Development of Magnetic Flux Surface Measurement Method on TOKASTAR-2*)

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The measurement method of magnetic flux surfaces on TOKASTAR-2 was developed. The electron gun was designed and fabricated. Calculation of the orbit of electrons showed that low energy of injected electrons, typically less than 50 eV, was proper for the measurement to suppress large deviation of the electron orbits from the magnetic flux surfaces. The preliminary experiment for the method using a fluorescent screen showed that the acceleration voltage of 80 V was required and we need significant improvement of the electron gun to apply the method using a fluorescent screen to TOKASTAR-2. The experiment for the method using a probe showed that the required acceleration voltage was 10 V so we found that the method using a probe was proper for a small plasma confinement device with weak magnetic field like TOKASTAR-2.

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1. Introduction

Plasma confinement in a stellarator device relies on formation of closed magnetic flux surfaces by external coils. Therefore, measuring magnetic flux surfaces experimentally is significant for stellarator experiment.

TOKASTAR-2 is a plasma confinement device which has two coil systems, one for tokamak and the other for stellarator [1]. The purpose of TOKASTAR-2 is to study the influence of helical magnetic field application to the tokamak plasma and the influence of the plasma current to helical plasma.

Figure 1 shows the schematic view of the TOKAS-TAR-2 coil systems. The TOKASTAR-2 coil systems consist of eight Toroidal Field (TF) coils (50 turns each), two Pulsed Vertical Field (PVF) coils (20 turns each), threeblock Ohmic Heating (OH) coils, two Helical Field (HF) coils (98 turns each), two Additional Helical Field (AHF) coils (126 turns each) and two Vertical Field (VF) coils (100 turns each). The VF coils are installed outside of the vacuum vessel and the other coils are inside it. The TF coils, the PVF coils and the OH coils are connected to pulsed power supplies with capacitor banks while the AHF coils, the HF coils and the VF coils are connected power supplies with steady state operation. The tokamak coil system and the stellarator coil system can be operated independently.

The stellarator coil system was designed to make



Fig. 1 Schematic view of the TOKASTAR-2 coil systems.

closed magnetic flux surfaces without any plasma current. However, due to the influence of manufacturing errors, installation errors of coils and error fields, the location and shape of the helical magnetic flux surfaces can be deviated from the ideal ones. Generally, detection of electrons injected by an electron gun is used to measure vacuum flux surfaces. The deviation of electron orbits from flux surfaces becomes larger for larger electron energy with larger drift velocity and hence lower acceleration voltage is preferable. The allowable acceleration voltage would be lower especially in a small device with weak magnetic field. On the other hand, the electron current injected by an electron gun would be smaller for a lower acceleration voltage. Therefore the acceleration voltage should be carefully determined for flux surface measurement in small devices. The required electron current would depend on the method for detecting electrons. The object of this paper is feasibility study to measure the magnetic flux surfaces experimentally showing how to decide the acceleration voltage and the method for detecting electrons to mea-

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Fig. 2 Schematic view of the method using a probe.

Injected electron

sure magnetic flux surfaces in a small device with weak field.

2. Method for Measurements

Signal output

No signa

Two methods are commonly employed to detect electrons and measure magnetic flux surfaces experimentally. One is a method using a fluorescent screen and the other is a method using a probe [2-4]. In both methods electrons emitted from an electron gun are detected in vacuum, without plasma. These methods are based on the property that injected electrons travel along the field lines. Figure 2 shows a schematic view of the method using a probe. The electron gun and the probe are located at different toroidal positions. The position of the probe is scanned horizontally and vertically at a fixed toroidal position. If the point where electrons were injected and the position of the probe are on the same magnetic flux surface, injected electrons hit the probe and generate the probe current. The shape of the magnetic flux surface is obtained connecting the probe positions where the probe current is detected.

Figure 3 shows a schematic view for a plan to apply the method using a fluorescent screen to TOKASTAR-2. The electrons are injected by the electron gun at a certain point and circle along the field lines just like in the method using a probe. A highly transparent fluorescent mesh screen is installed on a side of one of the TF coils. A part of electrons hit the fluorescent screen while most of the electrons do not hit the fluorescent screen but keep on circling around the torus since the screen is highly transparent. The electrons hit the fluorescent screen at the other laps and the points hit by the electrons emit fluorescent light. The image of fluorescent light is observed by a CCD camera.

These methods need development of an electron gun and analysis of the orbit of electrons commonly. On the other hand, the method using a probe takes longer time than the other since the measurement should be repeated by changing the probe position horizontally and vertically covering the measurement area inside the walls. It also needs a mechanical system to move the probe horizontally and vertically. Thus, the method using a fluorescent screen



Fig. 3 Schematic view for a plan to apply the method using a fluorescent screen to TOKASTAR-2.

is basically superior to the method using a probe. Then, we designed the electron gun and analyzed the orbit of injected electrons first. After that, we examined whether the method using a fluorescent screen can be applied to TOKASTAR-2. In examination, we focused on estimation of the acceleration voltage required for fluorescent light emission.

