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Ion Heating during non-inductive plasma startup and sustainment in VEST

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In tokamak configuration, increasing magnetic helicity, the linkage of toroidal and poloidal flux, means increasing toroidal plasma current, thereby increasing the performance of tokamak plasma. To inject magnetic helicity, the DC (electrostatic) Local Helicity Injection (LHI) technique using 3D magnetic flux ropes has been conducted in the spherical torus (ST)[1]. LHI can be used as a means of current drive for tokamak and a non-inductive startup for the ST that deals with the limited-central-inductive-flux swing. During the operation of this technique, several physical processes are required, such as plasma merging via magnetic reconnection and the Taylor relaxation process that convert the localized injected helicity into global helicity and macroscopic plasma current. Finally, a closed flux surface that resembles a tokamak plasma (tokamak-like state) can be formed and can be sustained or maintained through LHI. During the operation of LHI, the change in magnetic topology is required, transitioning from flux ropes following the 3D helical open field to tokamak-like plasma in closed flux surface. This change necessitates the merging activity via magnetic reconnection. Two types of merging configuration according to phases of the technique are confirmed, 1) rope-rope merging, 2) rope-main plasma merging.

To form 3D helical flux ropes in VEST, the LHI system consisting of two arc plasma guns and two pulsed powers is developed [2]. According to discharge conditions, the typical normalized effective toroidal loop voltage value can range from 1.4 to 2.4 V-m. In this research, ion Doppler spectroscopy is used to measure ion temperature, which is used to evaluate merging activity. The main spectral line is CIII (464.7nm), the strongest impurity line in VEST.

For rope-rope merging, when both the axial magnetic field, the sum of toroidal and poloidal field, is sufficiently lowered and the beam energy is sufficiently increased, the flux ropes undergoing external kink mode are merged via magnetic reconnection, resulting in a linear relationship between the discharge power and ion temperature. In addition, when the distance between the ropes is reduced, the ion temperature is also increased, which is consistent with the calculation results that show an increased reconnection field angle in the 3D reconnection configuration.

As the merging process is ongoing, the second type of merging is shown, rope-main plasma merging. When the vertical magnetic field is adjusted to give high proximity between flux ropes and the main plasma, the toroidal plasma current is driven up to 15 kA with an injection current of 1.5 kA. At the same time, the edge localized peaked profile of ion temperature is measured at the low-field side, indicating where the strong reconnection activity takes place. In addition, the increased CIII/II ratio is observed during the current ramp-up phase, meaning improved confinement. The magnetic reconstruction results using FEM show the formation of CFS in the toroidally averaged sense. As the coupling (proximity) between the toroidal plasma and flux ropes is maintained, the toroidal plasma current is driven non-inductively with peaked profiles of ion temperature. At the end of the discharge, as the radial force is not balanced, the coupling is halted (decreased proximity), decaying the toroidal plasma, indicating the end of the Taylor relaxation phase. In this phase, the flattened radial profile of ion temperature is measured.

These findings offer new conditions for the successful operation of the DC Helicity Injection technique in nuclear fusion research and provide new observations related to the onset problem of magnetic reconnection.

References

[1] Bongard, Michael W., et al. "Advancing local helicity injection for non-solenoidal tokamak startup." Nuclear Fusion 59.7 (2019): 076003.
[2] Park, Jong Yoon, et al. "Identification of kink instability in 3D helical flux ropes at VEST." Physics of Plasmas 29.5 (2022).

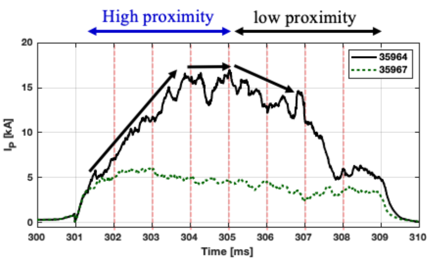

Figure 1. Time evolution of toroidal plasma driven by LHI in VEST

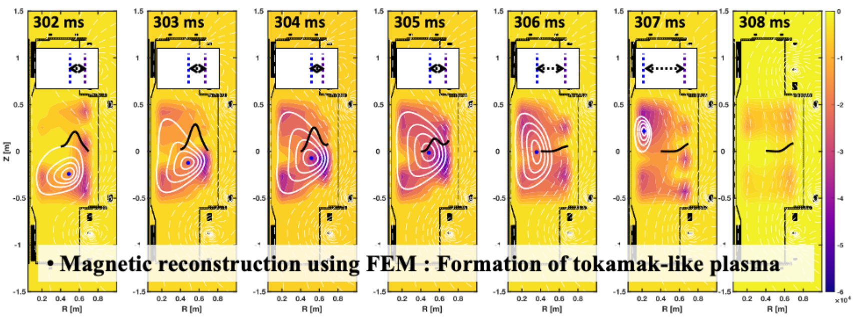

Figure 2. Magnetic reconstruction results using FEM for shot 35964.
The white closed line shows the toroidally averaged CFS.
The black line at the middle of figure is ion temperature profile for a given time.