Observation of Sheet Structure During Coaxial Helicity Injection in the QUEST Spherical Tokamak

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(Received 22 April 2025 / Accepted 5 July 2025)

A sheet structure has been observed in a coaxial helicity injection experiment conducted on the spherical tokamak QUEST. After a bubble burst, a high-speed visible camera captured a formation of the sheet in the region between the main plasma and the ring electrode. Subsequently, the sheet faded out, resulting in the formation of closed flux surfaces.

Keywords: spherical tokamak, coaxial helicity injection, magnetic measurement, high-speed camera, magnetic reconnection, QUEST

DOI: 10.1585/pfr.20.1202045

Transient coaxial helicity injection (CHI) is a powerful non-inductive methods of plasma current I_p start-up [1, 2]. CHI applies a transient high-voltage pulse between centered coaxial electrodes to generate a discharge, initiating the tokamak configuration. In the spherical tokamak (ST) QUEST, CHI uses a coaxial ring electrode insulated from the central post (CP) [3]. Figure 1 illustrates the plasma flux surfaces generated by CHI. The discharge current between the electrodes, namely the injection current I_{inj}, is generated following these processes: (i) the fuel plenums are filled with Hydrogen gas; (ii) the 3 × 1 mF capacitor bank is charged (up to 3.3 kV); (iii) the gas is injected from the plenums into the space between CP and ring electrode; (iv) the capacitor voltage is applied to the ring electrode. If I_{inj} exceeds the threshold for the bubble burst condition, plasma is injected toward the top of the vacuum vessel [4]. The plasma then expands like a bubble, forming open flux surfaces as shown in Fig. 1(a). If the separation of oppositely directed magnetic field lines (in the reconnection region) is sufficiently small, magnetic reconnection occurs. The magnetic field lines are disconnected from the electrodes, thereby forming closed flux surfaces as shown in Fig. 1(b).

Simulation study have reported the formation of sheet-like current structures at Sweet-Parker type magnetic reconnection after CHI [5, 6]. High current flows in the toroidal direction on the sheet. Sheet structure appears before the formation of closed magnetic surfaces with the CHI on STs. In the CHI experiments on HIST, such sheet structures were

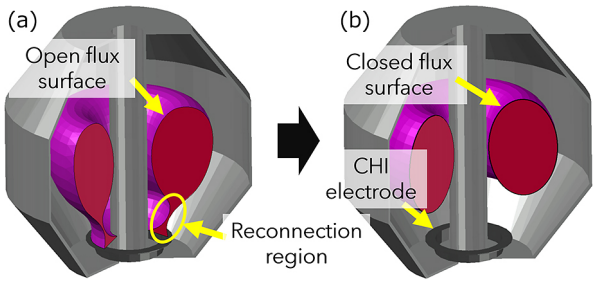

Fig. 1. Closed flux surface formation during CHI on QUEST. (a) Plasma with open flux surfaces (I_{inj} > 0 kA). (b) Plasma with closed flux surfaces (I_{inj} = 0 kA).

reconstructed from magnetic measurements [7]. On QUEST, sheet emission structures were captured using a high-speed visible camera (Photoron, Nova S6) at 24,000 fps (frame interval 41.7 μs), as shown in Fig. 2. These images recorded formation of the sheet structure with open flux surfaces around the reconnection region, and its disappearance before closed flux surfaces formed.

A sheet emission structure is observed above the ring electrode at 0.442 ms, as shown Fig. 2(b'). The sheet length estimated from the images ranges from 100 to 300 mm, varying with each discharge. Since the images show the structure on both sides of the CP, it is presumed axisymmetric. Waveforms of the currents for this discharge are presented in Fig. 3(a). The toroidal current remains above I_p = 80 kA even after I_{inj} = 0 kA, indicating that this discharge generated closed flux surfaces. The plasma had an electron temperature of a few eV, and electron density $n_e \sim 10^{19} - 10^{20}$ m^{-3}.

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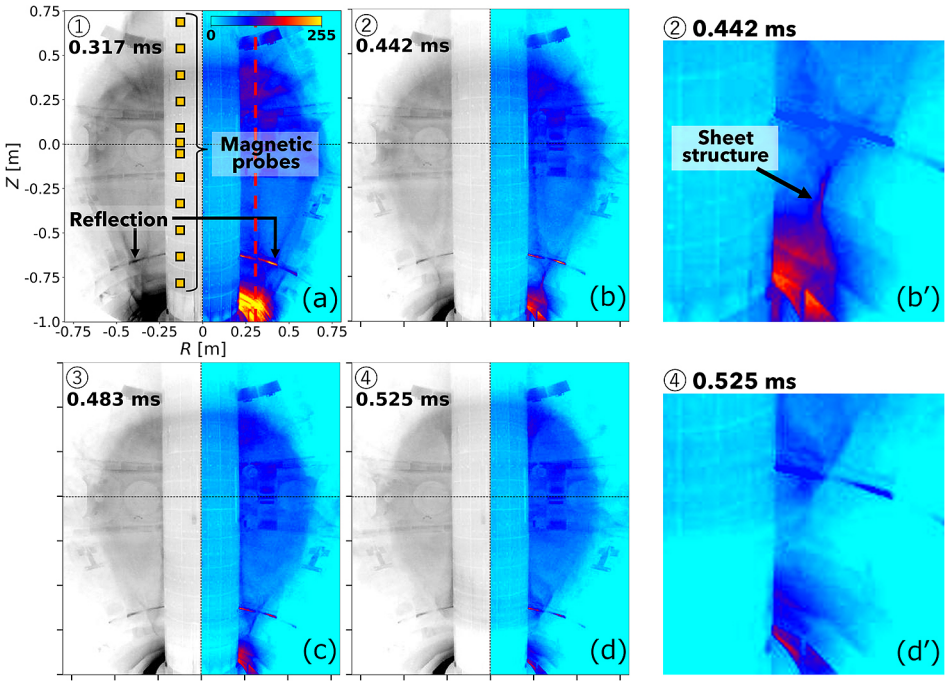

