Initial Results from High-Field-Side Transient CHI Start-Up on QUEST*)

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Transient coaxial helicity injection (t-CHI) current start-up using a new design simple electrode configuration has been implemented on the QUEST. Discharges injected from the low field side (LFS) and from the high field side (HFS) were examined. Compared to the LFS injection case, the HFS injection has the advantages of providing access to a higher toroidal field and better controlling the location of the injector flux footprint location. Although the present PF coils on QUEST are not well positioned to form the injector flux on the HFS injector region and there has been a frequent occurrence of the spurious arcs, known as absorber arcs, HFS injection has shown flux evolution in a shape that is suitable for the formation of closed flux surfaces. The discharges were improved by installing an in-vessel-coil and adding a new cylindrical electrode to the existing CHI electrode. The results show that the new cylindrical electrode allowed the flux to evolve stably while allowing both the inner and the outer injector flux footprint to remain in the vicinity of the cylindrical electrode. This configuration which inherently generates a narrow injector flux footprint width resulted in discharges that strongly suggested the persistence of the CHI generated plasma after the injector current was reduced to zero. These studies have informed us of the need to improve the CHI gas injection system so that the absorber arcs could be better controlled in the HFS injection configuration.

Keywords: CHI, non-inductive current drive, spherical tokamak, magnetic reconnection, ECH

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1. Introduction

Transient coaxial helicity injection (t-CHI) current drive has been developed on HIT-II experiment at the University of Washington [1] and in NSTX at the Princeton Plasma Physics Laboratory [2] as a non-inductive current start-up method for a low aspect ratio spherical (ST) tokamak device. The advantages of lower construction cost and higher plasma beta are expected in future nuclear fusion reactors based on the ST configuration. In a t-CHI discharge, the toroidal current is generated by the injector current flowing along magnetic field lines that connect electrically insulated electrodes. Electromagnetic forces cause these field lines, initially localized to the injector region, to expand into the vessel and then reconnect in the injector region, producing closed flux surfaces. Results on HIT-II and NSTX show that the subsequent inductive current drive efficiency is improved if some current is initially generated by t-CHI [1, 2]. We have implemented t-CHI current start-up on QUEST [3] using a new design simple electrode configuration [4]. As shown in Fig. 1 (a), in the QUEST electrode configuration, a bias electrode is mounted on top of the lower divertor (endplate), and this is biased as a cathode against the vacuum vessel wall, which acts as an anode. The bias electrode is insulated by a ceramic break sandwiched between the bias electrode and lower divertor. In the conventional electrode configuration used in HIT-II and NSTX, the entire inner and outer vacuum vessel walls

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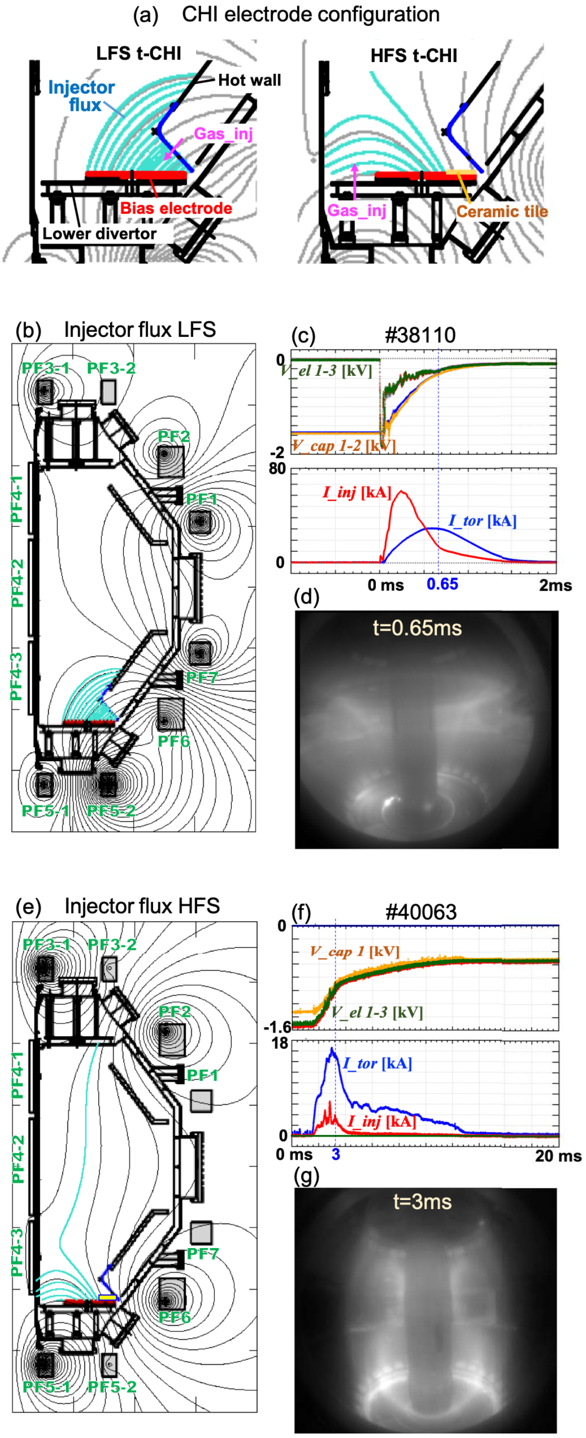

