Investigation of merging/reconnection heating during solenoid-free startup of plasmas in the MAST Spherical Tokamak

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Abstract
We present results of recent studies of merging/reconnection heating during central solenoid (CS)-free plasma startup in the Mega Amp Spherical Tokamak (MAST). During this process, ions are heated globally in the downstream region of an outflow jet, and electrons locally around the X-point produced by the magnetic field of two internal P3 coils and of two plasma rings formed around these coils, the final temperature being proportional to the reconnecting field energy. There is an effective confinement of the downstream thermal energy, due to a thick layer of reconnected flux. The characteristic structure is sustained for longer than an ion–electron energy relaxation time, and the energy exchange between ions and electrons contributes to the bulk electron heating in the downstream region. The peak electron temperature around the X-point increases with toroidal field, but the downstream electron and ion temperatures do not change.

Keywords: spherical tokamak, magnetic reconnection, guide field, heating

(Some figures may appear in colour only in the online journal)
and localized electron heating around the X-point mostly by sheet current dissipation [14–16]. These laboratory experiments demonstrated that energy could be channeled effectively into ions via magnetic reconnection. However, the electron temperature tends to be as low as ~15 eV for most of the laboratory experiments due to the presence of low-Z impurities, probe diagnostics inside the vessel, and convective loss under low toroidal field condition. The duration time of most of the merging startup plasma tends to be less than a few milliseconds due to severe losses after merging (~10 ms even in the latest record in C-2 [17, 18]).

The world’s largest application of merging plasma startup in MAST (Mega Ampere Spherical Tokamak) achieved remarkable success in addressing these issues. Temperatures resulting from reconnection exceeded ~1 keV at maximum both for ions [12] and electrons [19], with individual ion energies ranging up to several tens of keV [20], pulse duration times exceeded 100 ms without solenoid [21], and merging startup plasmas successfully underwent transitions to quasi-steady and H-mode regimes [22, 23]. For the last decade, the MAST (CCFE)—TS (University of Tokyo) collaboration on reconnection studies mainly concentrated on pioneering this attractive startup scenario, and ion heating measurements were limited to single chord NPA [20] or charge exchange spectroscopy (CXRS) data obtained outside the core region of magnetic reconnection (the CXRS measurements were restricted to \( r > 0.8 \) m [24], due to the impact radius of the neutral beam). However, in the last three years, a new 32 channel ion Doppler tomography system was installed at the midplane on MAST [25, 26] in addition to 130 channel YAG- and 300 channel Ruby-Thomson scattering systems; our collaboration made significant progress with detailed 2D internal profile measurements and revealed the formation of fine structures associated with magnetic reconnection for the first time [27]. This paper addresses the latest results of merging plasma startup experiments in MAST: electron and ion heating during high field reconnection both for the in-plane reconnecting component (0.07 T < \( B_{\text{rec}} \sim 0.015 \) T) and the out-of-plane toroidal guide field (\( B_i > 0.3 \) T).

