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Securing High β_N JT-60SA Operational Space by MHD Stability and Active Control Modelling

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Abstract. MHD stability and its active control of reference JT-60SA scenarios is numerically studied with particular attention to high β_N plasmas. The qualification of high performance tokamak scenarios is one of the main missions of the JT-60SA device, both in support to ITER and in view of the definition of an optimized DEMO design. Neoclassical Tearing Modes and Resistive Wall Modes will be probably among the most challenging MHD instabilities to be overcome in order to reach this final goal. In the framework of the European-Japanese collaboration on JT-60SA preparation, the main effort presented in this paper is the development and application of some of the main European MHD codes to JT-60SA specific issues. The implementation of these numerical tools is described, taking into account a careful description of the main sources of instability and including the possibility of their active control. Two plasmas, representative in one case of the full current, single null, inductive reference scenario (Scenario2, according to the JT-60SA Research Plan definition) and in the second case of the high β_N, fully non inductive reference scenario (Scenario 5), are taken as inputs. For the Scenario 2-like plasma, Neoclassical Tearing Modes are studied as most relevant MHD instabilities and the active stabilization of (m,n)=(2,1) mode provided by electron cyclotron waves is numerically investigated. Resistive Wall Modes are instead considered as the most challenging limiting MHD instability in the Scenario 5-like case and the development of a fully 3D model including closed loop active control by a set of active coils is presented.

1. Introduction

JT-60SA (Super Advanced) is a large superconducting tokamak facility being realized under the Broader Approach Satellite Tokamak Programme jointly by Europe and Japan, and under the Japanese national program. JT-60SA will confine break-even equivalent deuterium plasmas for long pulse duration (typically 100 s) with a maximum plasma current of 5.5 MA. With its first plasma scheduled in 2019, one of its main goals is to qualify steady state regimes for ITER and for future reactors like DEMO [1,2].

Reactor relevant non-inductive plasma scenarios have to rely on high bootstrap current fractions and this result can be achieved only in high normalized plasma pressure (β_N) plasmas, exceeding both the threshold for neoclassical tearing mode (NTM) destabilization and the so called Troyon no-wall beta limit for external kink instabilities. In JT-60SA these advanced conditions will be achieved thanks to a careful tailoring of operational scenarios and to the development of advanced, real time, active control schemes able to prevent the growth of the main performance limiting MHD instabilities. In support to ITER safe operations JT-60SA should optimize effective real-time stabilization schemes for m/n=2/1 and 3/2 NTMs by ECCD using movable mirrors and high frequency (>5kHz) Gyrotron modulation at for plasmas having the ITER-relevant non-dimensional parameters (ρ^*, ν^* and β). JT-60SA should also determine the MHD stability boundary of long pulse high pressure (β_N ~3) plasmas by exploring Resistive Wall Mode (RWM) feedback stabilization with active coils and high-resolution magnetic diagnostics with the ITER-like plasma shape. In view of DEMO design, the sustainment of fully non inductive, high β_N plasmas well above the no-wall ideal MHD stability limit (β_N ~3-4.5) will be one of the central research subject of JT-60SA; this should lead to the identification of MHD stability boundaries for DEMO-equivalent highly shaped plasmas and to the determination of the requirements for RWM stabilization in terms of plasma rotation, rotation shear and other possible effects.

To prepare for a safe and reliable scientific realization of high β_N scenarios in JT-60SA, a coordinated effort on MHD stability and control modeling is ongoing in the framework of a joint European-Japanese collaboration [3]. In this work we report on the latest results on key issues in MHD stability and control of JT-60SA advanced tokamak plasmas, with particular reference to NTM and RWM physics. A description of the reference plasmas taken as inputs for the MHD stability and control studies is given in Section 2. Section 3 deals with NTM stability and control in inductive H-mode full current plasma, while in the following Section 4 the issue of RWM stability and control in Advanced Scenario plasma is tackled. Final comments and conclusions are presented in Section 5.

