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Ion heating during merging/reconnection startup of ST in MAST

大型球状トカマク装置MASTの合体・リコネクションを用いた急速イオン加熱実験

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We applied the merging/reconnection startup of spherical tokamak (ST) developed in TS-3 and TS-4 to the world largest ST device: MAST and measured its ion heating characteristics for the first time. This CS-free startup converts the anti-parallel reconnecting magnetic field (B_{rec}~B_p) energy of two merging ST mainly into ion thermal energy. It was observed to (i) heat ions in the downstream region by reconnection outflow and electrons at X point by sheet current dissipation. In MAST, the time scale of reconnection is comparable to ion-electron energy relaxation time and (ii) both characteristic heating profile are transferred to each other and finally forms triple peak structure. (iii) The reconnection heating power scales with B_{rec}^2 energy both in TS-3/TS-4 and MAST, leading us to an upscaled scenario of CS-free startup and heating by merging/reconnection. .

1. Introduction

For the last decade, MAST-univ.Tokyo collaboration pioneered a CS-free startup and heating scenario for ST plasmas using merging/reconnection scheme. The high power heating of magnetic reconnection documented ~200eV in TS-3 and ~1.2keV in MAST in addition to the plasma current of 0.4MA in MAST without any assist of centre solenoid[1]. In TS-3, using several 2D in-situ probe and 2D ion Doppler tomography diagnostics around X point of magnetic reconnection, electron heating at X point and ion heating at downstream were revealed[2][3]. While in MAST merging experiment, ultra-fine profile measurement of electron temperature and density was performed at midplane during reconnection by use of 130 channel YAG Thomson scattering diagnostics, highly localized electron heating at X point and formation of shock structure at the downstream of outflow acceleration was also found[1].

However, in the past collaboration, ion temperature profile during reconnection has never been performed. The existing 64 channel CXRS measurement spanned outside r > 0.8m (outside the possible heating area of magnetic reconnection), core ion temperature increase during reconnection was only measured by single chord NPA diagnostics and detailed ion heating characteristics was not clear before M8 campaign of MAST experiment. Then, in the final campaign before MAST upgrade engineering (M9 campaign in 2013), a new collaboration to install ion Doppler tomography diagnostics[3] at midplane in MAST was accepted and detailed ion heating profile measurement during reconnection startup has been achieved for the first time. This presentation mostly focus on the ion heating characteristics during merging reconnection startup of ST in MAST experiment.

2. Merging/reconnection startup of ST in MAST

Figure 1 shows the schematic of MAST vacuum vessel with flux plot, fast camera image and typical waveform of standard shot using merging startup (no NBI shot 28040). During t = 0-15ms, the flux swing of P3 coil generates initial two ST around the P3 coils and then merge together at midplane. During reconnection, electron temperature rapidly increase from ~10eV to 400eV and plasma current reaches ~0.3MA. After reconnection, compression heating is also applied using P4 and P5 coils and then Ohmic current drive ramp up the plasma current upto desired value and keep the flat top (They call such an operation to save the solenoid flux during start up as ”standard shot” or “hybrid startup”).

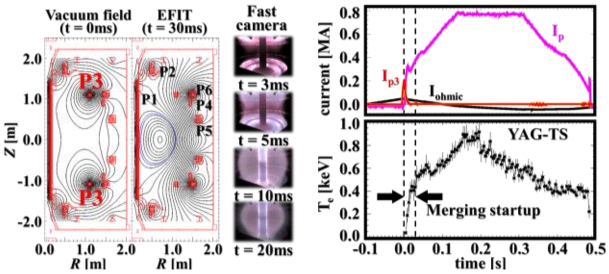

Fig.1. Merging (hybrid) startup operation in MAST

3. Electron heating profile during reconnection

During merging startup, reconnection heating of electrons forms characteristic profile. Figure 2 shows the 130 channel YAG-Thomson scattering measurement of electron temperature profile around X point. With the much faster time scale of Ohmic heating of centre solenoid, magnetic reconnection quickly increases electron temperature ~200eV within 1ms at X point, while electron density profile shows clear peak flow which suggests reconnection outflow and finally forms shock-like discontinuous density profile at the downstream. For the outflow heating mechanism of magnetic reconnection, ion temperature increases should occur around there. Figure 3 shows 2D electron temperature profile around X point at t = 10ms using 284 channel Ruby-TS system in a fully non-inductive operation without any assist of centre solenoid. The measured electron heating forms highly localized profile at X point, while electron temperature also increases at downstream with the delay of 5ms, comparable time scale of τ^{E}_{ei}.

