Vertical Injection of Compact Torus into the STOR-M Tokamak

D. Liu, C. Xiao, A. K. Singh, A. Hirose
Plasma Physics Laboratory, University of Saskatchewan, Saskatoon, Canada

e-mail contact of main author: xiaoc@sask.usask.ca

Abstract. Vertical compact torus injection into the STOR-M tokamak has been conducted with the University of Saskatchewan Compact Torus Injector (USCTI). The injector stayed at the horizontal position and the CT was bent by 90° using a curved conducting drift tube. The curved drift tube did not have significant effects on the CT velocity. Furthermore, the curved drift tube did not change the magnetic field topology. Preliminary vertical CT injection experiments have been carried out on the STOR-M tokamak. CT injection induced prompt increase in the electron density and in the soft x-ray radiation level. Further modifications of the 90 degree bend are underway to improve the CT parameters and to further study the effects of CT injection on the tokamak plasma parameters.

1. Introduction

Since compact torus (CT) injection as a means to centrally fuel a reactor-grade tokamak was proposed more than a decade ago by Parks [1] and Perkins *et al.* [2], active research efforts have been made to validate its feasibility. CT injection experiments have been carried out on several tokamaks in the USA, Canada and Japan. The first disruption-free injection experiment was carried out on TdeV [3] and the first tangential injection experiment was carried out on STOR-M [4]. CT injection experiments have also been conducted on JFT-2M [5]. The common feature of all of these experiments is injecting the CTs from the outer board of the tokamak in the low field side. The CT has to travel against the magnetic field gradient force which dissipates the directional kinetic energy of the CT and eventually stops it and can even cause complete reflection. In order to achieve central fuelling, the following basic requirement has to be met,

$$\frac{1}{2}\rho v^2 > \frac{B^2}{2\mu_0} \tag{1}$$

where r is the CT mass density, v the CT velocity, and B the toroidal magnetic field at the center of the tokamak. The experimental observations and results from numerical simulations based on the conducting sphere [6,7] and non-slipping models [8] approximately agree with the prediction given in eq. (1).

As there is no magnetic field gradient in the vertical direction in a tokamak, it is expected to be more beneficial to inject CTs vertically from the top or bottom of the tokamak. In this case, CTs will still be horizontally pushed outwards by the magnetic field gradient, resulting in a curved trajectory. However, this can be compensated for by shifting the injection location horizontally inward [9]. The non-slipping model also revealed the advantage of vertical injection over horizontal injection [8].

Technically, it is not practical to install CT injectors vertically. Fukumoto *et al.* [10] proposed to use a curved drift tube to bend the CT injection direction by 90 degrees while keeping the injector in the horizontal position. They have also conducted bench tests with a single stage injector and compared results at various bending angles at 0, 45, and 90 degrees. It has been demonstrated that the curved drift tube has no adverse effects on the CT velocity although the magnetic field and electron density decrease in all cases similarly, presumably due to natural decay of the CT. The CT velocity was relatively low at about 40 km/sec.

There are several unresolved questions surrounding the vertical CT injection experiments. Firstly, all the simulations start with a known CT velocity at the boundary of the tokamak. The process in which the CT penetrates the tokamak magnetic field filling part of the tokamak port (drift tube) is not considered in the simulations. This problem [11] remains the same for both horizontal and vertical CT injection configurations. Actually, the magnetic field at the tokamak edge at the top or bottom is stronger than in the outer board of the tokamak. Secondly, larger vertical ports on the top or bottom of a tokamak are scarce compared with the horizontal ports due to limitations imposed by the toroidal field coils. Finally, the bending drift tube experiments by Fukumoto *et al.* need to be conducted with higher CT velocities and different sizes of drift tubes.

In this paper, we present the results of bending drift tube experiments for initial CT velocities up to 200 km/sec. Preliminary results on the effects of vertical CT injection on the STOR-M tokamak discharges will be shown. Finally, several issues concerning the vertical injection experiments will be discussed.

