Plasma start-up by using transient coaxial helicity injection on HIST

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1. Introduction

An advantage of the Spherical Torus (ST) is the low aspect ratio and so elimination of a central solenoid coil is required for attractive high-beta fusion reactors based on the ST concept. The steady-state Coaxial Helicity Injection (CHI) is one of useful current drive methods for ST and spheromak plasmas, where dynamo activities are required to transport inwardly injection currents toward core regions, leadings to a degradation of confinements. In the transient-CHI (T-CHI), only axisymmetric reconnection during plasmoid ejection process from an injector is thought to be necessary for generating a high quality closed flux. The T-CHI without requiring for dynamo is a promising candidate for the non-inductive plasma start-up in a reactor-size ST device. So far, the T-CHI method has been successfully applied to NSTX for the start-up followed by inductive ramp-up. This coupled discharge has achieved plasma currents larger than 1 MA [1]. However, understanding the physics of the flux closure during T-CHI still remains as a key issue [2,3]. Internal magnetic field measurements in a smaller machine make it possible to confirm the generation of closed flux surfaces. Thus, we have recently tried the internal magnetic probe measurement to investigate the flux closure in the T-CHI experiments on HIST (R=0.30 m, a=0.24 m, A=1.25) [4]. In the recent experiment, T-CHI has generated toroidal currents up to I_t=40-60 kA under the condition of the presence of closed flux. A result from the measurement has provided us a verification of the generation of an X-point followed by magnetic reconnection due to the $\boldsymbol{J}\times\boldsymbol{B}$ plasma flow from the gun. The closed poloidal flux increases proportionally with the toroidal plasma current as increasing the injection voltage across the inner and outer gun electrodes. We also has found that MHD stabilities of the formed magnetic configurations depends on an amplitude of the injector (gun) bias flux. The lower bias flux increases the edge current density larger after the flux closure, causing the kink instability of the open field line which was already observed in the steady-state CHI current derive.

2. Experimental set-up

The HIST device can form and sustain the high and low-q ST plasmas by utilizing the variation of the external toroidal field (TF) coil current I_{tf}=0~125 kAturns. Figure 1 shows the schematic diagram of the HIST device and main diagnostics. The detail explanation of the HIST is represented in the reference [5]. The start-up discharge bank (V_{max}=10 kV, C=2.6 mF) are used to breakdown the gas injected between the coaxial electrodes.

The HIST device has surface poloidal pick-up coils to calculate plasma currents, electrostatic double probes, Ion Doppler Spectrometer (IDS) and so on. A six-channel λ probe incorporating small size Rogowski and flux loops is used to measure toroidal current density J_t and toroidal flux profiles on the flux conserver (FC) midplane. To measure time evolutions of poloidal flux Ψ_p contours, we inserted 2D magnetic pick-up coil arrays on the poloidal cross section as shown by Fig.1. This 2D flux plots data provide us the maximum value of the poloidal flux. We can measure the radial profile of the electron temperature and the density by using the electrostatic probe with voltage sweeping.

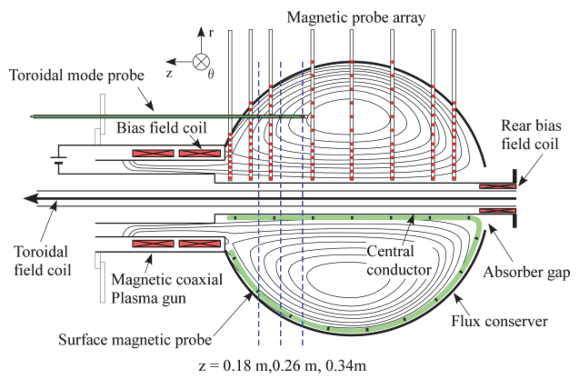

FIG.1. Schematic diagram of the HIST device and diagnostics. 2D magnetic pick up coils location for measurements of poloidal magnetic flux Ψ_p contours.