Fig. 1 Results of t-CHI discharge injected from LFS and HFS. (a) Configuration of CHI electrode, (b) (e) injector flux configuration, (c) (f) wave forms of two capacitor voltage, *V_cap 1-2*, electrode voltage at three toroidal locations, *V_el 1-3*, injector current, *I_inj*, toroidal current, *I_tor*, (d) (g) camera image of evolving discharge.

are used as the cathode and the anode; these are insulated by ceramic breaks inserted into the top and bottom parts of the vacuum vessel wall itself. The t-CHI research on QUEST aims to develop a reactor relevant [5] electrode configuration in which the insulator needed to separate the divertor plates electrically need not be part of the external vacuum structure, as on NSTX and HIT-II. Also, QUEST is well-positioned to study the heating and steady-state current drive of a CHI generated plasma using ECH [6, 7].

2. Results of t-CHI from LFS and HFS

We examined cases of t-CHI discharges injected from low field side (LFS) and high field side (HFS) to investigate which configuration is more suitable for forming closed flux surfaces on QUEST CHI operation. Figure 1 shows the results of typical t-CHI discharges from the LFS and HFS injection cases.

LFS case: The injector flux, (b) is formed in the LFS case using the injector flux to connect the bias electrode to the outer vessel wall (lower hot wall). The waveform (c) shows the discharge initiation due to the application of high voltage on the bias electrode. As the voltage across the electrode drops (due to the generation of a conducting plasma), about 58 kA of injector current flowing along injector flux field lines is generated. The injector flux evolves due to the injector current, as shown in the camera image, (d), in which the toroidal current is increased up to about 36 kA.

HFS case: The injector flux, (e) is formed in the HFS region by connecting the injector flux between the bias electrode and inner vessel wall (center stack). As shown in (a), in this configuration, ceramic tiles cover the outer portion of the bias electrode to prevent discharge initiation between the electrode and the outer wall. In CHI terminology, the region opposite to the injector region is known as the absorber region. The discharge evolution process is similar to that for the LFS case, but as seen in frame (g), the discharge is now much more localized inside the vessel. The results of the discharge from HFS show some advantages and some disadvantages compared to those from LFS. While the current multiplication ratio of the toroidal current to the injector (during the current decay phase) is about 1-2 for the discharge from the LFS, the ratio is improved and close to 5 for the discharge from the HFS, as shown in the waveform, (f). The substantial reduction of the injector current results in about ten times longer pulse duration than the discharge from LFS. The camera image, (g) shows that the flux evolves in a shape that is beneficial for forming closed flux surfaces. One of the weakest points for the discharge initiation from the HFS is the difficulty of forming a suitable injector flux using the existing PF coil set on QUEST. Because the PF5-1 coil is far away from the injector region, a relatively high coil current is required, and the resulting flux footprint is also widespread and beyond the main injector region.

