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Completion of JT-60SA Construction and Contribution to ITER

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Construction of JT-60SA is progressing on schedule towards completion of assembly in March 2020 and the first plasma in September 2020. As of January 2020, manufacture and assembly of all the main tokamak components have been successfully completed satisfying technical requirements including functional performances and dimensional accuracies. Development of plasma actuators and diagnostics is also going well such as achievement of long sustainment of high energy intense negative ion beam. Commissioning of the power supply and the cryoplant has also satisfied requirements. Development of all the control systems and evaluation procedures of tokamak operation has been completed towards the Integrated Commissioning starting in April 2020, and plasma operation scenarios in the first plasma phase have been established. Unique importance of JT-60SA for H-mode and high-beta steady-state plasma research has been confirmed using advanced integrated modellings. These experiences of assembly, integrated commissioning and plasma operation of JT-60SA contribute to ITER risk mitigation and efficient implementation of ITER operation.

Introduction
The JT-60SA (R/a =3m/1.2m, I_p-max =5.5MA, heating power = 41MW x 100s) project [ref.1] was initiated in 2007 under the framework of the Broader Approach agreement by EU and Japan for early realization of fusion energy by conducting supportive and complementary works for ITER towards DEMO. Construction of JT-60SA is progressing successfully towards completion of assembly in Mar. 2020 and the first plasma in Sep. 2020 by the very close collaboration between QST in Japan, F4E in Europe, EU Voluntary Contributors and EUROfusion. The JT-60SA Research Plan [ref.2] covering its machine lifetime of ~ 20 years coordinated with ITER and DEMO schedules has been established with variety of plasma prediction using integrated modeling codes [ref.3]. Recently in Nov. 2019, a new collaboration arrangement between ITER and JT-60SA was signed which covers assembly, integrated commissioning and operation/experiments for finalization of ITER component design, risk mitigation and efficient implementation of ITER operation.

Tokamak Construction
After the last IAEA FEC [ref.1], manufacture of all remaining tokamak components has been completed successfully including, superconducting Centre Solenoid (CS), thermal shields, Cryostat Top Lid, Cryolines, etc. As of Dec. 2019, the closure of the vacuum vessel has been accomplished, and the tokamak has been covered by the Cryostat Vessel Body (Fig.1). All the tokamak components have been assembled with excellent dimensional accuracy of ±1mm thanks to careful and smooth positioning using specially designed jigs, high accuracy measurement by Laser trackers, and fine adjustment utilizing sims. The magnetic field error is now expected below 10⁻⁴ B_t as designed. Commissioning operation of all large power supply systems, the Quench Protection Cirquit, the Switching Network Units and Super Conducting Magnet Power Supplies, has also been progressed with few residual commissioning activities still ongoing. The commissioning operation of the Cryoplant (equivalent refrigeration capacity of 9 kW at 4.4K) has also been successfully completed by satisfying the required performances.

Plasma Hating Systems
For the heating systems, Positive-ion source NBs (85keV, 100sec, 20MW by 12 unit), Negative-ion source NBs (500keV, 100sec, 10MW by 2 units), ECH with multiple frequency Gyrotron (110GHz & 138GHz for 100s and 82GHz for 1 sec) and movable launchers, R&D have been steadily progressing and the targets of their development have been achieved. In particular, high energy intense hydrogen negative ion beams with 500 keV, 154 A/m² for 118 s, which exceeds the requirement for JT-60SA, has been demonstrated by using a semi- cylindrical negative ion source with a three-stage accelerator. This result was realized by integration of i) stable voltage insulation by suppression of arching, ii) precise beam control and iii) stable negative ion production by maintaining the temperature balance in the negative ion source.

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Integrated Commissioning and Control Systems
From April 2020 to Feb. 2021, the integrated commissioning is planned with the first plasma in Sep. 2020

and subsequent 5 months of machine commissioning with plasmas ('the first plasma phase'). In this phase, the goal of plasma operation is to demonstrate equilibrium controllability of MA-class (<2.5MA) diverted plasmas with the full performance superconducting coil systems, 1.5MW ECH and upper divertor. For such tokamak operations, the Supervisory Control System and Data Acquisition System (SCSDAS) has been developed having the roles of (a) plant monitoring and machine state management, (b) discharge sequence management, (c)real-time plasma control, (d) device protection and human safety, (e) data storage, archive, and database management etc. For plasma controls, we have simulated operation scenarios of the first plasma phase with a newly developed advanced codes with control logics, such as pre-magnetic optimization scheme, plasma equilibrium control with iso-flux control method, control gain optimization method, and strategies for accessing stable operational regimes. Figure 2 shows the discharge scenario at I_p=2.5MA. EC wall cleaning operations and EC-assisted breakdown are also explored with optimized EC injection and toroidal / horizontal field. These results in the JT-60SA first plasma phase will contribute to highly valued subjects in ITER first plasma/subsequent operations.![Feedback-controlled plasma current wave form at I_p=2.5MA with upper divertor.

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Scenario Development for ITER and DEMO and Risk Mitigation of ITER
After machine enhancements in 2021-2022, physics experiments will start in 2023 using in-vessel coils, particle fueling and pumping with lower divertor, enhanced diagnostics and high heating power of 26MW at I_p up to 5.5 MA. Toward this phase, variety of predictions of H-mode and high-beta steady-state plasmas covering divertor-SOL-Pedestal-Core have been progressing using advanced integrated modellings including newly-developed globally optimized steady-state transport solver GOTRESS coupled with turbulence models and pedestal models, Gyrokinetic theory based neural-network transport modeling DeKANIS, etc. These studies have confirmed the unique and important characteristics of JT-60SA (highly-shaped, high-beta, 500keV high energy ions, electron heating, controllable rotation etc.) for study of fusion plasma physics such as impacts of fast ions and plasma shape on microturbulence. As for operation scenario development of high-beta steady-state with controlled divertor heat load, an important result has been achieved using the integrated divertor code SONIC upgraded to treat multiple impurity species simultaneously. The result has shown that 'mixture-seeding of Ar with small amount of Ne'can keep the peak heat load below allowable 10MW/m² together with smaller Ar concentration in the SOL and core plasmas than an Ar-only case. These studies have also confirmed significant roles of JT-60SA for ITER risk mitigation (disruption and ELM mitigation) including magnetic perturbation effect on both transient and stationary heat load, vertical displacement event, plasma response to massive gas injection, pedestal and ELM stability and control with Pellet and RMP.

[ref.1] P. Barabaschi, Y. Kamada, H. Shirai and JT-60SA Intrgrated Project Team,
Nucl. Fusion **59** (2019) 112005.
[ref.2] JT-60SA Research Plan - Version 4.0, Sept. 2018,
http://www.jt60sa.org/pdfs/JT-60SA_Res_Plan.pdf
[ref.3] G. Giruzzi, M. Yoshida et al., Plasma Phys. Control. Fusion, **62** (2020) 014009.

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