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Application of reconnection heating for solenoid-free plasma startup in TS-6 and ST40

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Here we report the recent results from TS-6 and ST40 namely on *Merging/Compression* (M/C) plasma startup which utilizes impulsive energy release during magnetic reconnection [1][2]. We have clearly revealed the detailed 2D structure of reconnection heating by use of 96CH/320CH 2D ion Doppler tomography and 30CH/144CH Thomson scattering diagnostics in ST40 and TS-6 respectively, and found the fine structure around the current sheet of magnetic reconnection whose scale is smaller than ion skin depth. In addition to the physics investigation, we have successfully updated the previous record of reconnection heating in ~ 1kJ/m^3 in MAST (B_{rec} ~ 0.1T) into 10 times higher regime ~ 10kJ/m^3 (B_{rec} ~ 0.3T). The results are well scaled with the thermal energy increment $\Delta U_i = 1.5\Delta n_e \kappa_B T_i$ as $\Delta U_i \propto B_{rec}^2$ and it was found that 10keV heating experiment can be designed by enabling the high field reconnection drive with B_{rec} > 0.6T when n_e ~ 2×10^{19}/m^3. In ST40 experiment, electron heating also exceeds 1keV and the high temperature plasma startup has successfully been connected to semi-steady scenario after merging [3]. Those detailed processes of M/C startup plasma will be presented in the conference.

Magnetic reconnection is a fundamental process which converts magnetic energy to plasma thermal energy through topological rearrangement of magnetic field lines [1]. As in astrophysical high energy events such as solar flares, the explosive energy release was demonstrated in many laboratory experiments in the last 3 decades. The established temperature depends on the amplitude of reconnecting component of magnetic field B_{rec} (poloidal field B_p in Tokamak) and several milestone temperatures was achieved in TS-3 (~ 250eV), MAST (~ 1.2keV) and ST40 (~ 2.3keV) as in $\Delta T_i \propto B_{rec}^2$ scaling. The active driving method of magnetic reconnection is called *Merging/Compression* (M/C) and its application is now widely used in many new spherical tokamak (ST) devices such as TS-6 (2018~) [4], ST40 (2018~) [5] and SUNIST-2 (2024~). The method also helps to save the significant amount of solenoid flux consumption during plasma startup and enables high toroidal field (B_t) design such as B_t ~ 2T in ST40 nevertheless of its low aspect ratio configuration (limited space for center stack). The high field design leads to the first 100MK record in spherical tokamak and it is also well known as the important milestone: the first 100MK achievement by a private fusion company [6].

For those application experiments, there is strong toroidal field B_t (guide field which is perpendicular to reconnecting field B_{rec}). In comparison with zero-guide field condition, the existence of the perpendicular component on reconnection plane alters the contribution of parallel electric field $E_{/\!/} = \boldsymbol{E}\cdot\boldsymbol{B} = (E_t B_t + E_p B_p)/B$ during reconnection. Ion-electron decoupling around X-point forms quadrupole potential profile and its originated poloidal electric field E_p leads to global particle acceleration and E×B drift structure. Typically, $E_p B_p$ affects global structure in the outflow region and $E_t B_t$ makes localized characteristic structure around the X-point. In TS-6, its contribution to ion acceleration /heating was clearly detected by the 320CH 2D ion Doppler tomography and it was found that the characteristics structure gets flipped when guide field direction is reversed [7]. In ST40, the contribution of parallel electric field also leads to clearer electron heating (~ 1keV) with peaked profile around the X-point where the spontaneously formed toroidal electric field E_t exists. After merging, the peak T_e is sustained around the magnetic axis, while the high T_i in the downstream forms poloidally ring-like hollow (double-peak) structure via parallel heat transport process as in TS-6 [7][8] because the high guide field condition ($B_t > B_p$) helps to suppress perpendicular heat conduction ($\kappa^i_{/\!/}/\kappa^i_{\perp} \sim 2(\omega_{ci}\tau_{ii})^2 >> 1$). With the series of experiments, $\Delta T_i \propto B_{rec}^2$ scaling has been upgraded to $\Delta U_i \propto B_{rec}^2$ and the previous record of thermal energy increment ΔU_i ~ 1kJ/m^3 in MAST has successfully been upscaled to ΔU_i ~ 10kJ/m^3 in ST40 [3].

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