J. Plasma Fusion Res. SERIES, Vol. 9 (2010)

# Progress of JT-60SA project towards an integrated research for ITER and DEMO

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(Received: 30 October 2009 / Accepted: 12 April 2010)

The project mission of JT-60SA is to contribute to early realization of fusion energy by supporting exploitation of ITER and by complementing ITER for DEMO. The JT-60SA has been designed as a highly shaped large superconducting tokamak with variety of plasma actuators in order to satisfy all of the central research needs for ITER and DEMO. By integrating advanced studies in each research field, the project proceeds 'simultaneous & steady-state sustainment of the key performances required for DEMO' with 'integrated control scenario development'. Procurements are on schedule towards the first plasma in 2016.

Keywords: JT-60SA, ITER, DEMO, Fusion device, Fusion plasmas, Integrated Performance and control

## 1. Introduction

Construction of JT-60SA [1] has been conducted as a joint program between the Broader Approach Satellite Tokamak program implemented by Europe and Japan, and the Japanese national program. The project mission of JT-60SA is to contribute to early realization of fusion energy by supporting exploitation of ITER [2] and by complementing ITER with resolving key physics and engineering issues for DEMO reactors [3]. An integrated design and construction activities in Japan and Europe have been progressed intensively, and the project foresees its first plasma in 2016 [1].

In order to establish the JT-60SA research plan, we have to consider the location of JT-60SA relative to ITER and DEMO in the time schedule of the fusion research strategy. The operation of JT-60SA will start earlier than ITER operation. In addition, the tight experiment schedule of ITER requires exploration of key physics and operational techniques in satellite devices. Therefore, experiences and achievements in JT-60SA are expected to contribute to smooth and reliable implementation of the ITER experiments. Once the ITER operation starts, efficient collaborations between JT-60SA and ITER are required. In this period, the flexibility of JT-60SA will contribute to ITER in various research fields. Also, an integration of achievements in JT-60SA high-β steady-state plasmas and in ITER burning plasmas is required to make DEMO reactor designs more realistic and attractive. This paper summarizes capabilities of JT-60SA for these studies based on assessment of research needs for ITER and DEMO.

## 2. Plasma Regimes of JT-60SA

The JT-60SA device is capable of confining break-even-equivalent class high-temperature deuterium plasmas lasting for a duration (typically 100 s) longer than the timescales characterizing the key plasma processes, such as current diffusion and particle recycling, with superconducting toroidal and poloidal field coils. JT-60SA should also pursue full non-inductive steady-state operations with high values of the plasma pressure exceeding the no-wall ideal MHD stability limits (Fig.1). In order to satisfy these requirements, the JT-60SA device has been designed to realize a wide range of plasma equilibrium, with the capability to produce both single and double null configurations, covering a DEMO-equivalent high plasma shaping factor of S (= $q_{95}I_p/(aB_t)$) ~7 and a low aspect ratio of A~2.5 at the maximum plasma current of $I_p$=5.5 MA and additional heating power up to 41 MW. The plasma size and the shape of JT-60SA are shown in Fig.2. Compared with JT-60U [4], the plasma elongation at the separatrix, $\kappa_x$, is high (~1.9) together with the high plasma triangularity at the separatrix, $\delta_x$, (~0.5). The plasma size is about 0.5×ITER

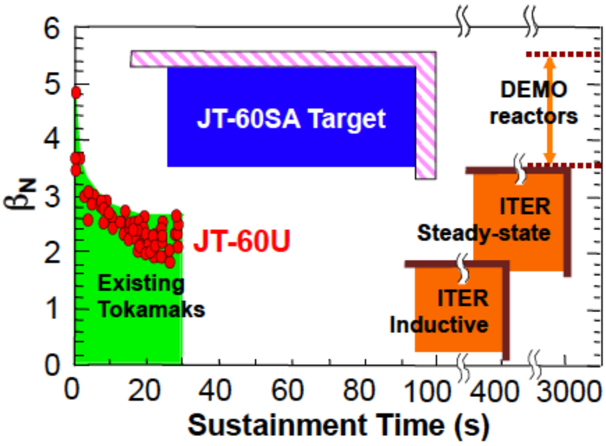


*Fig.1 The high $\beta_N$ target regime of JT-60SA*

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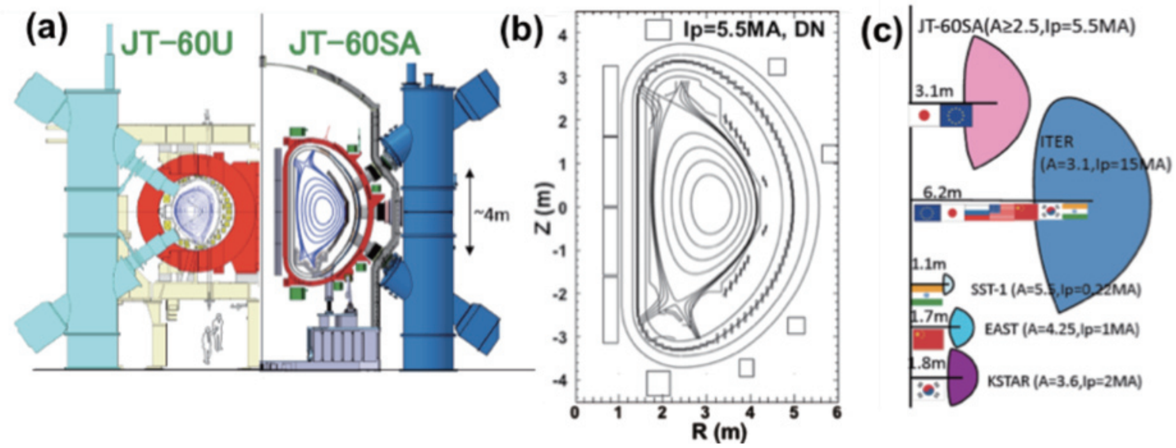



*Fig.2 (a) Plasma size and shape of JT-60SA compared with JT-60U, (b) an JT-60SA double null equilibrium at Ip=5.5MA and (c) plasma cross section of world non-circular superconducting tokamaks.*

which locates between ITER and other non-circular cross-section superconducting tokamaks [5-7]. An integrated knowledge of these super conducting tokamaks will establish reliable nuclear fusion science and technology towards DEMO.

