Current Start-Up Using the New CHI System

Kengoh KURODA, Roger RAMAN[1)], Kazuaki HANADA, Makoto HASEGAWA, Takumi ONCHI, Masayuki ONO[2)], Thomas JABOE[1)], Brian A. NELSON[1)], Masayoshi NAGATA[3)], Osamu MITARAI[4)], Kazuo NAKAMURA, Hiroshi IDEI, John ROGERS[1)], Shoji KAWASAKI, Takahiro NAGATA, Arseniy KUZMIN, Shinichiro KOJIMA, Osamu WATANABE, Aki HIGASHIJIMA, Yuichi TAKASE[5)] and Atsushi FUKUYAMA[6)]

Kyushu University, Kasuga, Fukuoka 816-8580, Japan
[1)]*University of Washington, Seattle, WA 98195, USA*
[2)]*Princeton University, Princeton, NJ 08543, USA*
[3)]*University of Hyogo, Himeji, Hyogo 671-2280, Japan*
[4)]*Institute for Advanced Fusion and Physics Education, Kita-ku, Kumamoto 861-5525, Japan*
[5)]*University of Tokyo, Kashiwa, Chiba 277-8561, Japan*
[6)]*Kyoto University, Kyoto 606-8502, Japan*

(Received 2 March 2017 / Accepted 24 March 2017)

Coaxial Helicity Injection (CHI) has now been implemented in QUEST. The goals for the first transient CHI experiments were to establish reliable gas breakdown conditions, and to measure CHI-produced toroidal current generation. Both these objectives were successfully met. Toroidal currents up to 29 kA were measured. Interestingly, these first plasmas on QUEST also suggest the formation of small amounts of closed magnetic flux surfaces.

Keywords: non-inductive current drive, CHI, spherical tokamak, solenoid free fusion plant, ECH

DOI: 10.1585/pfr.12.1202020

Establishment of methods for solenoid-free plasma current start-up, with robust and stable non-inductive current drive on tokamaks increases the prospects for a compact and low aspect ratio fusion reactor, which has the advantages of lower construction cost and higher plasma beta. QUEST is a mid-size spherical tokamak (ST) device [1], in which plasmas are produced mainly by electron cyclotron heating (ECH), and with minimal use of the central solenoid. Non-inductive toroidal plasma currents up to 70 kA have been achieved on QUEST using 28 GHz microwave injection [2]. We have now implemented coaxial helicity injection (CHI) capability on QUEST. We aim to generate more than 100 kA of initial toroidal plasma current with transient CHI and ramp this seed current non-inductively using the high-power 28 GHz microwave system. In this paper we report results from the first CHI experiments on QUEST.

CHI [3], a useful method for non-inductive current drive, has been studied in the HIT-II and NSTX STs, in which the compatibility of CHI startup with conventional Ohmic heating and current drive has been verified [4, 5]. It is projected that the capability of CHI for current startup would be significantly enhanced if ECH is used to heat the CHI plasma, and this is planned to be tested in NSTX-U for a full non-inductive current start-up and ramp-up scenario [6].

author's e-mail: kuroda@triam.kyushu-u.ac.jp

QUEST is equipped with important capabilities that will extend CHI studies to new parameter regimes. The internal vessel walls on QUEST are all metallic; this should be beneficial to CHI as it would reduce the influx of low-Z impurities in to the plasma, which are the prime source of energy loss in low temperature plasmas. The CHI electrode configuration on QUEST is also simpler, and different than the ones on HIT-II and NSTX, and it may be easier to implement this configuration in a fusion reactor [7]. The primary difference is that on NSTX and HIT-II, the insulator is also the vacuum boundary, whereas on QUEST, the insulator is sandwiched between the electrode plate and the divertor plate. However, CHI start-up in this new electrode configuration needs to be demonstrated. This is an important part of the CHI program on QUEST.

Figure 1 shows the side view of the QUEST internal structure. The nominal toroidal field at the machine axis (at $R_0 = 0.64$ m) is 0.25 T at its maximum limit. There are four poloidal field coils above and below the vessel mid-plane; these are normally operated in a series configuration, with two coils connected to a single power supply. As shown in Fig. 1, we installed an electrically insulated bias-electrode on the lower end-plate, and a corresponding ground-electrode is attached to the hot wall. These toroidally continuous structures are the CHI electrodes. The ground-electrode has provisions for two CHI gas injectors at two toroidally displaced locations.

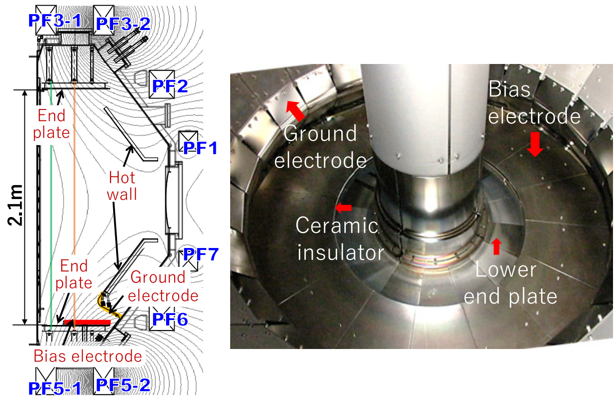

Fig. 1 QUEST internal structure and picture showing hot wall, end-plates and CHI electrodes. Gray contours indicate typical magnetic flux surface formed by poloidal field coils, PF1-PF7. Orange and green lines show a fundamental harmonic ECR layer of 8.2 GHz and a second harmonic ECR layer of 28 GHz microwaves, respectively.

