ION AND ELECTRON HEATING VIA MAGNETIC RECONNECTION DURING MERGING/COMPRESSION PLASMA STARTUP IN ST40

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1. HIGHLIGHT OF THE WORK

Here we report the latest report on the high field application of merging/compression (M/C) and reconnection plasma startup in the ST40 spherical tokamak using 96CH 2D ion Doppler tomography and 30CH Thomson scattering diagnostics which were installed in the last 2 years. The new findings and achievements in the last 2 years are summarized as follows: (i) the new 2D 96CH ion Doppler tomography clearly revealed ion heating on the trajectory/downstream of reconnection outflow jet and its confinement/transport process. (ii) Electron density also increase at the same region, while electrons are heated around the X-point (or magnetic axis) and electron temperature profile forms a peaked profile. (iii) Quasi-steady sustainment/confinement of M/C startup plasma current and ion temperature has been demonstrated. (iv) Based on series of M/C experiments, $I_p \propto I_{MC}$ scaling was upscaled to I_p ~ 600kA. (v) Full pressure profile measurement leads to the evaluation of energy conversion ratio of the dissipated magnetic energy of reconnecting field B_{rec} and it was found that ~ 30% of released magnetic energy was converted to ion thermal energy and the previously demonstrated $\Delta T_i \propto B_{rec}^2$ scaling has successfully been upgraded to $\Delta U_i = 1.5(\Delta n_e \kappa_B T_i) \propto B_{rec}^2$ scaling (ΔU_i ~ 10kJ/m^3 which was 10 times higher than the record in MAST was explored in ST40) for the first time.

2. MERGING/COMPRESSION PLASMA STARTUP

Merging/compression (M/C) is one of the efficient ways of central solenoid (CS)-free plasma startup method. Low aspect ratio configuration of spherical tokamak enables higher beta than tokamaks but the limited space for the centre solenoid sacrifices the duration time of current drive and the maximum toroidal field if the conventional solenoid startup is used. The CS-free startup method was first pioneered in START and TS-3 in 1990's and effectively used to achieve the high beta plasma performance $\beta > 40\%$. MAST demonstrated first 1 keV heating by M/C in 2000's and achieved longer pulse duration time than 100ms in fully CS-free scenarios by suppressing current decay rate with the high temperature startup. In 2010's, the underlying heating physics via magnetic reconnection was investigated and $\Delta T_i \propto B_{rec}^2 \propto B_p^2$ scaling provides the design criteria of upgraded M/C experiments. The idea leads to the design of high field MC coils in ST40 and ΔT_i ~ 2keV was demonstrated in 2018 with the fully CS-free operation. From 2019, M/C-solenoid hybrid scenario and auxiliary heating by NBIs have been explored and the world first achievement of 100MK spherical tokamak in 2022 is now widely known in public. However, nevertheless of those achievements, previous publication mostly relies on 0-D measurement such as line-average density/temperature and detailed reports on M/C process with proper profile measurement has never been published. As a major progress in the last 3 years, 30CH Thomson scattering measurement and 32CH 1D Doppler tomography was installed in 2023. Next year in 2024, the U-Tokyo Doppler tomography was upgraded to a 96CH 2D imaging system. In the proposed paper, here we report the detailed heating process of magnetic reconnection during M/C plasma startup in ST40.

3. ION AND ELECTRON HEATING DURING MERGING COMPRESSION IN ST40

Figure 1 shows the time evolution of fast camera images during M/C in ST40 (major radius R_0 ~ 0.4m) and 2D ion temperature profile (T_i) measured by 96CH 2D ion Doppler tomography which was shipped from the university of Tokyo (16CH (radial) × 6 vertical arrays). As in the fast camera images, two plasma rings are initially formed around MC coils. Around 7ms, vertically pushed plasmas are disconnected from MC coils and merging/reconnection occurs. Reference flux profile from EFIT reconstruction at t = 10ms is also shown (R_0 ~ 0.4m). In ST40, direct measurement of field profile is not available but the measured 2D ion temperature profile at t = 7ms suggests that X-point/current-sheet is located around (r, z) ~ (0.4m, 0.0m) and reconnection outflow propagates toward (r, z) ~ (0.3m, 0.0m) and (0.5m, 0.0m) and forms characteristic double-peak structure based on outflow heating mechanis. At t = 8ms, the high T_i region propagates toward vertically mostly by parallel heat conduction ($\kappa^i_{//}/\kappa^i_{\perp} \sim 2(\omega_{ci}\tau_{ii})^2 >> 1$) and ions are globally heated inside the closed flux surface at t = 9ms.

Figure 2 shows a synchronized measurement of electron temperature T_e, density n_e and ion temperature T_i at t = 8ms (Fig. 2 left) and more detailed time evolution of T_e, electron pressure p_e and energy increment $\Delta U_e/\Delta t = 1.5(\Delta n_e \kappa_B T_e/\Delta t)$ (Fig. 2 right). As reported in MAST [1], T_e typically increases at the central region (r ~ 0.5m) where X-point is expected to exist, while n_e and T_i forms broad/hollow profile through outflow acceleration/heating. As shown in Fig. 2 right, T_e is initially tens of eV before the reconnection heating starts but it starts to increase around t = 7ms when the merging plasmas are detached from MC coils. At t = 8ms, T_e and p_e forms the characteristic peaked structure at the central region where current sheet dissipation and parallel acceleration occur, and then the peak T_e and p_e become wider at t = 9ms. Between t = 7ms and 8ms, $\Delta U_e/\Delta t$ forms peaked structure in 3MW/m^3. Then, between t = 8ms and 9ms, collisional coupling between electrons and ions also supplies additional electron heating (~ 2MW/m^3) at r = 0.40m and 0.55m where T_i profile forms characteristic double-peak. Finally bulk electrons and ions are both heated through merging compression startup.

