CONFERENCE PRE-PRINT

Magnetic flux surface mapping system at Chinese First Quasi-axisymmetric Stellarator

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Abstract

The Chinese First Quasi-axisymmetric Stellarator (CFQS), jointly developed by Southwest Jiaotong University (SWJTU) in China and the National Institute for Fusion Science (NIFS) in Japan, is the world's first operational quasi-axisymmetric stellarator employing non-planar modular coils. It is designed to experimentally explore plasma confinement characteristics in the quasi-axisymmetric (QA) magnetic field configuration. One of the essential commissioning tasks after device construction is to measure closed and nested flux surfaces with quasi-axisymmetry. A dedicated magnetic flux surface mapping system has been developed for CFQS, mainly consisting of a movable electron gun, a high-transmittance fluorescent mesh, and a high-sensitivity CCD camera. This system enables flexible scanning from the magnetic axis to the last closed flux surface, while ensuring that the electron beam is emitted as parallel as possible to the magnetic field lines. During initial commissioning at the CFQS-Test device with 0.1 T magnetic field, the system successfully obtained the first magnetic surface images, both in three-dimensional field-line-tracing mode and in two-dimensional Poincaré section mode. These results demonstrate the diagnostic capability to visualize nested surfaces, magnetic islands, and potential error fields with high fidelity. The establishment of this system not only validates the QA configuration of CFQS, but also provides a robust tool for future investigations of magnetic topology, error field correction, and divertor configuration studies.

1. INTRODUCTION

For stellarator devices, the existence of closed, nested and rotating magnetic flux surfaces is an essential prerequisite and can be straightly obtained in the vacuum condition. Therefore, unlike a tokamak, the magnetic configuration can be mapped by using magnetic flux surface mapping techniques even without plasma operation [1,2].

The CFQS is designed to have the major radius R_0=1.0 m, the toroidal magnetic field B_t=1.0 T, and the toroidal periodic number N_p=2. In August 2024, CFQS-Test device has begun commissioning with a magnetic field strength of 0.1 T [3-5]. Like other stellarators, it is well-suited for using flux surface mapping techniques to analyze the magnetic field because of the steady operation during the experiment [6]. So, a crucial experiment to verify the QA magnetic field configuration is prepared by developing the magnetic flux surface mapping system. To cover the designed magnetic axis and the last closed magnetic surface, the electron gun drive mechanism can cover two-dimensional spatial positions in both radial and poloidal directions. Meanwhile, the emission direction of the electron gun can also change with the rotational motion of the drive rod, ensuring that the emission direction of the electron gun is as parallel as possible to the magnetic field lines, thereby minimizing the Larmor radius. The movable fluorescent mesh with a transmittance of 0.95 is designed to serve both the coverage of the entire magnetic surface and the periodic motion of the electron beam in the toroidal direction. The high-sensitivity camera is required to have long exposure times under dark conditions to capture the light emitted by the fluorescent agent (ZnO) to obtain the geometric profile of the magnetic surface.

An overview is provided of the diagnostic setup for the CFQS flux surface mapping and the initial experimental results on CFQS-Test device are also presented.

2. EXPERIMENTAL SETUP

Consistent with previous stellarator implementations [1,7], the CFQS flux surface mapping system comprises an electron gun, a fluorescent mesh, and a high-sensitivity camera. The fundamental is that the low-energy electron beam emitted by the electron gun travels along magnetic field lines. When it passes through the mesh coated with a fluorescent agent (ZnO), it reacts with the agent, producing visible light [8]. This light is then captured by a high-sensitivity camera to record images of the magnetic surfaces. Through these images of the magnetic surfaces, we can obtain physical information about the magnetic configuration, such as error fields caused by manufacturing and assembly, the magnetic island configuration, and so on [9,10].

The geometric arrangement of the mapping system is illustrated in Figure 1. The emission direction of the electron gun (counterclockwise), the camera's shooting angle, and the positioning of the electron gun are designed to minimize the impact of scattered light on the fluorescent mesh imaging.

