EUROFUSION WPSA-CP(16) 15067

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Preprint of Paper to be submitted for publication in
Proceedings of 26th IAEA Fusion Energy Conference

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Abstract. The JT-60SA tokamak, being built under the Broader Approach agreement jointly by Europe and Japan, is due to start operation in 2019 and is expected to give substantial contributions to both ITER and DEMO scenario optimization. A broad set of preparation activities for an efficient start of the experiments on JT-60SA is being carried out, involving the elaboration of the Research Plan, advanced modelling in various domains, feasibility and conception studies of diagnostics and other sub-systems in connection with the priorities of the scientific programme, development and validation of operation tools. The logic and coherence of this approach, as well as the main activities undertaken are presented and summarized.

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 programme. The JT-60SA tokamak is due to start operation in 2019 [1] and will be at the forefront of the international fusion programme for many years, both before and during the D-T phase of 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. Efficient start-up of operation and scientific exploitation of such a large experimental device by an international team is a challenging enterprise, in many aspects similar to what is expected for ITER. A significant amount of resources and experimental time will be required by this initial phase, which can be substantially reduced by adequate preliminary work, in the long years of machine construction. In order to optimize such a start phase, a broad set of preparation activities has been carried out for a few years and is now significantly intensifying. They involve the elaboration of the JT-60SA Research Plan [2], advanced modelling in various domains (scenario, MHD and control, fast particles, edge, divertor, etc.), feasibility and conception studies of diagnostics and other sub-systems (H&CD, matter injection and pumping, W plasma facing components (PFC), etc.) in connection with the priorities of the scientific programme, development and validation of operation tools (data and analysis system, remote participation, magnetic control, wall conditioning etc.). These activities are carried out in a coordinated way by a joint Japanese-EU JT-60SA Research Unit, with the EU team organized in the framework of the EUROfusion WPSA work package, in close interaction with the F4E JT-60SA project home team. An overview of these common activities is presented in Sec. 2, including a few relevant examples. Conclusions and an outlook of the future activities are presented in Sec. 3.

2. Overview of EU-Japan preparation activities for JT-60SA exploitation

The main parameters of JT-60SA, as well as a description of the main plasma scenarios can be found in the JT-60SA Research Plan [2]. The most specific characteristics of the machine (size, shaping capability, pulse length, heating and current drive system, diagnostic and control systems) [3] qualify JT-60SA as a tokamak particularly suited for experimental investigation of high beta regimes, fast ion physics, control of high performance scenarios over long pulses. Moreover, by a dedicated experimental programme, JT-60SA will be able to timely address specific ITER risk mitigation issues, such as disruption prevention and mitigation, runaways, ELM avoidance and control, L-H transition, mastering heat loads, test of high-priority diagnostics, real-time control strategies and event handling, etc. JT-60SA can also be used to provide a full-scale test of the ITER data model, analysis and remote participation tools. The activities for preparing the machine exploitation are particularly focused on these scientific goals and are summarized in this Section.

2.1 Modelling

Scenario modelling. Prediction of the main scenarios is the basis on which all the other activities are built: analysis of the MHD stability, performance of the various sub-systems, operation strategies. In order to develop sound foundations for such predictions, a procedure for validation of models and benchmark of integrated modelling codes has been set up and applied, using selected discharges of JT-60U and JET [4]. The main conclusion of this study is that the CDBM heat transport model [4,5] can be safely used for simulation of H-mode, hybrid and advanced scenarios, providing accurate or, in some cases, conservative estimates of the electron and ion temperatures. Moreover, benchmark of various integrated modelling codes, both Japanese and European, has proved satisfactory [4], which will allow, in the future, sharing scenario modelling work among various groups. The validated models and codes are then used to predict flat-top phases of the main reference scenarios; integrated modelling of transient phases (ramp-up, ramp-down) is now in progress. In particular, ramp-up strategies with low central solenoid flux consumption (assisted by both NBI and ECCD) have been elaborated by simulations with the TOPICS code [6], a subject of great importance for access to advanced scenarios in ITER and DEMO. Because the threshold $\beta_N > 4l_i$ is easily exceeded during this type of ramp-up, ideal MHD stability of external kink modes has also been analysed, with and without a conducting wall, as shown by the example in Fig. 1.