Figure 3 shows demonstration of sustainment/connection of M/C startup parameters (I_p and T_i) to a quasi-steady plasma scenario and supporting scaling of the startup method. Fig. 3 (a) is the typical waveform of M/C driving coil current I_{MC} and plasma current I_p. The startup of I_p uses the induction of MC driving PF (MC) coils and the formed I_p linearly increases as a function of I_{MC} (feed current × turns) as shown in Fig.3 (b). In the I_p ~ 400kA scenario with I_{MC} ~ 400kA·turn, T_i increases in the order of ~ 1keV as shown in Fig.3 (c). After merging, slowly lamped solenoid is used to sustain the flat top I_p. Reconnecting field B_{rec} (~ $B_p \propto I_p$: Fig.3 (d)) is the source of reconnection heating and global thermal energy increment $\Delta U_i = 1.5(\Delta n_e \kappa_B T_i)$ increases in proportion to the released magnetic energy $\Delta U_i \propto B_{rec}^2$ (Fig.3 (e): ~ 30% of released magnetic energy). The peaked electron heating at the X-point region also shows similar characteristic (Fig.3 (f): $\Delta U_e \propto B_{rec}^2$).

4. CONCLUSION

First detailed investigation of reconnection heating process during M/C startup in ST40 has been conducted and the rapid plasma heating/startup process has successfully been revealed using the new 2D 96CH Doppler tomography and the 30CH Thomson scattering diagnostics. The high field application of M/C heating scenario in ST40 successfully demonstrated to form ~ 10 times higher pressure than MAST based on B_{rec}^2 scaling and its sustainment/connection to steady scenario.

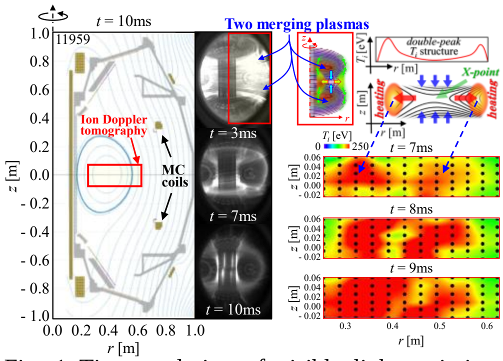

Fig. 1 Time evolution of visible light emission (fast camera) and 2D ion temperature profile during merging/reconnection phase in ST40 (Major radius R_0 is ~ 0.4m as in EFIT at t = 10ms).

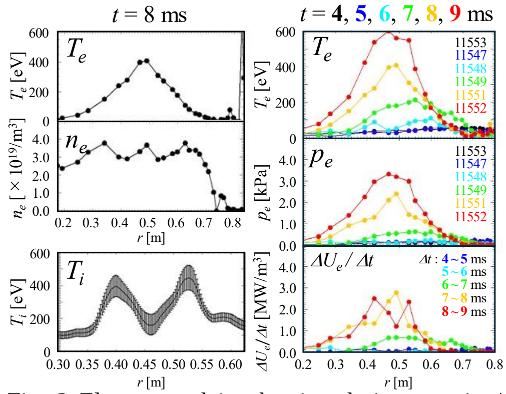

Fig. 2 Electron and ion heating during merging/ reconnection phase. T_e typically forms peaked profile around the central region, while n_e and T_i forms broad/hollow profile. Characteristic energy deposition is observed around X-point (r ~ 0.5m) and the outflow region (r ~ 0.40m and 0.55m) through ion-electron energy relaxation.

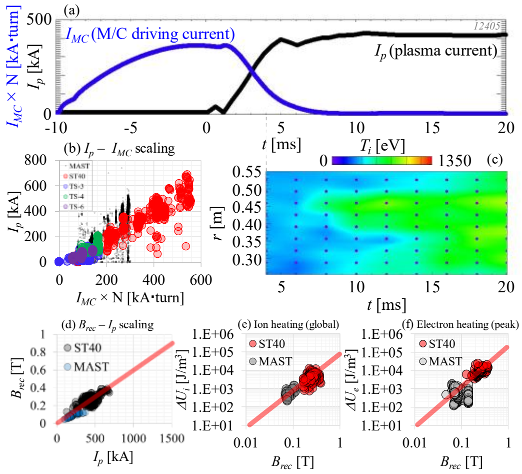

Fig. 3 Demonstration of sustainment/connection of M/C startup parameters (I_p and T_i) to a quasi-steady plasma scenario and M/C startup performance summary. M/C startup I_p can be amplified by increasing M/C driving coil current: $I_p \propto I_{MC}$. The amplification of plasma current I_p leads to the formation of higher poloidal/reconnecting magnetic field: B_p ~ $B_{rec} \propto I_p$. The increment of global thermal energy ΔU_i depends on the released magnetic energy of reconnecting field: $\Delta U_i \propto B_{rec}^2$. Electron heating around the X-point also shows similar trends: $\Delta U_e \propto B_{rec}^2$.

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