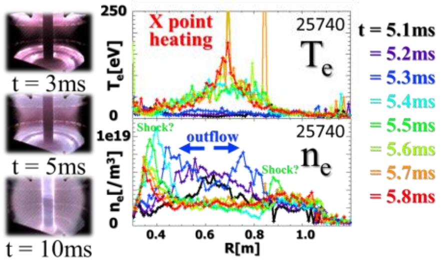

Fig.2. Thomson scattering measurement of T_e and n_e during merging/reconnection startup in MAST

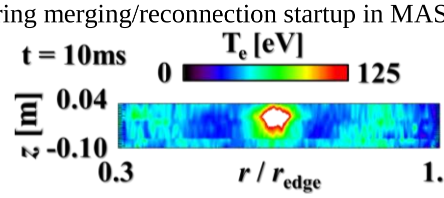

Fig.3. 2D T_e profile (284 channel Ruby-TS):

3. Ion heating profile during reconnection

To verify the contribution of $T_i - T_e$ relaxation to the downstream electron heating, ion temperature profile measurement has been achieved for the first time using 32 channel Doppler tomography diagnostics. Figure 4 shows the measured 2D profile of ion temperature during reconnection startup. As measured in the laboratory experiment in TS-3[2], ions are mostly heated at the high density region which is formed by reconnection outflow. In addition, the heating profile forms ring structure which suggests the confinement of outflow heating profile at the closed flux surface which is formed by reconnected field.

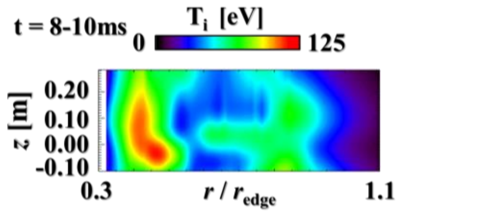

Fig.4. 2D T_i profile (32 channel Doppler tomography)

The achieved reconnection heating depends on reconnecting field B_{rec} which is controlled by the startup coil (P3) current I_{p3}. Figure 5 shows the achieved ion heating scales with the square of reconnection magnetic field amplitude B_{rec}^2 ($\propto I_{p3}^2$). The extrapolation of this scaling agrees well with the record ion temperature [1] ~1keV (measured by NPA) using I_{p3} ~ 300kA turn.

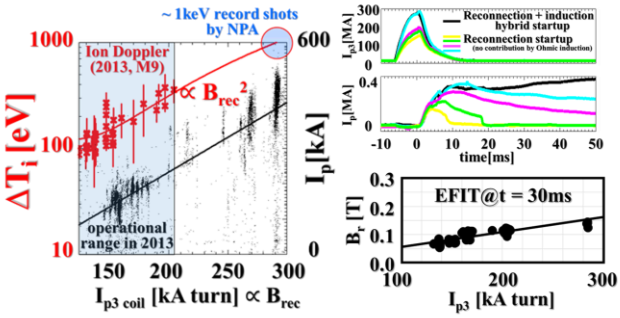

Fig.5. Achieved startup parameter scales with B_{rec}^2

5. Conclusion

The series of merging startup study consistently solved the causes and mechanisms for the merging/ reconnection heating of ST plasma: (1) magnetic reconnection heats ions at downstream and electrons at X point. (2) interaction of ion and electron heating profiles, (3) the B_{rec}^2 scaling of reconnection heating. These results lead us to the scenario development of merging/reconnection startup and heating as a promising CS-free startup of ST plasmas.

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