Fig. 2. (a)–(d) High-speed camera images at the indicated times during the CHI experiment. The gray scale image on the left is the original and the color image on the right is processed to enhance feature visibility. In image (a), the yellow marks indicate the positions of the magnetic probes. (b') and (d') are expanded images near the ring electrode.

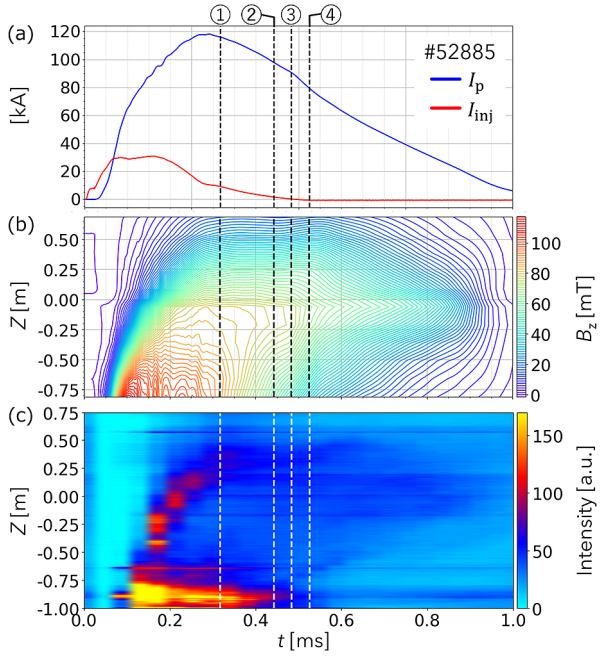

Fig. 3. (a) Variation of currents during the CHI experiment. Blue and red lines represent I_p and I_{inj} respectively. (b) Contour plot of B_z obtained by interpolating the magnetic probe measurements. The black dashed lines correspond to the timings of images in Fig. 2. (c) Time evolution of the vertical profile of the emission intensity at R = 0.28 m (the red dashed line in Fig. 2(a)). The afterglow near the electrode is likely due to residual gas. This discharge was generated with hydrogen gas at 0.5 MPa and the capacitor bank charged to 2.5 kV.

A probe array was used to measure the profile of vertical magnetic field B_z during the closed flux surface formation process. The array consisted of 12 magnetic coils, covered by stainless steel (SS316) tiles, installed on the CP. The positions of the probes are shown in Fig. 2(a). A contour plot generated from these signals is shown in Fig. 3(b). After the breakdown, the peak of B_z evolves along +z-direction from the bottom to the equatorial part of the device. This provides an interpretation of the closed magnetic surface formation process, corresponding to the camera images. During the period that I_{inj} > 5 kA, the plasma sheet is connected to the ring electrode, as seen in Figs. 2(a) and (b). At t = 0.483 ms, the sheet structure begins to separate vertically and forms an X-point, while B_z in the lower part decreases. A closed flux surface is formed at t = 0.525 ms, as shown in Figs. 2(d) and (d'). Subsequently, the B_z profile becomes symmetric along the z-direction and the values decay with I_p. In addition, the high B_z can be observed near the electrode before the formation of the closed magnetic surface at t = 0.525 ms. It indicates that a locally high toroidal current is generated. Fig. 3(c) shows the time evolution of the emission intensity profile obtained from the camera images. It shows that plasma evolves from the bottom to the top, and its front is bright. From beginning of the discharge, strong emission is observed near the electrode. However, such emission is clearly suppressed after the closed flux surface is configured. The sheet is recognizable only right before the reconnection, but it may have been generated from the beginning of discharge.

This paper reports observations of sheet structures in CHI plasmas after bubble burst, including the first observation using a high-speed camera. Future experiments are planned

to gain further understanding of the sheet structure formation process. Ion temperature may be high in the sheet through the reconnection events. To measure ion temperature and plasma flow by Doppler spectroscopy, high speed spectroscope measurements focused on the sheet structure are in preparation. The magnetic probe array currently measures only down to $z = -813$ mm. The downward extension of the array is planned for further understanding. An internal probe would be a powerful tool to measure the sheet directly, provided it does not significantly perturb the formation of closed flux surfaces. The generation of multiple magnetic islands or plasmoids from the sheet structure has also been reported [6, 8], making this a worthwhile subject in CHI plasma studies.

This work was supported in part by the U.S. Department of Energy under Grant DE-SC0019415, the NIFS Collaboration Research Programs (NIFS23KUTR178, NIFS22KUTR167). The experiment was conducted with the support of Kyoto Fusioneering Ltd.

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