### 2. Merging plasma startup in MAST

Figure 1 illustrates the geometry of magnetic reconnection, the definition of the coordinates, and several waveforms of a merging plasma startup operation in MAST. After proper prefill of Deutrium gas, P3 coils generate initial two plasma rings which merge together at midplane as visualized in the fast camera images [28] and mostly contributes to drive magnetic reconnection in MAST [29, 30]. P1 is centre solenoid (nearly constant during startup) [31], P2 generates double null divertor configuration after merging [32], P4 and P5 control radial equilibrium [33] and P6 coils control the vertical position [34]. Toroidal field is 0.3–0.8 T around diffusion region (produced by \( T_{\text{P}} \times 24 \) turns) and reconnecting field is roughly \( B_{\text{rec}} \sim 0.07–0.15 \) T (based on EFIT reconstruction [35] of the radial component of poloidal field \( B_i \)); ion skin depth \( c/\omega_{pi} \sim 0.1 \) m, ion Larmor radius \( r_i < 0.01 \) m and ion cyclotron frequency \( \omega_c > 10 \) Mrad s\(^{-1} \) [26, 27]. The plasma outer midplane separatrix radius \( r_{\text{sep}} \) is constantly monitored by 2048 pixel linear D\(_0\) camera ranging \( r < 1.8 \) m [36]. The 300 channel Ruby- and 130 channel Nd:YAG-Thomson scattering systems measured electron temperature and density at \( z = 0.015 \) m and \( z = -0.015 \) m (with respect to the geometric midplane of the vacuum vessel rather than the plasma) with spatial resolution of ~15 mm and ~10 mm respectively including optical blurring [37, 38]. Ruby-TS (TV Thomson) system has 302 pixels for wavelength ranging 585.10 < \( \lambda < 901.15 \) nm with instrumental function of ~10 nm (FWHM) but single time frame in each MAST pulse. YAG-TS (filter type) has 5 spectral channels for wavelength (central wavelength (nm) / bandwidth (nm)): 755/170, 917/155, 1017.5/45, 1047.5/15, and 1057.7/5.5) and 8 lasers ~30 Hz for 8 time frames (the number of spatial points was increased from 36 to 130 in 2009 (available after 22961)). 32 channel ion Doppler tomography diagnostics measures ion temperature profile at midplane with spectral resolution of 0.0078 nm/pixel (512 pixels for wavelength) at 529.05 nm (CVI line) and has viewing chords in 0.25 < \( r < 1.09 \) m [26].

As shown in figure 2, the P3 ramp down current \( I_{\text{P3}} \) leads to the formation of initial two plasma rings, magnetic reconnection starts around \( t \sim 5 \) ms with a large spike of central Mirnov coil signal \( V_{\text{Mirnov}} \propto d\Phi/dt \) at \( r \sim 0.2 \) m, \( z \sim 0 \) m [39]. The fast camera image in figure 1 also shows that two plasma rings formed at the top and bottom of the vessel move toward midplane around \( t \sim 5 \) ms. During the initial spike of \( V_{\text{Mirnov}} \) which detects downstream reconnect flux with the microsecond time scale, 130 channel Thomson scattering measurement of \( n_e \) and \( T_e \) was performed at 8 time frames with the interval of 0.1 ms in the shot 25739 (\( B_{\text{rec}} \sim 0.11 \) T and \( r_{\text{sep}} \sim 1.0 \) m). Before merging (\( t = 5.2, 5.3 \) ms), electron temperature is as low as ~10 eV and electron density has a peak around the X-point. After \( t = 5.4 \) ms, the built up density starts to decay and radial profile of electron density shows the shift of double peak structure which indicates outflow acceleration toward radial direction (both inward and outward [27] but more in high field side as reported in [29]). For the closed flux type reconnection of spherical tokamak (ST) merging, outflow acceleration is damped downstream and forms double peak profile with shock-like steep density gradient. Electron temperature rapidly increases at \( t = 5.5 \) ms when \( V_{\text{Mirnov}} \) signal reaches its maximum and then forms peaked distribution around the X-point at \( r/r_{\text{sep}} \sim 0.7 \).

### 3. Fine structure formation by reconnection heating around the X-point

Figure 3 show 2D electron temperature and density profiles during discharges 21374–21380 (P6 coils are used to shift the vertical position of plasma for 2D Thomson scattering measurement [34]). After \( t = 5 \) ms, outflow ejection continues to increase electron density downstream and forms current sheet like structure, while electron temperature profile forms characteristic peaked structure around the X-point with the scale of ~0.06 m < \( c/\omega_{pi} \sim 0.1 \) m. In contrast to the no guide
Figure 1. Magnetic field configuration before and after merging, and several waveforms of a solenoid-less plasma startup scenario in MAST (routinely used in $\sim 15,000$ shots before MAST upgrade). Two plasma rings generated around P3 coils merge together around $t \sim 5$ ms as visualized in fast camera images and forms a spherical tokamak plasma through magnetic reconnection process.