Comparison of the two cases: In comparison, absorber arcs were well controlled for the LFS injection case. The injector flux for the LFS case evolves well, but the outer flux footprint that connects to the outer vessel wall continues to move away from the inner flux footprint location as the

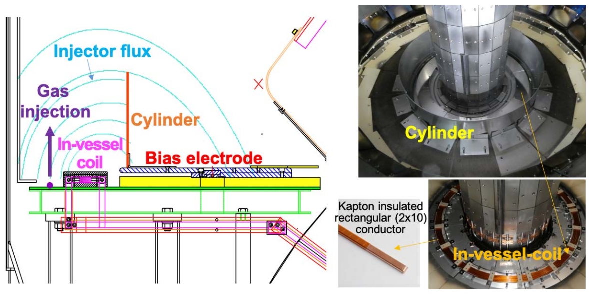

Fig. 2 Modification of t-CHI system. Temporarily installed in-vessel-coil and cylinder attached to the bias electrode.

injected flux expands into the vessel. This results in the discharge developing a very wide flux footprint width configuration that is not favorable for inducing reconnection in the injector region.

When the injector flux is formed in the HFS region, the inner flux leg connecting to the inner vessel wall will be fixed during the flux evolution because the flux leg is held by the higher density flux on the HFS region. On the other hand, because the outer flux footprint is not well controlled, it is easy for the expanding outer flux to connect to the outer vessel wall, resulting in alternate current paths along the vessel wall, as shown in the camera image (g).

The gas injection location is also different for the two cases, as shown in (a). The initiation of the discharge from LFS was easier than that of the discharge from HFS because the gas injection nozzle installed on the hot wall was designed to initiate the discharge by directing the gas plume onto the electrode surface. Here easier discharge initiation means that when voltage is applied to the electrodes, the injected gas promptly breaks down in the injector region, and current starts to flow along the desired path, which is along the injector flux. For this to be possible, it is necessary to satisfy the Paschen conditions primarily in the injector region. This is described in figure 6 in ref [4], the relevant points we briefly summarize here. For the LFS, as the gas was injected from the ground electrode to the high-voltage electrode, it was easier for sufficient gas molecules to be quickly deposited in the injector region and allow a discharge to occur along the magnetic field lines connecting these electrodes. The discharge in the injector took place before the injected gas had time to spread to other locations.

In comparison, for the HFS, there was no direct gas injection from the ground electrode to the high voltage electrode. The gas was directed up into the vessel (right in Fig. 1 (a) and also Fig. 2 described later) and towards the center stack, which was at the same potential as the gas injection region. Consequently, the gas had to spread around before a sufficient gas pressure developed in the injector region. Simultaneously, the gas had also migrated to other areas outside the injector region, where the presence of much longer magnetic field line length allowed the Paschen condition to be satisfied at much lower gas pressure, which allowed the discharge to start in these undesirable locations also. This system was installed to provide some gas injection capability for HFS cases. Experimental schedules did not permit time for a more suitable system to be installed for this campaign. Consequently, a large amount of gas was injected to attain breakdown, which also resulted in some of the injected gas leaking to the absorber region and resulting in the formation of undesirable absorber arcs as noted above.

3. Improvements of t-CHI Discharge from HFS

To better localize the injector flux footprint locations (to induce reconnection in this region), two improvements were made: First, as shown in Fig. 2 a temporary in-vessel-coil was installed to obtain additional results to help with the design of a more permanent coil. This coil is composed of 12 turns wound Kapton insulated copper rectangular conductor. Second, a steel cylindrical electrode was attached to the bias electrode so that the outer leg of the injector flux is limited to the radius of this cylinder.

