FIRST JT-60SA PLASMA OPERATION AND PLANS IN VIEW OF ITER AND DEMO

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JT-60SA (R=3m, a=1.2m) is the world's largest superconducting tokamak jointly built by Europe and Japan in the framework of the Broader Approach [1]. JT-60SA aims at addressing some of the technological and physics challenges, such as the long pulse steady-state plasma operation at high beta, which will characterize future tokamaks producing net electrical energy by fusion reactions. The start-up of JT-60SA, which culminated in the first JT-60SA plasma achieved on 23rd October 2023 and Operation-1 (OP-1) until the end of 2023, paves the way for a new generation of large superconducting tokamaks, such as ITER, providing essential information in several key engineering and physics aspects.

Before the first plasma, and for the first time in a superconducting tokamak, Global Paschen tests were carried out for the qualification of the superconducting coils and an interlock system was developed to quickly shut down coil currents in case the cryostat vacuum was degraded. Such safety measures enabled the smooth progress of the integrated commissioning phase, the first plasma and the subsequent operation.

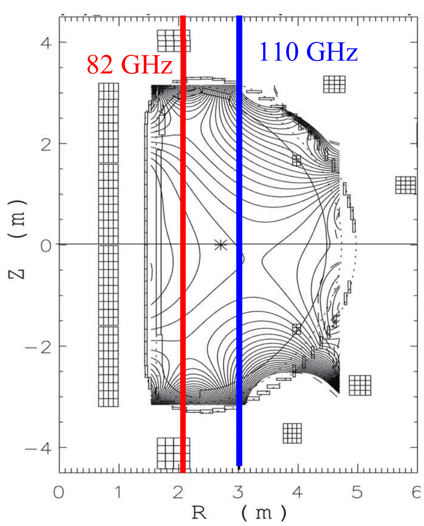

Fig 1. Poloidal field map obtained with TPC including the ECRH resonance layers that produced the first tokamak plasma E100613.

The first plasma was obtained in OP-1 at toroidal current I_P=130 kA and Toroidal magnetic field B_t=2.0T while the whole OP-1 reached I_P=1.2MA plasmas in diverted configuration [2]. The development of such plasmas has provided important information that is key for future devices such as ITER or DEMO. In particular, one important ingredient that accelerated this development - the first plasma was obtained after just two days of operation - was the extensive modelling "predict first" activity carried out before 2023. For example, in a similar way to ITER, in JT-60SA the available parallel electric field ($E_{\|}$) is low and therefore plasma breakdown can be a challenge. However, extensive simulations showed that the Trapped Particle Configuration (TPC), used for the first time on a tokamak this size, could provide a smooth breakdown in conditions of low $E_{\|}$ with the assistance of ~1.5 MW of Electron Cyclotron Resonance Heating (ECRH), as shown in Fig. 1 [3]. In fact, the first attempted breakdown using TPC was successful at only $E_{\|}$ ~0.15 V/m. Such examples suggest that the level of maturity of plasma models starts to be high enough to assess and guide future tokamak devices.

Other major challenges that future large superconducting tokamaks will face during the start-up were also addressed. This is the case of equilibrium reconstruction, plasma control, disruption characterization and runaway electrons generation. The plasma Last Closed Flux Surface (LCFS) was reconstructed by using Cauchy Condition Surface (CCS) scheme, in which boundary integral equations are solved inside the LCFS using few magnetic measurements as expected in DEMO [4]. Furthermore, a validation of the ITER real-time reconstruction algorithms for the plasma current, centroid position, boundary and for the poloidal beta has been performed using the data collected during the first operation of the JT-60SA tokamak. The accuracy of the reconstruction is evaluated against plasma equilibria computed with the CREATE-NL nonlinear code [5]. Importantly, the ITER requirements on the estimation of the plasma current are met. Moreover, fully controlled MA-level plasma was successfully attained using density feedback control in diverted plasmas as well plasma shape and position control by using the adaptive voltage allocation (AVA) scheme, which adaptively adjusts the balance between the position and shape control and the Ip control under the saturated power supply voltage condition [6]. Without AVA, coil voltages were mostly saturated, leading to plasma current and vertical oscillations. Further verification of plasma shape, including strike points, was carried out using visible fast cameras such as the EDICAM [7]. These results show the importance of plasma control techniques and plasma boundary identification for the reliable start-up of large superconducting tokamaks.

