J. Plasma Fusion Res. SERIES, Vol. 8 (2009)

Enhancement of Performance of Compact Toroid Injector for LHD

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(Received: 3 September 2008 / Accepted: 4 February 2009)

The compact toroid (CT) injector of SPICA (SPheromak Injector using Conical Accelerator) has been developed as an advanced fueller to centrally fuel the Large Helical Device (LHD). The primary challenges are the large magnetic field strength of LHD (~ 3 T) and the long CT transportation distance (~ 4 m). Initial tests showed the injector performance is insufficient for central fuelling; enhancement of SPICA is required. The performance of SPICA with different accelerator length was investigated to optimize the CT parameters: S-type (accelerator length = 1.328 m) and M-type (1.978 m). As results, CT speed just before CT ejection achieved at 206 km/s in the M-type. The magnetic field profiles indicated a typical spheromak configuration, and the peaked CT density was above 8×10^{20} m^{-3} in the flux conserver connected to the muzzle on both the S and M-type SPICA. In addition, the CT passed through a 1.8 m drift tube without significant decay in CT density was observed. Through the series of experiments, the performance of SPICA has been improved effectively by optimization of the conical accelerator length and CT plasma has been successfully ejected from the injector, leading to CT transport in long distance.

Keywords: compact toroid injection, SPICA, fuelling, LHD.

1. Introduction

Direct fuelling the core of a fusion reactor has several advantages, e.g. profile control by localized fuel deposition and enhancement of reactor performance since the plasma temperature and density peak there. For tokamaks, several fuelling techniques such as gas puffing, cryogenic pellet injection have been developed and implemented successfully in the present-day tokamaks. As an alternative, compact toroid (CT) injection has been considered as an advanced technique to centrally fuel reactor-grade tokamaks and promising results have been obtained [1-5]. An accelerated CT is able to penetrate into the center of a tokamak provided that the kinetic energy density of the CT exceeds magnetic field energy density of the tokamak. This can be described as: $\rho_{CT}V^2/2>B^2/2\mu_0$, where ρ_{CT} is the CT mass density, V is the CT velocity and B is the field strength at the tokamak center. The compact toroid injector of SPICA (SPheromak Injector using Conical Accelerator) has been developed as an advanced fueller for the Large Helical Device (LHD) at NIFS since 1998 [6, 7]. The main goal for fuelling the LHD by CT injection is to form a CT and accelerate it subsequently to penetrate a 3 Tesla magnetic field of LHD after a ~ 4 m transportation distance (the distance from the CT injection port to the center of LHD plasmas).

In 2005, the SPICA achieved CT parameters to penetrate into LHD plasmas at a magnetic field of $B \sim 0.8$ T [8]. However, to fulfill the goal of central fuelling, CT transport and penetration in long distance from the injector to the plasma core can cause problems at a higher B. The injector is thus required to enhance the performance much more than previously obtained. We have investigated issues on the structural properties of the SPICA (L-type: the accelerator length is 2.628 m). Although the design of the conical accelerator was optimized by numerical analysis, the accelerating CT plasma appeared to deteriorate around the end of the conical accelerator. Furthermore, the ejected CT plasma rapidly decayed through the long distance transfer.

In this article, we report the experimental results of enhancement of SPICA performance with different accelerator configurations. Our focus is on the investigation of characteristics of CT plasma being accelerated and ejected on the S-type (1.328 m) and M-type (1.978 m) accelerators to prevent the deterioration in CT parameters. As results, CT speed just before CT ejection achieved at 206 km/s on the M-type. The magnetic field profiles indicated a typical spheromak configuration, and the peaked CT density was above 8×10^{20} m^{-3} in the flux conserver connected to the muzzle on both the S and M-type accelerators. In addition, the CT passed through a 1.8 m drift tube without significant decay in CT density. Through the series of experiments, the performance of SPICA has been improved effectively by optimization of the conical accelerator length and CT plasma has been successfully ejected from the injector, leading to CT transport in long distance.

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The paper is organized as follows: the description of SPICA and CT plasma diagnostics is given in Section 2. The enhancement of SPICA performance with S- and M-type accelerator configurations is presented in Section 3, which is followed by a brief summary in Section 4.