The typical parameters of JT-60SA are shown in Table 1. The maximum plasma currents are 5.5 MA for a highly shaped configuration (A=2.5, $\kappa_x$=1.95, $\delta_x$=0.53) and 4.6 MA for an ITER-shaped configuration (A=2.6, $\kappa_x$=1.81, $\delta_x$=0.43). Inductive operations at $I_p$=5.5 MA for the flat top duration of 100 s are possible with the available flux of ~9 Wb. The heating system provides 34 MW of NB injection and 7 MW of ECRF. The divertor target is water-cooled in order to handle the heat flux up to 15 MW/m$^2$ for long time durations up to 100 s [8,9]. With these capabilities, JT-60SA enables explorations in ITER- and DEMO-relevant plasma regimes in terms of the non-dimensional parameters (such as the normalized poloidal gyro radius $\rho^*$, the normalized collisionality $\nu^*$, and the normalized plasma pressure $\beta_N$) (Fig.3) together with high densities in the range of $1\times10^{20}$/m$^3$ (Fig.4).

In DEMO reactors, we need to sustain high values

*Table 1. Typical plasma parameters for JT-60SA operation scenarios*

| | Parameters | #1 Full Ip Inductive DN 41MW | #2 Full Ip Inductive SN 41MW | #3 Full Ip Inductive SN 30MW High density | #4 ITER like Inductive SN 34MW | #5 High βN Full CD SN 37MW |
|---|---|---|---|---|---|---|
| Size & Configulation | Plasma current, $I_P$ (MA) | 5.5 | 5.5 | 5.5 | 4.6 | 2.3 |
| | Toroidal magnetic field, $B_T$ (T) | 2.25 | 2.25 | 2.25 | 2.28 | 1.71 |
| | Major radius, $R_P$ (m) | 2.96 | 2.96 | 2.96 | 2.93 | 2.97 |
| | Minor radius, a (m) | 1.18 | 1.18 | 1.18 | 1.14 | 1.11 |
| | Aspect ratio, A | 2.5 | 2.5 | 2.5 | 2.6 | 2.7 |
| | Elongation, $\kappa_x$, $\kappa_{95}$ | 1.95, 1.77 | 1.87, 1.72 | 1.86, 1.73 | 1.81, 1.70 | 1.92, 1.83 |
| | Triangularity, $\delta_x$, $\delta_{95}$ | 0.53, 0.42 | 0.50, 0.40 | 0.50, 0.40 | 0.41, 0.33 | 0.51, 0.41 |
| | Safety factor, $q_{95}$ | 3.2 | 3 | 3 | 3.2 | 5.7 |
| | Shape Factor (=q95Ip/(aBt)) | 6.7 | 6.3 | 6.2 | 5.7 | 6.9 |
| | Plasma Volume (m3) | 132 | 131 | 131 | 122 | 124 |
| Absolute Performance | Fusion gain, ( QDT equivalent) | ~0.6 | ~0.5 | ~0.4 | ~0.3 | ~0.2 |
| | Heating Power Pheat (MW) | 41 | 41 | 30 | 34 | 37 |
| | Ion Temperature, Vol-ave., Central (keV) | 6.3, 13.5 | 6.3, 13.5 | 3.7, 7.9 | 3.7, 8.0 | 3.3, 6.2 |
| | Electron Temp., Vol-ave., Central (keV) | 6.3, 13.5 | 6.3, 13.5 | 3.7, 7.9 | 3.7, 8.0 | 3.1, 5.9 |
| | Electron Density, line-average, Vol-ave., Central (E20/m3) | 0,63, 0.56, 0.77 | 0.63, 0.56, 0.77 | 1.0, 0.9, 1.23 | 0.91, 0.81, 1.11 | 0.5, 0.42, 0.68 |
| | Stored Energy (Thermal, Fast ion) (MJ) | 22.4, 4.0 | 22.2, 4.0 | 21.1, 1.3 | 18.0, 1.5 | 8.4, 2.6 |
| | Energy Confinement Time τE(s) thermal, total | 0.54, 0.64 | 0.54, 0.64 | 0.68. 0.75 | 0.52, 0.57 | 0.23, 0.30 |
| | flat top duration (s) | 100 | 100 | 100 | 100 | 100 |
| Normalized Performance | Confinement improvement, HHy2 | 1.3 | 1.3 | 1.1 | 1.1 | 1.3 |
| | Normalized beta, $\beta_N$ | 3.1 | 3.1 | 2.6 | 2.8 | 4.3 |
| | Bootstrap current fraction, fBS | 0.29 | 0.28 | 0.25 | 0.3 | 0.66 |
| | Non inductive CD fraction, fCD | 0.51 | 0.5 | 0.36 | 0.43 | 1 |
| | Normalized density, ne/ nGW | 0.5 | 0.5 | 0.8 | 0.8 | 0.85 |
| | Fuel Purity, nDT/ ne | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| Non Dimentional Parameters | Toroidal beta, βt (%) | 6.5 | 6.5 | 5.4 | 5 | 5.1 |
| | Poloidal beta, βp | 0.85 | 0.81 | 0.67 | 0.82 | 2.0 |
| | fast ion beta, βfast (%) | 0.98 | 0.98 | 0.31 | 0.4 | 1.22 |
| | Normalized Gyro radius, ρ*(poloidal) | 0.020 | 0.019 | 0.015 | 0.018 | 0.035 |
| | Normalized Collisionality, ν* | 0.014 | 0.014 | 0.063 | 0.059 | 0.051 |