2. Experimental Setup

In order to perform vertical CT injection experiments on the STOR-M tokamak, a 90^o bending drift tube was added to the University of Saskatchewan Compact Torus Injector (USCTI). The original USCTI consisted of a formation and an acceleration section in a coaxial configuration. The radii of the outer/inner electrodes are 5 cm and 1.8 cm, respectively. The surface of the electrodes was coated with either tungsten or chromium to minimize the impurity content in the CT. An internal solenoid with radius smaller than the inner formation electrode was used to produce bias magnetic flux for CT formation. Hydrogen gas was injected into the circular gap between the inner and outer electrodes through four fast electromagnetic valves evenly spaced azimuthally around the outer formation electrode. Two identical capacitor banks (20 μF, 20 kV) were employed for consecutive formation and acceleration discharges. The time delay between these two discharges can be controlled in the μsec range. The estimated lifetime of the CT produced by USCTI is about 20 μsec based on the size and the electron temperature of the CT.

2.1. Bench Test Setup

Figure 1 shows the setup of the bench test experiments. A straight and a curved stainless steel drift tube (with an inner radius r = 5 cm, common curvature radius of R = 16 cm, and wall thickness of 0.2 cm) were attached to the exit of the CT injector. A stainless steel cone (compressor) compressed the radius of the CT from 5 cm to 3 cm to match a vertical port available on STOR-M. In the diagram, P0 to P7 represent the magnetic probes and L1 the Langmuir probes. The probe assembly P6 at the exit of the 90^o bend consisted of an array of several magnetic probes at different radial positions and was used to measure the radial profile of the CT magnetic field. Other magnetic probes measured the magnetic fields at the outer electrode surface. The Langmuir probe was used to measure CT density and temperature. The density was also measured with a He-Ne interferometer. A multi-channel optical spectrometer was used to simultaneously monitor the H_α radiation intensities from several locations along the drift tube. The inner acceleration electrode was extended up to the flange near the P3 probe. The linear distances from the probes to the probe P3 are marked in the brackets in Fig.1. The drift tube section marked with L1 was added to ensure that the distance from P3 to P7 (97 cm) is the same as the distance from P3 to the STOR-M tokamak center in the actual vertical CT injection experiment setup. The voltages of CT formation and acceleration bank used were 18/14 kV and the bias flux was 1.4 mWb.

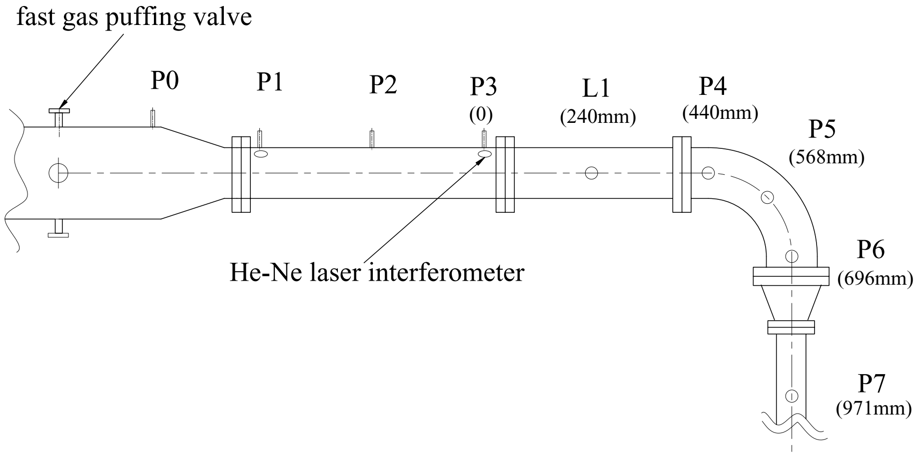

FIG. 1. Schematic diagram of bending drift tube and diagnostic locations.

2.2. Injection Experiment Setup

The injection experiment was performed in the STOR-M tokamak. The STOR-M is a small tokamak (R = 46 cm, a = 12 cm) with ohmic heating only. STOR-M is equipped with a position feed-back control system. A combination of horizontal rail limiter at r = 12 cm and circular limiter at r = 13 cm near the mid-plane is made of stainless steel. The parameters of tokamak plasma were monitored with various diagnostics. A 4 mm microwave interferometer was used to measure the electron density averaged along the central chord. A monochromator aiming horizontally through the center of the chamber was employed to monitor the H_a emission intensity. In addition, a 4-channel soft X-ray (SXR) camera was set up to monitor the SXR emission from the plasma near the tokamak center. At the plasma edge, a rake Langmuir probe array was employed to measure floating potential. A set of Mirnov coils outside the vacuum chamber was used to monitor m = 2, 3 MHD activities. For a typical STOR-M discharge, the toroidal magnetic field (B_t) was 0.7 T, plasma current (I_p) 20 kA, and electron density in the range $(0.5 \sim 2)\times 10^{13}$ cm^{-3}.

