# Development of a neutral particle flow fueling system by using a compact torus plasma injector for LHD

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**Abstract**. The Compact toroid CT fueler of SPICA (SPheromak Injector using Conical Accelerator) for LHD has been developed at NIFS. Recently, in order to apply CT injection technique to more effective fueling, production and injection of super-high speed neutral particle flow (NPF) have been studied. The NPF injection has a potential ability to fuel more effectively than supersonic gas jet and can play a specific part beyond neutral beam injection. We have then proposed a fueling system of CT-based NPF injection and launched experiment on production of super-high speed NPF by using the SPICA injector.

## 1. Introduction

Injection of accelerated compact torus (CT) plasmas has been proposed as an advanced method of central fueling in a fusion reactor [1]. The CT injection has been experimentally demonstrated on several tokamaks [2-11]. The new technology for CT injection has been also researched and developed to enhance CT injection performance [12-14]. Recent CT injection experiment has been performed on the Compact Plasma wall interaction experimental Device (CPD) in Kyusyu University in Japan to study on advanced fueling into Spherical Tokamak (ST)[15-17]. The CT injector of UH-CTI (the former HIT-CTI), the power supplies and the related equipment had been used for CT injection on JFT-2M at JAERI (currently JAEA) [18,19]. On the new ST device of QUEST, CT injection experiment will be continuously conducted.

In the research on CT injector, SPICA (SPheromak Injector using Conical Accelerator) was developed for an advanced fueler into the Large Helical Device (LHD) at NIFS [20, 21]. The injector achieved CT parameters to penetrate into LHD plasmas at a magnetic field of 0.8 T. However the CT magnetic field and density decreased on the phase of CT acceleration, and the ejected CT plasma rapidly decayed through the long distance transfer. Although the design of the conical accelerator (the accelerator length of 2.628 m) was optimized by numerical analysis, the accelerating CT plasma appeared to deteriorate around the end of the conical accelerator. We thus investigated problems on the structural properties of the accelerator on SPICA to improve the CT acceleration and ejection. The performance of CT acceleration was improved effectively by optimization of the conical accelerator length, and the modified SPICA (the accelerator length of 1.978 m) injector successfully ejected CT plasmas without the deterioration in CT parameters. The accelerated CT plasmas can penetrate in a 1.8 m drift tube with a density on the order of $10^{21}$ $m^{-3}$[22]. However, for practical setup of the CT injector on a large plasma confinement device such as LHD, the system should be simple and reliable for easy operation and maintenance. The present SPICA has two-stage coaxial electrodes for CT formation and acceleration to obtain the high performance. The power supplies equipped with ignitron switches are rather difficult to deal with. We thus attempted single-stage operation by connecting only the acceleration bank unit to both electrodes.

A new technique for fueling by using a plasma gun was reported by Rozhansky *et al.*[23]. They experimentally demonstrated that both fast plasma and neutral gas jets generated by a plasma gun penetrated into a ST plasma on Globus-M. The plasma jet is neutralized to be fast neutral gas jet owing to recombination with traveling from the gun to the separatrix. This motivated us to take a new approach of CT injection to more effective fueling. That is production and injection of super-high speed neutral particle flow (NPF) by using a CT injector. The super-high speed NPF can be actively produced through charge-exchange (CX) reaction between CT plasma and neutral gas in a neutralizer cell. Thus we proposed a fueling system of CT-based NPF injection, and launched the study on production of super-high speed NPF by using the single-stage SPICA injector.

This paper describes characteristics of the single-stage SPICA and the investigation of NPF production by using it.

