Integrated modelling of JT-60SA scenarios with the METIS code

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1. Introduction

JT-60SA is a large fully superconducting new tokamak device being built under the Broader Approach Satellite Tokamak Programme jointly by Europe and Japan, and under the Japanese national program [1]. The JT-60SA tokamak will be at the forefront of the international fusion programme for many years, both before and during the D-T phase of the ITER operation. It will support the ITER experimental programme as a satellite machine and at the same time provide key information for the design of DEMO scenarios. The preparation of its scientific programme is now progressing in the framework of a Japan-EU collaboration and will progressively integrate advances coming both from experiments on other tokamaks and theoretical developments [2,3]. As for ITER and DEMO, integrated modelling of full discharges will be the main ingredient to perform this preparation effectively and on a coherent basis. This is based on a hierarchy of simulation codes, each level of accuracy being used in order to prepare and rationalize the higher simulation level. For instance, at CEA/Cadarache, this hierarchy consists of the codes HELIOS (0-D) [4], METIS (0.5-D) [5] and CRONOS (1.5-D) [6]. Here, sets of simulations of some of the reference JT-60SA operation scenarios [2,3] performed with the 0.5-D code METIS will be presented and discussed. These simulations will be used to illustrate the main properties of the JT-60SA scenarios and of the related scientific objectives.

2. The METIS code

METIS computes the time evolution of the global plasma quantities for given waveforms of the control parameters. It solves the current diffusion equation taking into account an approximate equilibrium evolution. Simplified treatment of the sources and of spatial dependences allow simulation of a discharge in a CPU time of the order of one minute, while keeping account of all the main non-linearities of the evolution. This approach allows completing the 0-D analysis with radial profiles and time evolutions, although with less accurate results than with a full 1.5-D code (which typically takes 10^3 - 10^4 times larger computation times). The equilibria and profiles obtained by the METIS code can then be used for various purposes, e.g., benchmark of H&CD calculations done with different codes, or simple MHD calculations not requiring high-resolution equilibria, such as estimates of

NTM suppression by ECCD.

METIS simulations for JT-60SA have the following main characteristics:

1. a 2-D, time-dependent equilibrium is used, but based on equations for the time evolution of equilibrium moments: radii, elongation, triangularity, Shafranov shift, etc., using the separatrix computed by the TOSCA free-boundary equilibrium code [7]
2. heat transport coefficients are renormalized in order to enforce prescribed confinement scaling laws (in particular, L and H-mode in the varius phases of the discharge)
3. the full current diffusion equation is solved numerically
4. density and temperature profiles are obtained by simplified solutions of the transport equations: discrete time slices are considered, on which stationary equations are solved. Pedestal values are imposed, consistent with pedestal scaling laws [8].
5. a coarse time-space grid (typically 300 x 21) is used in order to minimize the computation time (~ 1 minute per simulation).

3. The JT-60SA reference scenarios

The main parameters of the JT-60SA reference scenarios are shown in Table 1. They include both H-mode scenarios (#1, 2, 3, 4-1) and advanced scenarios (#4-2, 5-1, 5-2, 6). All of them have been simulated by the METIS code, and the global parameters compared with those presented in Ref. [3], that have been obtained by means of the ACCOME code [9] with assigned density and temperature profiles. The main global quantities computed by METIS are shown in Table 2. They compare very well with those presented in Ref. [3].

