Development of curved drift tubes for the vertical CT injection

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1. Introduction

Spheromak-type compact toroid (CT) injection method is an advanced technology for refueling in future fusion reactor [1]. The non-disruptive central refueling had been demonstrated for the first time in the TdeV tokamak [2]. Recent CT injection has been studied not only for refueling but also for the plasma control including H-mode triggering [3,4]. The other experiments, however, also indicate adverse effects of the toroidal magnetic field on CT injection [5]. CT injection has so far been tested with horizontal injection which is subject to a force due to the gradient in the magnetic pressure along the path. In the JFT-2M tokamak, CT has been injected horizonatally in the midplane as shown in Fig. 1 [6-9]. In this case, CTs were transported from CT source through a linear drift tube. When a CT is injected horizontally from the low field side, it is decelerated by the gradient in the toroidal field. If a CT is injected vertically from a port at the bottom of the tokamak as the vertical arrow in fig. 1, CT may enter the tokamak core region with less resistance since the magnetic gradient is absent.

Recently, Suzuki et al. reported the theoretical investigation of vertical CT injection in non-slipping sphere model [10]. When a CT with a speed of 300 km/s is injected into a device region applied a toroidal field of 0.8 T, in the cases of horizontal CT injection, the CT penetrates into the region but stops, then bounces back to the drift tube region. Whereas, in the case of the vertical injection, the CT still penetrates. The penetration length of the CT is longer than the horizontal injection case. The vertical CT injection may be more advantageous to CT injection efficiency than the horizontal.

We have proposed installation of a CT injector with a curved drift tube as shown in fig. 2. This installation would provide flexibility of design and arrangement of the CT injection system.
In the case of vertical installation of CT injector

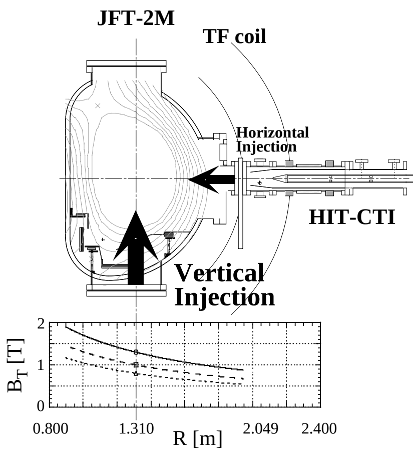

Fig.1 Schematic of HIT-CTI installed on JFT-2M and directions of vertical and

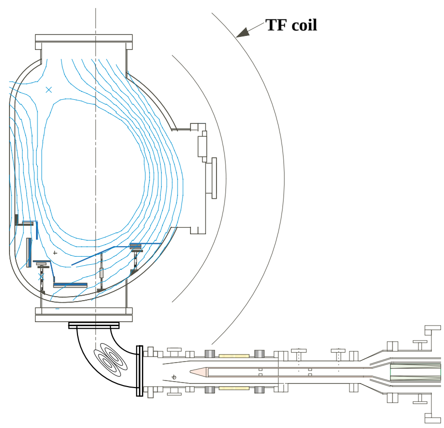

Fig.2 Conceptual drawing of installation of a CT injector on a tokamak for vertical CT injection.

2. Experimental setup

Preliminary experiments to demonstrate CT propagation in curved drift tubes have been performed using the HIT-CTI2 at the Himeji Institute of Technology. The experimental setup of a CT injector with a curved drift tube with a 45º bend (Dashed lines show straight and 90º bend.) is shown in Fig. 3. The CT injector is a magnetized coaxial plasma gun which consists of one-stage coaxial electrode system for CT formation and acceleration. The CT injector was connected to a large vacuum chamber with a liner tube and two types of curved drift tube with inner radius r = 66.9 mm. These curved drift tubes had a common curvature radius of R = 190 mm. CTs were injected into the chamber passing these drift tubes.

The power supply for the injector was a bank of 1 mF, 6.5kV capacitors with a total energy storage capacity of 21 kJ. The peak gun current is 60 kA. The bias poloidal field in the injector regions produced by a solenoidal coil which fit over the outside of the injector assembly. Two fast gas puff valves are placed on the both sides of the gun region. These valves provided hydrogen gas between the electrodes.

