Rapid Communications

MHD Simulation of Current Drive by Repetitive Plasmoid Injection in Helicity-Driven Spheromaks

KAGEI Yasuhiro, NAGATA Masayoshi, SUZUKI Yoshio[1,2], KISHIMOTO Yasuaki[2] and UYAMA Tadao
Himeji Institute of Technology, Himeji 671-2201, Japan
[1]Center for Promotion of Computational Science and Engineering,
Japan Atomic Energy Research Institute, Tokyo 110-0015, Japan
[2]Naka Fusion Research Establishment, Japan Atomic Energy Research Institute, Ibaraki 311-0193, Japan

(Received 17 January 2003 / Accepted 11 February 2003)

The dynamics of spheromak plasmas in coaxial helicity injection (CHI) systems has been investigated using three-dimensional magnetohydrodynamic (MHD) numerical simulations. It was found that toroidal current is driven by repetitive asymmetric plasmoid injection, which is related to the $n = 1$ oscillations. In addition, we propose that multiple pulse operation of the helicity injection is effective for improving confinement because it reduces the $n = 1$ fluctuations.

Keywords:
coaxial helicity injection, spheromaks, repetitive plasmoid injection, MHD, simulation

Coaxial helicity injection (CHI) has demonstrated the ability to form and sustain spheromak and spherical tokamak (ST) plasmas on several devices [1,2]. In these experiments, magnetic field fluctuations with toroidal mode number $n = 1$ are observed during sustainment, and these fluctuations are considered responsible for the current drive. However, the detailed physical mechanism understanding this phenomenon is not yet well understood. Sovinec *et al.* demonstrated numerical simulations of helicity-driven spheromaks [3], but the detailed dynamics of toroidal current generation in the gun-driven-system was not clearly revealed. In order to reveal this, 3-D magnetohydrodynamic (MHD) numerical simulations for spheromak plasmas were executed.

The simulation region consists of two cylinders, each with a center post: one is a gun region ($0.175 \leq r \leq 0.65$ and $0 \leq z \leq 0.5$), the other a confinement region ($0.15 \leq r \leq 1.0$ and $0.5 \leq z \leq 2.0$), as shown in Fig. 1. Grid sizes ($N_r \times N_\theta \times N_z$) are ($39 \times 64 \times 40$) and ($69 \times 64 \times 121$) in the direction of the gun and the confinement regions, respectively. Bias magnetic flux penetrates electrodes at the inner and outer boundaries of the gun region. Boundaries of the confinement region are assumed to be perfectly conducting walls. The initial spheromak configuration is given by numerically solving $\nabla \times \boldsymbol{B} = \lambda \boldsymbol{B}$ (λ is the force-free parameter) under these boundary conditions. The governing equations are one-fluid MHD equations, as follows:

$$\partial \rho \boldsymbol{V}/\partial t = -\nabla\cdot\rho\boldsymbol{V}\boldsymbol{V} + \nabla\times\boldsymbol{B}\times\boldsymbol{B} - \nabla p - \nabla\cdot\Pi \quad (1)$$

$$\partial \boldsymbol{B}/\partial t = -\nabla\times(-\boldsymbol{V}\times\boldsymbol{B} + \eta\nabla\times\boldsymbol{B}) \quad (2)$$

$$\partial p/\partial t = -\nabla\cdot(p\boldsymbol{V} - \kappa\nabla(p/\rho)) - (\gamma-1)\left(p\nabla\cdot\boldsymbol{V} + \Pi : \nabla\boldsymbol{V} - \eta(\nabla\times\boldsymbol{B})^2\right) \quad (3)$$

$$\Pi = \nu\left(2/3(\nabla\cdot\boldsymbol{V})\,\mathbf{I} - \nabla\boldsymbol{V} - {}^{t}(\nabla\boldsymbol{V})\right) \quad (4).$$

In this simulation, the mass density is spatially and temporally constant for simplicity. All physical quantities are normalized by initial mass density ρ_0, typical Alfvén speed V_A, and maximum length of the cylinder radius L_0. The conductivity κ, the resistivity η, and the viscosity ν are fixed to 1×10^{-3}, 2×10^{-4}, and 1×10^{-3} in the normalized units $(\gamma - 1)^{-1} k\, n_0 L_0 V_A$, $\mu_0 L_0 V_A$, and $\rho_0 L_0 V_A$, respectively. The simulation starts with the application of a toroidally symmetric radial electric field ($E_{\rm inj}$) across a gap between two electrodes.

The parameters used in this simulation are $\lambda = 4.95$

---

author's e-mail: skagei@elct.eng.himeji-tech.ac.jp

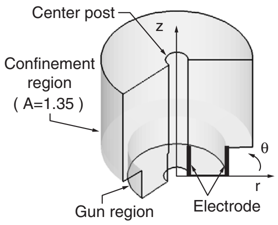

Fig. 1 Schematic diagram of the simulation region.