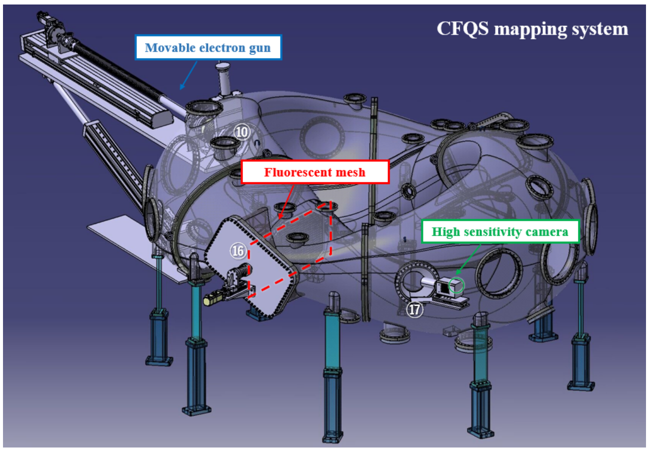

FIG. 1. *Geometric arrangement of the CFQS magnetic flux surface mapping system.*

2.1. Electron gun and driving mechanism

The electron gun is the core part of the mapping experiment. The low-energy electron beam emitted from the electron gun travels along the magnetic field lines, outlining the complete magnetic surfaces. The electron gun is designed with dimensions of approximately $12mm \times 12mm \times 15mm$ and includes a housing that shields the filament light which is shown in Figure 2. The small size is intended to minimize the impact of electrons striking the back of the electron gun after moving toroidally around the CFQS.

During the CFQS experiment, the electron beam can exit the gun parallel to the magnetic field lines through an orifice which is about 1mm in diameter and the energy of the electrons could be adjusted between 20 to 250 eV, and this tunability is used to balance the images brightness and spatial resolution of the flux surface to obtain the best results during mapping experiments.

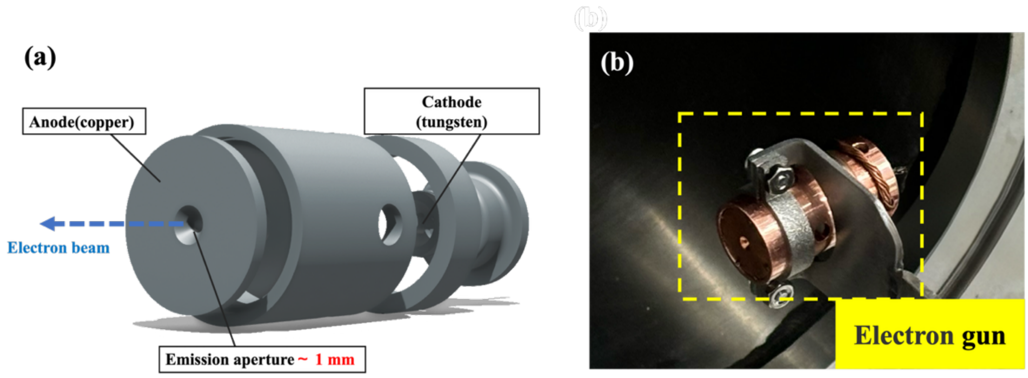

FIG. 2. The structure and material of electron gun (a) and its photograph of in CFQS-Test device (b).

Regarding the materials for the electron gun's cathode and anode, copper was employed for the anode. For the cathode, a tungsten-based material enhanced with barium oxide (BaO) coatings was selected. This coated tungsten cathode demonstrates excellent electron emission efficiency at relatively lower operating temperatures, typically ranging from 1000°C to 1500°C, owing to the significant reduction in work function provided by the coatings. Furthermore, tungsten offers a significant cost advantage, primarily due to its comparatively simpler production process and the ready availability of raw materials. Figure 3 shows the emission curve of the electron gun obtained during the testing process, with a filament current of 0.60 A.

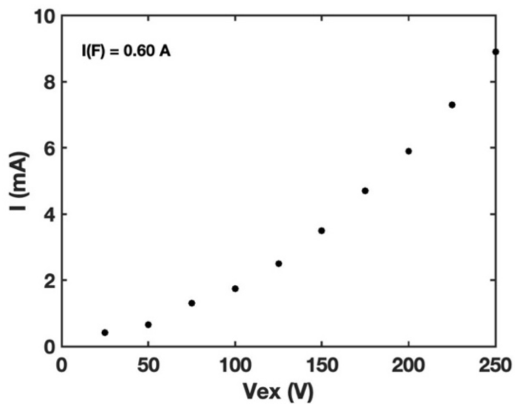

FIG. 3. The measured extracted electron beams current as a function of extracting voltage.

Due to the complex magnetic field configuration of the stellarator and the necessity for electrons to scan from the magnetic axis to the last closed flux surface, the design of the electron gun's drive mechanism is very crucial. In CFQS mapping system, the electron gun's drive mechanism is designed to possess three degrees of freedom: horizontal tilt (about ±18 degrees), axial movement along the rod (about 700 mm), and rod rotation (about ± 30 degrees). The first two adjustments allow the electron gun to reach the magnetic axis and different magnetic surfaces, while the latter ensures that the emission direction of electrons remains as parallel as possible to the magnetic field lines, thereby minimizing the Larmor radius.