We mounted magnetic probes at G3 to G6 side ports and magnetic probe arrays at G3 and G6 upper ports for magnetic field measurements and Langmuir double probes at D1 and D2 ports for electron density measurements.

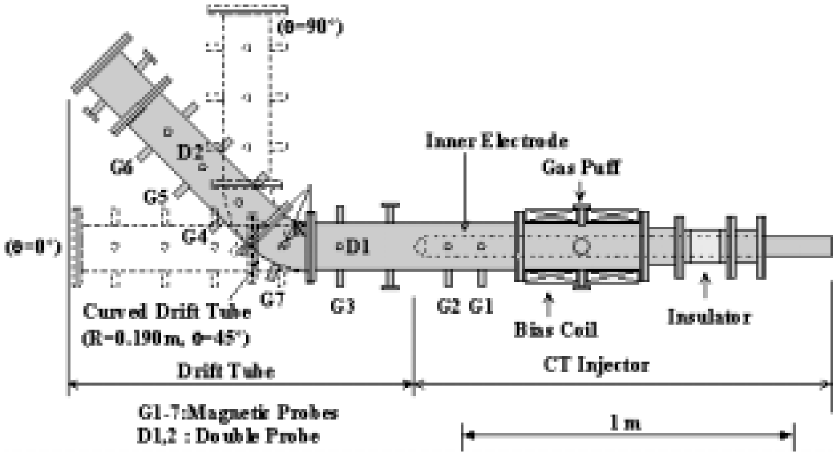

Fig.3 Schematic of a CT injector and a drift tube with 45º bends (dashed line is the case of a liner (0º) and 90º bends).

3. Experimental results

Initially, we measured poloidal and toroidal magnetic fields B_p and B_t, electron density n_e and CT speed v_{CT} transported through the straight drift tube. Same measurements were then made with curved drift tubes with 45º and 90º. Figure 4(a) shows B_p versus the distance from the point G3 in front of the bend entrance, where B_p are normalized by the mean values of B_p measured at G3 in the case of a liner tube. It can be seen that bending in the drift tube does not affect the plasma parameters in an appreciable manner. B_p decreases similarly with the propagation distance with or without bend. The electron density n_e is not affected by bend either as shown in fig. 4(b).

The data points demote the time of passage of CTs based on magnetic probe measurements in fig. 4(c). The speed of CTs estimated from the CT transmission is 37 km/s for liner tube (θ=0°), 41 km/s for 45° bend and 37 km/s for 90° bend, respectively. The deceleration of CT due to the bend of the curved drift tube was not observed.

Figure 5 shows the decay of B_p of CTs in transport with curved drift tubes. The decay depends on the plasma resistivity and the size of the drift tube. The decay time of B_p from the experimental data are: τ_d= 22μs for liner tube, 29μs for 45° bend and 26μs for 90° bend. These values are consistent with an estimate based on Ohmic dissipation $\tau_d = \mu_0/\eta\lambda^2$, where η is the plasma resistivity and λ is the eigenvalue in the force-free Maxwell's equation $\nabla \times \mathbf{B} = \lambda \mathbf{B}$. For linear drift tube, the formula gives τ_d= 24μs, where a = 0.067 m, l = 0.5 m, T_e = 10 eV, $n_e = 1\times10^{21}$ m^{-3}. It appears the CT decay time is not affected by the presence of bend and CT remains intact after passing the bend section.

We observed the magnetic structure in traveling CTs. The profile of B_p and B_t before and after passing the 45° bend are shown in Fig 6. It has been confirmed that a plasmoid at the final location of the G6 port has a typical spheromak configuration and the CT was transported without destruction after passing the bend. The magnetic structure and its integrity appear to be well conserved even in the curved section of the drift tube. Potential detrimental effect due to the curvature centrifugal force in the curved drift tube has not manifested itself in experiments.