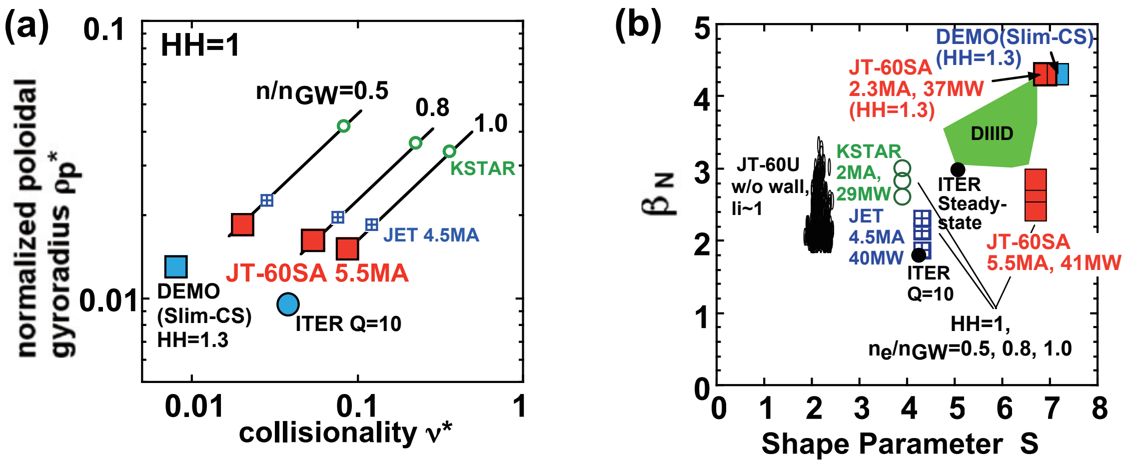



*Fig.3 Non-dimensional plasma parameter regimes of JT-60SA: (a) the normalized collisionality and the normalized poloidal gyro radius, (b) the normalized beta and the shape factor*

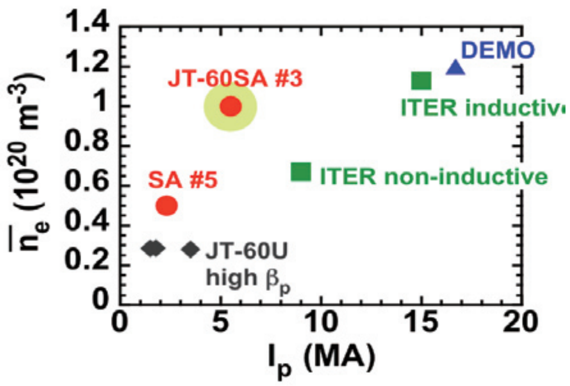



*Fig.4 Line averaged electron density and plasma current for JT-60U, JT-60SA, ITER and DEMO*

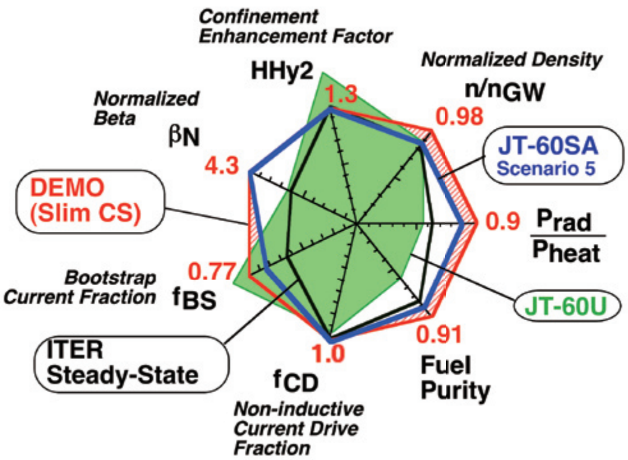



*Fig.5.Integrated plasma performance in DEMO (Slim-CS[3]), JT-60SA, ITER[11], and JT-60U[12]. In all cases, $q_{95}$=5.4-6.0.*

of the energy confinement improvement factor (the HH-factor), the normalized beta $\beta_N$, the bootstrap current fraction, the non-inductively driven current fraction, the plasma density normalized to the Greenwald density, the fuel purity, and the radiation power normalized to the heating power simultaneously in the steady-state [10]. However, such a high 'integrated performance' has never been achieved. The most important goal of JT-60SA for DEMO is to demonstrate and sustain this integrated performance. JT-60SA allows exploitations of full non-inductive steady-state operations with 10MW/500keV tangential NNBCD and 7MW of ECCD. Assuming HH = 1.3, the expected $I_p$ for a high $\beta_N$ (=4.3) full non-inductive current drive operation is 2.3MA with $P_{heat}$ = 37 MW (NNB 10 MW, PNB 20 MW, and EC 7 MW). This plasma regime satisfies the research goal of the highly integrated performance as shown in Fig.5.

## 3. Capabilities of plasma actuators

JT-60SA has strong heating and current drive power allowing variety of heating, current-drive, and momentum-input combinations. The total heating power is 41 MW, which consists of 34 MW of NB injection (24 MW of PNB and 10 MW of NNB, see Fig.6) and 7 MW of ECRF. The positive ion source based neutral beams (PNBs) at 85 keV consist of 2 units of co-tangential beams (4 MW), 2 units of counter-tangential beams (4 MW), and 8 units of near perpendicular beams (16 MW). The negative ion source based neutral beam (NNB) system provides 10 MW/500 keV co-tangential injection. The 7 MW/110 GHz ECRF system allows a real time control of the deposition location by steerable mirrors and high frequency (>5 kHz) modulation.