2. Reference input plasmas

Before going into the details of NTM and RWM stability and control modeling in JT-60SA plasmas, a short description of the input equilibria is given in this section. Reference scenarios for JT-60SA operations are described in the JT-60SA Research Plan [4], mainly in terms of 0D quantities. In a recent paper [5], in order to extrapolate results from present day tokamaks to JT-60SA regimes, several transport models implemented in two integrated modelling codes CRONOS [6] and TOPICS [7] have been benchmarked against JET and JT-60U experimental data obtaining an optimum set of models used then to give a more detailed prediction of JT-60SA reference scenarios. For this final extrapolation, obtained by the CRONOS code, magnetic and geometric parameters together with the amount of additional power were taken as inputs from the 0D reference description while heat and particle transport together with pedestal were simulated. In Figure 1 the case of a

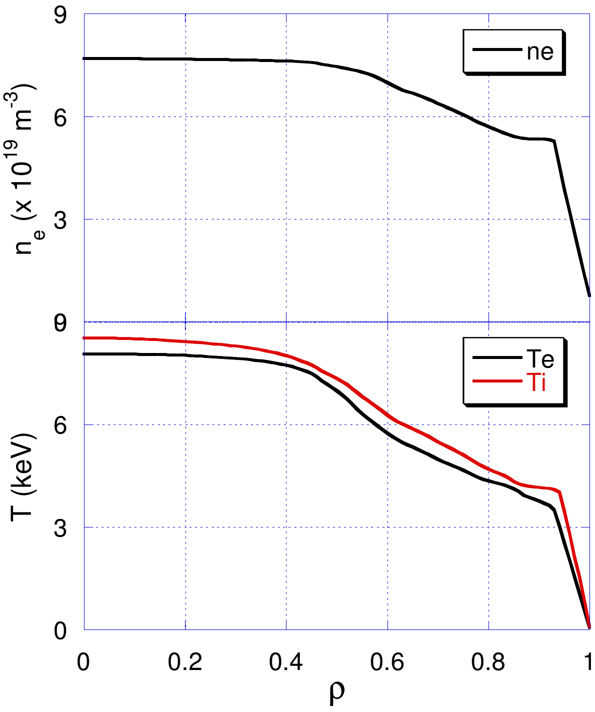

Figure 1. Electron density (top panel) and ion and electron temperatures (bottom panel) for a reference inductive H-mode scenario (Scenario 2, low density) .

plasma representative of the reference inductive H-mode scenario (Scenario 2, low density) is shown. This corresponds to a full current (I_p=5.5 MA), full power (P_{add}=41MW), single null scenario with β_N=3.2 and Greenwald fraction f_G=0.5. In this case the transport model GLF23 has been used for simulating both density and temperatures; more details on the modelling procedure and on the general results obtained for JT-60SA can be found in [5]. This scenario will be in Section 3 the starting point for the study of NTM stability and control.

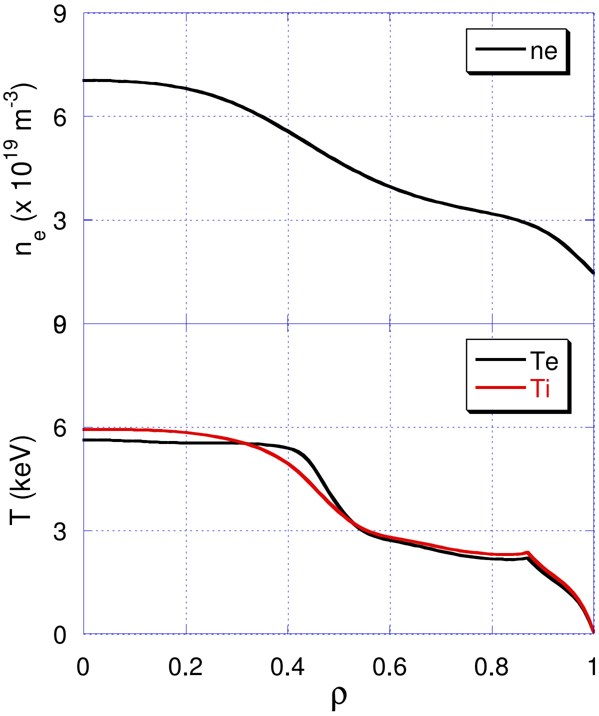

Figure 2. Electron density (top panel) and ion and electron temperatures (bottom panel) for a reference Scenario 5, plasma.