	#1	#2	#3	#4-1	#4-2	#5-1	#5-2	#6
	Inductive	Inductive	High density	ITER-like	Advanced Inductive	High β Full-CD	High β,f_G Full-CD	300s High β
configuration	DN	SN	SN	SN	SN	SN	SN	SN
I_p (MA)	5.5	5.5	5.5	4.6	3.5	2.3	2.1	2.0
B_T (T)	2.25	2.25	2.25	2.28	2.28	1.72	1.62	1.41
R/a (m)	2.96/ 1.18	2.96/ 1.18	2.96/ 1.18	2.93/ 1.14	2.93/ 1.14	2.97/ 1.11	2.96/ 1.12	2.97/1.11
k / δ	1.95/ 0.53	1.87/ 0.50	1.86/ 0.50	1.81/ 0.41	1.80/ 0.41	1.90/ 0.47	1.91/ 0.45	1.91/0.51
V (m^3)	132	131	131	122	122	124	124	124
q_{95}	3	3	3	3	4.4	5.8	6	4
$H_{98(y,2)}$	1.3	1.3	1.1	1.1	1.2	1.3	1.38	1.3
P_{add} (MW) $P_{NNB}/P_{PNB}/P_{EC}$	41 10/24/7	41 10/24/7	30 10/20/0	34 10/24/0	37 10/20/7	37 10/20/7	30 6/17/7	13.2 3.2/6/4
$\bar{n}_e$ ($10^{19}m^{-3}$) /f_G	6.3 / 0.5	6.3 / 0.5	10 / 0.8	9.1 / 0.8	6.9 / 0.8	5.0 / 0.85	5.3 / 1.0	2.0 / 0.39

Table 1: *Main parameters of the JT-60SA reference scenarios. DN, SN: double null, single null confirguarations*

	#1	#2	#3	#4-1	#4-2	#5-1	#5-2	#6
	Inductive	Inductive	High density	ITER-like	Advanced Inductive	High β Full-CD	High β,f_G Full-CD	300s High β
β_N	3.5	3.5	2.6	2.8	3.1	4.4	4.2	3.3
β_p	0.87	0.76	0.68	0.86	1.36	1.88	2.60	0.91
$\langle T_e\rangle/\langle T_i\rangle$ (keV)	5.7/ 6.2	5.7/ 6.2	3.4/ 3.6	3.3/ 3.5	3.5/ 3.4	2.9/ 2.8	2.5/ 2.4	3.1/2.7
f_{bs}	0.25	0.24	0.22	0.27	0.41	0.61	0.74	0.32
f_{ni}	0.48	0.47	0.30	0.38	0.65	1.01	1.05	0.67

Table 2: *Main global quantities computed by the METIS code for the reference JT-60SA scenarios: normalised beta, poloidal beta, volume-averaged temperatures, bootstrap and non-inductive fractions.*

Examples of profiles and equilibria obtained by METIS are shown in Figs. 1, 2 for the advanced inductive (or hybrid scenario) 4-2 and in Figs. 3, 4 for the high-beta, fully non-inductive scenario 5-1. The heating power is a combination of positive NBI, negative NBI and EC waves, assumed to be deposited at normalised radius ρ ~ 0.4-0.5. The ECCD profiles and efficiencies, estimated on the basis of simple analytical formulas, have been checked by means of ray-tracing calculations, for wave frequencies of 138 or 110 GHz depending on the magnetic field values.