JT-60SA studies power and particle handling at the full injection power of 41 MW for 100 s using the lower and upper water-cooled divertors compatible with the maximum heat flux of 15 MW/m$^2$ [8]. The W-shaped divertor with a V-corner enhances divertor radiation. The divertor pumping speed can be changed by 8 steps up to 100 m$^3$/s for the lower divertor. The fuelling system consists of the main and divertor gas puffing for multiple gas species and high- and low-field-side pellet injection.

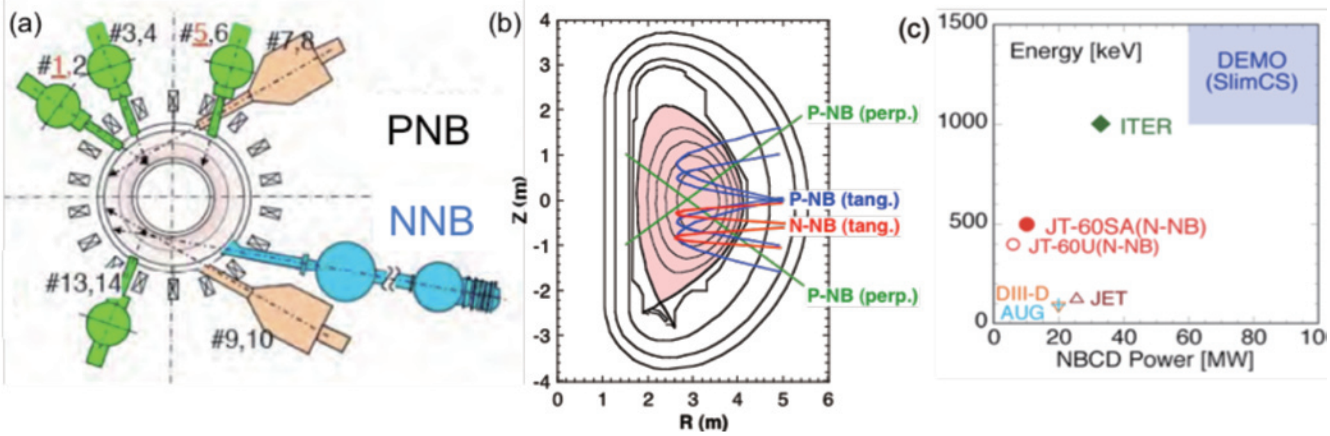



*Fig.6. (a) TheJT-60SA NBI system, (b) NB injection trajectories for PNBs and NNBs, and (c) accelerating voltage and power of NB injection for tokamaks*

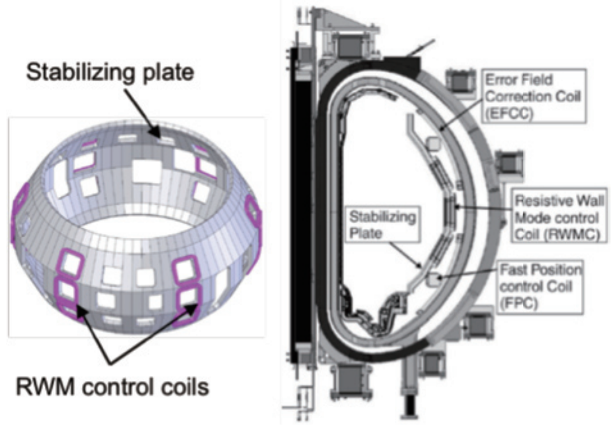



*Fig.7 Stabilizing plate, RWM control coil, Fast Position Control Coils (FPC), and Error Field Correction Coils (EFCC)*

In order to allow exploitations of high beta regimes, JT-60SA is equipped with the stabilizing shell matched to the high shape factor configurations, the resistive wall mode (RWM) stabilizing coils, and the error field correction/generation coils (Fig.7) in addition to the high power heating & current drive & momentum-input systems. The error field correction/generation coils also allows the resonant magnetic perturbation (RMP) for type-I ELM suppression for the various plasma regimes.

At present, 26 systems are in preparation for plasma diagnostics with high space and time resolutions sufficient for conducting the physics research and plasma real-time controls. In particular, by combining these diagnostics systems with the plasma actuators listed above, advanced real-time control schemes for the highly self-regulating plasmas will be developed.

## 4. JT-60SA Research Areas for ITER and DEMO

### 4.1 Establishment of Integrated Plasma Control

The fusion plasma is a self-regulating combined system (Fig.8). The most important objective of JT-60SA is to understand this system and to establish the suitable control schemes, and to demonstrate steady-state sustainment of the integrated performance. The key points are as follows:

i) Fusion plasmas are governed by strong linkages among radial profiles of the plasma current density, the plasma pressure and the plasma rotation both in the core plasma region and in the pedestal region. This self-regulation becomes stronger at higher beta.

ii) Fusion plasmas have a global or semi-global nature (such as structure formation of the internal transport barriers, stiff radial profiles of H-mode etc.) combining the whole plasma regions from the core to the pedestal. This nature produces radial structures or resilience of plasma parameters.

iii) The pedestal plasma, giving the boundary condition to the core, and SOL / divertor plasmas have also a strong linkage including plasma processes, neutral particle processes, and plasma-material interactions (for example, the pedestal density profile is strongly affected by penetration of neutrals, the neutral particle distribution is affected by the atomic – molecular processes in the divertor etc.).

iv) Time scales of the processes determining the fusion )