As written in the introduction, one of the main scientific targets of JT-60SA will be the study and qualification of non-inductive, advanced tokamak scenarios that have been proposed as basis for a steady state DEMO reactor. This kind of scenarios will be realized in JT-60SA at lower plasma currents with profiles that very likely will couple a high β_N value to the presence of internal transport barriers. In the JT-60SA Research Plan they are represented by Scenario 5 in the reference scenario list. An integrated simulation of such plasmas is indeed a challenging exercise. An example of such simulations is given in [8] where the TOPICS integrated transport code was used to simulate an advanced tokamak plasma giving insights on the q-profile preparation during ramp-up, on current and toroidal rotation profile control and on heat flux to the divertor. In Figure 2 density and temperature profiles are shown instead for a more recent simulation performed with the transport model CDBM implemented in CRONOS using boundary conditions (pedestal top pressure, heating: 17MW NBI +7MW ECRH and density profile) from an equivalent simulation run with TOPICS. This scenario will be the basis of RWM stability and control studies presented in Section 4.

3. Neoclassical Tearing Mode stability and control in an inductive H-mode plasma

Neoclassical Tearing Modes (NTMs) MHD instabilities can be easily triggered in standard H-mode, high β_N plasmas. They can either cause moderate confinement degradation, as it is often the m/n=3/2 case, or they can lead to full plasma disruptions, as it can happen for the more dangerous m/n=2/1 mode. In this work the NTM stability and control in JT-60SA is studied starting from an inductive, H-mode, single null plasma representative of Scenario 2-like performances, as explained above in section 2.

3.1.NTM stability

The amplitude evolution of NTM instabilities in the reference scenario is investigated by solving the Generalized Rutherford Equation where several terms affecting NTM stability (such as bootstrap, curvature, polarization, non-inductive driven current, heating, wall…) are implemented and solved. An equation for mode frequency evolution is then obtained by balancing the braking torque due to eddy currents, the viscous drag (with anomalous viscosity) and the inertial braking due to a growing momentum of inertia [9]. It is worth noting that numerical modules solving these equations have been also included in the framework of the European Integrated Tokamak Modelling effort [10], paving the way to a self-consistent evaluation of the effects of NTM evolution on transport also for the JT-60SA case similarly to what is being done for some JET test cases.

3.2.NTM control

In JT-60SA the main tool for NTM control will be a double-frequency (110 GHz and 138 GHz) electron cyclotron system [11], providing an injection power up to7 MW from 9 gyrotrons; the EC wave injection angle can be changed both poloidally and toroidally by using a linear-motion launcher. The available ECH power will develop following a staged approach.

In order to study in advance the possibility of realizing and controlling some of the target scenarios also at reduced system capabilities, EC power and driven current densities have been estimated by the GRAY beam tracing code taking into account the latest antenna design available. For this Scenario 2 the EC power was continuously injected from the low field side with various toroidal angles between 6° and 13° corresponding to a full EC power absorption and a full e^{-1} current density width from 0.13 to 0.16 m. At 13° toroidal angle for a EC current of -5.4 kA, EC current density of -3.1 kA and current density width of 0.17m full stabilization of the 2/1 mode can be obtained. In Figure 3 the (2,1) mode evolution is modeled in the presence of active control for 3 different levels of EC power and two mode width detection values. This numerical test shows that 3MW of EC power are sufficient to stabilize the most dangerous (2,1) NTM when applied at a detectable mode width of 0.045 m and 0.06 m.

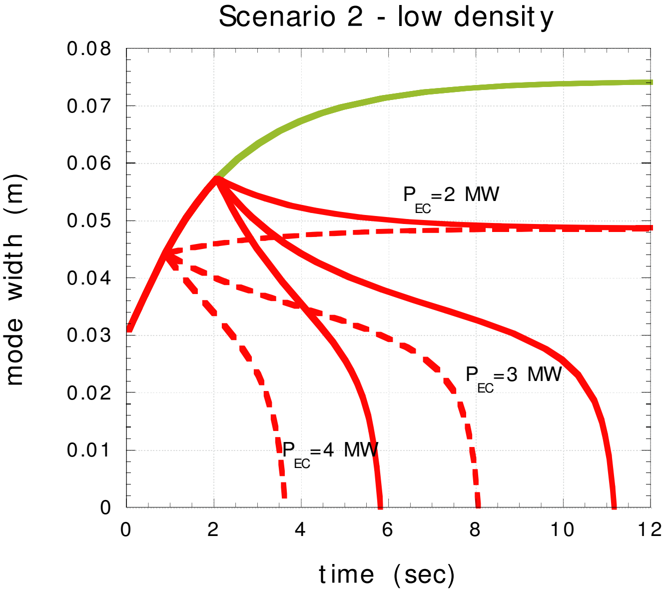

Figure 3. Modelling of (2,1) mode evolution in the presence of active control for a plasma representative of JT-60SA reference Scenario 2. 3MW of EC power are sufficient for the mode suppression. Three levels of EC power are applied at 0.045m (dashed lines) and 0.06 m (full lines) of the mode width.