Figure 2. Typical features of merging/reconnection startup on MAST: P3 coils generate two plasma rings and drive magnetic reconnection around $t \sim 5$ ms. During the initial spike of central Mirnov coil ($\propto dB/dt$), electrons are transported radially from the X-point ($r/r_{sep} \sim 0.7$), forming a shock-like steep density profile, while electron temperature rapidly increases within $\sim 1$ ms around the X-point.
(toroidal) field experiment in MRX where electron energy gain is quickly transported downstream [15, 40], the higher toroidal field in MAST strongly inhibits perpendicular heat conduction, expected to scale as $1/B_{t}^{2}$, and the established profile is sustained on millisecond time scales. At $t = 10\,\text{ms}$, cross-validation with the 300 channel Ruby-Thomson scattering measurement is also performed and successfully reproduces the highly localized hot spot around the X-point. By this time a sufficient number of electron–electron collision times have elapsed since the fast reconnection event around $t = 5\,\text{ms}$ ($\tau_{ee} < 0.1\,\text{ms}$) for the electron distribution to have become fully thermalized. In addition, electron temperature profile also forms characteristic high $T_{e}$ area downstream. It is located around the high density region where reconnection outflow should dissipate, suggesting the effect of energy relaxation between electrons and ions to equilibrate both temperatures ($\tau_{ee} \sim 4\,\text{ms}$ for $T_{e} = 100\,\text{eV}$ and $n_{e} \sim 1 \times 10^{19}\,\text{m}^{-3}$).

Figure 4 illustrates the 2D ion temperature profile in pulses 30366–30368, 30376–30377 ($B_{\text{rec}} \sim 0.08\,\text{T}$). Ion heating mainly occurs in downstream region globally due to conversion of plasma outflow energy into thermal energy mostly by viscosity dissipation [15] and shock-like compressional damping of outflow jet [12, 16] as in the two fluid simulation which includes such fundamental collisional viscous dissipation [41]. Smaller ion heating also occurs around X-point by electron–ion energy equilibration. For the high guide field reconnection experiment in MAST, the ratio of collisional thermal diffusivities $\chi_{||}^{i}/\chi_{\perp}^{i} \sim 2(\omega_{ci}\tau_{ci})^{2} \gg 10$ is much higher than that of other laboratory experiments ($\chi_{||}^{i}/\chi_{\perp}^{i} \sim 1$ for zero guide (toroidal) field operation in MRX [42]). Thus, the toroidal configuration also plays an important role in determining the temperature profile. Outflow heating downstream forms a ring structure of closed flux and enhances the local energy relaxation between ions and electrons in the millisecond time scale of $\tau_{ee}$, eventually causing electron heating in the outflow region.

Figure 5 shows the comparison of electron and ion heating on two different toroidal field conditions $B_{t} = 0.4$ and 0.8 T when $B_{\text{rec}} \sim 0.08\,\text{T}$. $T_{e}$ around the X-point ($r/r_{\text{sep}} \sim 0.6$) increases with $B_{t}$, probably because the higher...
guide field strongly inhibits cross-field thermal transport ($\sim 1/B_t^2$), so that the electrons remain in the region of high toroidal electric field for longer (the comparison of electron thermal energy $U_e$ shows that the decay of peak structure). The higher toroidal field also affects the ion temperature profile around the X-point probably due to enhanced exchange with electrons. Because the perpendicular heat conduction of ions, like that of electrons, is expected to scale as $1/B_t^2$, ions also gain energy around the X-point from electrons in the presence of higher $B_t$, finally forming a triple peak structure. However, bulk ion heating downstream does not change, as demonstrated also in the merging experiment with intermittent plasmoid ejection in TS-3 [43] and PIC simulations [44].