## 2. Experimental setup

We trialed the single-stage SPICA with connecting only the acceleration bank unit to both electrodes. By using the simple SPICA injector, we started the research on production of super-high speed NPF. The experimental setup is shown in *FIG.1*. SPICA accelerates a CT plasmoid and injects it into a long drift tube as a neutralizer cell (a length of 1.8 m, a volume of $5.5\times10^{-2}$ $m^3$). At the upper port of P8 along the cell, piezoelectric valve was mounted to puff hydrogen gas into the cell. The characteristics was tested, and the trigger timing and the width of a pulse driving a piezoelectric valve were optimized in consideration of neutral gas diffusion, leading to the pressure of up to $10^{-2}$ Torr in the neutralizer cell. We also arranged measurement systems to investigate the performance of the simple SPICA and the production of NPF. PIN diodes (L1-4) were mounted at P1, P4, P7 and P10/P11 for the observation of CT transit, and a He-Ne laser interferometer was at P6 for CT plasma density at the muzzle of SPICA. Then the interferometer was moved to be set at the side port of P9 for that in the end region of the neutralizer. A piezoelectric pressure sensor was positioned at P11 to detect a fast increase in pressure in the flux conserver (FC). One end of the optical fiber from a spectrometer was placed at the upper port of P9 to observe visible light emitted from CT plasmas.

The experimental scenario is considered as follows; the single-stage SPICA accelerates a CT plasmoid and injects it into the neutralizer cell filled with hydrogen gas, then super-high speed NPF is produced owing to CX reaction between the CT plasma and the neutral gas on the back ground. In the operation of SPICA, the charging voltage of the acceleration bank was set at 25 kV for the performance test of the single-stage SPICA and 15 kV for the production test of NPF.

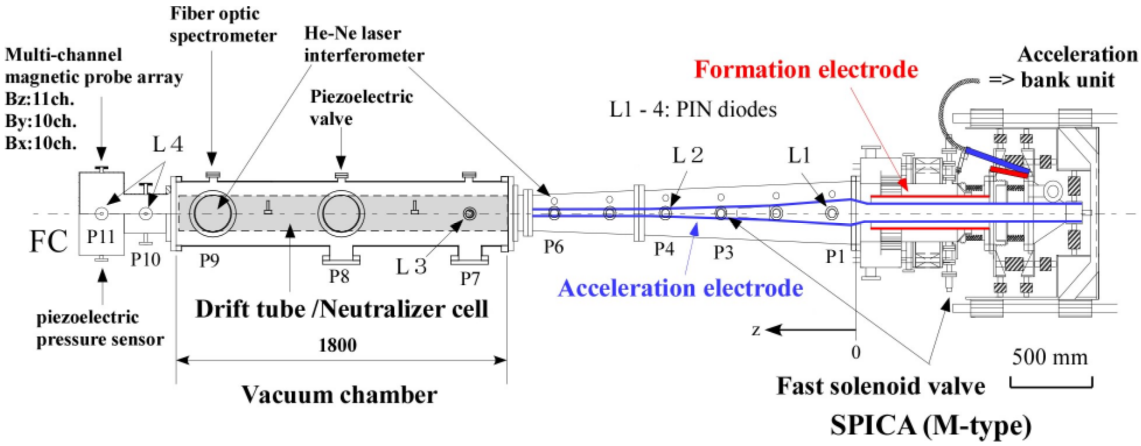


*FIG. 1. Schematics of SPICA injector and neutralizer cell.*

## 3. Experimental results and discussions

In the first phase of the experiment, we investigated performance of CT acceleration and ejection on the single-stage SPICA. *Figure2* shows the typical time evolution of PIN diode signals and the CT density. The CT was accelerated to 76 km/s between L2 and the interferometer, and its density was up to $1\times10^{22}$ m$^{-3}$ at the muzzle of the injector. In the FC a fast increase in pressure due to the CT plasma and its trailing plasma was also detected by the piezoelectric pressure sensor. The kinetic energy density of the hydrogen CT is calculated at 34 kJ/m$^3$, which is an energy density to penetrate into a LHD plasma at a magnetic field of 0.3 T. Although the energy density is rather low, the density is remarkably high. If the CT plasmoid is completely neutralized, the particle inventory of NPF is estimated to be $2\times10^{20}$ from the full-width at half-maximum of the electron density signal and $5\times10^{20}$ from the full-width at the base. These values correspond to respective density increments of $7\times10^{18}$ m$^{-3}$ and $2\times10^{19}$ m$^{-3}$ in an LHD plasma at the volume of 30 m$^3$. Here, considering that the fueling efficiency of 40% obtained in CT injection on JFT-2M [7], the particle inventories are $8\times10^{19}$ and $2\times10^{20}$. In the penetration process, the NPF has a kinetic energy of 100 eV and would have a thermal energy of less than 1 eV. Thus the radial diffusion is two orders smaller than the NPF penetration. The speed of NPF is two orders larger than that of supersonic gas jet with a laval nozzle, while the penetration depth of NPF is estimated roughly at 6 mm, which is several hundredths of that of NBI. The input power is, however, calculated to be 32 MW since the NPF is injected at a short pulse of about 100 μs. The injector corresponds to a NBI at 100eV and 320kA. It would be almost impossible to develop such a NBI. The NPF injector by using CT injection technique can be useful as a new fueling device.

