Electromagnetic Coupling and Localized Core Fueling via Compact Torus Injection in the KTX Device

Ge ZHUANG [1,*], Tao LAN [1,*], Qilong DONG [1], Chijin XIAO [2], Yongkang ZHOU [1], Zhilin MAO [1], Zeqi BAI [1], Jie WU [1], Wenzhe MAO [1], Chu ZHOU [1], Ahdi LIU [1], Zhengwei WU [1], Weixing DING [1], Jinlin XIE [1] and KTX team

[1] Department of Plasma Physics and Fusion Engineering, University of Science and Technology of China, Hefei 230026, People's Republic of China

[2] Department of Physics and Engineering Physics, University of Saskatchewan, Saskatoon, SK S7N 5E2, Canada

[*]E-mail of corresponding author: lantao@ustc.edu.cn and gezhuang@ustc.edu.cn

Abstract

Compact torus (CT) injection is a promising technique for active control of plasma density profiles in magnetic confinement fusion devices. To explore CT trajectories and fuel deposition features, we designed a progressive experimental scheme using a high velocity compact torus injector (KTX-CTI) with an integrated diagnostic system on the Keda Torus eXperiment (KTX) reversed field pinch device. The magnetic configuration was systematically varied to examine CT electromagnetic behavior under three operating conditions. Experimental results demonstrate that CT injection drives eddy currents in the conducting shell and vacuum vessel, leading to strong, measurable electromagnetic coupling between the CT and surrounding conducting structures. An image current loop model was developed to interpret the observed phenomena, showing excellent agreement with experimental data. A toroidal magnetic field significantly accelerates CT magnetic structure breakdown; their electromagnetic interactions induce highly localized fuel particle deposition associated with rapid magnetic flux variations, which these effects enable precise core fueling and remarkable plasma density profile modification. These findings demonstrate CT injection as an effective, controllable localized fueling technique for magnetic confinement fusion devices, while the proposed model establishes a robust framework for analyzing CT-based fueling electromagnetic dynamics.

1. Introduction

Compact torus (CT) injection technology has demonstrated significant potential for providing localized core fueling in large-scale fusion reactors [1, 2]. However, progress is currently hindered by the lack of accurate theoretical models describing CT fueling characteristics and insufficient experimental data on key mechanisms. The concept of using CT injection for fueling magnetically confined fusion devices was originally proposed by Parks and Perkins *et al.* in 1988 [3, 4]. Since then, CT injection has been applied in various experimental fusion devices, such as the ENCORE tokamak [5, 6], TdeV tokamak [7, 8], JFT-2M tokamak [9-12], STOR-M tokamak [13-15], and the C-2U field-reversed configuration (FRC) [16]. These studies have preliminarily verified the feasibility of CT injection as a non-disruptive central fueling method for fusion devices. However, a critical challenge remains in clarifying the penetration and fuel deposition behavior of CTs in fusion environments—an understanding that will ultimately determine the viability of this technique for central fueling in large-scale reactors.

To investigate the CT's trajectory and fuel deposition characteristics, the magnetic field configuration was systematically varied to examine the electromagnetic behavior of CT under three distinct scenarios: (1) zero magnetic field (vacuum), (2) one-dimensional magnetic field (toroidal magnetic field only), and (3) two-dimensional magnetic field (normal tokamak discharge with plasma). During these experiments, both electromagnetic signals and plasma density variations are precisely measured throughout the CT injection process. This step-by-step approach is critical to elucidate the underlying theoretical mechanisms and building a foundation for CT fueling applications in fusion devices. The rest of this paper is organized as follows. Section 2 describes the experimental setup and diagnostic layout, including the diagnostics implemented on the KTX-CTI and the KTX device. Section 3 presents the experimental observations of CT injection under the three operational scenarios. Section 4 offers a comprehensive analysis of the experimental results and introduces a image current loop model as a preliminary description of the electromagnetic effects induced by CT injection into the KTX device. This section also provides a summary of the key findings.

2. **Experimental set-up**

In this thesis, to address the diagnostic challenges (CT motion and fueling parameters) arising from the short transit time of the CT within the fusion device (on the order of microseconds) and the complexity of its penetration process, we developed and implemented a progressive experimental scheme equipped with an integrated diagnostic system on the Keda Torus eXperiment (KTX) fusion device. The layout of these diagnostics for fast-response measurements is shown in Figure 1. The diagnostic system includes the terahertz interferometers, the two-dimensional magnetic probe array, the H_α detector array, the Langmuir probes, and the Rogowski coils. A CT parameter diagnostic system was deployed on the KTX-CTI device, which enabled the measurement of characteristic parameters of the CT before its injection into the KTX (Keda Torus eXperiment) device.