3. Experimental results and summary

The gun capacitor bank was sized so as to be able to provide the energy needed for gas breakdown of all the injected gas and heating to meet and exceed the inductive stored energy in the resulting plasma discharge and capable of providing adequate current to exceed the bubble burst current requirement. Figure 2 shows time evolutions of the toroidal current I_t, the closed poloidal flux Ψ_p, the gun current I_{gun} and the gun voltage V_g in the high and low gun bias operations. The $\Psi_{p.closed}$ is calculated by the flux contours measurement. The bias flux is about 1.6 mWb for the low

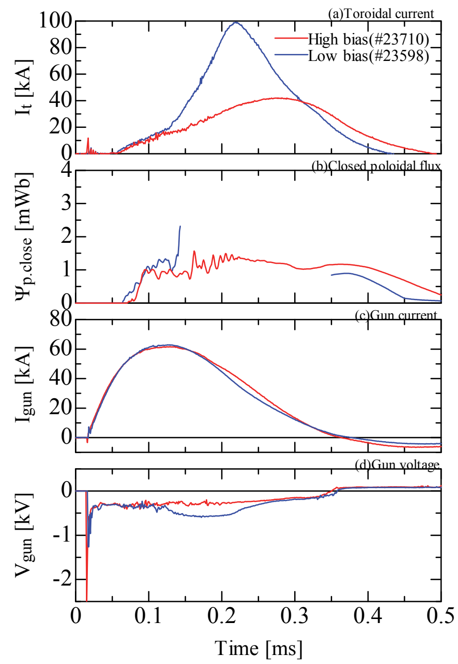

FIG.2. Time evolutions of the toroidal current I_t, the closed poloidal flux $\Psi_{p.closed}$, the gun current I_{gun} and the gun voltage V_{gun}.

bias flux. The toroidal current peaks at t=0.25-0.3 ms and then decays due to the resistivity. The total poloidal flux is amplified over the bias flux. The gun current I_{inj} injected effectively into the FC region is less than about 10% of the measured gun current I_{gun}, because the gun current dissipates almost in the gun electrode region. The toroidal current in the low bias case is two times larger than that in the high bias case, but for the former case, the plasma becomes unstable and ordered closed flux surfaces disappear after t=0.14 ms.

Figure 3 (a) (b) shows the time evolution of poloidal flux contours in the both high and low bias cases during the current start-up phase. The plasmoid is ejected from the gun muzzle, after then the magnetic reconnection occurs to create the X-point. We can see in the figure that the closed flux region is surrounded by the open field lines intersecting with electrodes. The plasmoid ejected from the gun has not reached to the bottom of the FC until t=0.1 ms. The ratio of the closed flux to the total flux is about 40 %. After reaching the bottom of the FC, the plot of poloidal flux contours at t=0.165 ms are distorted in the low bias case as shown by Fig.3 (b). This means that the assumption of axi-symmetry in calculating the poloidal flux from a measured B_z component is not valid at this time. However, this unstable configuration interestingly recovers to the original axi-symmetric state when the plasma starts to decay. During this plasmoid injection phase, the toroidal current density j_t profile is peaked around the magnetic axis (R=0.3 m). After the plasma reaches the bottom of the FC, the j_t profile becomes hollow rapidly because the gun current injected continuously tends to flow along the inner and outer edge open field lines. The higher toroidal current seen in the low bias case is attributed to the injection current flowing in the edge region. During the decay phase, the inner edge current diffuses toward the magnetic axis.