4. Resistive Wall Mode stability and control in a fully non inductive, Advanced Tokamak plasma

It is well known that in Advanced Tokamak (AT) plasmas the so-called no-wall threshold for ideal external kink mode destabilization can be reached at β_N values that strongly limit the operational space of such scenarios, in absence of additional passive (e.g. plasma rotation) or active (e.g. external coils) stabilizing effects [12,13].

JT-60SA steady state scenarios, which are affected by ideal kink-like instabilities, also present new challenges for RWM stability studies given their targets in terms of β_N (~4) and bootstrap current fraction (~70%). A further challenge is given by the presence of a population of fast particles generated by high-power, high energy (10 MW at 500 keV) negative neutral beam injection system, which will influence the ideal kink stability as well.

4.1.RWM stability

Several effects can modify the stability characteristics of the external kink in a real plasma, also without any active control strategy.

These effects can range from the stabilizing contribution of passive conductors surrounding the plasma and of plasma flow, to more subtle effects given by the interaction of thermal and fast particle populations with the MHD plasma stability; an excellent review of the present knowledge on these issues can be found in [13].

Studies of these effects in the case of JT-60SA typical AT plasmas have already started both in Japan [14] and in Europe [15]. It is interesting to highlight here that in [14] one can find the application to JT-60SA of a new extension of the kinetic-MHD theory that self-consistently includes the effects of macroscopic plasma flow [16]. The basis of the work presented here is instead given by the application of the 2D stability code MARS-F/K [17].

This code was used in [pigatto16] to study plasma flow and drift kinetics stabilizing effects in the advanced tokamak plasma presented in Section 2. In this work we present new preliminary results provided by the CarMa code [18] that couples MARS-F MHD stability results to a realistic 3D finite element description of the machine boundaries surrounding the plasma. In Figure 4 the 3D current density pattern corresponding to the unstable n=1 eigenmode is shown, as computed by the CarMa code. A more detailed description of the coupling procedure and of the features of 3D structures together with some preliminary results can be found in [19]. The results refer to the equilibrium configuration reported above, scaled to a β_N of around 2.7. In the model the most unstable eigenvalues can be selected and identified as RWMs from their growth rates and from the comparison with the 2D problem solved in 2D by MARS. Synthetic magnetic probes have been added to the 3D model to document e.g. how the most unstable RWM would appear. From a total of 108 magnetic probes available in JT-60SA for real time measurements, 39 will be placed on the stabilizing plate close to the plasma on the low field side. Figure 5 shows the spatial distributions of the magnetic field tangential component in the poloidal plane as measured by the uppermost and lowermost toroidal arrays of sensors, located onto the stabilizing plates (6 probes each in toroidal direction); please note that by tangential component here we mean the field component tangential in a poloidal section to the plane where the sensor is installed (i.e. mainly, but not exactly, poloidal in a physical reference frame). It interesting to note that, due to the 3D features of the stabilizing plate, which exhibits holes with no periodical symmetry, the most unstable eigenvalue is actually split into two, with different imaginary part (phase) and slightly different growth rates. A largely prevailing n=1

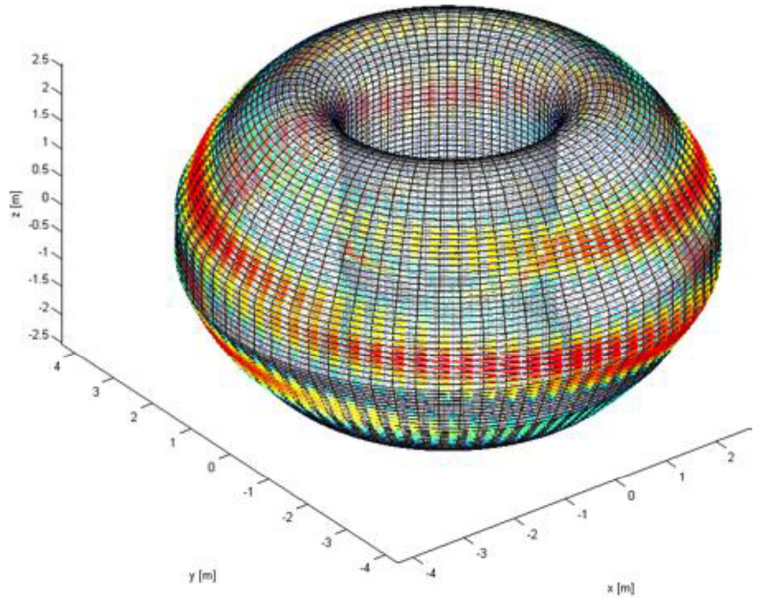

Figure 4: 3D view of the current density pattern corresponding to the unstable n=1 eigenmode, computed by the CarMa code.

