Application of Tomographic Ion Doppler Spectroscopy to Merging Plasma Startup in the MAST Spherical Tokamak*)

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This paper describes recent advances in merging/reconnection experiments in MAST, namely tomographic ion Doppler spectroscopy capability from 2013 which solves the problem of the absence of ion temperature profile measurement during the solenoid-less startup. Providing 32 channel line-integrated spectra from $0.25\,\mathrm{m} < r_{\mathrm{tangential}} < 1.1\,\mathrm{m}$ are connected to a grating spectrometer with the focal length of 1.0 m and grating frequency of 1800 L/mm, and tomographic reconstruction is applied to measure local ion temperature profile. This system successfully contributes to the study of ion heating during merging/reconnection startup and revealed that magnetic reconnection mostly heats ions in the downstream region of outflow jet and also found its contribution to bulk electron heating as well as the localized heating at X point with the time scale of energy relaxation between ions and electrons.

Keywords: spherical tokamak, magnetic reconnection, acceleration and heating, energy conversion, solenoid-less startup, plasma diagnostics, ion Doppler spectroscopy and computer tomography

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For the last decade, MAST-univ.Tokyo collaboration pioneered a central solenoid-free startup of spherical tokamak (ST) and heating scenario for ST plasmas using merging/reconnection scheme [1–3]. The high power heating of magnetic reconnection [4, 5] documented ~200 eV in TS-3 and ~1.2 keV in MAST in addition to the higher plasma current formation of 0.4 MA without solenoid [6–9]. In laboratory experiments, fundamental electron and ion heating mechanism during magnetic reconnection was well investigated using several 2D in-situ probe and 2D ion Doppler tomography diagnostics around the X point of magnetic reconnection [7,8,10–13]. In MAST, sub-cm fine profile measurement of electron temperature and density revealed highly localized electron heating at the X point of magnetic reconnection and formation of shock structure of electron density profile in the downstream region of outflow jet by use of 130 channel YAG-Thomson scattering diagnostics [8, 14].

However in the past decade, the investigation of ion heating of magnetic reconnection in MAST was limited to the discussion of achieved parameters or EFIT reconstruction because the existing 64 channel charge exchange system does not have viewing line inside $r < 0.8\,\mathrm{m}$ where r is major radius due to the innermost impact radius of the neutral beam [8, 9, 15] (in addition, even if the beam diagnostics is available, NBI might complicate the reconnection process itself). From 2013 (M9 campaign), MAST-univ.Tokyo collaboration addressed this issue by the temporary repurposing of an existing collecting lens to provide a 32 chord tomographic ion Doppler spectroscopy capability and revealed the detailed heating structure of high field reconnections in MAST [16, 17]. Here, this invited paper briefly reviews the solenoid-less startup of spherical tokamak using merging/reconnection in MAST and mainly focuses on the detail of the new ion temperature measurement as a summary of the recent major progress.

Figure 1 shows the typical waveform of plasma startup in MAST (shot number 28040 in M8 campaign). As shown in the fast camera images, a pair of internal PF (P3 coils) generate two initial plasma rings at the top and the bottom of the vacuum vessel and they merge together with magnetic reconnection. In addition to the plasma current formation of $I_{\mathrm{p}} \sim 0.3\,\mathrm{MA}$ ($\propto I_{\mathrm{P3}}$: P3 coil current [9, 17]. $120\,\mathrm{kA\ turn} < I_{\mathrm{P3(peak)}} < 300\,\mathrm{kA\ turn}$), electron temperature quickly goes up to 500 eV with much faster time

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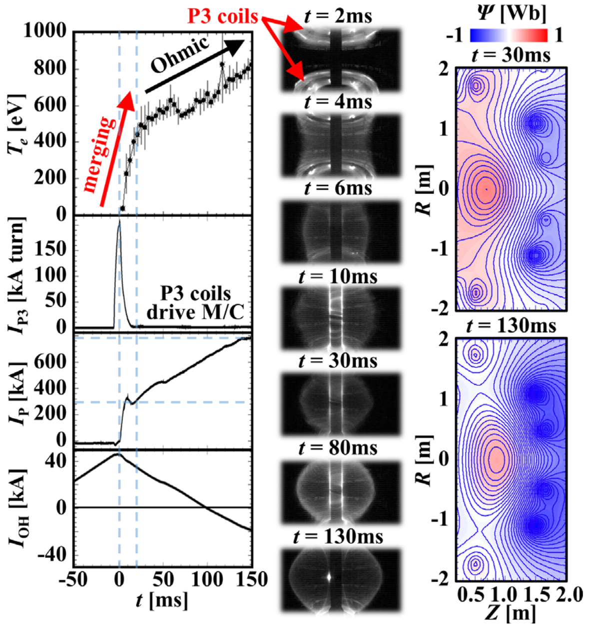

Fig. 1 Typical waveform of *standard shot* in MAST (merging/reconnection and Ohmic ramp-up hybrid operation). Merging startup was routinely used to save significant amount of solenoid flux for the initial hot plasma formation with much faster time scale than Ohmic heating.

