MHD simulation of kink instability and plasma flow during sustainment of coaxial gun spheromak

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Taylor's MHD relaxation theory says that a turbulent MHD system relaxes to a minimum magnetic energy state subject to the constraint that the global magnetic helicity is conserved, but it provides no mechanism of how the relaxation process is achieved and how the toroidal current I_t is driven. Low-q toroidal plasmas such as spheromak and RFP which tend to easily self-organize are traditionally an object of the relaxation physics study. Many experiments to understand the mechanism of relaxation process and current drive using a magnetized coaxial plasma gun (MCPG), i.e., helicity injector have been carried out for spheromak. The relaxation phenomena such as plasmoid ejection, helical twist, magnetic reconnection, and rotation are observed in the helicity injection experiments and in solar flares and astrophysical jets as well. Comprehensive understanding of the relaxation mechanism underlying physics in helicity injection system has fundamental importance to both laboratory and space plasmas.

Recently, the repetitive plasmoid injection and merging model that the plasma flow ejected from the MCPG may play an important role is proposed as a possible current drive mechanism. In order to verify the validity of this model, the internal magnetic field and flow measurements have been conducted in the HIST device. The intermittent plasma ion flow (20-40 km/s) has been observed to be correlated with the fluctuations of I_t and toroidal mode number n=1 mode. It is necessary to compare experiments with numerical simulations.

We have performed the 3-D nonlinear MHD simulations to investigate the MHD relaxation process and associated plasma flow in the helicity-driven spheromak plasma. During the sustainment, the plasma with helical distortion of the central open flux column moves from the gun region toward the confinement region. This helical distortion is due to a kink instability triggered by the gun current along the twisted central open flux column. As the result, the magnetic reconnection event occurs at the X-point near the gun muzzle, and then the toroidal flow (~ 37 km/s) is driven there. This flow is superimposed on the $\boldsymbol{E}\times\boldsymbol{B}$ plasma rotation with a frequency of ~16 kHz induced by the applied electric field and is in the opposite direction to I_t. This result is consistent with the flow observation in the HIST, HIT-II, and NSTX experiments. The magnetic reconnection event results in the generation of the closed field lines like a plasmoid. This magnetic configuration is in a non-axisymmetric partially relaxed state with a strong poloidal flow in the periphery region. In the next stage, the toroidal flow driven by the magnetic reconnection stays at the inboard while new toroidal flow is intensively induced in the opposite direction at the outboard. This new plasma flow is suggested to be associated with the anti-dynamo effect. After that the new plasma is ejected from the gun region and this process is repeated with a time interval of ~ 200 Alfvèn transit times. Therefore, the toroidal current is considered to be driven by the physical mechanism that the non-axisymmetric plasmoid is repetitively provided by the MCPG.