Figure 3 shows improved results due to these modifications. The injector flux in CHI discharges is generated by driving current in the poloidal field coil that is positioned near the injector location. Shot #42640 is a discharge when the injector flux magnitude is low, in which about 3 mWb injector flux is formed by 0.5 kA of in-vessel-coil current and 1.0 kA of PF5-1 coil current. The in-vessel coil and the PF 5-1 coils are used to generate the injector flux. At the t = 37.1 ms, the discharge is initiated outside the cylinder, and an absorber arc also arises. This is because some injector flux that extends above the height of the steel cylinder connects to the absorber region, and as previously noted, the unoptimized gas injection system provides the needed gas to initiate these absorber arcs.

However, the discharge then transitions to the inside of the cylinder at t = 37.25 ms, and at t = 37.5 ms the flux evolves above the vessel midplane. After the flux evolution, and after some of this extended flux decays, a detached plasma is seen to persists in the camera image even though the injector current has been reduced to zero at t = 38.75 ms. The camera images are encouraging. They suggest the formation of closed flux plasma because a doughnut-shaped plasma at the vessel mid-plane, apparently not connected to any other part of the vessel, could probably only exist if currents are flowing on closed field lines. But magnetic measurements are also needed to confirm closed flux formation. Unfortunately, the extensive absorber arching, which in some discharges produces a transient negative current signal, does not permit the Rogowski coil to clearly detect the CHI produced toroidal current. The occurrence of the short duration negative toroidal current is not well understood, but it could be due to some of the absorber arc currents flowing on field lines that are not part of the main injector flux and which could have an

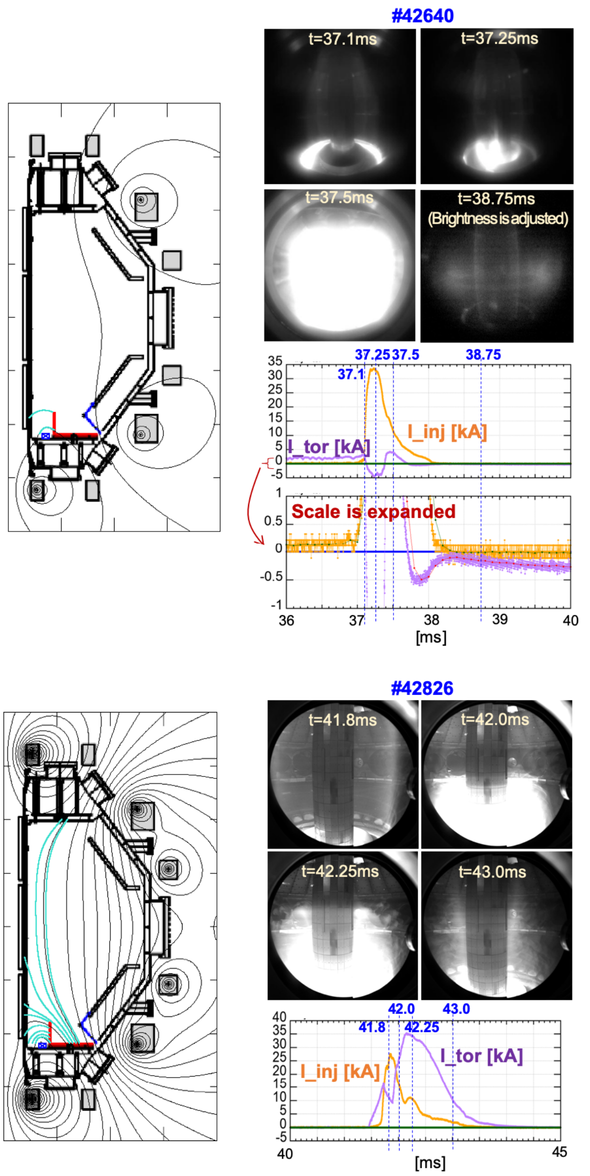

Fig. 3 Results of discharges improved by the modification of t-CHI system.

opposite field line pitch.

