EXPERIMENTAL RESEARCH ON THE PENETRATION BEHAVIOR OF COMPACT TOROID FUELING ON EAST

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Compact Torus (CT)[1] technology has developed rapidly in recent years, CT is a high-density, self-organized plasma configuration characterized by its robust magnetic topology and high directional kinetic energy density. Due to these properties, CT exhibits exceptional capability to penetrate strong magnetic fields, making CT injection one of the most promising techniques for core fueling in future fusion reactors. A compact torus injection system (EAST-CTI)[2] has been developed and successfully deployed for fueling experiments on the Experimental Advanced Superconducting Tokamak (EAST)[3]. Currently, the detection of injection depth during compact torus injection (CTI) core fueling processes primarily relies on electron cyclotron emission imaging (ECE)[4] and reflectometer (REFL)[5] diagnostics. While ECE and REFL offer advantages in plasma diagnostics, they suffer from limitations such as reduced accuracy due to high-temperature experimental environments, localized measurement constraints, and the complexity of data interpretation requiring specialized expertise.This investigation demonstrates an innovative methodology employing high-speed CCD imaging systems[6] to systematically document fuel injection dynamics in CTI core configurations, combined with image processing techniques and deep learning models to analyze the CCD images and quantify the dynamic variation of injection depth. As illustrated in Figure 1, the Compact Torus Injection (CTI) system is installed at the H-port of the EAST device. The visible light camera system is positioned at the F-port, with the EAST-CTI device at the H-port falling within the horizontal field of view of this camera. Consequently, this configuration enables the camera to capture the complete core fueling process during CTI operation.

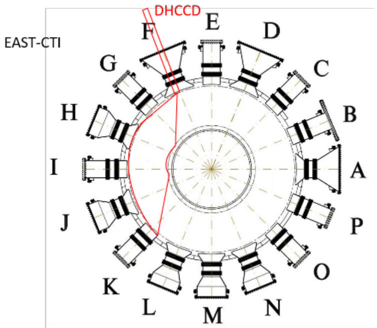


Fig1. Horizontal overhead view of the EAST device with 16 ports. The compact tours injection device is located at port H and the camera is located at port F. The red area is the horizontal field of view of the camera.

During the core fueling process of Compact Torus Injection (CTI), visible light camera image analysis reveals a distinct convex structure in the plasma density distribution within a millisecond timescale. This convex structure exhibits a dynamic evolution characterized by initial inward contraction followed by outward expansion. The boundary of this transient structure is defined as the "cold radiation ring" (as illustrated in Figure 2(a)). The temporal variation of the cold radiation ring's spatial position directly reflects the dynamic changes in CTI injection depth. By employing CCD image recognition techniques to extract and enhance the edge features of the cold radiation ring, quantitative analysis of its positional evolution provides critical insights into the fuel penetration dynamics post-CTI injection. In order to study the injection depth during the core fueling process of the compact torus, this paper uses image processing techniques to analyze the images captured by a visible light camera. First, the images captured by the visible light camera are calibrated experimentally to complete the conversion between image coordinates and real-world coordinates. After enhancing the image edges using Sobel and Prewitt edge detection algorithms[7], the deep learning U-Net[8] neural network model is used for image segmentation, completing the recognition of the injection depth during the core fueling process of the compact torus. The recognition results are shown in Figure 2(b).

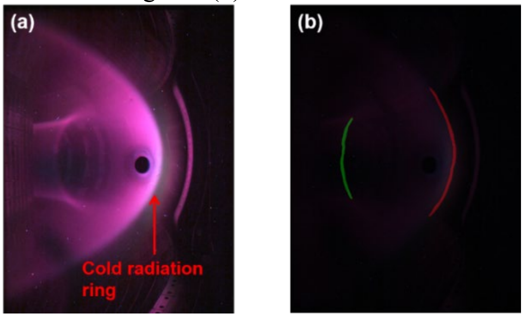
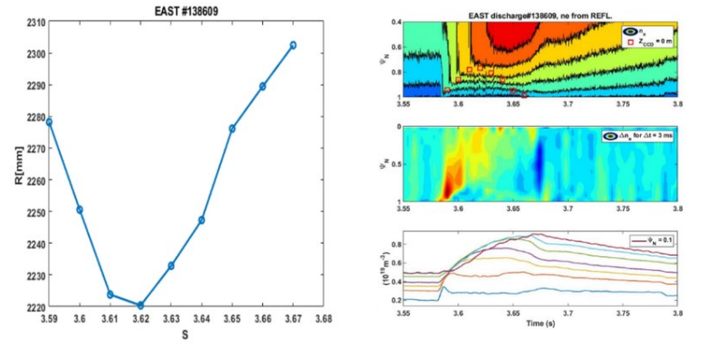


Fig2. Visible camera image of the CTI core fueling. (a)The red clippings are the raised edges, i.e., the cold radiating rings. (b)U-Nnet test results.

As illustrated in Figure 3, the depth variation detected via the CCD camera exhibited a temporal evolution characterized by an initial inward contraction followed by subsequent outward expansion. This observed trend demonstrated strong self-consistency with diagnostic results from both Electron Cyclotron Emission (ECE) and Reflectometry (REFL), thereby confirming the validity and feasibility of the methodology proposed in this study.The development of this algorithm holds critical importance for efficiently and accurately assessing injection depth in CT core fueling.



(a) (b)

Fig3. Comparison of changes in injection depth. (a) U-Net detects changes in depth. (b) REFL Reflectometer Density.

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