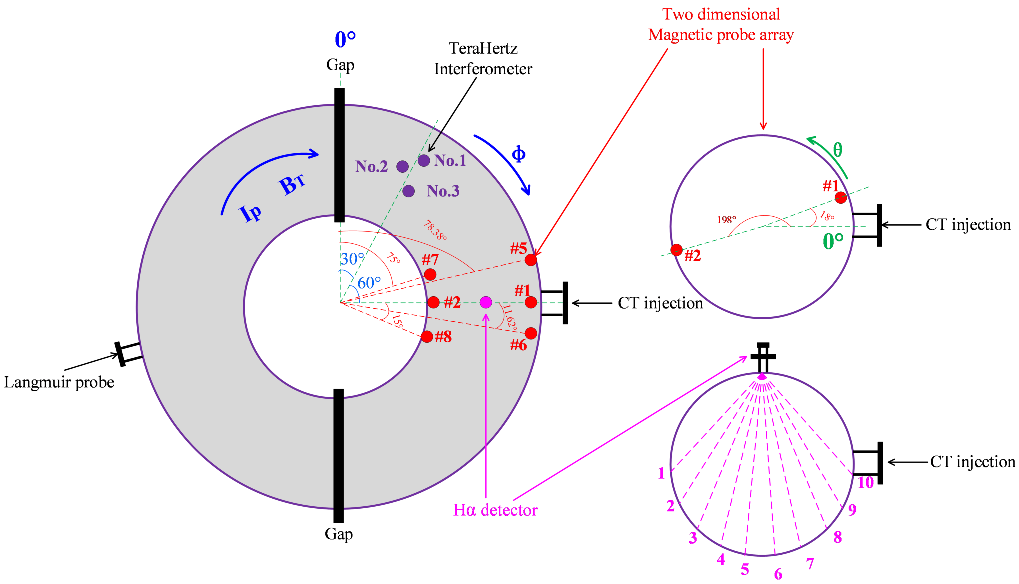

Figure 1. Schematic of the diagnostic setup for fast measurements on the KTX device (Topview).

3. Experimental observations

Figure 2 presents the typical results of CT injection into KTX during tokamak plasma discharge (Shot 242375). The toroidal field and ohmic field bank power supplies discharged at $t = -22$ ms and $t = 0$ ms, respectively, generating a toroidal magnetic field of $B_0 \approx 0.05$ T near the magnetic axis. Between $t = 5$-6 ms, after the initiation of the ohmic bank discharge, the plasma current peaked at approximately 76 kA. The CT formation bank discharged around $t =$ 9.4 ms, injecting the CT plasma into the KTX device. Figures 2(h-j) compare the plasma density waveforms measured by the three-channel terahertz interferometer, with and without CT injection (red and blue curves, respectively). Evidently, CT injection significantly alters both the density waveform and profile of the bulk plasma. Notably, after CT injection, the bulk plasma exhibits a secondary density peak, with measured peak values of 1.16×10^{19}, 1.48×10^{19}, and $1.45 \times 10^{19}\ \mathrm{m}^{-3}$ from the outer to the inner channels, respectively. This indicates that in the presence of bulk plasma, fuel particle deposition shifts toward the core region and decreases on the LFS.

A comparison between Figures 3(a) and 3(b) reveals that under the influence of the toroidal magnetic field, fuel particles deposition from the CT occurs approximately 30 μs earlier than in the absence of the field. This indicates that the toroidal magnetic field not only impedes CT penetration and accelerates fuel particle deposition but also effectively confines the deposited plasma, causing it to circulate along the magnetic field lines. This lead to more localized fuel deposition in the presence of a background magnetic field within the fusion device, highlighting CT fueling as a promising technique for localized fueling and precise density profile control.