4. Application of reconnection heating for solenoid-less startup scenario

Before MAST upgrade (shot number $< 30471$), $\sim 15000$ pulses of MAST operation routinely used merging plasma startup to save significant amount of solenoid flux for initial hot plasma formation. Figure 6 shows non-solenoid operation in pulses 15721 (red) and 28875 (blue), and merging/induction...
hybrid operation in pulses 6536 (black) and 28860 (green) with P3 coil current of $I_{P3\ max} \sim 200 \text{kA} \cdot \text{turn}$ and $\sim 300 \text{kA} \cdot \text{turn}$, respectively. The peak current of P3 coils determines the startup performance and this is not affected by the use of the solenoid (the achieved plasma current linearly increases as in figure 7 (top)). Higher P3 current increases reconnecting field $B_{rec}\propto I_p\propto I_{P3\ max}$ and contributes more heating based on $B_{rec}^2$ scaling [12, 14, 16]. The high temperature startup quickly exceeds the radiation barrier, the pulse duration time of $\sim 100 \text{ms}$ was achieved in 28875 ($I_{P3\ max} \sim 200 \text{kA} \cdot \text{turn}$) and more in 15721 ($I_{P3\ max} \sim 300 \text{kA} \cdot \text{turn}$) without solenoid. For solenoid assisted hybrid scenario, the startup parameters could be sustained by slow-ramp Ohmic induction and 6536 successfully demonstrated fully flat top operation just after merging (in most of MAST pulses, more ramp scenarios as in 28860 (flat top time finishes after the end of Ohmic down swing) were usually used for the plenty of physics campaigns which require high performance plasma ($\sim 3 \text{keV}$ at maximum) [23, 32, 33]). Those results suggest clearly simplified future upgrade scenario: higher plasma current startup by applying higher current of merging startup coils $I_{P3}$ to increase reconnecting field $B_{rec}$ and slow-ramp Ohmic induction to sustain the merging parameters, or reduced space for solenoid and more space to achieve high $B_{rec}$ for more friendly to non-inductive operation with RF and NBI after merging. Now those upgrade scenarios were accepted in ST40 (Tokamak Energy Ltd.) using merging startup coil current of $\sim 0.5 \text{MA} \cdot \text{turn}$ with toroidal field of $\sim 3 \text{T}$ and in TS-U (the University of Tokyo) with reconnecting field of $B_{rec} > 0.2 \text{T}$ [45, 46].

5. Conclusion

In summary, detailed mechanism of plasma heating during the high field CS-free startup by merging/reconnection was investigated in MAST using a 130 channel YAG- and a 300 channel Ruby-Thomson scattering and a new 32 channel ion Doppler tomography diagnostics. 2D detailed imaging measurement of temperature profile around the diffusion region has been achieved for the first time and it was found that high guide (toroidal) field reconnection heats electrons locally around the X-point and ions globally downstream. The 2D profile of electron temperature forms highly localized peaked structure around the X-point with the characteristic scale length of $\sim 0.06 \text{m} < c/\omega_{pi} \sim 0.1 \text{m}$, while ion temperature increases downstream where reconnected field forms thick layer of closed flux surface and inside the diffusion region with the thickness of $c/\omega_{pi} \sim 0.1 \text{m}$. $T_i - T_e$ energy relaxation process, which is too slow for short pulse laboratory experiment ($\tau_{duration} \ll \tau_{ei}^E$) and too fast ($\tau_{event} \gg \tau_{ei}^E$) for solar flares, also affects both temperature profiles for the high guide field experimental condition with better energy confinement in MAST. With the delay of $\tau_{ei}^E$ after the rapid temperature increase of electrons around the X-point and ions downstream, the equilibration process to form triple peak structure for both profiles by $T_i - T_e$ relaxation was observed for the first time and helps to bridge the gap of time scale between typical laboratory experiments and astrophysical events. The toroidal guide field mostly contributes to the formation of the peaked electron temperature profile around the X-point and not to bulk ion heating downstream under the ultra-high guide field condition in MAST ($B_t > 0.3 \text{T}$). Achieved reconnection heating increases in proportional to released reconnecting (poloidal) magnetic field energy and the performance improves with higher current of merging startup coils ($B_{rec}^2 \propto I_p^2 \propto I_{P3\ max}^2$). Although the absence of direct magnetic probe measurement limits the possible discussion of the formation mechanism of the characteristic heating profile, it should be noted that the ultra-fine non-invasive optical diagnostics in MAST successfully reveal the existence of highly peaked electron temperature profile around the X-point without breaking the structure whose scale is comparable to typical invasive probe diagnostics. In addition, the high field merging experiments successfully demonstrated the application of reconnection heating in high guide field regime which is preferable for better confinement in practical operation, and achieved successful connection to long pulse operation up to hundreds of millisecond both with and without solenoid. Further upgrade projects are now on progress in Tokamak Energy Ltd. and the University of Tokyo, and are expected to report new results in the near future.
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