Figure 2 shows the interface between USCTI and STOR-M. The stainless steel tube with probe L1 in Fig. 1 was replaced with a short ceramic break and a bellows was added between USCTI and STOR-M. The inner dimension of the oval vertical port is approximately 6.3 cm extended in the toroidal direction and 19 cm extended in the radial direction.

3. Experimental Results

3.1. Bench Test Results

During the bench test experiments, a higher acceleration voltage (14 kV, compared to 10 kV used in the previous tangential injection experiment) was crucial to ensure that CT was able to travel through the 90^{o} bend and the compressor. Figure 3 shows the poloidal magnetic fields measured at P3 (0 cm, near the injector exit), P4 (44 cm), P5 (57 cm), P7 (70cm) and P7 (97 cm, after the compressor). The vertical scale for the last trace is magnified by a factor of 10. The data indicates that the CT velocity before the compressor in the bending drift tube is approximately constant at 220 km/sec. The estimated velocity between the P6 and P7 positions is about 30 km/sec. This particular shot shows that the magnetic field strength does not change significantly in the drift tube. It should be pointed out that the magnetic field strength did show decay in the drift tube in some other shots, particularly in earlier experiments. The significant decay of magnetic field occurred in the compressor. During the time (10 msec) for CT to travel through the compressor from p6 to p7, the magnetic field strength decreases to about one tenth of its value just before the compressor. This decay is much faster than the estimated lifetime of 20 msec.

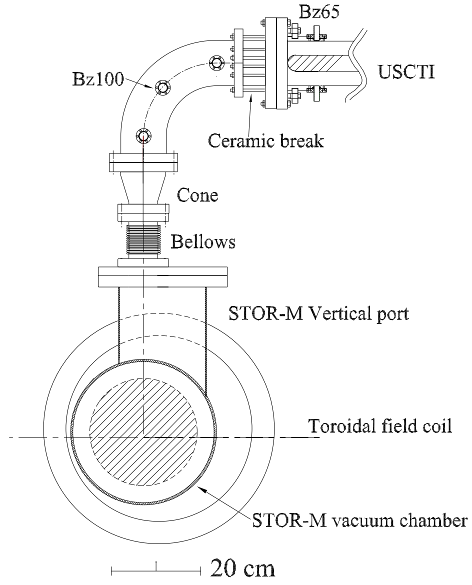

FIG. 2. Arrangement of experiments for vertical CT injection into STOR-M.

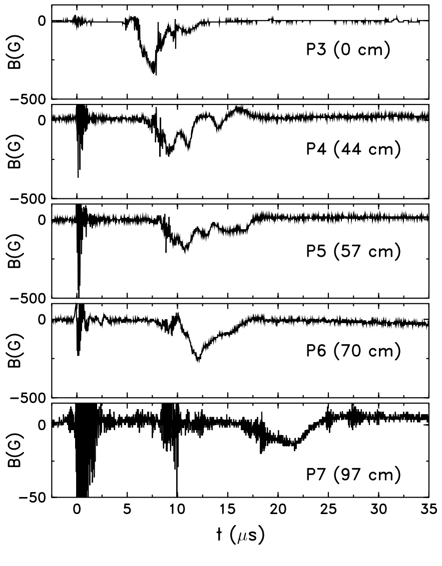

FIG.3. Poloidal CT magnetic field measured at locations 0, 44, 57, 70, and 97 cm from the CT formation region along the drift tube (shot number: 157629)

The radial profiles of the toroidal (B_t) and poloidal (B_z) magnetic field measured by the magnetic probe array P6 across the minor CT cross-section are shown in Fig. 4. The toroidal magnetic field does not change direction across the minor radius and the poloidal magnetic field changes the direction. The profiles indicate that the CT configuration remains intact in the drift tube. At the P6 location, the CT density measured by a Langmuir probe is $(0.6 \sim 1)\times 10^{21}$ cm^{-3}.