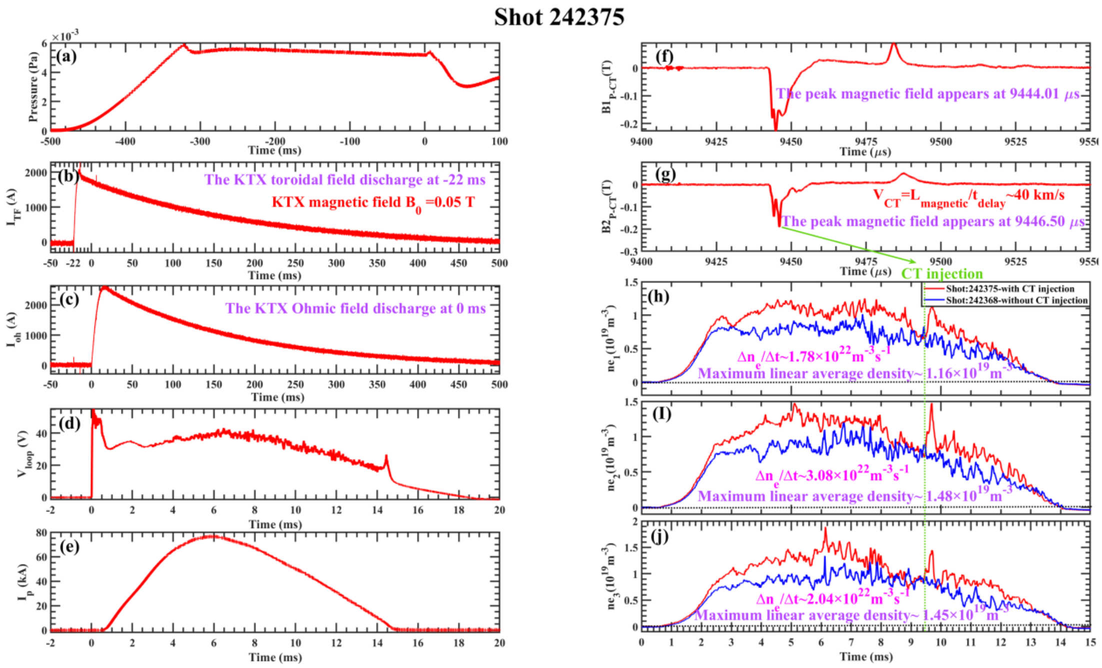

Figure 2. Waveforms during CT injection into KTX under tokamak plasma discharge conditions.

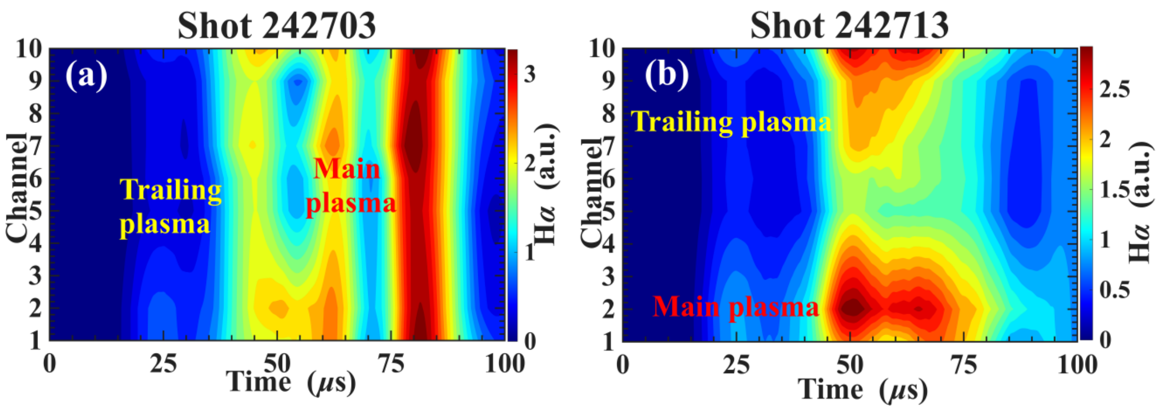

Figure 3. Contour plot of H_α measured by the H_α diagnostic system for CT injection into KTX under vacuum conditions (no toroidal magnetic field and no bulk plasma) and with the toroidal field only (no bulk plasma).

4. Discussion and summary

The experimental results reveal that CT injection induces eddy currents in the conducting chamber wall. The interaction between the CT and these eddy currents results in an electromagnetic coupled signal measured by the 2D magnetic probes on the KTX device. To extract the physical information contained in the magnetic probe signals and to investigate the electromagnetic interaction between the CT and the KTX copper shell, a image current loop model was developed based on the CT's electromagnetic characteristics. As illustrated in Figure 4(a), the model simplifies the CT as a current loop and employs the mirror method to represent the induced eddy currents as an image current loop. The image current loop shares the same geometry and coaxial alignment as the current loop but carries a current of equal magnitude in the opposite direction. Figure 4(b) presents a comparison between the simulated and measured magnetic flux signals at the magnetic probe #2. The simulation results show good agreement with the experimental data. For the first time, the electromagnetic characteristics of a CT in a fusion experimental device have been quantitatively determined, yielding a CT magnetic field amplitude of 0.007 T and a toroidal current amplitude of 890 A.