The electron gun and drive mechanism are situated at Port 10 in the CFQS. Figure 4 shows a cross-sectional of the electron gun port and the spatial range it can reach (yellow area) and its photo in CFQS-Test device.

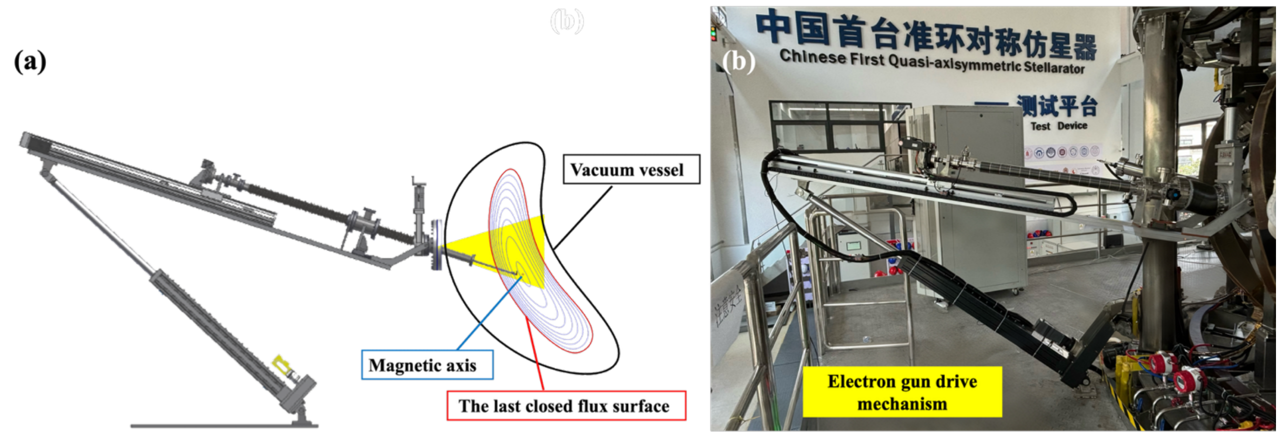

FIG. 4. Schematic diagram of the electron gun drive mechanism (a) and its photograph of in CFQS-Test device (b).

2.2. Fluorescent mesh

Utilizing a fluorescent mesh, the electron trajectories can be imaged. The mesh is installed at port 16 in the CFQS which is about 90 degrees position of the magnetic surface. The size of the mesh is about $0.4\text{m} \times 0.6\text{m}$ (includes the entire 90-degree angle of the last closed flux surface) as shown in Figure 5(a). And Figure 5(b) shows an image of fluorescent mesh shoot by the high-sensitivity camera in CFQS-Test device. Besides, to increase the passing rate of the electron, the mesh has 0.95 transparency and $20\text{mm} \times 20\text{mm}$ grids. It can also slowly move 20 mm periodically to cover the entire space of the magnetic surface.

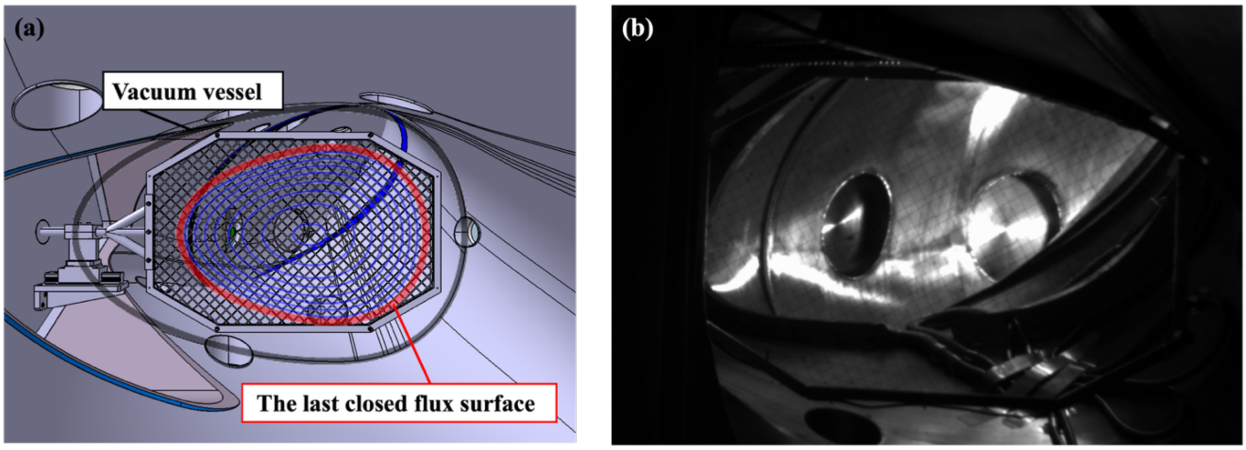

FIG. 5. *(a)The diagram of the fluorescent mesh in the CFQS device, with red circles representing the last closed flux surface. (b)The image of fluorescent mesh shoot by the high-sensitivity camera.*

Powder (ZnO: Zn) is used as a fluorescent agent coating on the mesh. When struck by electrons, this material emits yellow-green visible light at a wavelength of approximately 500 nm, which can be captured by a high-sensitivity camera [8].