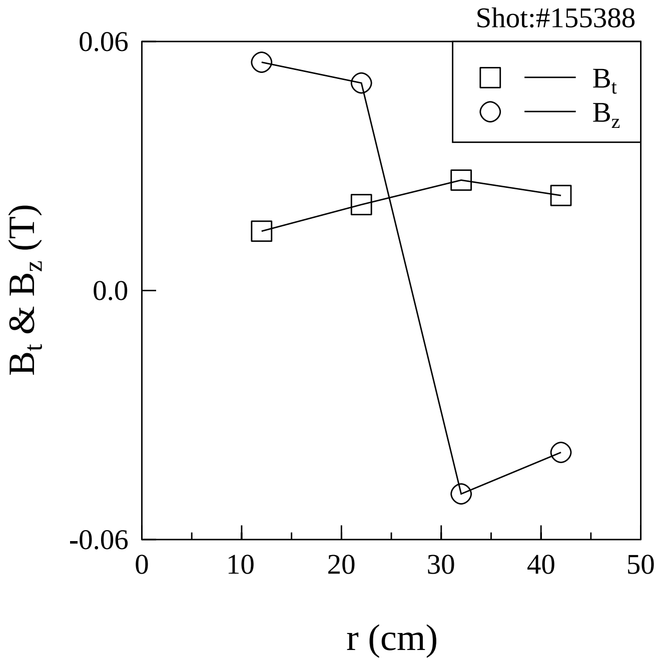

FIG. 4. Profile of magnetic field of a traveling CT at the exit of the 90 degree bend.

3.2. Preliminary Results of Vertical CT Injection into STOR-M

Preliminary vertical CT injection experiments have been performed on the STOR-M tokamak. During the discharge shown in Fig. 5, a CT was injected at 14 msec from the top along the vertical diameter of the tokamak. The traces are (from top): plasma current, I_p, loop voltage, V_L, electron density, $\bar{n}_e$, plasma horizontal displacement, ΔH, H$_\alpha$ radiation level, and floating potential, V_f. CT injection does not disrupt tokamak discharge. The electron density increases abruptly before decreasing again, presumably due to the fueling effect. Compared with the doubling of the density observed previously during the H-mode triggered by tangential CT injection into STOR-M, the density increase following vertical CT injection is small, but it is clearly identifiable. Other plasma parameters remain essentially intact after vertical CT injection.

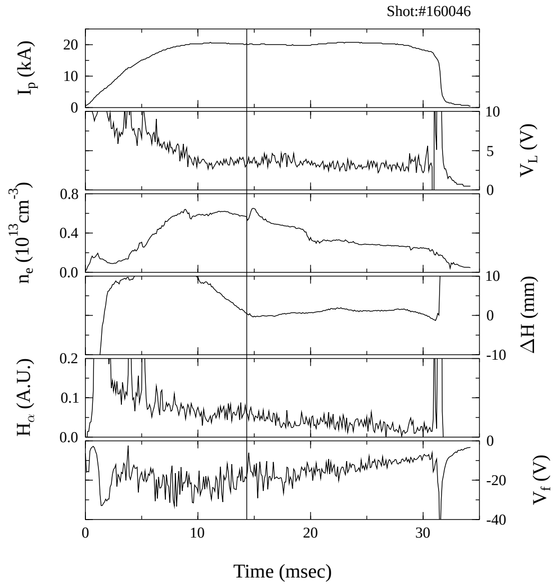

FIG.5. Evolution of the STOR-M plasma parameters with vertical CT injection at 14 msec.

Figure 6 shows the response of the SXR emission to vertical CT injection at 15.1 msec. The SXR emission increases to a higher level within 1 msec and stays at that level for about 5 msec before decreasing. An increase in the SXR emission from the central chord usually indicates an increase in the temperature and/or density in the center region. Figure 7 depicts the $m = 2$ and $m = 3$ Mirnov oscillations during a shot with vertical CT injection at 17 msec. It can be clearly seen that CT injection led to suppression of $m = 2$ Mirnov oscillations for about 2 msec, but had no effects on the $m = 3$ Mirnov oscillations. The Mirnow oscillation phenomena are similar to those observed earlier during the H-mode triggered by tangential CT injection into STOR-M [4].