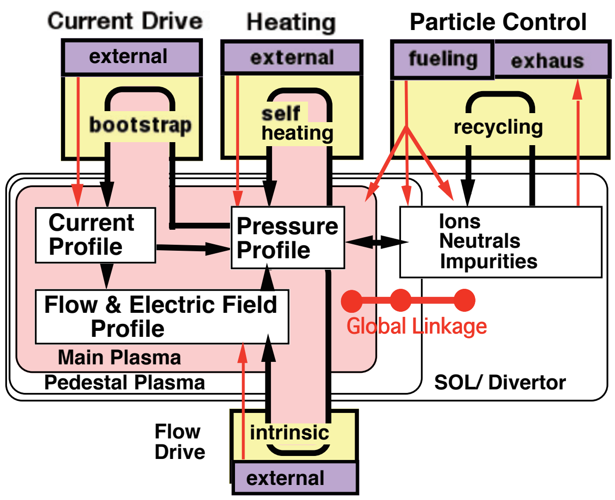



*Fig.8 Parameter linkages in the fusion plasma system*

plasma system span from the growth time of ideal MHD instabilities (~μs), parallel and perpendicular transport time (~ms~sec), the current diffusion time (sec - 10 sec) to the wall saturation time (~100 sec).

The allowed fractions of external control (Fig.8) are small. In case of 70% of the bootstrap current fraction, for example, the fraction of external current drive is 30%. With this small fraction, the total current profile should be controlled. Concerning the study on the 'self regulating combined system', JT-60SA explores the system with respect to the subjects i) – iv) and the external controllability of current and rotation. The α–heating (self-heating) effects are studied in ITER. By integrating the explorations in JT-60SA and ITER, we can establish the physics basis of the whole system shown in Fig.8. For establishment of the integrated control schemes, JT-60SA promotes the following studies:

*(1) for ITER and DEMO*

JT-60SA identifies operational boundaries, decides control margin, clarifies plasma responses, selects the optimum and minimum set of actuators and diagnostics, determines the control logic (such as non-linear gain matrix and real time prediction etc.) and demonstrates the real-time control in long pulse discharges.

Controllability of plasma equilibrium including recovery after plasma events has to be clarified within engineering limitations of the super conducting coil system. Particle controls have to be demonstrated under saturated wall conditions. Current profile controls have to be demonstrated around the relaxed current profile with bootstrap current fraction <50 % (for ITER) and >50 % (for DEMO).

These experiments should be conducted in the ITER and DEMO-relevant regimes in terms of non-dimensional parameters together with high densities in the range of $1\times10^{20}/m^3$. This is because the key processes in the pedestal, SOL, and divertor plasmas involve atomic processes determined by dimensional parameters such as temperature and density.

*(2) for ITER*

In order to contribute to the Q=10 operation, JT-60SA demonstrates required integrated performances of H-mode with the ITER-like plasma shape at high plasma current (4-5.5MA) and high density ($\sim1\times10^{20}/m^3$) by applying the plasma controls planned in ITER such as RMP, pellet injection, divertor pumping etc.

*(3) for DEMO*

JT-60SA explores and demonstrates the required integrated performance in steady-state such as shown by Fig.5. The high power (10MW) off-axis NNB current drive system is used for optimization of the weak / negative magnetic shear plasmas.

JT-60SA determines the operational boundaries and control margin in particular at high $\beta_N$ exceeding the no-wall stability limit and at the high radiation fraction >90% of the heating power, and their composite state.

JT-60SA studies 'the self-regulating combined system' and develops a suitable integrated control system with a minimum set of actuators and diagnostics applicable for DEMO.

### 4.2 MHD Stability and Control Studies

*(1) for ITER and DEMO*

JT-60SA explores disruption mitigation by applying magnetic fluctuations or massive gas injection in high $I_p$ large bore plasmas for ITER and DEMO.

*(2) for ITER*

JT-60SA optimizes effective real-time stabilization schemes for m/n=2/1 and 3/2 NTMs by ECCD using movable mirrors and high frequency Gyrotron modulation at >5kHz for the high $I_p$ and low $q_{95}$ plasmas having the ITER-relevant non-dimensional parameters. Compatibility with RMP is also investigated.

JT-60SA demonstrates long pulse high $\beta_N$~3 ITER-shaped plasmas and determines the stability boundary by exploring RWM stabilization with RWM-control coils.

For disruption avoidance, JT-60SA develops disruption prediction schemes such as using the neural network and control logics. JT-60SA also explores fast VDE (Vertical Displacement Event) controls by using vertical stabilization coils.

*(3) for DEMO*

Long sustainment of high $\beta_N$ plasmas above the no-wall ideal stability limit is the central research subject of JT-60SA. JT-60SA demonstrates long pulse high $\beta_N$ >4 plasmas and determines the stability boundary for DEMO-equivalent highly shaped plasmas (Fig.3(b)). At the same time, JT-60SA clarifies the minimum requirements for RWM stabilization by plasma rotation without control coils, and quantifies the operational margin. Since these plasmas have high $q_{min}$ (>1.5), m/n=2/1, 5/2 and 3/1 NTMs have to be stabilized simultaneously.

Disruption limits at high $\beta_N$ and at high radiation with impurity seeding are identified.

