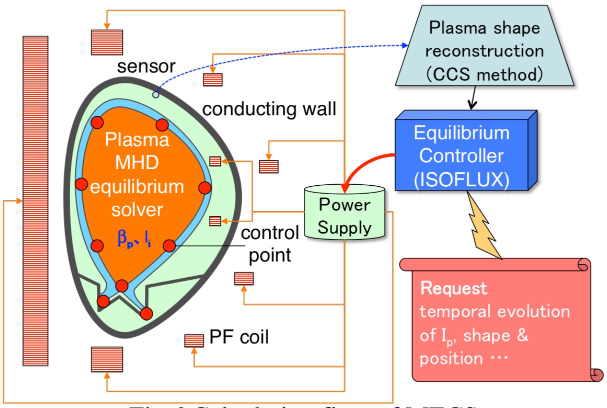

Fig.6 Calculation flow of MECS

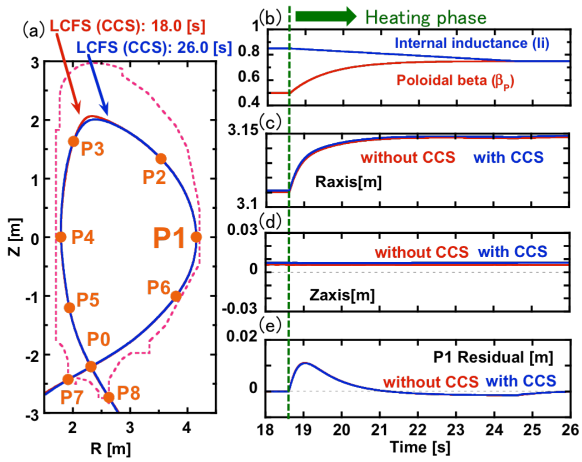

Fig.7 MECS simulation for JT-60SA. (a) Locations of control points and LCFS by CCS. Waveforms of (b) β_p and l_i, (c) R_{axis}, (d) Z_{axis} and (e) P1 residual without and with CCS.

4. Summary

Towards the prediction and control of JT-60SA plasmas, integrated modelling has advanced in both physics and engineering aspects; physics modelling: RWM stability with the toroidal rotation and kinetic effects, toroidal rotation with NTV and BC model, impurity transport in core and SOL / divertor plasmas, plasma current ramp up with reduced CS flux consumption, control engineering modelling: integrated real-time control for kinetic parameters, MHD equilibrium control. To study the burning plasma control in JT-60SA, a module to simulate α heating by a part of NBs will be developed and the integrated control will be improved to control it. For more self-consistent modelling, couplings of IMPACT+SONIC and MECS+TOPICS will be considered. These developed models will be further applied to the development of JT-60SA scenario.

This work was partly supported by JSPS KAKENHI Grant Number 26420862 and was partly carried out using HELIOS supercomputer system at International Fusion Energy Research Centre, Aomori, Japan, under Broader Approach collaboration between Euratom and Japan, implemented by Fusion for Energy and JAEA.

Reference:

[1] JT-60SA Research Plan v3.1, http://www.jt60sa.org/pdfs/JT-60SA_Res_Plan.pdf
[2] N. Hayashi et al. 2010 Phys. Plasmas **17**, 056112
[3] J. Shiraishi et al. 2014 Proc. IAEA FEC, TH/P6-12
[4] M. Honda et al. 2014 Proc. IAEA FEC, TH/5-1
[5] K. Hoshino et al. 2014 Contrib. Plasma Physics **54**, 404
[6] T. Wakatsuki et al. this conference, P5.144
[7] T. Suzuki et al. 2013 Proc. 40th EPS Conf. on Plasma Physics, P2.136
[8] Y. Miyata et al. 2014 Plasma Fusion Res. **9**, 3403045