Nonlinear dynamics of magnetic and velocity field structures generated by multi-pulsing coaxial helicity injection in spherical torus plasmas

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Refluxing approach of coaxial helicity injection (CHI) which operates in multi-pulsing CHI (M-CHI) has been proposed [1]. In the M-CHI scenario, current driven phase to perform the CHI by applying the gun voltage and decay phase to obtain the excellent confinement by partially decaying the plasma current and magnetic field are separated in time. Sustainment of the magnetic field of spheromak with a high electron temperature in quasi-steady state was for the first time demonstrated by the M-CHI in the SSPX device [2]. To explore the usefulness of the M-CHI for spherical torus (ST) configurations, the double pulsing operations have been tested in the HIST device, demonstrating the flux amplification and the sustainment of the ST [3]. The purpose of this study is to investigate the physical mechanism to rebuild the magnetic fields and to amplify the currents by using resistive nonlinear 3D-MHD simulations [4]. We focus our attention on the effects of the M-CHI on dynamics of the high-q ST.

The dynamics of the helicity–driven ST (HD-ST) usually involves the nonaxisymmetric helical distortion of a central open flux column (COFC) so that a 3D simulation geometry is essential to reproduce the distortion properly. All variables are treated in a normalized form. The length, magnetic field, and number density are normalized by the maximum length of the cylinder radius, \( L_0=0.5 \text{m} \), the strength of the characteristic magnetic field, \( B_0=0.2 \text{T} \), and the initial ion number density in the hydrogen plasma, \( n_0=5.0 \times 10^{19} \text{m}^{-3} \), respectively. Under these normalizations, the velocity and time are normalized by the Alfvén velocity, \( v_\Lambda=620 \text{km/s} \), and the Alfvén transit time, \( \tau_\Lambda=0.81 \mu \text{sec} \), respectively. We adopt the simulation system shown in Fig. 1 and use a 3D full-toroidal cylindrical \((r, \theta, z)\) geometry. We divide the simulation region into two cylinders with a central conductor inserted along the symmetry axis. One is a gun region corresponding to a magnetized coaxial plasma gun region, and the other is a confinement region. The insertion of a toroidal field current \( I_{tf} \) along the geometry axis inside the central conductor produces a vacuum toroidal field, creating a tokamak configuration. In this paper, we set \( I_{tf}=1.2 \) because we consider a high-q HD-ST configuration \((q>2)\).
The governing equations to be solved in the simulation are the set of nonlinear resistive MHD equations. To solve the equations, we use the second-order finite differences method for the spatial derivatives and the fourth-order Runge-Kutta method for the time integration. The grid numbers are set to \((N_r, N_\theta, N_z) = (39, 64, 40)\) in the gun region and \((N_r, N_\theta, N_z) = (69, 64, 121)\) in the confinement region. A bias magnetic flux penetrates electrodes at the inner and outer boundaries of the gun region to drive the plasma current by applying an electric field.

We use a perfect conducting boundary at the wall of the confinement region. The initial conditions are given by an axisymmetric MHD equilibrium, which can be obtained by numerically solving a Grad-Shafranov equation under these boundary conditions. In the simulation, the mass density is spatially and temporally constant. The no-slip wall condition is assumed at all boundaries except for the gap between electrodes. The \(\mathbf{E} \times \mathbf{B}\) drift velocity is given at the gap. We also impose that the heat flux can pass through all the boundaries.

On the basis of the simulation results, the mechanism to rebuild the magnetic fields is investigated. The poloidal flux contours of the axisymmetric MHD equilibrium with finite pressure gradients used as the initial condition are shown in Fig. 1. The conductivity \(\kappa = 1.0 \times 10^{-3}\), viscosity \(\mu = 1.0 \times 10^{-3}\), and resistivity \(\eta = 1.2 \times 10^{-4}\) are assumed to be uniformly constant throughout the entire region. A toroidally symmetric radial electric field \(E_{\text{inj}}\) of \(1.0 \times 10^{-2}\) is applied to the gap between gun electrodes in the shape of pulses. Figure 2 shows the time evolutions of the \(E_{\text{inj}}\), toroidal current \(I_t\), poloidal flux \(\psi_p\), and magnetic energy \(W_{\text{mag}}\) for the toroidal Fourier mode. As shown in Fig. 2, \(I_t\) is successfully sustained against resistive dissipation during the driven phase. After \(E_{\text{inj}}\) vanishes at \(t = 200 \tau_A\), \(I_t\) starts to decay due to the resistivity. When \(E_{\text{inj}}\) is applied again at \(t = 300 \tau_A\), the \(I_t\) value increases from 0.35 up to 0.74 for about 100 \(\tau_A\), resulting in the effective current amplification. However, the significant flux amplification is not observed from the time evolution of \(\psi_p\) because the current sheet which is generated by the plasmoid merging with the pre-existing HD-ST does not rapidly decay. In spite of applying \(E_{\text{inj}}\) at \(t = 300 \tau_A\), the flux amplification does not occur at all, since the plasmoid cannot be ejected from the gun region due to the magnetic pressure of pre-existing HD-ST. The \(W_{\text{mag}}\) of the high-\(n\) modes is relatively large magnitude during the driven phase.
However, the fluctuation level of \( n=0 \) mode compared with other modes which has temporally constant value of about \( 4 \times 10^3 \) is much larger. Thus the dynamics is almost axisymmetric. During decay phase, the \( n=1-5 \) components decrease, indicating to relax to an axisymmetric state. Figure 3 shows the time evolution of magnetic fields on the poloidal cross section. During the driven phase, the HD-ST causes a helical distortion of the COFC because of current flowing along the COFC. At \( t=912 \tau_A \), the plasmoid starts to be ejected from the gun region due to the Lorentz force. At \( t=948 \tau_A \), it is merged with the pre-existing HD-ST. As the result, the amplification of \( I_t \) and \( \psi_p \) occurs. After the plasmoid ejection, the closed field lines cannot be observed in the confinement region. During the decay phase, the closed field lines are regenerated there due to the dissipation of the magnetic fluctuation energy. At \( t=1167 \tau_A \), the helical distortion of the COFC becomes small, and then ordered magnetic field structures are rebuilt. Figure 4 shows the time evolution of velocity fields on the poloidal cross section. During the driven phase, the strong poloidal flow \( v_z (=E_r B_t) \) moves from the gun to confinement region due to the Lorentz force. The vortices of the poloidal flow \( v_p \) are also caused around the upper confinement region by above \( v_z \). From \( t=926 \tau_A \) to \( t=970 \tau_A \), the negative toroidal flow \( v_t \) which is the same direction as \( I_t \) is driven around the COFC region by inductive toroidal electric field \( E_t (=v_z B_r) \) because of the plasmoid ejection. After that, the positive \( v_t \) which is associated with the dynamo effect is generated around the COFC region. During the decay phase \( (t=1167 \tau_A) \), both \( v_t \) and \( v_p \) decay, and then the configuration approaches a static MHD equilibrium of HD-ST due to the dissipation of magnetic fluctuations to rebuild the closed field lines. Just after turning off the \( E_{\text{inj}} \) \( (t=1101 \tau_A) \), the \( v_p \) which moves from the confinement to gun region is caused by the pressure gradients. The vortices of \( v_p \) then expands all over not only confinement region but also gun region.
References


Fig. 2 Time evolution of vector plots of poloidal field $B_p$ on the poloidal cross section at the $\theta=0$ plane.

Fig. 3 Time evolution of vector plots of poloidal flow velocity $v_p$ and contours of toroidal flow velocity $v_t$ on the poloidal cross section at the $\theta=0$ plane.