We have measured the toroidal n-mode using 8 pick-up coils located in the

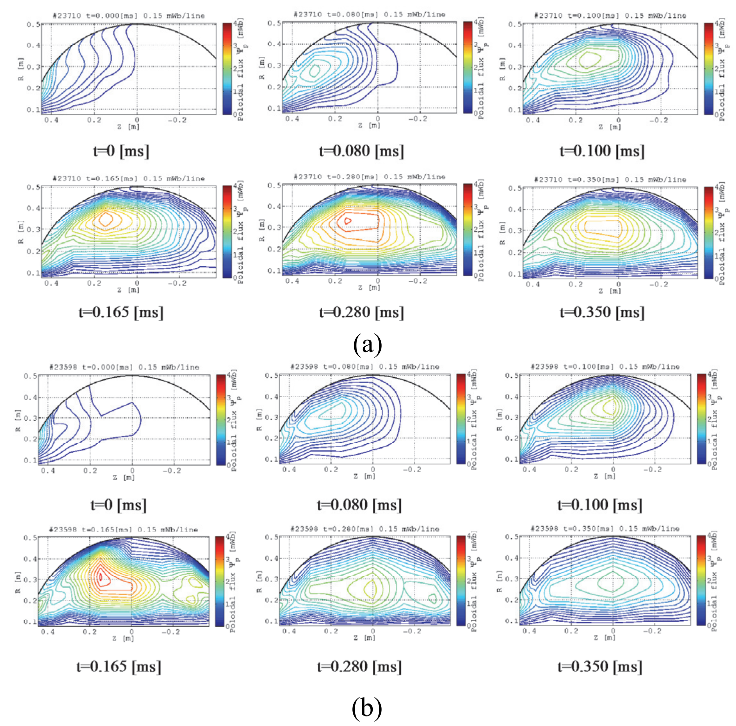

FIG. 3(a)(b) Comparison of poloidal flux contour plots between high bias (a) and low bias (b) operations

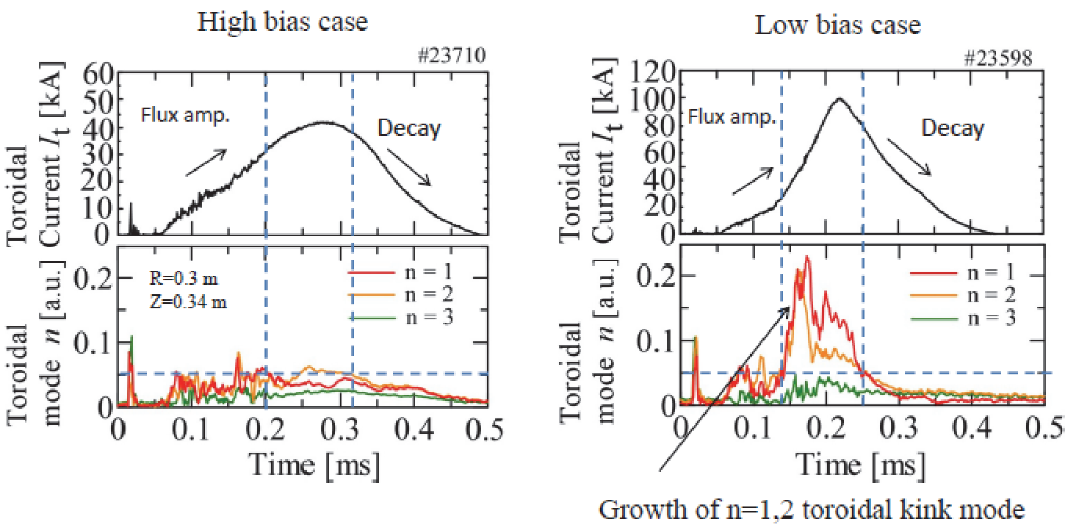

FIG. 4. Comparison of toroidal mode n between high and low bias cases

toroidal direction. Figure 4 shows the comparison of the *n*-mode between high and low bias cases. The time evolution of the *n*-mode for the case of lower bias shows the rapid growth of the *n*=1 and 2 modes at *t*=0.14 ms corresponding to the distortion time of the flux contours. The result indicates an occurrence of the kink instability due to an excess injection current at the edge. When the configuration relaxes to the original state around *t*=0.25 ms, correspondingly the amplitude of these modes decreases below the critical level of triggering the kink mode.

We have verified the formation of the closed flux (flux closure) in the T- CHI start-up by measuring internal magnetic fields. The excess current injected at the edge after the formation causes the kink instability leading to destroy of the axisymmetric configuration. To avoid this phenomenon, it is important to shorten a pulse length of the injector current and drop to zero level just after the magnetic configuration is formed.

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