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Overview of Coordinated Spherical Tokamak Research in Japan

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Spherical tokamak (ST) research in Japan 1 is being conducted as a nationally coordinated program of university-scale ST devices under the ST Research Coordination Subcommittee organized by National Institute for Fusion Science (NIFS). The roles of university ST research include: (1) unique and challenging research through creativity and innovation which might be considered too risky for large ST devices, (2) establishment of the scientific basis for achieving ultra-high beta and ultra-long pulse (Fig. 1),

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(3) contribution to the scientific basis for practical and economically competitive fusion power, complementing the mainline tokamak research (JT-60SA, ITER, etc.), and (4) development and training of a future generation of world-leading tokamak scientists. Specific research topics include: (a) development of start-up, current drive, and control techniques without the use of the central solenoid (CS), (b) formation and sustainment of very high beta plasmas, and (c) demonstration of steady-state operation and the study of steady-state issues such as heat and particle control, divertor physics, and plasma-wall interaction.

(a)-1. Plasma current (I_p) start-up by RF waves: Electron cyclotron wave (ECW) at 2.45 GHz and 5 GHz are used to excite the electron Bernstein wave (EBW) via O-X-B mode conversion on LATE (Kyoto U.). Highly overdense ST plasmas (up to 7 times the plasma cutoff density) are formed when the fundamental EC resonance layer is located in the plasma core, and EBW is excited in the 1st frequency band ($\omega_{ce} < \omega < 2\omega_{ce}$). Whereas EBW in the 1st frequency band heats the bulk electrons, EBW in the 2nd frequency band is absorbed by high-energy electrons and drives I_p. Intermittent plasma ejections across the plasma boundary synchronized with poloidal field decrement were observed in highly overdense plasmas. Oscillations in the Alfven frequency range and potential increase were observed, suggesting the loss of high-energy electrons. The 28 GHz RF injection system on QUEST (Kyushu U.) can regulate wave polarization and parallel index of refraction ($N_{||}$) with a beam radius focused down to 50 mm. $I_p > 100\ kA$ was achieved by injecting X-mode with $N_{||} = 0.78$, assisted by poloidal field induction. The RF power is likely absorbed by energetic electrons. Electron temperature of up to 0.5 keV was obtained by injecting X-mode with $N_{||} = 0.1$, indicating that effective bulk heating is possible. In I_p start-up experiments using the lower hybrid wave (LHW) on TST-2 (U. Tokyo), top-launch was found to be more efficient for Ip ramp-up than outboard-launch. A 2-dimensional phase space model explaining X-ray emission shows that LHW driven radial transport is the dominant loss mechanism of fast electrons, and higher density is preferable in the present situation [2]. This is the first clear demonstration of RF driven electron transport.

(a)-2. CS-less I_p start-up by non-RF methods: In transient CHI, magnetic reconnection plays an important role in the formation of closed flux surfaces during I_p start-up. Plasmoid-driven reconnection following the tearing instability of the elongated current sheet and associated ion heating in the presence of the toroidal guide field were investigated on HIST (U. Hyogo) [3]. Several small-scale plasmoids generated during the injection phase merge with each other to form one or two large-scale closed flux surfaces during the decay phase. Transient CHI is also investigated on QUEST (US-JA collaboration). Investigation of synergistic effects of electron beam injection and EBW current drive in overdense plasmas has begun on LATE [4].

(a)-3. Optimization of inductive plasma start-up: In low voltage inductive I_p start-up with ECW pre-ionization on TST-2, application of a weak vertical field with positive decay index during breakdown was found to be beneficial at low pre-fill pressure and high ECW power. Application of ECW power extended the low pressure limit for breakdown as well as the high pressure limit for burn-through. An MHD equilibrium model with fast electron orbits taken into account, and a model to simulate electron diffusion in both velocity space and real space are being developed.

(b) Access to high temperature and/or beta regime: Reconnection heating for direct access to burning plasmas, being investigated on TS-3U, TS-4U, UTST (U. Tokyo), will be reported in Ref [5].

(c) Demonstration of steady state operation by high-temperature wall: A high-temperature wall plays an essential role in reducing wall-stored hydrogen and facilitates hydrogen recycling. A clear extension of pulse duration at the wall temperature of 473 K was observed on QUEST by water cooling, indicating that recycling can be controlled by wall temperature. During long duration discharges, a high concentration of neutral particles was achieved behind the bottom divertor plate [6].

Stabilization using helical field coils: Suppression of the oscillation and the outer displacement in the radial position was observed by applying the helical field to the tokamak plasma on TOKASTAR-2 (Nagoya U.), which is an ST-helical hybrid device equipped with parallelogram-shaped partial helical field coils [7].

ST research in Japan has produced many innovative results including (i) I_p start-up by LHW (TST-2), EBW (LATE), ECW/EBW (QUEST), CHI (HIST, QUEST), electron beam (LATE); (ii) optimization of ECW-assisted inductive start-up and pre-ionization by AC operation of the Ohmic coil (TST-2); (iii) extension of ion heating by plasma merging (TS-3U, TS-4U, UTST); (iv) hydrogen recycling control with high-temperature wall (QUEST); and (v) radial position stabilization by superposed helical field (TOKASTAR-2).

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