The results of a discharge (shot #42826) with a higher injector flux, in which about injector flux is formed by 2.0 kA of in-vessel-coil current and 3.0 kA of PF5-1 coil current, also show that the flux evolves from within the cylindrical electrode region at $t = 42.0$ ms and $t = 42.25$ ms. In this case, the flux evolved only up to the vessel midplane before shrinking without the detachment. However, due to reduced absorber arcing, the toroidal current is better resolved, and it increased to 35 kA, which is the maximum current for discharges from the HFS configuration. The higher injector current at $t = 41.8$ ms may result from the initial current paths connecting to the outer wall before the main discharge initiation inside the cylinder or it could be due to currents initially flowing on field lines that have a short length, and consequently lower resistance.

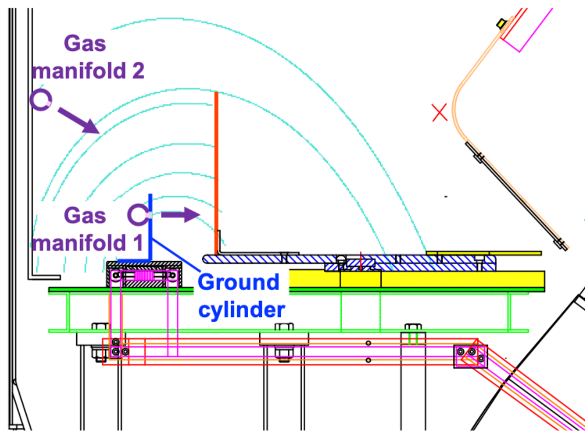

Fig. 4 Design of new gas injection system for the discharge from HFS. The gas is injected uniformlyfrom eight spray nozzles on each gas manifold 1 and 2 towards the bias electrode.

These two modifications have clearly helped improve the t-CHI discharges on QUEST. What is particularly important is that both the inner and outer flux footprints are located in the vicinity of the cylinder, thus maintaining a narrow injector flux footprint configuration. Based on studies on NSTX, the 35 kA toroidal current in shot 42826 suggests that if that plasma were to extend into the vessel fully, the toroidal current would rapidly increase to much higher values. That should result in a persisting plasma, such as in discharge 42640, but with a higher toroidal current.

These results suggest that the primary limitation of these new discharges is the generation of the absorber arcs, which both limits the flux evolution fully into the vessel and corrupts the current measurements due to the presence of strong absorber arcing. The HFS discharges can be improved by modifying the gas injection system to direct the injected gas directly on to the new steel electrode like the LFS injection case. The LFS studies have clearly demonstrated absorber arc-free discharge initiation capability by using a correctly designed gas injection system, as described in ref [4]. As previously noted, there was insufficient time to design and install such a gas injection system for the previous campaign. Figure 4 is a cartoon showing the main elements of the new gas injection system for the HFS experiments. In some ways, this should be superior to the gas injection system used for the LFS case as the plenum operating pressure will be doubled, and gas injection is from eight ports that inject gas uniformly around a gas manifold. Also, two separate gas manifolds are planned to be used to more optimally control the gas conditions in the injector region. These improvements to the gas injection system are now in progress.

4. Summary

Transient coaxial helicity injection (t-CHI) current start-up using a new design simple electrode configuration that is more suitable for reactor implementation, has been tested on QUEST in two different configurations. These are for cases when the CHI electrode is biased with respect to the outer wall (LFS case) or towards the center stack (HFS case). Good plasma evolution and absorber arc control are achieved for the LFS cases. However, as the injected flux expands into the vessel, the injector flux footprint widens, a condition that is not favorable for generating a closed flux plasma configuration.

In the HFS case, the flux evolves while maintaining a narrow injector flux footprint configuration, one that is suitable for the flux in the injector region to reconnect and generate closed flux plasmas. Indeed, one of the discharges shows promising data from a fast camera that indicates the presence of what appears to be a circular plasma in the vessel midplane after the CHI injector current is reduced to zero. However, in the HFS cases, extensive absorber arcing (due to a gas injection system that was not designed for this mode of operation) does not at this time allow us to clearly measure the CHI produced toroidal current. The design of an improved gas injection system is now in progress to better control the absorber arcs in the HFS configurations. It is anticipated that after this hardware improvement, QUEST should be able to generate t-CHI discharges similar to those on NSTX and HIT-II.

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