### 4.3 Confinement and Transport Studies

*(1) for ITER and DEMO*

The confinement and transport (heat, particle, momentum) characteristics including detailed physics processes such as plasma turbulence are clarified for understanding of the self-regulating combined system shown in Fig.8 and for establishment of the integrated plasma control at the ITER- and DEMO- relevant non-dimensional parameters such as low vales of ρ* and

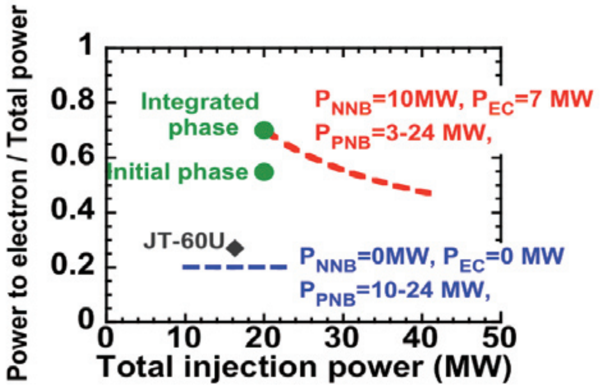



*Fig.9. Fraction of the electron heating power to the total heating power*

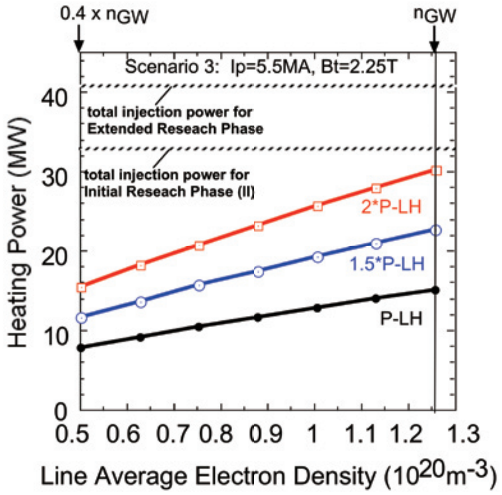



*Fig.10. The L-H transition threshold power vs. electron density for JT-60SA at Ip=5.5MA*

ν* as shown in Fig.3(a). In addition, these studies have to be conducted with ITER and DEMO relevant heating conditions; such as dominant electron heating and low central fueling enabled by NNB and ECH, and low external torque input enabled by NNB, ECH, perpendicular PNBs and balanced injection of CO and CTR tangential PNBs. Effects of the electron heating fraction and plasma rotation are also clarified by changing combinations of these heating systems (Fig.9).

*(2) for ITER*

Confirmation and extrapolation of the energy and the particle confinement time for ITER Q=10 H-mode plasmas are conducted using high $I_p$ high density plasmas (Fig.10) including hydrogen and helium discharges under the ITER-relevant heating conditions mentioned above.

JT-60SA promotes burning simulation experiments by using variety of NBs, and clarifies plasma responses and controllability by applying the plasma controls planned in ITER. The key point is whether the fueling control can be a reliable burn control scheme or not.

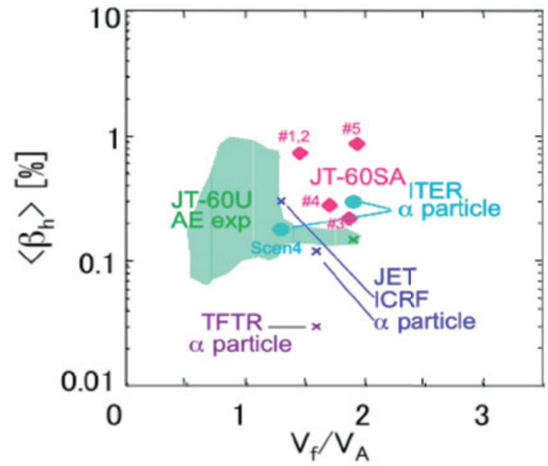



*Fig.11. Fast ion beta vs. fast ion velocity normalized to Alfven velocity*

*(3) for DEMO*

As the most important subject for DEMO, JT-60SA clarifies transport characteristics and plasma responses to external drives for the highly self-regulating plasmas at high values of $\beta_N$ and the bootstrap current fraction.

Confirmation and extrapolation of energy and particle confinement are conducted using DEMO- equivalent highly shaped high $\beta_N$ plasmas. Particle confinement and exhaust, in particular high Z impurities, in high energy confinement (HH~1.3) plasmas should be clarified.

### 4.4 High Energy Particle Studies

*(1) for ITER and DEMO*

Utilizing the high power and high energy NNB, JT-60SA clarifies stability of Alfven Eigenmodes (AEs) and effects of AEs on fast ion transport at ITER and DEMO-equivalent values of the fast ion beta 0.2 – 1 % with $V_f/V_A$ (fast ion velocity / Alfven velocity) = 1.5 -2 (Fig.11) over a wide range of the safety factor profile from monotonic to reversed. In addition, an application of AEs to a control scheme of a-particles is investigated. In order to improve predictivity of behaviors of α-particles, behaviors of tritons produced by DD reactions are studied. Interactions between high energy ions and MHD instabilities, such as sawtooth, NTM, EWM (Energetic particle driven Wall Mode) /RWM, are studied using NNBs.

*(2) for ITER*

Current drive capability with high energy NBI is studied using the 500 keV 10 MW NNB (Fig.6(c)).

*(3) for DEMO*

Off axis current drive and profile controllability are evaluated with off-axis NNB (Fig.6(b)).