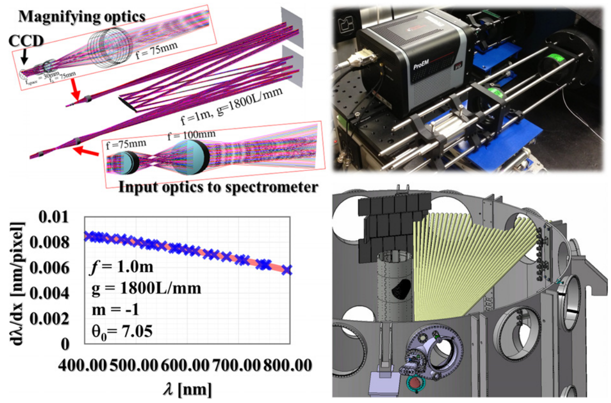

Fig. 2 32 chord tomographic ion Doppler spectroscopy system composed of Czerny-Turner grating spectrometer (focal length $f = 1.0$ m, grating frequency $g = 1800$ L/mm) and a collecting lens ranging $0.25\,\mathrm{m} < r_{\mathrm{tangential}} < 1.1\,\mathrm{m}$.

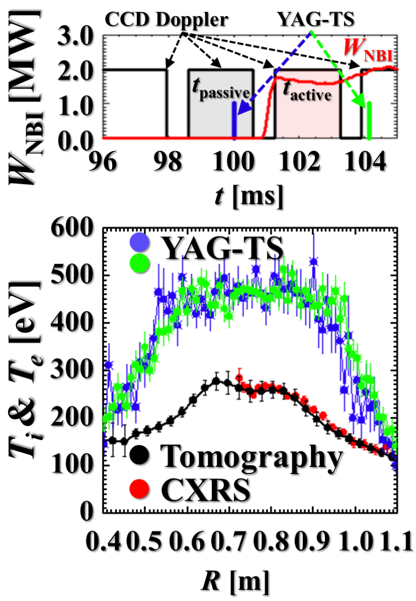

Fig. 3 Typical temperature profile of Ohmic ramp up plasma at $t \sim 100$ ms (shot 30380: NBI fired at $t \sim 101$ ms, Thomson scattering measurement at $t = 100.0$ ms (blue) and 104.2 ms (green), and Doppler spectroscopy measurement at $t_{\mathrm{passive}} = 98.6$ ms (black) and $t_{\mathrm{active}} = 101.3$ ms (red) with the exposure time of 2.0 ms.

scale than Ohmic heating. After exceeding the radiation barrier of low Z impurities, plasma current I_P is slowly ramped up to the desired current and then kept at the flat top current in several hundreds of milliseconds (even without solenoid, the high performance startup achieved $\tau_{\mathrm{duration}} > 100$ ms [18]). Before MAST upgrade engineering, ~50% of ~30000 pulses in MAST routinely used merging/reconnection for plasma startup (usually ohmic assisted hybrid operation), several physics campaigns have been conducted during the extended steady phase by saving significant amount of solenoid flux for startup [18, 19].

A new ion temperature measurement system composed of following system was installed in 2013 as shown in Fig. 2: a collecting lens and fibres (the existing equipment [15, 20, 21] was temporarily moved from the sector 7 to the sector 9 midplane viewing port. The viewing range was changed to span $0.25\,\mathrm{m} < r_{\mathrm{tangential}} < 1.1\,\mathrm{m}$), 32 channel new patch fibres (400 μm core (silica), NA = 0.22) to transfer the collected spectra to a Czerny-Turner grating spectrometer (focal length $f = 1.0$ m, grating frequency $g = 1800$ L/mm, slit width 200 μm), input optics ($f = 75$ mm and 100 mm), magnifying optics ($f_\lambda = 75$ mm and 75 mm, $f_{\mathrm{space}} = 75$ mm and 30 mm) for the correction of astigmatism and proEM camera (Princeton Instruments: 512 × 512 pixels, 16 μm/pixel, 2.65 ms/frame for binned 32 spectra and 230.4 μs for image shift time). For the fast frame rate operation, a ferroelectric liquid crystal FLC shutter was used to reduce smearing effect which causes cross-talk for neighboring spectra in the CCD image. In experiment, CVI line ($\lambda = 529.05$ nm) is mainly used and the time evolution of 32 channel spectra are recorded by 512 pixels wavelength channels typically with 0.0078 nm/pixel.