2.3. Observation system

The primary component of the observation system is a high-sensitivity CCD camera (Andor iKon-M 934 Series) which is shown in Figure 6. Its sensor has a resolution of 1024×1024 pixels and peak quantum efficiency is about 90%. With high quantum efficiency, deep cooling, and ultra-low noise, the Andor iKon-M 934 camera is an ideal choice for capturing weak luminescence from the fluorescent agent on the mesh in the mapping experiments. The camera is installed on the atmospheric side of a vacuum window. To keep the viewing geometry as close as practicable to normal incidence on the fluorescent mesh, an auxiliary optical path is employed and the working distance from the lens to the mesh is about 1.2 m.

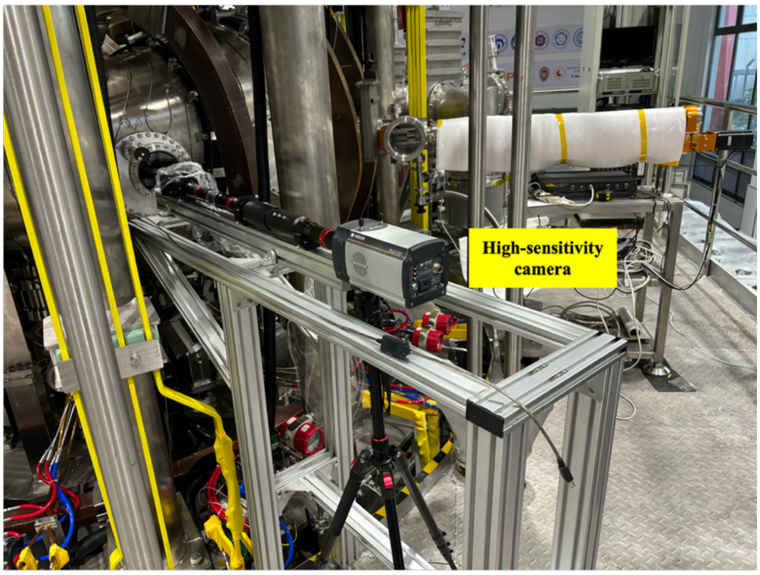

FIG.6. *The photograph of high-sensitivity camera and optical path in CFQS-Test device*

3. INITIAL MAPPING RESULT IN CFQS-TEST DEVICE

In the CFQS-Test device, three types of coils are employed: Modular Coils (MC coils), Toroidal Field Coils (TFC coils), and Poloidal Field Coils (PFC coils). The MC coils are used to generate the standard quasi-axisymmetric magnetic field configuration, while the TFC coils and PFC coils are employed to produce the other configuration, thereby achieving other magnetic field configurations. An essential part of the mapping experiment is to verify the quasi-axisymmetric magnetic field configuration of CFQS. As shown in the Figure 7, only the MC coils will be utilized. For example, with a 0.1T magnetic field, a current of approximately 31.25kA is passed through the 16 sets of MC coils to generate this standard magnetic field configuration.