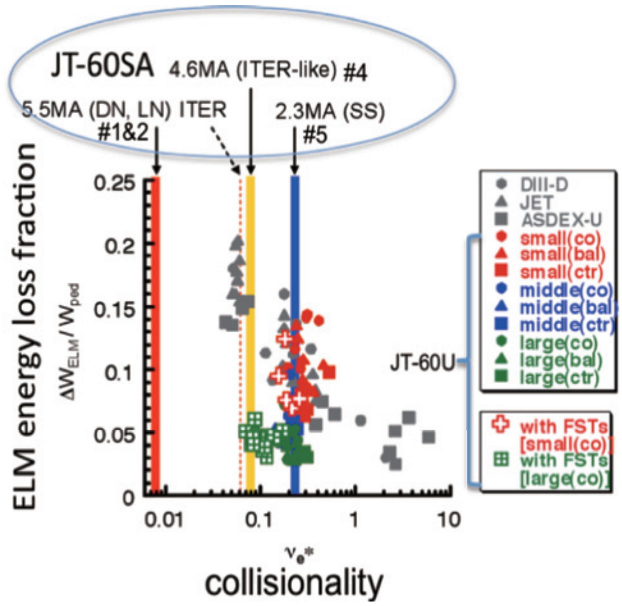



*Fig.12. ELM energy loss fraction to the pedestal stored energy vs. the pedestal collisionality*

### 4.5 Pedestal studies

*(1) for ITER*

The L-H transition conditions (Fig.10), such as the threshold power, are quantified for hydrogen, helium and deuterium plasmas in the high $I_p$ (4-5.5MA) and high density ($n_e/n_{GW}$=0.5-1, $n_e$=0.5 – $1\times10^{20}/m^3$) regime in particular with the ITER-like plasma shape and high power electron heating by ECH and NNB. The pedestal structure, the width and the height, and inter-ELM transport are clarified over wide ranges of $I_p$ and density in order to predict the performance of Q=10 plasmas.

Type-I ELM energy loss is a function of the pedestal collisionality ν*. Since JT-60SA pedestal plasmas can cover a wide range of ν* as shown in Fig.12, JT-60SA clarifies the type-I ELM energy loss and the transient heat load on to the divertor plats. At the same time, effects of RMP and pellet pace making for ELM mitigation are clarified in such ITER-relevant pedestal conditions.

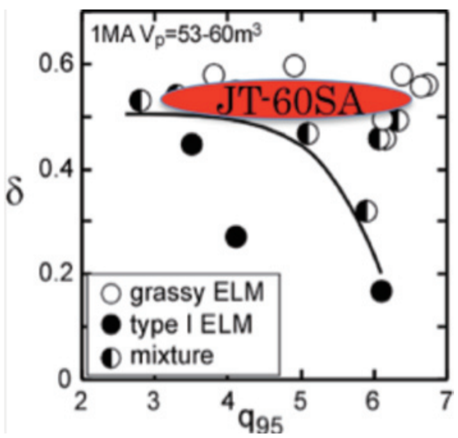



*Fig.13. The Grassy ELM regime found in JT-60U and the JT-60SA operation regime [13]*

*(2) for DEMO*

The L-H transition conditions are clarified for DEMO-equivalent highly shaped plasmas. In order to predict the pedestal characteristics for DEMO plasmas, the pedestal structure, the ELM stability and the inter-ELM transport characteristics are clarified over wide ranges of plasma shape up to DEMO-equivalent shape. The high triangularity shape of JT-60SA plasmas locates well inside the region suitable for appearance of small ELMs (Grassy ELMs) as shown in Fig.13. JT-60SA expands the Grassy ELM regime and demonstrates ELM mitigation without RMP application.

### 4.6 SOL, Divertor and Plasma-Material Interaction

One of the most important mission of JT-60SA is to demonstrate divertor power and particle handling with simultaneous sustainment of the high core plasma performances under a high heating power (up to 41MW) for a long time duration (up to 100s). The JT-60SA device is designed to produce equilibria aligned for the ITER-like divertor structure ('2cm SOL' enters the vertical divertor target for all cases shown in Table 1).

*(1) for ITER and DEMO*

JT-60SA demonstrates fuel and impurity particle controls by utilizing variety of the fuelling and pumping systems. Compatibility of the radiative divertor with impurity seeding and sufficiently high fuel purity in the core plasma should be demonstrated. The key point is to clarify whether a wide range of the divertor plasma controllability can be realized independently of the main

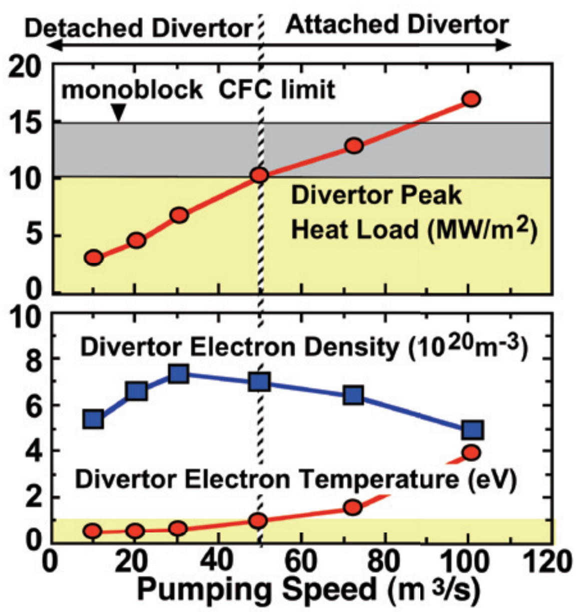



*Fig.14 Effect of divertor pumping speed (S-pump): By changing S-pump, the divertor heat load can be controlled with constant separatrix-mid-plane density.*

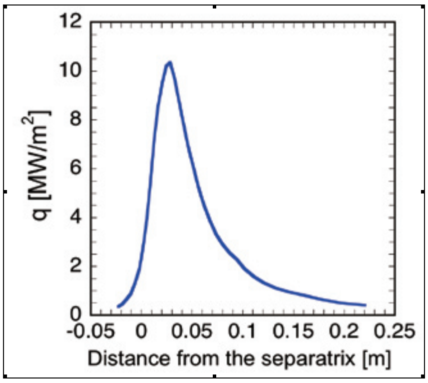



*Fig.15. Heat flux on the divertor target for 41 MW injection. ($I_p$=5.5MA, $n_{e,ave}$~$1\times10^{20}$ $m^{-3}$ at $f_{GW}$=0.8)*

plasma condition by utilizing the pumping and particle seeding from the divertor area as shown in Fig.14.