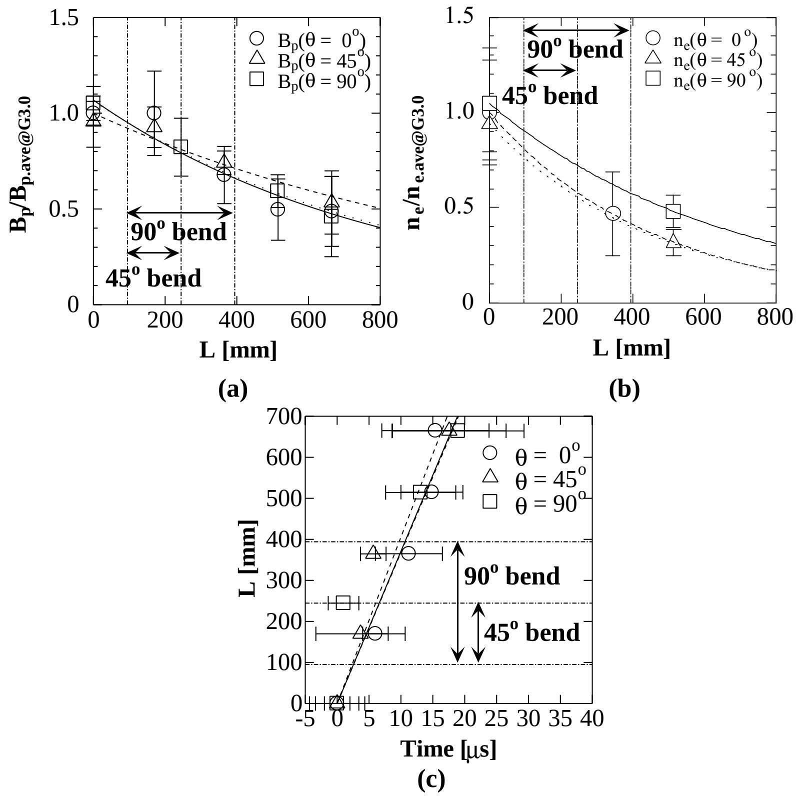

Fig.4 (a) Poloidal field of a traveling CT at each transit point, (b) Electron density of a traveling CT at each transit point, (c) CT transition in a drift tube.

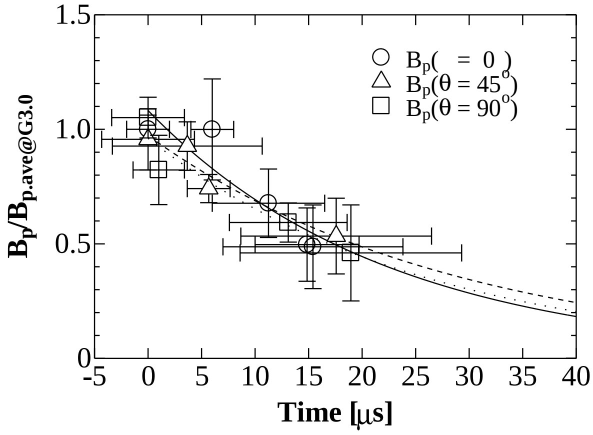

Fig.5 Decay time of poloidal field in traveling CTs.

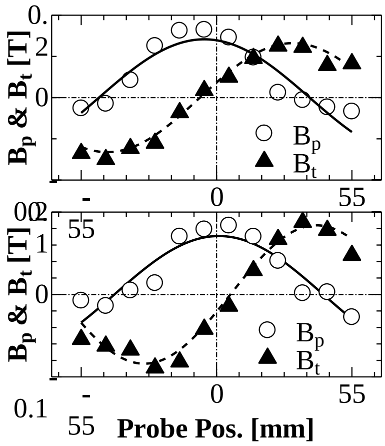

Fig.6 Poloidal and toroidal field profiles of a CT at G3 (L=0mm:before bend passage) and G6 (L=644mm:after bend).

4. Conclusions

CT injection has so far been tested with horizontal injection which is subject to a force due to the gradient in the toroidal magnetic field along the path. Vertical injection eliminates the force and thus may be more advantageous to CT injection efficiency. As preparatory experiments toward vertical injection, we have developed a curved drift tube to change the direction of CT propagation. It has been observed that a CT can be transported smoothly through curved drift tubes with 45º and 90º bends without appreciable change in the CT parameters. Magnetic field, electron density and speed of CTs transported through both 45º and 90º bends are similar to those observed in a linear drift tube. The further studies are required to investigate higher speed CT transport with a curved drift tube.

Reference

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