2. SPICA accelerator configurations and CT plasma diagnostics

In this section three different SPICA accelerator configurations will be introduced. The SPICA is a two-stage plasma gun of conical coaxial electrode configuration. After the successful assembly of the SPICA in 1999, a long accelerator with 2.628 m length (L-type) was first adopted to carry out initial tests. Fig.1 shows the L-type SPICA consists of a CT formation region and a 2.628 meters long accelerator. The working gas, pure hydrogen normally, is puffed by a solenoid valve located in the formation region (details of this region are described clearly in ref. [7]). The CT plasma is formed through the gas discharge by the high voltage applied between the inner and outer electrodes. The formation bank has a capacitance of 200 μF, and the maximum current is 300 kA. After the CT detaches from the formation region it will be accelerated to high speed by **J**×**B** force, where **J** is the radial discharge current and **B** is the toroidal magnetic field associated with **J**. The current reaches a maximum of 400 kA using the acceleration bank with a capacitance of 120 μF.

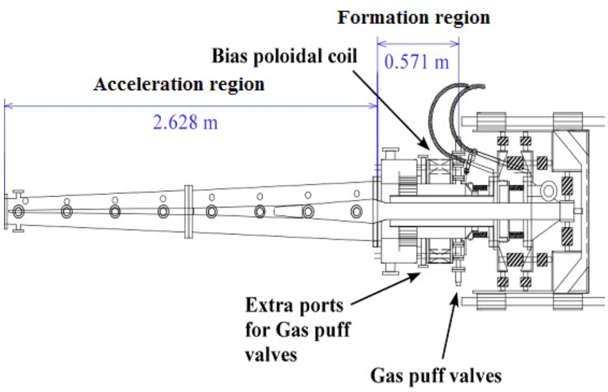


Fig.1 L-type SPICA equipped with 2.628m CT accelerator.

Although the design of the conical accelerator was optimized by numerical analysis, the initial test results showed that the accelerated CT plasma appeared to deteriorate around the end of the conical accelerator. Furthermore, in the experimental demonstration of CT injection into the 3.6 m long test chamber, the performance was not high enough to realize the core CT penetration into LHD. Therefore, CT injection experiment into a flux conserver has been performed in order to optimize the operation parameters and two different accelerator configurations were adopted in the further tests.

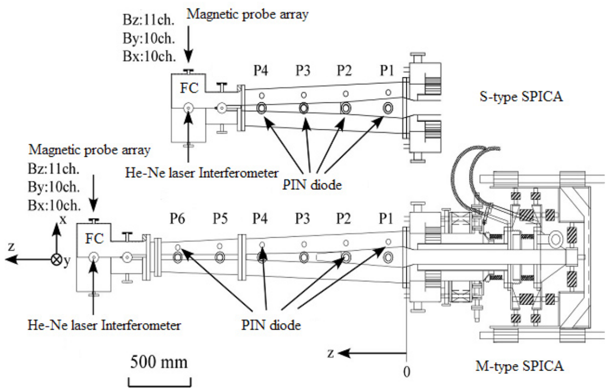


Fig.2 Schematic views of the S-type and M-type SPICA with plasma diagnostics

Fig.2 shows the accelerator configurations of the S-type and M-type SPICA. The accelerator lengths are 1.328 m and 1.978 m, respectively. To monitor CT plasma parameters, magnetic probe arrays were used to measure the CT magnetic field profile in a flux conserver (FC). A He-Ne laser interferometer (λ = 633 nm) was used to monitor line-averaged electron density of the CT. Multi-channel PIN diodes were used to collect visible light emission from the CT plasma along its trajectory and the CT velocity can be inferred by time-of-flight method using the light signals.

3. Experimental results

3.1 Performance improvement in S- and M-type SPICA

We have observed the accelerated CT plasma appeared to deteriorate around the end of the conical accelerator in the L-type SPICA. To enhance the SPICA performance the experiments on optimization of the accelerator length were performed. By shortening the accelerator length, the typical spheromak magnetic profiles were obtained in both S- and M-type SPICA as showed in Fig.3. The poloidal magnetic field of CT (B_Z) is proportional to $J_0(x)$, where J_0 is the zero order Bessel function of the first kind and x is the radius of the FC; the toroidal magnetic field of CT (B_y) is proportional to $J_1(x)$, where J_1 is the first order Bessel function. The results confirmed that the plasma injected in the FC was indeed a spheromak, not just a plasma flow.