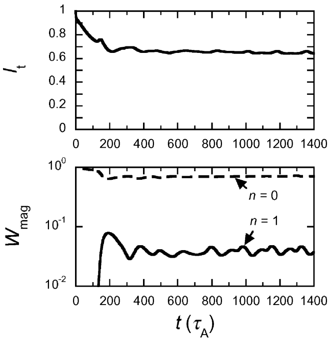

Fig. 2 Time evolutions of toroidal current (I_t) and normalized magnetic energy (W_{mag}).

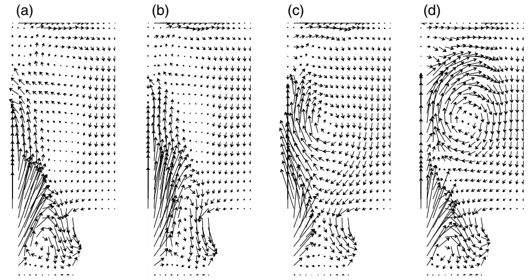

Fig. 3 Vector plots of poloidal magnetic field on a poloidal cross section at t=1,131τ_A (a), t=1,145τ_A (b), t=1,166τ_A (c), and t=1,202τ_A (d).

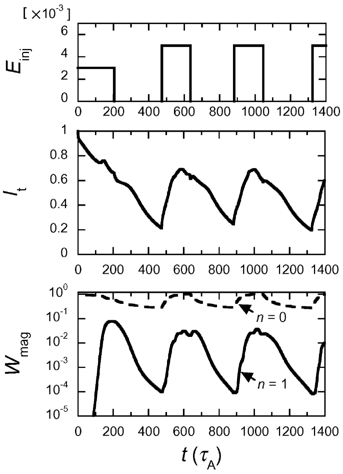

Fig. 4 Time evolutions of toroidal current (I_t), and. normalized magnetic energy (W_{mag}) when E_{inj} is applied in the shape of pulses.

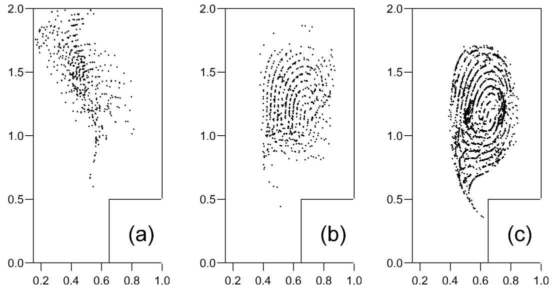

Fig. 5 Poincaré plots of magnetic field on a poloidal cross section at t= 261τ_A (a), t= 356τ_A (b), and t= 459τ_A (c).

and the safety factor on axis $q_0 = 0.7$ at $t = 0$. Figure 2 shows the time evolutions of toroidal current and magnetic energy in the $n = 0$ and $n = 1$ modes in the case of $E_{inj} = 3.0 \times 10^{-3}$. Toroidal current is successfully sustained against resistive decay with the $n = 1$ oscillations. In the current drive phase, a helical distortion of a central open flux column, rotating toroidally, which is in good agreement with SPHEX observations [4], can be observed. We found that an asymmetric plasmoid is generated by the distortion on the gun side, and that the current is periodically fed from it, as shown in Fig. 3. Although the toroidal current is driven by such a mechanism, closed flux surfaces vanish due to a significant amount of field distortion. Next, the case of multiple pulse helicity injection was investigated (Fig. 4). During $E_{inj} = 0$, the $n = 1$ mode dissipates and closed flux surfaces are formed, as shown in Fig. 5. A large amount of closed flux is expected to exist when the magnetic energy in the $n = 1$ mode gets down to ~10^{-4}. At that time the toroidal current remains at about 0.23, which is approximately one-third of the sustained current (0.65) in the previous continuous helicity injection case (see Fig. 2). Multiple bursts of helicity from the source are attempted using an SSPX device [5]. Our results suggest that controlled multiple-burst operation may be effective for improving confinement.

We thank Prof. T. Hayashi for fruitful discussion.

[1] H.S. McLean *et al.*, Phys. Rev. Lett. **88,** 125004 (2002).
[2] T.R. Jarboe *et al.*, *19th IAEA Fusion Energy Conf.*, Lyon, IAEA-CN-94/IC/P-10 (2002).
[3] C.R. Sovinec *et al.*, Phys. Plasmas **8**, 475 (2001).
[4] R.C. Duck *et al.*, Plasma Phys. Control. Fusion **39**, 715 (1997).
[5] S. Woodruff *et al.*, *Proc. of US-Japan Workshop* on *Physics of Compact Toroid Plasmas* (2002).