A first analysis and classification of the causes for disruptions have been done after the results of OP-1. This is important because it is known that disruptions in the initial operation phase are due to the lack of maturity of the operation. Therefore, characterizing disruptions is important for speeding-up the learning curve of operations in future tokamaks such as ITER. Vertical Displacement Events (VDE) were responsible for the vast majority of disruptions in highly elongated plasmas [8], as the stabilization plate was not yet installed in this phase. Therefore, VDE predictors and control algorithms were developed using machine learning techniques with magnetics probe data, showing that these novel techniques are also suitable for the start-up tokamak phases characterized by scarce input data [9]. This is the first time that these techniques are used for the start-up of a large tokamak and therefore is an essential information for ITER. While MHD events have been observed, sawteeth and n=1 tearing modes, a direct link to disruptions has not been established. Conversely, the generation of runaway electrons, observed in both disruptive and non-disruptive plasma phases, has been correlated to the onset of magnetic reconnection of the tearing mode even in non-disruptive phases. As shown in Fig. 2, these results were obtained with plasmas that closely follow the L-mode energy confinement time scaling ITER-89P, thus connecting past results with new large superconducting machine development.

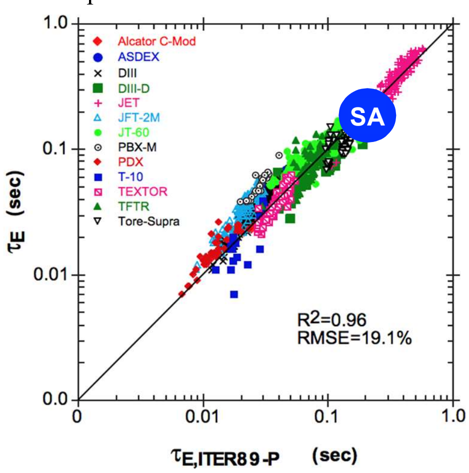

Fig 2. Comparison between the energy confinement time derived for the JT-60SA plasmas in OP-1 and the one obtained from the ITER-89P scaling for different tokamaks.

While most of the OP-1 was carried out using Helium, Hydrogen was also used to test breakdown and plasma development. Similar results were obtained in H compared to He. The use of H further allowed to test wall cleaning techniques, such as glow discharge, that proved efficient and whose characterization is essential to ITER. The use of Electron Cyclotron Wall Cleaning (ECWC) has been proven also efficient to condition the wall, notably when using the ECRH O-mode**.**

JT-60SA will restart operation in 2026 following a series of upgrades, such as Carbon Plasma Facing Components (PFC) including a lower divertor, stabilization plates, Error Field Correction Coils, essential diagnostics and substantially increased input power including Negative-ion based NBI (N-NBI) at 500 keV. The experimental programme for future operations is guided in the JT-60SA Experiment Team by significant modelling “predict first” activity, which shows that access to and development of H-mode in conditions of future burning plasmas, i.e. with high electron heating, low torque, fast ion-driven perturbations and high beta will be possible with high N-NBI and ECRH input power [10]. The integration of such elements into a steady-state long pulse operation will be done with the installation of W PFC after the initial campaigns.

The lessons learnt on JT-60SA during OP-1 and the preparation of future operations will significantly help ITER and DEMO to minimize risks and start operation smoothly. In this framework, it is shown that the continuous interplay between operation and modelling is a key point that will have to be part of the regular exploitation of next-step devices.

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