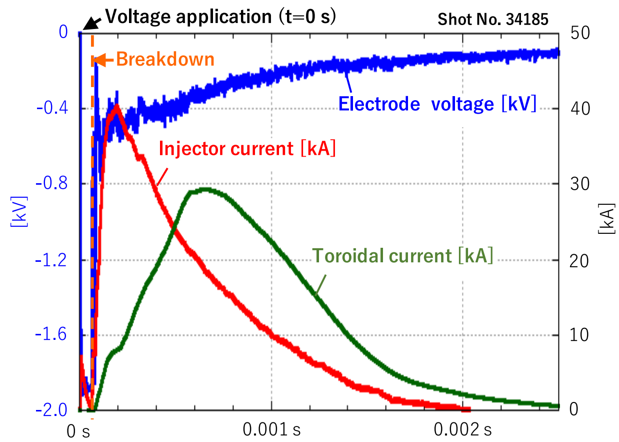

Fig. 2 Shown are the measurements from fast voltage monitors across the electrodes, the CHI injector current and toroidal current.

A CHI discharge sequence on QUEST involves the following steps: 1) Toroidal field at $B_{t0} = 0.25$ T is applied and then the injector flux configuration is formed by driving current in four pairs of poloidal field coils. The injector flux connects the bias and ground electrodes as shown in Fig. 1. 2) The CHI gas valves inject H_2 gas in the injector region between the two electrodes. 3) At the time when gas pressure in the injector region reaches a high value (about 10 ms after the valves are opened), about −1.8 kV of voltage is applied to the bias-electrode using a capacitor bank power supply. This causes the injected gas to ionize and the resulting injector current along the injector flux generates the CHI plasma.

In the first CHI experiments conducted on QUEST we investigated the conditions needed to attain gas breakdown. For attaining reliable breakdown we had to use 20 to 30 kW of 8.2 GHz ECH for pre-ionization before step 2. For the magnetic configuration shown in Fig. 1, it was found that breakdown could be reliably obtained when the current in PF5-2 coil below the electrode, which is the main CHI injector coil, was below 40% of its maximum current allowance rating. The breakdown became unstable when the PF5-2 coil current was higher than this value. This was attributed to the need for an adequate magnetic field line connection length between the cathode bias-electrode and the anode ground-electrode to satisfy the Paschen condition for breakdown. Future experiments will expand the breakdown conditions to higher levels of injector flux by improving the gas injection system to allow it to transiently increase the gas pressure in the injector region while simultaneously reducing the amount of injected gas.

Figure 2 shows that the voltage across the electrodes rapidly drops at the time of breakdown. This is the first indicator of the electrode being electrically connected to the vessel through conductive plasma. The first millisecond shows the injector current to increase, and with it the toroidal current also increases and reaches a peak value of 29 kA. The toroidal current continues to increase as the injector current decays in time. In some of these discharges, the toroidal current is present even after the injector current has been reduced to zero. These are indications of the presence of a closed flux plasma decaying in time, after the externally driven injector current, which flows on open field lines, is reduced to zero. This observation, combined with other observations from a slow mid-plane camera (not shown here), which shows a bright region moving from the lower end-plate to the upper end-plate, indicates that the CHI plasma must be disconnecting from the injector flux in the lower end-plate and drifting up. Such plasmas must carry closed field line currents, as they are no longer connected to the injector flux [8]. In these first experiments, because the PF3-2 and PF5-2 coils are driven in pairs, the PF3-2 coil above the upper end-plate is in a polarity so as to attract the CHI plasma. In future experiments, the upper coil will be driven with the current opposite to the CHI-produced toroidal current so as to trap the CHI plasma at the vessel mid-plane and to provide plasma equilibrium control. Images from a downward looking fast camera on the upper part of the vessel (not shown here) show the visible emission to be most spread out at the time of peak toroidal current. Better resolution is needed from the mid-plane camera to correlate it with the observations from the upper camera; this will be studied in future experiments.

In summary, these first results obtained from the newly installed transient CHI system on QUEST are very encouraging for future CHI studies on QUEST. Reliable gas breakdown, an essential first step, has been successfully demonstrated in a new CHI electrode configuration. The generation of toroidal current has also been successfully measured. These first plasmas carry up to 29 kA of toroidal current. The data also suggests that some of this current must be flowing on closed field lines. Future experiments will aim to increase the toroidal current and to control the equilibrium of the CHI plasma, followed by initial test of heating the CHI plasma with 28 GHz ECH.

This work is supported by US DOE grants DE-FG02-99ER54519 and DE-AC02-09CH11466, NIFS bilateral collaboration project NIFS14KUTR103 and RIAM international collaboration frame work No.9.

[1] K. Hanada *et al.*, Plasma. Fusion. Res. **5**, S1007 (2010).

[2] H. Idei *et al.*, Proc. 26th IAEA Fusion Energy Conference (2016) EX/P4-50.

[3] T.R. Jarboe, Fusion Sci. Technol. **15**, 7 (1989).

[4] R. Raman *et al.*, Phys. Plasmas **11**, 2565 (2004).

[5] R. Raman *et al.*, Phys. Plasmas **18**, 092504 (2011).

[6] R. Raman *et al.*, Nucl. Fusion **53**, 073017 (2013).

[7] R. Raman *et al.*, Fusion Sci. Technol. **68**, 674 (2015).

[8] F. Ebrahimi and R. Raman, Phys. Rev. Lett. **114**, 205003 (2015).