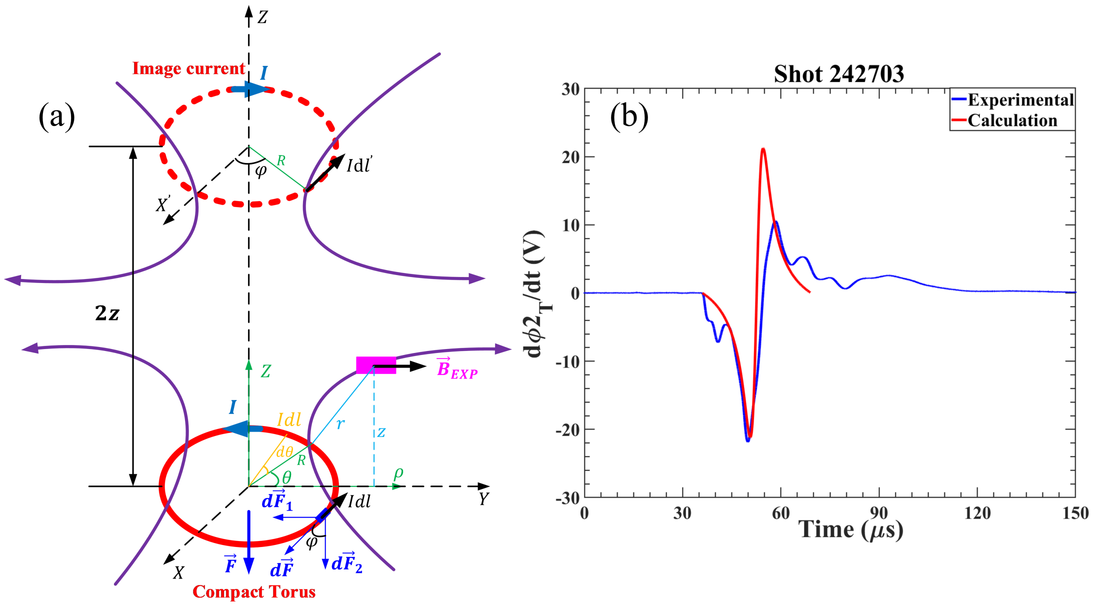

Figure 4. (a) Image current loop model. (b) Comparison of the simulation results from the image current loop model with experimental measurements.

As shown in Figure 5, after CT injection, the CT's substantial initial kinetic energy allows it to compress the magnetic field lines due to its inertia, bending the KTX toroidal magnetic field. As these field lines relax back to equilibrium, they exert additional compressive forces on the CT. In response, the CT is compressed by the restoring force from the distorted field lines, causing it to expand in both toroidal and poloidal directions. This can cause the CT plasma to split into two or more distinct plasmoids, accelerate the collapse of its magnetic topology, and ultimately lead to the deposition of fuel particles along the magnetic field lines. Notably, the electromagnetic interaction between the CT and the toroidal field leads to a more localized fuel deposition.

In summary, this study systematically investigated the electromagnetic characteristics and fueling dynamics of CT injection in the KTX fusion device. It has been experimentally demonstrated that CT fueling is a rapid process dominated by the electromagnetic interaction between the CT, the toroidal magnetic field, and the bulk plasma. This thesis demonstrates the localized characteristics of CT fueling and provides both theoretical insights and experimental advancement for advancing CT fueling technology and designing fueling systems for future fusion reactors.

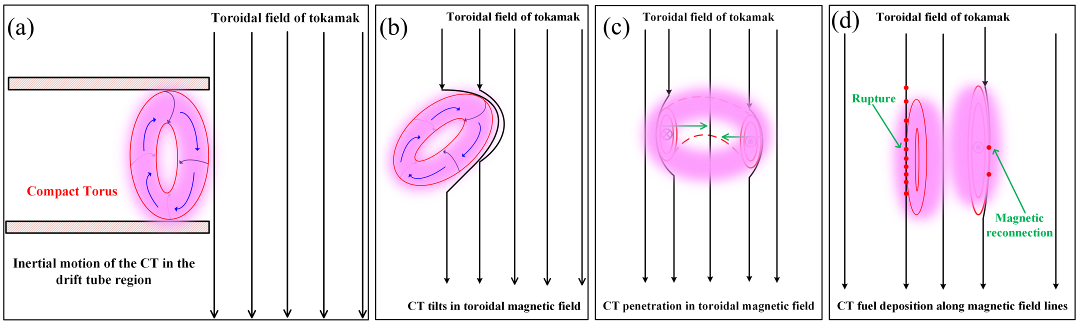

Figure 5. Schematic of CT penetration and fuel deposition in the KTX device.

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