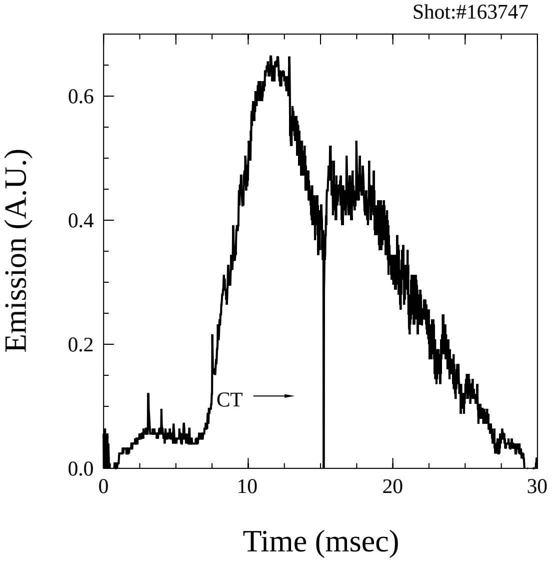

FIG.6. Soft X ray emission from the central chord.

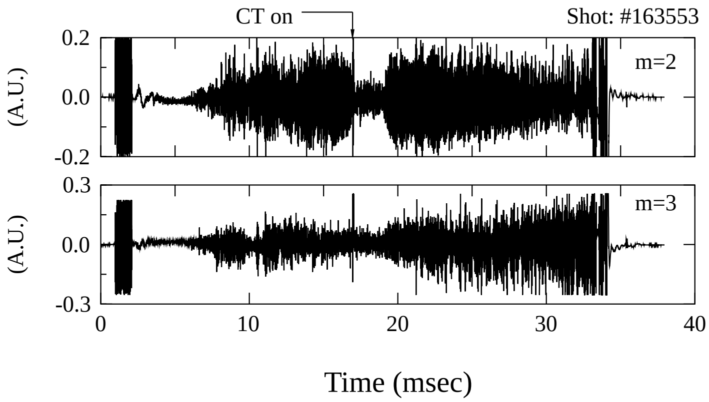

FIG.7. m = 2 and m = 3 Mirnov oscillations

4. Discussions

In our experiments, a bending drift tube has been used to redirect the CT injection direction from horizontal to vertical to perform vertical CT injection into STOR-M. The CTs are able to follow the drift tube. The CT velocity remains nearly constant at all locations in the drift tube. However, the compressor slows down the CT and causes significant decrease in the CT magnetic field. Preliminary vertical CT injection experiments resulted in some encouraging phenomena including increases in electron density and SXR emission level although those phenomena are not reproducible at the moment.

Vertical CT injection is attractive due to the absence of the magnetic field gradient in the vertical direction within the tokamak. The results previously reported by Fukumoto *et al.* and also reported in this paper suggest that a bending drift tube can be used to effectively alter the CT direction. However, initial CT penetration through the magnetic field in the tokamak port is still considered a major difficulty for vertical CT injection experiments. A magnetic field opposite to the toroidal magnetic field may be applied in the tokamak port portion where tokamak toroidal magnetic field presents. The same can be done for horizontal CT injection if CT penetration through the port is a problem.

Further campaigns on vertical CT injection experiments will start soon on STOR-M. A curved inner electrode coaxial with the curved outer electrode (up to the compressor) will be added to improve the parameters of CTs, particularly its velocity, after the compressor and to allow further studies on the effects of vertical CT injection on the tokamak discharge.

Acknowledgments

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References

[1] PARKS, P. B., Phys. Rev. Lett. **61** (1988) 1364

[2] PERKINS, L. J., et al., Nuclear Fusion **28** (1988) 1365

[3] RAMAN, R., et al., Phys. Rev. Lett. **61** (1994) 3101

[4] SEN, S., et al., Phys. Rev. Lett. **88** (2002) 18501

[5] OGAWA, T., et al., Nucl. Fusion, **39** (1999) 1911

[6] BOZHOKIN, S. V., Sov. J. Plasma Phys., **16** (1990) 702

[7] XIAO, C, HIROSE, A., ZAWALZKI, W., Nucl. Fusion, **38** (1998) 249

[8] SUZUKI, Y., et al., Nucl. Fusion **41** (2001) 873.

[9] XIAO, C., et al., Fusion Energy 1996, Motreal, IAEA-CN-64/AP1-1, VOL**. II** p. 963 (IAEA, Vienna, 2003)

[10] FUKUMOTO, N., et al., Fusion Energy 2002, LYON, IAEA-CN-94/FT/P2-07 (2002)

[11] YEE, J., BELLAN, P. M., Nucl. Fusion, **38** (1998) 711