Fig.4 depicts typical PIN diode signals (VL), CT density (n_e) and magnetic probe data (B_p) in both S-type (Fig.4(a)) and M-type SPICA (Fig.4(b)). The locations of diagnostic ports are labeled with P1, P2, P3, P4, P6 and FC in both shots for the S- and M-type. In these shots the CT parameters are n_e = 8.1×10^{20} m^{-3}, B_{CT} = 0.173 T (M-type

SPICA) and n_e = 9.6×10^{20} m^{-3}, B_{CT} = 0.086 T (S-type SPICA). In the S-type SPICA, CT speeds between VL2 and VL4 (P2 and P4) are estimated at 77 km/. Due to the relatively long CT acceleration electrode the CT velocity increases to 206 km/s in M-type (estimated by VL4 and VL5 signals (P4 and P6, just before CT ejection)). The significant increase in CT speed without degradation in CT magnetic field and electron density indicates enhancement of SPICA performance has been achieved in the M-type.

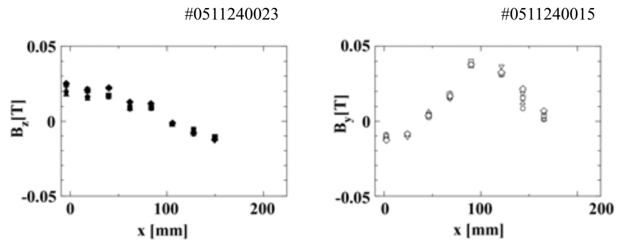
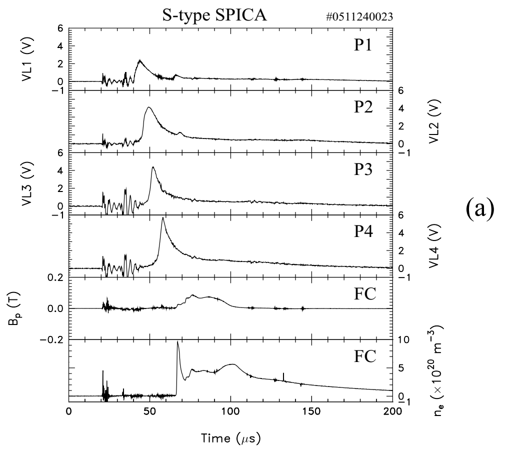


Fig.3 Magnetic profiles of the ejected CT in S-SPICA showing a typical spheromak configuration in the FC.



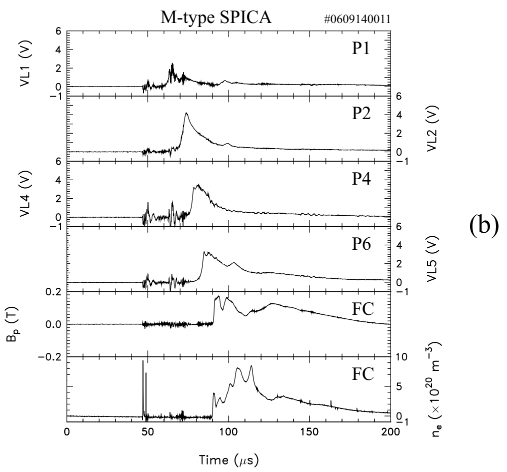


Fig.4 Typical discharge waveforms in (a) S-type and (b) M-type SPICA. Discharge conditions: I_{bias} = 210 A, V_{form} = 8 kV, V_{acc} = 12 kV for S-type and 15 kV for the M-type.

3.2 Long distance CT translation experiment in M-type SPICA

In this experiment CTs were formed and accelerated in the M-type SPICA. The injector was attached by a 1.8 meters long drift tube of the same outer diameter with the exit of the acceleration electrode (the dashed line, see Fig.5). The drift tube sit in a cylinder equipped with diagnostic ports. The typical discharge conditions were: V_{form} = 8 kV, V_{acc} = 14 kV. Fig.6 shows the discharge waveforms: from top: Visible light emission signals along CT trajectory, magnetic probe signal in the FC and the line-averaged electron density at the entrance of the drift tube (same location with Diode_3 in Fig.5).

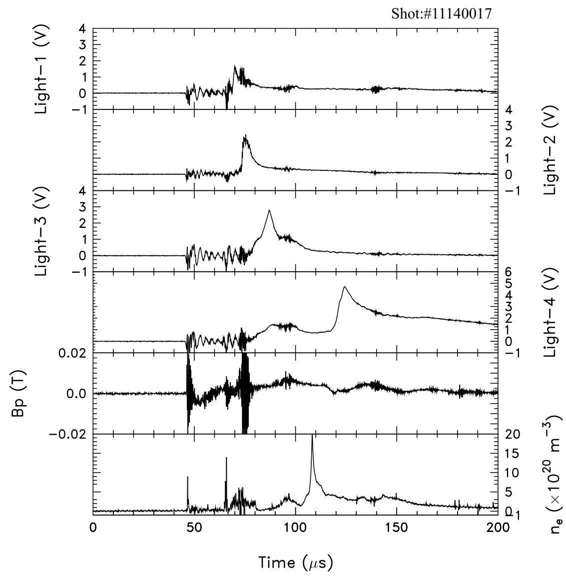


Fig.6 Typical discharge waveforms in M-type SPICA.