Figure 3 shows the performance of the tomographic ion Doppler spectroscopy compared with charge exchange spectroscopy (CXRS) and Thomson scattering diagnostics. The timing chart (Fig. 3, top) illustrates the power of NBI which starts at $t = 101$ ms (red), exposure time of ion Doppler measurement in each frame (black) and YAG laser pulses (blue and green). The ion temperature pro-

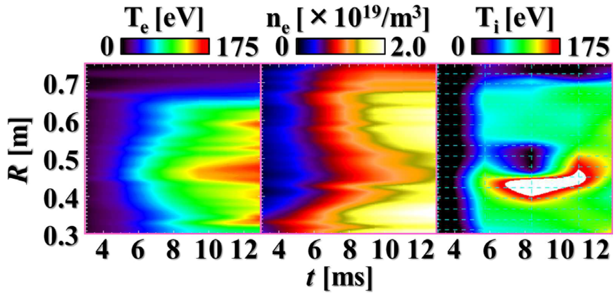

Fig. 4 Time evolution of electron temperature, density and ion temperature during merging/reconnection startup measured by YAG-Thomson scattering and time resolved ion Doppler tomography diagnostics. Electron temperature tends to be peaked at the X point ($r \sim 0.5$ m), while ions are globally heated in the downstream region of outflow jet. The energy exchange between ions and electrons also contributes bulk electron heating downstream.

file of "Tomography" used t_{passive} (black) before the neutral beam injection, and "CXRS" used the time frame of t_{active} and t_{passive} for the background subtraction from the active signal (Thomson scattering measurement supports the assumption that the difference in ion temperature between the two time frame is negligible). Although the cross validation is limited to the region outside the impact radius of the neutral beam, it should be noted that the discrepancy of the ion temperature between "CXRS" and "tomography" is less than 5% and successfully demonstrates the performance of the new diagnostics.

Figure 4 is a typical result of electron temperature, density and ion temperature profile measurement during merging/reconnection startup in a single discharge (28804: $I_{\mathrm{P3max}} \sim 150$ kA turn, Ohmic assisted hybrid operation). As reported in [17], fast reconnection event happens around 5 ms, then quickly heats electrons at the X point and ions downstream of outflow jet. Ions mainly gain energy in the downstream and thermalized where high density gradient suppresses radial transport. Electron temperature tends to be higher around the X point ($r \sim 0.5$ m) where electrons mainly gain energy by sheet current dissipation [16] (in this pulse, Z position is not optimized as in [17]), while initially lower in the downstream region where electron density is high. For the condition of $T_e < T_i$, energy equilibration time between ions and electrons $\tau_{ei}^{E} \propto T_e^{3/2}$ (~ 4 ms for $n_e \sim 1 \times 10^{19}/\mathrm{m}^3$ and $T_e \sim 100$ eV) tends to be shorter and bulk electrons quickly gain energy from ions in the downstream region. After the completion of equilibration, electron temperature tends to be higher with the additional Ohmic heating. From the view of solenoid-less startup scenario, the downstream heating is more important because the peaked electron heating at the X point is quite localized as reported in [17], while ions are globally heated in the downstream region. Therefore, outflow heating and its confinement is more important to improve the total performance of merging/reconnection startup. The achieved maximum bulk ion heating depends on the applied reconnecting field ($B_{\mathrm{rec}} \sim B_{\mathrm{p}}$), and hence on the current of merging startup coil I_{P3}. *Tokamak Energy Ltd.* and *the University of Tokyo* have started new projects to enhance reconnection heating over 1 keV for the future upgrade scenario by higher merging startup coil current [16, 22, 23].

In summary, this paper describes recent progress of the world's largest merging/reconnection experiment in MAST. The new 32 channel tomographic ion Doppler spectroscopy capability from 2013 successfully solved the problem of the absence of ion temperature profile measurement around the reconnection region, made a remarkable progress for MAST-univ.Tokyo collaboration in the last decade to understand the high power reconnection heating experiment. Magnetic reconnection mostly heat ions globally downstream and locally electrons at the X point. The discrepancy between both temperature is equilibrated by collisional coupling between electrons and ions, bulk electrons are also heated, quickly exceeding the radiation barrier of low-Z impurity, successfully connected to slow ramp Ohmic assisted scenario. The startup parameter depends on the driven current of merging startup coil I_{P3}. *Tokamak Energy Ltd.* and *the University of Tokyo* are currently collaborating to achieve higher startup coil currents in other devices, and this work is expected to produce results in the near future.

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