harmonic content can be appreciated in both eigenfunctions by a DFT analysis of the same measurements, as shown in Figure 6. Some information on the spatial structure of the unstable modes along the poloidal coordinate can also be obtained by examining the curves at the different poloidal angles of the 2 arrays.

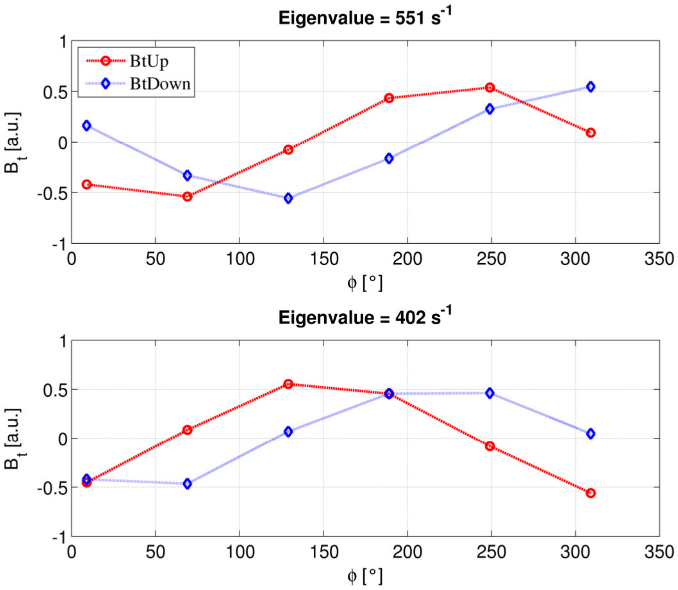

Figure 5. Spatial pattern of the two most unstable eigenvalues obtained from the open loop model. The tangential component of the field (here in arbitrary units) is shown against the toroidal angle corresponding to each sensor. The n=1 dominant harmonic component is clearly visible.

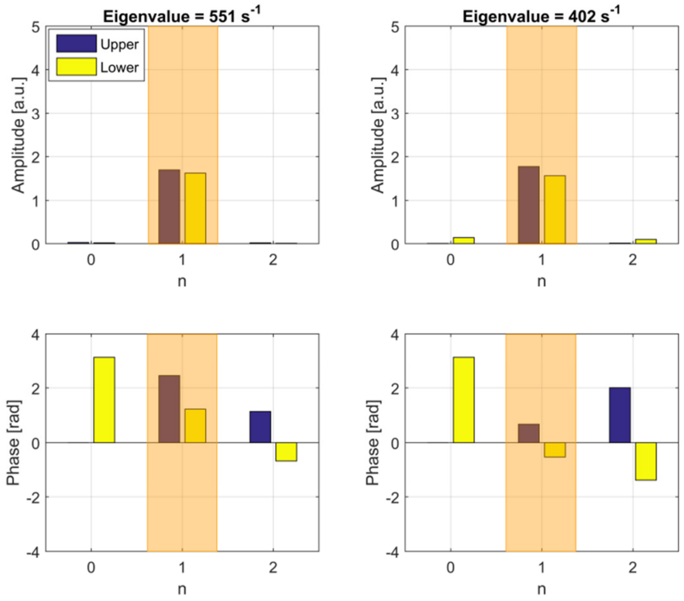

Figure 6. The spatial Fourier transform along the toroidal direction shows the dominant n=1 component in both unstable eigenvectors, both seen by the upper (blue) and lower (yellow) sensor arrays. The dominant n=1 components are highlighted by orange boxes.