To investigate the CT decay during its long distance transportation the CT electron density was scanned at three different locations: the entrance of the drift tube, the center and the exit of the drift tube (see Fig.5, the three measurement locations of the laser interferometer). It showed a slow decay in the CT density, ~ 22%, when the CT passing the 1.8 meters long drift tube, see Fig.7. This promising result will encourage further experiments on injection of CT into a 4 meters long drift tube to simulate the actual injection scheme in LHD using SPICA.

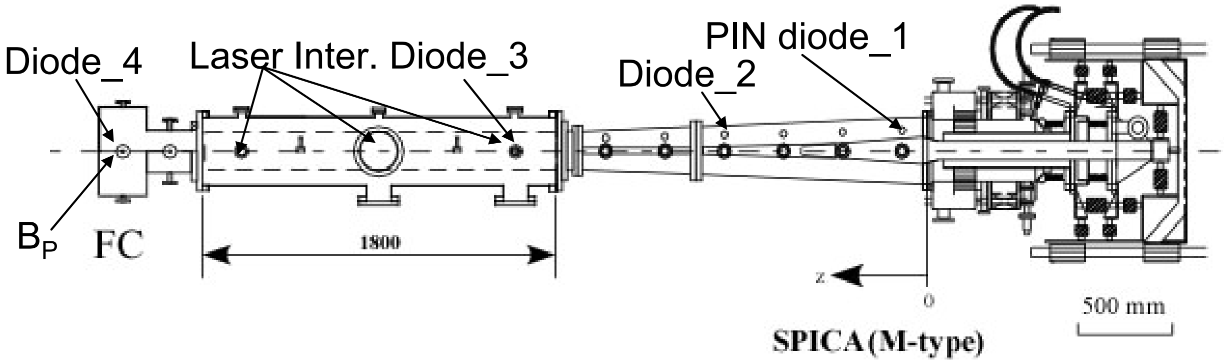


Fig.5 Experimental Setup for CT long distance transportation experiment using M-type SPICA.

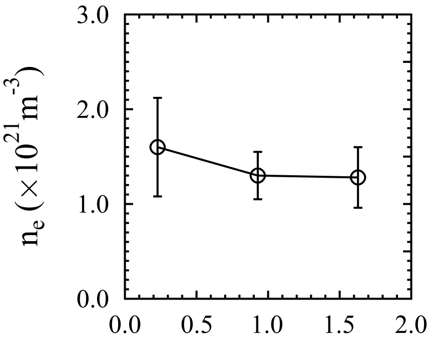


Fig.7 CT Density changes along the 1.8 m long drift tube.

4. Summary

The SPICA has been developed to centrally fuel LHD. The initial tests on the L-type SPICA showed that the injector was incapable of fulfilling this goal. Enhancement of SPICA performance is required. Experiments on optimization of SPICA accelerator length have been carried out. The effectively improved CT parameters have been obtained in the M-type SPICA (accelerator length = 1.978 m). The slow decay in CT density have been observed in the long distance CT transportation experiment on the M-type SPICA. The results indicate the performance SPICA has been improved effectively by optimization of the conical accelerator length and CT plasma has been successfully ejected from the injector, leading to CT transport in long distance.

Acknowledgements

The authors would like to thank Drs. T. Takahashi (Gunma Univ.), S. Masamune, H. Himura and A. Sanpei (Kyoto Inst. Tech.), T. Takahashi and T. Asai (Nihon Univ.), Y. Hirano (AIST), M. Inomoto (Univ. Tokyo), M. Irie (Waseda Univ.), H. Yamada and Y. Narushima (NIFS) for fruitful discussions. This work was performed with the support and under the auspices of the NIFS Collaboration Research Program (NIFS07KCPP004), and with the partial support of Grant-in-Aid for the Japan Society for the Promotion of Science (JSPS) Fellow (18·06760). The author, Dazhi Liu, thanks the JSPS postdoctoral fellowship for financial support.

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