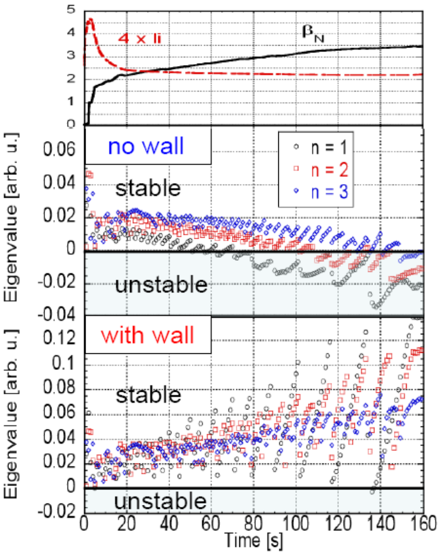

Fig. 1: *Time evolution of β_N and 4li during slow ramp-up (top). Eigen-values of the low-n external kink modes without a conducting wall (middle) and with a perfectly conducting wall (bottom)*

Edge and impurity modelling. The JT-60SA high power, long pulse scenarios will require adequate energy exhaust strategies, based on impurity seeding and control of the radiated power. The machine will start operation with carbon PFCs, then transition to W divertor and first wall is foreseen after achievement of high-β plasma scenarios, in order to accompany the initial heating experiments of ITER (beyond 2027). Therefore, simulations at different approximation levels have been carried out, for both C and W environment and exploring various seeding gases. Self-consistent edge-core simulations with simplified divertor geometry and neutral particles treatment have been performed with the COREDIV code [7-8], comparing seeding with argon, nitrogen, neon and krypton. Radiative divertor behaviour with tungsten wall and full treatment of the divertor geometry has been simulated by means of the SONIC code [9]. More sophisticated edge-core coupled simulations will be reported in this conference, both with the TOPICS code and argon seeding [10], and without seeding, by the JINTRAC code [11].

MHD. The simulated scenarios are then used as a basis for a full set of MHD stability and control simulations: linear and non-linear behaviour of the ELMs, Resistive Wall Modes (RWM), Neoclassical Tearing Modes (NTM), vertical stability, Alfvénic instabilities driven by fast ions. A series of EPED [12] runs were carried out for the various JT-60SA scenarios. It is found that the pedestal limiting MHD instability varies between scenarios: high density scenario (3) and the ITER-like scenario (4-1) are limited by high-n ballooning modes, while most other scenarios are limited by the low-n peeling modes. High-beta scenario stability is a particularly challenging MHD area in which JT-60SA plasmas are expected to give a unique contribution. RWM stability is being studied, including both energetic particles and rotation effects [13], that turn out to be strongly stabilising, when combined. Kinetic effects have also been included in simulations with the 2D MHD code MARS-F/K [14]. Full description of the machine conducting structures, in particular of the stabilising plates, have been implemented in order to study the 3D effects on the stability of the n=0 [15] and the n=1 [16] RWM, using various versions of the CarMa code. These studies include recovery from perturbations, such as ELMs, minor disruptions, H-to-L transitions etc., which may alter the plasma axisymmetric equilibrium. In particular, the maximum plasma perturbations that can be reacted on by any vertical feedback control system have been quantified. Active control of the RWM by a specific magnetic coil system will be a key ingredient of these scenarios and is being actively investigated by 3D electromagnetic computations. The codes CAFE and CARIDDI have been used to characterize the dynamic response of the MHD control system in JT-60SA, in the presence of the 3D conducting structures surrounding the plasma [17]. The ensemble of these studies should allow designing a comprehensive control strategy to cope with RWM and securing the high β_N JT-60SA operational space [18].

Energetic particles. Fast ions driven by NBI and the related Alfvénic instabilities need to be taken into account for the JT-60SA scenario development, with an impact of both their pressure and driven current distributions on the discharge performance. An example of the shear Alfvén mode frequency structure for the high-beta Scenario 5 of JT-60SA is shown in Fig. 2. The linear gyrokinetic code LIGKA [19] is used to compute ideal and kinetic continua, as well as the radial position, frequency, drive/damping and width of the gap modes for all relevant toroidal mode numbers, often found unstable in these scenarios. In Fig. 2, toroidal (TAE) and reversed shear (RSAE) Alfvén eigenmodes are shown. Note that the structure of the shear Alfvén continua is sensitive to current and pressure profiles, which in turn can be strongly rearranged by the effect of core MHD modes (e.g., ballooning and double tearing), unstable because of the radial localization of the negative-NBI drive (beam energy is 500 keV). Such complex interplay is currently under investigation, in particular using the global non-linear hybrid code MEGA [20]. The goal is to develop more reliable transport models for plasmas with radially localized beam drive.