*(2) for ITER*

In order to predict the heat removal capability in ITER, stability and controllability of the detached divertor condition are studied under a high heating power (up to 41MW) for a long time duration (up to 100s) with the ITER-like divertor structure having the vertical target and the 'V-shaped corner'. The peak heat flux is predicted to be suppressed within the monoblock capability (15 MW/$m^2$) by gas puffing for 41 MW injection (Fig.15).

*(3) for DEMO*

In order to demonstrate compatibility of highly radiative divertor conditions with high confinement core, JT-60SA conducts high-Z impurity seeding and investigates controllability of the heat flux.

Metallic divertor targets and first wall together with an advanced shape divertor will be installed in the extended research phase in order to demonstrate the high integrated performance with metallic wall,

## 5. Time schedule and research phases of JT-60SA

The construction schedule of JT-60SA is shown in Table 2(a). Up to now, procurements are on schedule towards the first plasma in 2016. Table 2(b) shows the expected research phases of JT-60SA, which consists of 1) the initial research phase (including the hydrogen and the deuterium phases), 2) the integrated research phase, and 3) the extended research phase

### 5.1 Initial Research Phase

1) Hydrogen Phase

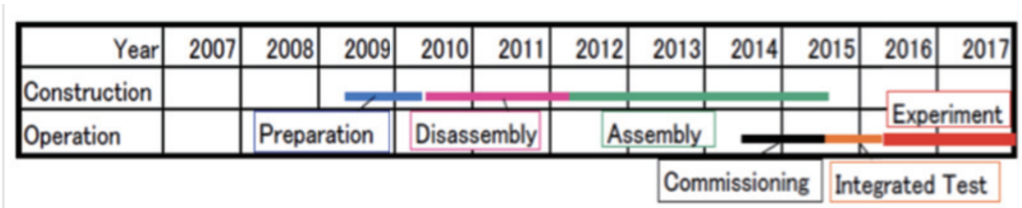
The main aim of this phase is the integrated commissioning of the whole system, as well as preparations for the deuterium operation at the full plasma current up to 5.5 MA and the heating power up to 23 MW. Lower single null divertor configurations with a partial mono-block target are planned in this phase. The material of the divertor target and the first wall is fully carbon. The divertor pumping speed up to 100 $m^3$/s can be changed by 8 steps for the lower divertor.

2) Deuterium Phase

The remaining commissioning related to neutron production and radiation safety will be carried out with deuterium operations up to the full technical performance allowable under the limitation of the annual neutron production $S_n$ of $4\times10^{19}$. After characterization of

*Table 2. (a) Construction Schedule of JT-60SA, (b) Phased operation plan*

(a)




(b)

| | Phase | Expected Duration | | Annual Neutron Limit | Remote Handling | Divertor | P-NB | N-NB | ECRF | Max Power | Power x Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Initial Research Phase | phase I | 1-2 y | H | - | R&D | LSN partial monoblock | 10MW | 10MW | 1.5MW x100s + 1.5MW x5s | 23MW | NB: 20MW x 100s 30MW x 60s duty = 1/30 ECRF: 100s |
| | phase II | 2-3y | D | 4E19 | | | Perp. 13MW Tang. 7MW | | | 33MW | |
| Integrated Research Phase | phase I | 2-3y | D | 4E20 | | LSN full-monoblock | | | 7MW | 37MW | |
| | phase II | >2y | D | 1E21 | Use | | | | | | |
| Extended Research Phase | | >5y | D | 1.5E21 | | DN | 24MW | | | 41MW | 41MW x 100s |

operational boundaries and experimental flexibilities, all of the experimental target regimes in JT-60SA have to be studied using relatively short pulses. The allowable heat flux onto the divertor plate is 10 MW/m$^2$ × 10 s and 2 MW/m$^2$ × 100 s for the lower divertor and 2 MW/m$^2$ × 100 s for the upper divertor. The heating power will be 20 MW for PNBs, 10MW for NNBs and 3 MW for ECRF.

### 5.2 Integrated Research Phase

The main mission of the JT-60SA will be investigated and demonstrated utilizing the high power long pulse discharges with the full mono-block lower single null divertor which allows the heat load of 15 MW/m$^2$ × 100s. The NB injection performance will be 20 MW × 100s or 30 MW × 60s with the duty cycle of 1/30. The ECRF power will be increased up to 7 MW × 100 s. At first, in Phase-I, $S_n$ will be limited below $4\times10^{20}$ in order to allow human access inside the vacuum vessel (after a cool down period of 1 year). The commissioning of the remote handling system has to be completed in this phase. Later, in Phase-II, $S_n$ will be increased up to $1\times10^{21}$, which requires remote maintenance of the in-vessel components. The material of the divertor target and the first wall is now considered to be carbon before achievement of the JT-60SA's main mission of the high-β steady-state. However, possibility of replacement to metallic materials will be discussed based on the results in JET and ASDEX-U.

### 5.3 Extended Research Phase

The capability of JT-60SA will be extended using higher heating power of 41 MW × 100 s with the full mono-block lower and upper divertors. Installation of the metallic divertor targets and first wall together with an advanced shape divertor will be conducted in this extended research phase based on progress of the research in the world tokamaks including ITER.

## Summary

This paper summarized the capability of JT-60SA in the research towards ITER and DEMO. The JT-60SA has been designed as a highly shaped large superconducting tokamak with variety of plasma actuators in order to satisfy all of the central research needs for ITER and DEMO. By integrating advanced studies in each research field, the project proceeds 'simultaneous & steady-state sustainment of the key performances required for DEMO' with 'integrated control scenario development '

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