4.2.RWM control

In JT-60SA feedback control of RWMs will be possible thanks to a set 18 of active coils located on the inner side of the stabilizing plate. Preliminary studies on the active control of RWMs have been performed using a plasma response model provided by the CarMa code. This model based approach has already been successfully adopted and validated in the experimental device RFX-mod [20]. It has also been used to model MHD mode analysis and control in FAST [21]. The final aim of the JT-60SA modeling work introduced here is the development of a full simulator, including a plasma response model with a 3D description of the passive structures, sensors, signal processing blocks and controller. In principle, the model can provide a number of virtual measurements so as to obtain a detailed map of the plasma response. Moreover, a vacuum version allows a full spatial and dynamic characterization of the magnetic field produced by the actuators in the presence of non-axisymmetric passive structures. As a first step, an eigenvalue analysis of the open loop (i.e. without any active external action) plasma response has been accomplished, as described in the section on RWM stability, and two unstable eigenvalues have been found. When moving to a possible active control strategy, as a first attempt a modal control scheme has been chosen, focusing on the n=1 harmonic of the tangential component of the magnetic field. This is proposed in agreement with experimental results obtained by the same approach in different experimental devices [22] that showed how this choice guarantees to reduce the coupling between the actuators and the feedback signal. Following the feedback control implementation strategy sketched in Figure 7, the discrete Fourier transform (DFT) of the signals from the upper and lower sensor arrays is calculated and the control relevant harmonics selected.

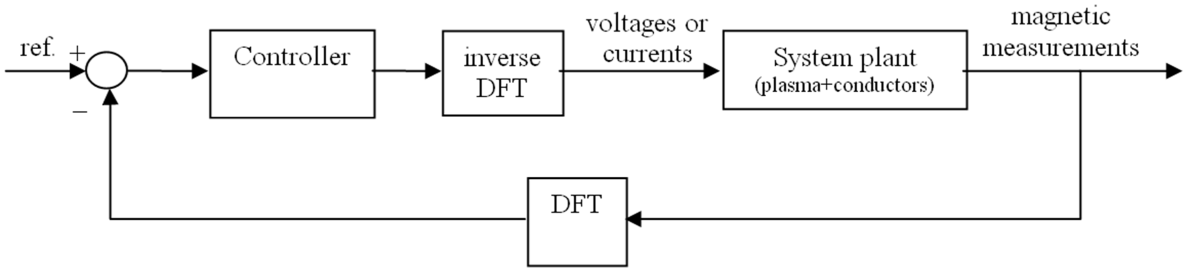

Figure 7. Block diagram of feedback system implemented in the closed loop model of RWM control.

A corresponding harmonic signal is obtained at the controller output, whose inverse transform is then evaluated along the toroidal coordinate, taking into account the coil periodicity (in this case equal to the sensor one) and the angular shift with respect to the sensors. In order to simplify the problem during this first approach, a subset of active coils have been chosen, namely the upper and lower toroidal arrays. This allows a one-to-one sensor-actuator correspondence with constant angular shift. A set of references for the upper and lower coil currents is generated, assuming an ideal current control scheme. A more realistic control system with a voltage reference input will also be designed in a following phase to assess the power requirements needed to stabilize different equilibria.

5. Discussion and Conclusions

Given the relevance of high β_N scenarios for the JT-60SA project, preparing in advance robust techniques for MHD active control is of paramount importance for securing a wide, ITER and DEMO relevant, operational space. EUROfusion, with the support of the Japanese research team, is contributing to this effort with the development of numerical tools able to model in a realistic way both MHD stability and active control. In this work NTM and of RWM studies have been selected as challenging issues where a successful MHD control has to be achieved. The modelling of the NTM case proved that, for the selected scenario, control can be obtained also at reduced power (3 MW) if early detection of the mode can be achieved. This information will be critical to assess the possibility of scenario development also during the so-called initial research phase, during which there will be reduced EC power availability. In future work also the expected stabilization threshold will be critically discussed, also taking into the support that JT-60SA can give to ITER studies on the same field (see e.g. [23]). RWM physics and control is complicated by the intrinsic 3D nature of the problem and by the need of including the (again 3D) effect of passive and active conductors surrounding the plasma. Under a coordinated EU-JA effort, CarMa code has been applied to the JT-60SA case to model in detail passive RWM stability. Thanks to its formulation, the CarMa model is now also inserted in a closed loop control simulator, using as inputs synthetic representations of the future magnetic sensors and as actuators a 3D model of the 18 active coils that will be installed in inner side of the stabilizing plate. This will allow developing and comparing numerically different control strategies, well before the execution of the real experiments.

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