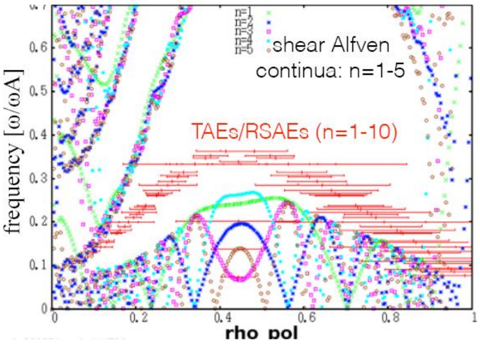

***Fig. 2**: Shear Alfvén continua and gap modes (here, TAE and RSAE with toroidal mode number n=1-10) for Scenario 5.*

2.2 Sub-systems

Diagnostics. Feasibility and conceptual studies are being performed to evaluate and qualify the use of various diagnostics (besides the baseline diagnostics that will be available from the first plasma on), in connection with the main scientific objectives of the Research Plan or with operation needs. For instance, diagnosis of the poloidal field profile by polarimetry has been studied in connection with the control of the current profile in advanced high-beta scenarios. A conceptual design of a multi-channel polarimeter driven by realistic 3D-CAD and physics scenarios has shown not only that this system meets the current profile measurement requirements but also that it has a strong potential for machine protection and control, by line integrated electron density measurement via the Cotton-Mouton effect [21]. Following the results of this feasibility study, implementation of a polarimetry system is being considered among the diagnostic upgrades for a further phase of the machine exploitation. A similar conclusion has been reached after the feasibility study of a Beam Emission Spectroscopy system as a plasma turbulence diagnostic [22]. Use of one of the deuterium heating neutral beams or of a dedicated lithium beam have been considered, the two solutions being feasible. Another turbulence diagnostic that is actively studied, in the framework of collaboration between NIFS and the EPFL, is Phase Contrast Imaging, using a tangential viewing implementation and spatial filtering based on magnetic shearing in order to obtain localized information on the turbulence [23]. In view of the already discussed importance of energetic particles distribution and confinement for JT-60SA scenarios, conceptual design studies of a Fast Ion Loss Detector system [24] are being carried out, with strong synergies with analogous developments for ITER. In fact, it is remarkable that the relevant dimensionless parameters (i.e., fast particles beta and ratio of their velocity to Alfvén speed) of the JT-60SA NBI-driven fast ions are in the same range as those of alpha particles in ITER. Such a diagnostic would be able to resolve the lost fast ion distribution both in gyroradius and pitch angle, as computed for JT-60SA by a synthetic diagnostic code and shown in Fig. 3. Besides these long term developments of the JT-60SA diagnostic system, diagnostics that could be useful for the commissioning and first phase of operation are also being considered. Among them, a wide-angle version of the EDICAM visible camera [25] is being designed, as a direct EU contribution to JT-60SA diagnostics. Several applications are possible: plasma breakdown observations (with detection of dangerous events, such as hot-spots and shinethrough), plasma boundary identification with a temporal resolution up to 1 kHz (comparable to magnetic equilibrium reconstruction), ELMs, disruptions and massive gas injection, SOL filaments statistical properties (correlation length, flow), in parallel to plasma overview measurements.

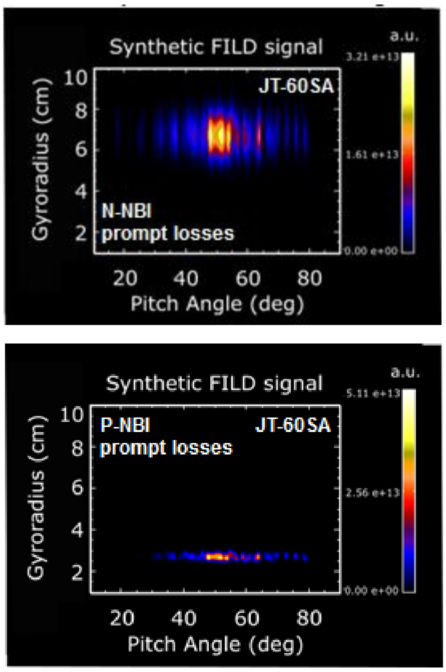

***Fig. 3**: FILD signals simulated by the synthetic diagnostic code FILDSIM for fast ions driven by both negative and positive NBI in JT-60SA.*