By using the simple SPICA injector, a CT plasmoid was injected into the neutralizer cell filled with hydrogen gas. Here, for the efficient operation, the bank charging voltage is decreased from 25 kV to 15 kV. Thus, the energy storage capacity of the bank is reduced to about one-third. The typical evolution of PIN diode signals and the CT density is shown in *FIG.3*. The CT density decreased at the muzzle, nevertheless the electron density of about $5\times10^{20}$ m$^{-3}$ remained at the end region of the neutralizer cell. Both plasma and NPF reached the FC, therefore Neutralization of the CT plasmoid was not completed. *Figure 4* shows the spectrum measured in the end region of the neutralizer cell. The several Balmar series lines appear discretely. We have considered applying spectroscopic analysis of detached divertor plasmas or pellet ablation clouds in LHD to that of the CT plasmas [24, 25]. Result of the rough analysis indicates the visible spectrum would be due to emission from the recombining plasma with an electron temperature of about 0.5 eV.

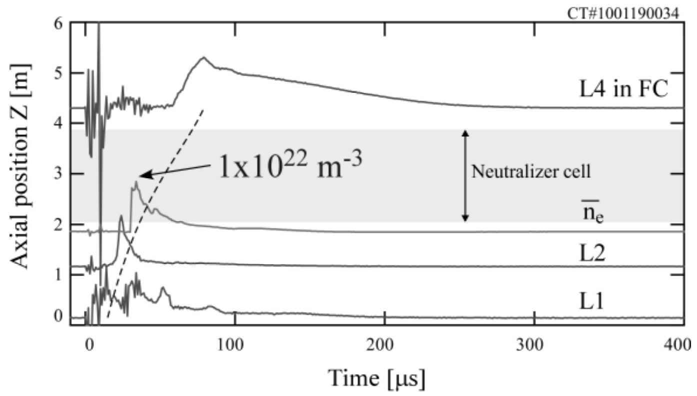


*FIG. 2. CT trace on the acceleration region and neutralizer cell without hydrogen gas . The vertical offsets are proportional to the axial location of each measurement. The dash line indicates the CT trajectory.*

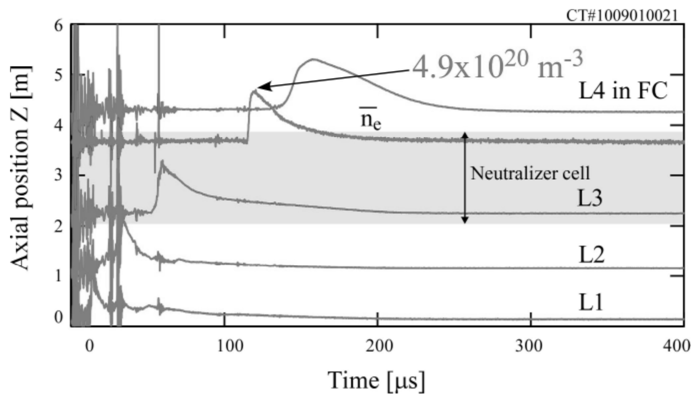


*FIG. 3. CT trace on the acceleration region and neutralizer cell filled with hydrogen gas. The vertical offsets are proportional to the axial location of each measurement.*