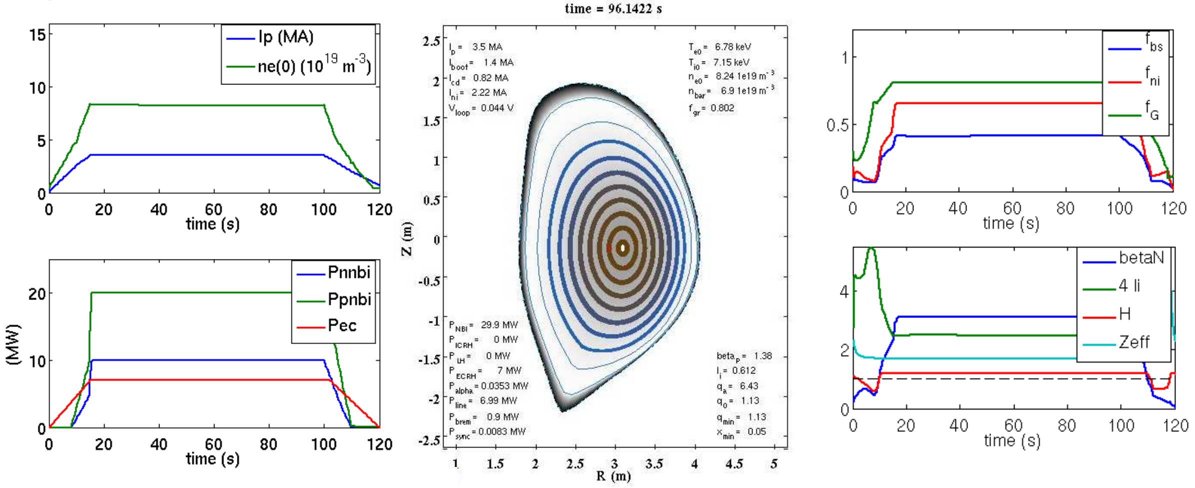

Fig. 1: *METIS simulations of Scenario 4-2 (advanced inductive). Time evolution of plasma current and central electron density (top left); time evolution of heating powers - positive NBI, negative NBI and ECRH (bottom left); magnetic equilibrium at the end of the flat-top phase (middle). Time evolution of bootstrap, non-inductive and Greenwald fractions (top right); time evolution of* β_N, $4l_i$, *H factor and* Z_{eff} *(bottom right).*

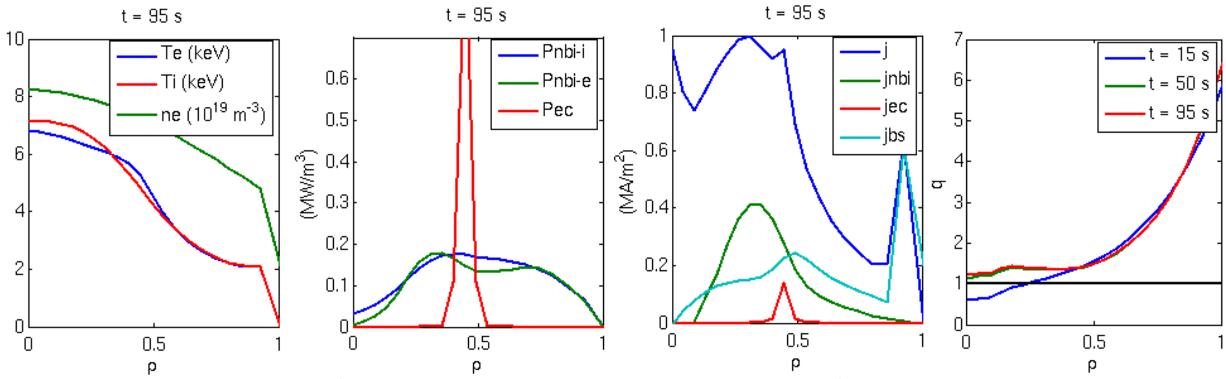

Fig. 2: *METIS simulations of Scenario 4-2 (advanced inductive). From left to right: temperature and density profiles at t = 95s; power deposition profiles (NBI power to ions and to electrons, EC power); current density profiles; safety factor profile evolution.*

Note that for both scenarios the flat-top duration ~ 100 s is sufficient to obtain stationary l_i and q-profiles. The negative NBI system is designed in order to drive non-inductive off-axis current, which effectively provides the scenarios with the desired q-profiles, i.e., flat and sawtooth-free for the advanced inductive scenario and reversed for the fully non-inductive. The detailed shape of the q-profile generally can be optimised by adjusting the timing of the application of NBI during the current ramp-up phase, as well as the location of the ECCD current. To this end, METIS allows efficient exploration of the impact of these parameters on the final q-profile, owing both to its computational speed and to the accurate solution of the current diffusion equation.