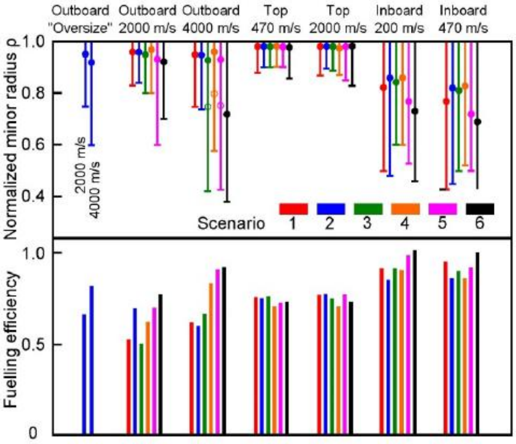

***Fig. 4**: Upper: Particle deposition depths calculated for different pellet launch sites and speeds for every considered target scenario. Dots represent the maxima of the deposition profile (open dots: secondary maxima); bars the deposition profile extension until 0.1 times the peak value. Lower: According fuelling efficiencies (deposited particle mass/pellet mass).*

Matter injection and pumping. One of the key elements of long pulse H-mode operation is the capability of mastering the particle balance by appropriate matter injection and pumping systems. In order to assess the operational window and to optimize the cryopump system design, extensive simulations of the divertor pumping system have been performed, with advanced numerical codes [26]. The impact of neutral gas dynamics on the particle removal process and the overall pumping efficiency in JT-60SA sub-divertor have been investigated by means of two different Monte-Carlo codes, with and without intermolecular collisions. As a first step, EU and Japanese codes have been successfully benchmarked. Then, simulations have been performed for a challenging case for pumping, namely a high density scenario where collisional effects in the sub-divertor are most prominent [27]. Finally, the cryopumps have been characterized in terms of heat loads and operational requirements derived from the results of the sub-divertor calculations. In the framework of the pellet system conceptual design studies [28], ablation and fuelling simulations have been carried out by means of the HPI2 code [29], in order to develop high-density pellet-fuelled scenarios and to assess the system capabilities for different injection geometries (inboard, outboard, top) and pellet speed (200 to 4000 m/s). Results are summarized in Fig. 4, showing that the injection configuration is most important for the pellet fuelling characteristics and inboard launch provides the best suitable solution despite its speed restriction and the unfavourable trajectory with respect to the flux tube geometry. A feasibility study of a Massive Gas Injection system has also started. Such a system would be of great importance for qualifying the methods and parameters to be used in ITER, where disruption mitigation will be indispensable.

ECRH system. In the JT-60SA tokamak four Electron Cyclotron wave launchers will be installed and used for local heating, current drive and plasma initiation by injection of high-power and long-pulse waves into the plasma at 110 and 138 GHz [30]. In order to characterize the optical and physical performances of the ECRH system in the full steering range, the antenna has been modelled and the beams simulated with the numerical electromagnetic code GRASP that offers the possibility to calculate the electromagnetic scattering from a general structure, including sequences of plane and curved reflectors [31]. The analysis of the EC stray radiation has also been carried out, both with modelling in the various conditions of low absorption and with studies of the possible detection systems [32].

Transition to tungsten PFCs. A feasibility study on the transition to W divertor and first wall is ongoing. In addition to the previously mentioned edge and scenario simulations with W environment [8-11], technical feasibility is addressed. In particular, one of the main issues for transition to W PFC in JT-60SA is the choice between massive W components vs W coated ones. W plating on graphite or CFC is now being considered and looks promising. Successful high heat flux tests of 0.5 mm vacuum plasma sprayed coatings produced in Japan on the ion beam facility GLADIS located at IPP/Garching have been carried out in the framework of these joint activities.

2.3 Operation

EC wall cleaning. Wall conditioning will be required in JT-60SA to control fuel and impurity recycling and to improve plasma performance and reproducibility. Because of the superconducting magnetic field, glow discharge cleaning will not be usable between shots (as in ITER) and Electron Cyclotron Wall Conditioning (ECWC) is envisaged, a technique that is not fully validated yet. To this end, dedicated experiments have been performed on TCV, at the 2nd EC harmonic in Helium plasmas [33]. The efficiency of ECWC was assessed from the amount of released D_2 fuel and an optimized combination of vertical and radial magnetic fields has been determined.