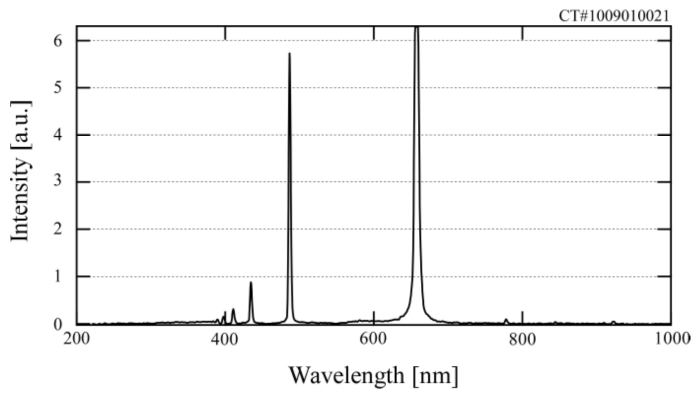


*FIG. 4. Visible spectrum measured in the end region of the neutralizer cell*

In addition, a Monte-Carlo simulation has been made to understand the neutralization process and investigate the conditions for high neutralization efficiency at the Gunma University [26]. As a result, dependence of neutralization efficiency on transit time of CT traveling into the neutralizer cell was found as shown in *FIG.5*. To complete neutralization of CT plasmoid, the transit time at a speed of 50 km/s requires 100 μs at a pressure of $1\times10^{-4}$ Torr and 20 μs at a pressure of $5\times10^{-4}$ Torr. Here, in the experiment, the neutralizer length is 1.8 m. The transit time is 18 μs at a CT speed of 100 km/s. It is also found that the efficiency decreases by less than only 10 % even if the speed varies from 50 km/s to 200 km/s. Therefore, a CT plasma ejected from the SPICA can be fully neutralized, passing through the neutralizer at a pressure of $5\times10^{-4}$ Torr. In the experiment, however, the complete neutralization was not observed. Moreover, a result of spectroscopic measurement indicated that the other reaction process in the neutralization should be considered.

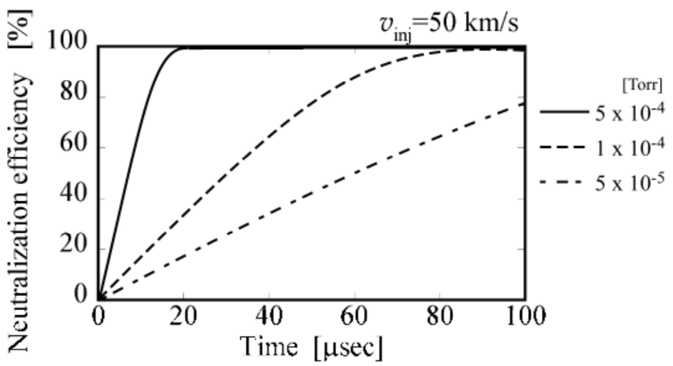


*FIG. 5. Calculational result of dependence of neutralization efficiency on transit time of CT plasma penetrating in the neutralizer cell at neutral gas pressures of $5\times10^{-4}$, $1\times10^{-4}$, $5\times10^{-5}$ Torr.*

## 4. Summary

In the first phase of the experiment, we modified the single-stage SPICA with connecting only the acceleration bank unit to both electrodes, resulting in successful CT acceleration and ejection by using the simple CT injector. In addition, by Numerical calculation, the CT parameter and neutralizer condition required to experimentally produce NPF was indicated. However, in the experiment, the complete neutralization was not achieved. Nevertheless, from estimating NPF parameters based on the obtained CT parameter, the performance advantage of NPF injection over supersonic gas jet and neutral beam injection was indicated. In the follow-on work, we intend to make quantitative measurement of neutralization efficiency, and also compare the experimental result with the calculation included the other reaction process in the neutralization.


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