These simulations performed with the METIS code constitute a preliminary exploration of the JT-60SA scenarios properties and at the same time the basis for a future extensive scenario simulation activity, using both EU and Japanese integrated modelling codes. The first step of this activity is the validation of the transport models to be used, based on selected JT-60U and JET discharges [10].

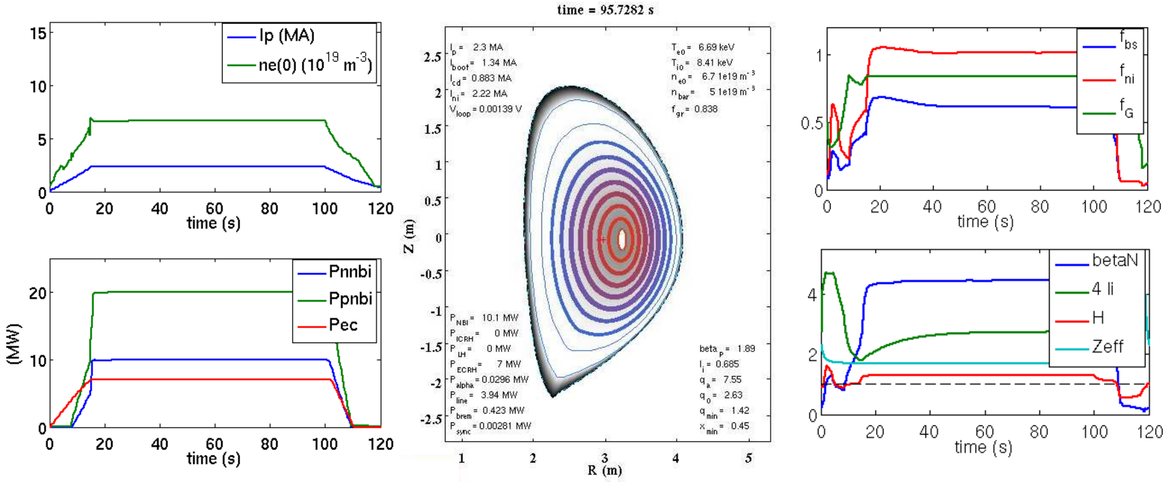

Fig. 3: *As in Fig. 1, for Scenario 5.1 (high beta, steady-state).*

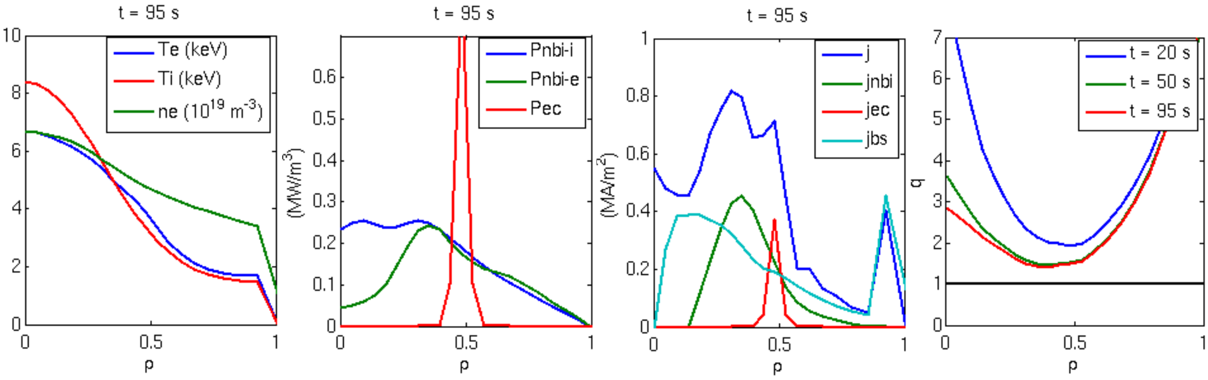

Fig. 4: *As in Fig. 2, for Scenario 5.1 (high beta, steady-state).*

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