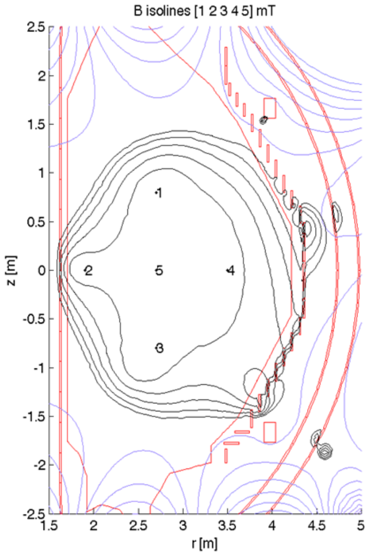

***Fig. 5**: Magnetic flux and field map at the breakdown time, computed by CREATE-L*

Breakdown studies. Optimum breakdown conditions have been explored by various magnetic simulation tools. An example of magnetic flux and field maps computed by means of the CREATE-L code [34] is shown in Fig. 5. ECRH assisted breakdown modelling studies have been carried out using the code BKD0 [35], solving a set of balance equations for energy and particles together with the circuit equation for the plasma current, to estimate the temporal evolution of plasma parameters. Wave trajectories are computed with the beam tracing code GRAY [36], including reflection by the wall facing the antenna. The analysis has quantified the amount by which the operational pressure domain is extended when using EC assisted breakdown, i.e., ~ 0.5 mPa per MW of additional injected power, when reflections are included.

Magnetic simulation and control tools. Various tools for magnetic equilibrium computation are being applied to JT-60SA discharge simulation, with specific controller developments, aiming at efficient control of plasma current, position, shape and vertical stability. The MECS code combines an isoflux controller with the Cauchy Condition Surface (CCS) method for reconstruction of the plasma shape [37]. Plasma equilibrium control during the heating phase has been simulated in order to test the capability of this control scheme to maintain a constant plasma shape while β_p and l_i evolve, as shown in Fig. 6. Other control architectures have been designed and tested by a set of tools based on the CREATE-L and CREATE-NL equilibrium codes, including models of the poloidal field coils power supplies [38]. Comparison of these independently developed sets of tools and control schemes is ongoing.

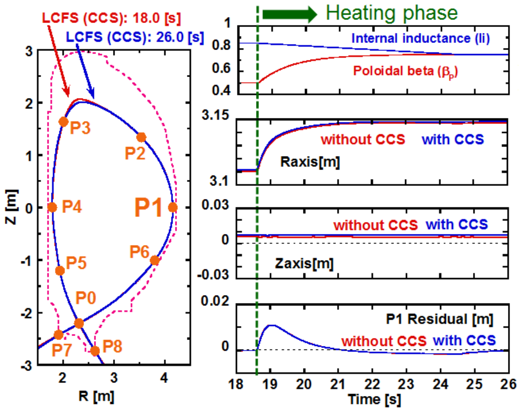

***Fig. 6**: Left: locations of the control points and LCFS by CCS at two times. Right: waveforms of (from top to bottom) β_P and li, Raxis, Zaxis and P1 residual without and with CCS. In the simulation without the CCS method, the quantities required for plasma equilibrium control are calculated directly from the equilibrium.*

Data and analysis tools. The JT-60SA data and analysis system is being developed, following modern principles and methods, optimized for operation by an international team, i.e., including remote participation tools. The main requirements of such a system have been collected and critically discussed [39]. Implementation of the IMAS [40] system (i.e. the ITER data and analysis suite) is foreseen, which would make of JT-60SA a full scale test bed of the future ITER scientific exploitation system. Preliminary tests on an EU machine should take place in the near future, including remote participation, which is developed in the framework of the ITER Remote Experimentation Center [41].

3. Conclusions and prospects

As the start of integrated commissioning and operation (scheduled for 2019) approaches, the coordinated Japan-EU activities for the preparation of JT-60SA exploitation enter now a phase characterized by important milestones. The main one is the elaboration of a "final" version of the Research Plan (v4.0), namely the reference document to be used for defining the programme of the first experimental campaigns. This version is intended to take fully into account the most recent version of the ITER Research Plan (due end 2016), because now the revised ITER schedule gives ample opportunities for substantial contributions by JT-60SA. Other milestones will be strongly connected to operation oriented activities: more and more detailed modelling of scenarios, including transients and controls, completion of design of sub-systems for the first phase of operation, precise definition of data and control systems, remote participation tools, elaboration of the structure and organisation of the experimental campaigns.

Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. The authors gratefully acknowledge members of the JT-60SA Integrated Project Team for data exchange and fruitful discussions.

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