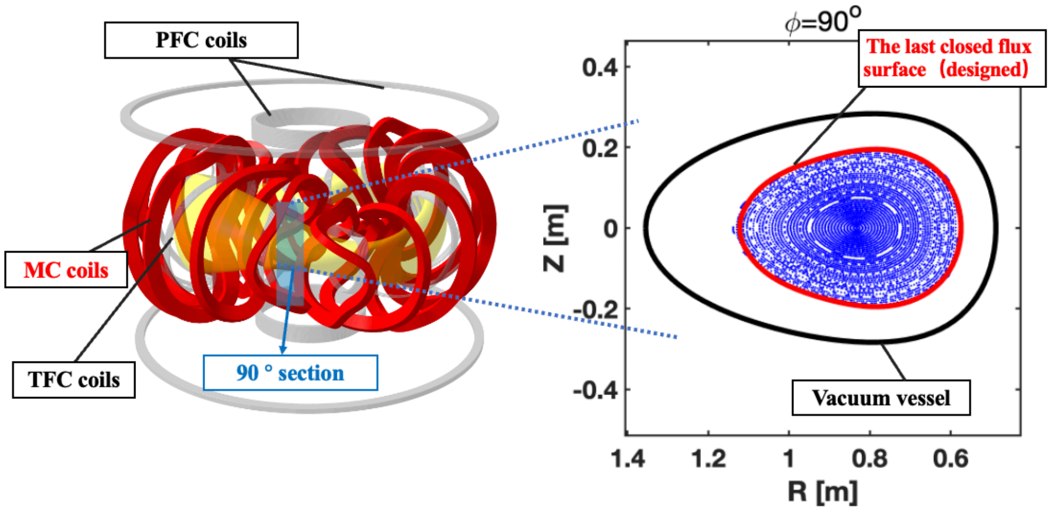

FIG. 7. *The standard QA configuration generated by only MC coils (red) and Poincare plot of the magnetic surface of the 90°section (fluorescent mesh position)*

The mapping system was first deployed on the CFQS-Test device device and could be operated in two modes: 3D magnetic field imaging and 2D Poincaré section imaging.

In the first mode, in which no fluorescent mesh is installed, the vacuum vessel is backfilled with argon (Ar) to a low neutral pressure (~10^{-4} pa). When the electron beam (~20 eV) is injected, the electrons follow magnetic field lines and electron-impact excitation of argon generates visible glow along the beam trajectory, thereby mapping the three-dimensional magnetic topology which shown in Figure 8(a).

Under high vacuum condition, the fluorescent mesh technique is employed to yields two-dimensional Poincaré sections of the flux surfaces in second mode. Figure 8(b) shows an experimental image of one magnetic flux surface measured by this mapping system. The experimental conditions are as follows: the vacuum level is approximately 10^{-5} Pa, the magnetic field strength is 0.1 T, the electron beam energy is around 40 eV, and the exposure time of the high-sensitivity camera is 55 s. These measurements provide the geometric information of magnetic configuration to precisely estimate errors in the CFQS magnetic field.

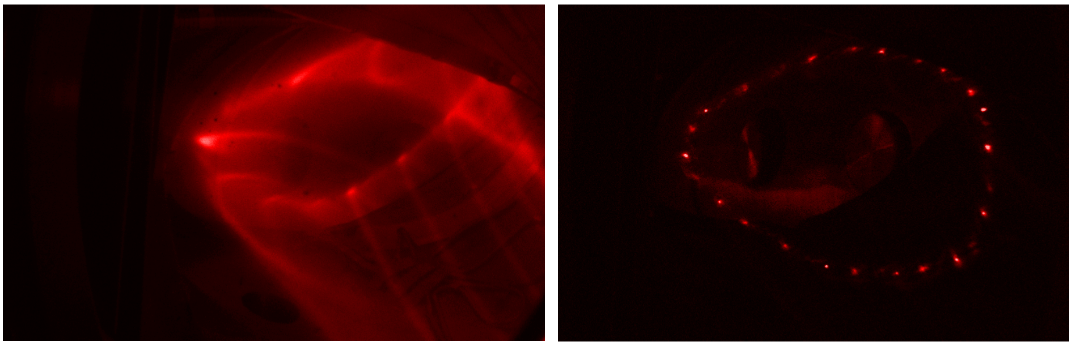

FIG. 8. *(a) 3D magnetic field image (without fluorescent mesh) (b) 2D Poincaré plot of magnetic topology*

4. SUMMARY AND OUTLOOK

In this work, a flux surface mapping system for the CFQS has been successfully designed, constructed, and tested. The diagnostic integrates a multi-degree-of-freedom electron gun, a ZnO-coated high-transmittance fluorescent mesh, and a high-quantum-efficiency CCD camera. This system is capable of tracing and visualizing all magnetic field surfaces accurately.

The system was first deployed on the CFQS-Test device at a magnetic field strength of 0.1 T. It operated in two modes: (1) 3D beam imaging in argon background gas, which provides direct visualization of magnetic field-line trajectories; and (2) 2D fluorescent mesh imaging under the high vacuum condition, which yields Poincaré plots of closed flux surfaces and allows estimation of error fields to be < 0.1% [11]. These initial experiments confirmed that the QA flux surfaces are formed precisely as designed.

Further optimization will be pursued to enhance spatial resolution and quality of mapping experiments—for example, reducing the electron gun aperture to ~0.5 mm and refining camera exposure strategies. The system will be applied in higher-field experiments (up to 1.0 T) on CFQS, enabling more detailed studies of QA magnetic topology, error field sources, and island divertor configurations.

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