3. Design of the Electron Gun

We designed and fabricated the electron gun for measurements. Figure 4 shows the assembly drawing of the electron gun. The electrons are emitted as thermion from the tungsten filament and injected through a 1 mm aperture in the filament holder surface. There were four important points in designing this electron gun. First, a part near the filament will become hot and hence the electrical isolation parts were made from ceramic. Second, we decided the diameter of the holder to be 7 mm so that the injected electrons will not hit the holder when they circle the torus. The vertical distance between the point where electrons are injected and the point where the electrons come after circling the torus once was evaluated to be 3.7 mm in a typical magnetic field configuration by a field line tracing code HSD [5]. Third, the radial position of the gun can be adjusted by using a bellows between R = 0.12 mand R = 0.16 m, where R is the major radius. Finally, the stainless-steel filament holder can be turned to adjust the injection angle between -15 degrees and +15 degrees from the equatorial plane keeping the vacuum of the device.

4. Analysis of the Electron Orbit

We calculated the orbit of electrons in the typical magnetic configuration condition using HSD. Figure 5 shows the result of the calculation. The outermost line indicates the last closed magnetic flux surface in this condition and the other lines indicate the orbits of the guiding center of the electron with several energy. The electrons were in-



Fig. 4 The assembly drawing of the electron gun.



Fig. 5 Orbit of electrons in the typical coil current condition.

jected parallel to the equatorial plane at R = 0.159 m, Z =0 m, on the last closed magnetic flux surface. The electrons will be injected at this point in this coil current condition in the measurements. The higher the energy of electrons was, the more largely the orbit of electrons deviated from the magnetic flux surface. When the energy of electrons was 50 eV or more, a part of the orbit was outside of the magnetic flux surface. The deviation between the last closed magnetic flux surface and the orbit of electrons became smaller on the outer side, around R = 0.16 m. The deviation is in inverse to the local rotational transform. Since the helical coils are located at R = 0.24 m, the local rotational transform is larger on the outer side than in the other areas and hence the deviation is smaller. From the analysis of electron orbits, we found that the lower energy of the electrons, typically less than 50 eV, was proper to measure the magnetic flux surfaces in TOKASTAR-2.

5. Preliminary Experiment for the Method Using a Fluorescent Screen

We performed preliminary experiment without magnetic field to estimate the electron energy required to observe the fluorescent agent emission. Agents P15 and P24 (designation of Joint Electron Device Engineering Coun-



Fig. 6 Layout of the preliminary experiment for the method using a fluorescent screen.



Fig. 7 Conditions for detecting fluorescence in the preliminary experiment.

cil, ZnO:Zn) were used because these agents have good emission efficiency for low energy electrons [6]. A fluorescent mesh screen made of the stainless steel wires with diameter of 0.2 mm was used. Figure 6 shows the layout of the preliminary experiment. The distance between the filament holder and the fluorescent screen was 10 cm. The electrons were injected by acceleration voltage, V_a , and emission of light was observed through the viewing port by eye. The acceleration voltage and the power of the filament were scanned.

Figure 7 shows the results of the preliminary experiment. As shown in Fig. 7, the electron energy larger than about 80 eV was required to observe the fluorescence of P15 and P24. Since the deviation between the orbit of electron with 80 eV and the magnetic flux surface is large as shown in Fig. 5, we concluded that significant improvement of the electron gun was needed to apply the method using a fluorescent screen to TOKASTAR-2.

The required electron energy in this experiment is quite larger than the work function of ZnO:Zn of about 2.5 eV [7]. This is because the light emitted from the hot filament and reflected on the fluorescent screen hinders detection of weak fluorescent light emission.

6. Preliminary Experiment for the Method Using a Probe

We performed preliminary experiment for the method



Fig. 8 Layout of the experiment for the method using a probe.



Fig. 9 (a) The time evolution of the probe current. (b) The observed current as a function of the acceleration voltage.

using a probe to estimate the lowest acceleration voltage for the probe to detect the current by injected electrons. The acceleration voltage was applied with a pulse circuit. The pulse width was 200 μ s. This corresponds to the flat top duration of TF coil current in TOKASTAR-2. The probe tip was in a square shape with 5 mm × 5 mm. The electric power of the filament was 9 W. Figure 8 shows the layout of the preliminary experiment. We measured the voltage of 1 M Ω resistance connected to the probe for evaluating the probe current. Figure 9 (a) shows the time evolution of the probe current. The probe current due to injected electrons is indicated by the arrows. The large spikes on the both sides of the flat part of the probe current are noise; they appeared even when the filament current was turned off. The current in the flat part between the two vertical dotted lines in Fig. 9 (a) was averaged for each shot. Figure 9 (b) indicates 20 shots average of the averaged current as a function of the acceleration voltage. We confirmed that the probe could detect the current for the acceleration voltage of 10 V and the pulse width of $200 \,\mu s$ so we decided that the method using a probe was proper for TOKASTAR-2.

7. Summary and Discussion

The method to measure magnetic flux surfaces on TOKASTAR-2 was developed. The electron gun was designed and fabricated. The orbit of injected electrons was calculated showing that the low energy of the electrons, typically less than 50 eV, was proper to measure the magnetic flux surfaces in TOKASTAR-2. The acceleration voltage required to observe fluorescent agent emission light was investigated for the fabricated electron gun and was found to be about 80 V, for which the deviation of electron orbits from the flux surface would be unacceptably large, and then we concluded that significant improvement of the electron gun was needed to apply the method using a fluorescent screen to TOKASTAR-2. On the other hand we confirmed that the probe could detect the electron current for the acceleration voltage of 10 V and the pulse width of 200 µs so we found that the method using a probe was proper for a small device with weak magnetic field like TOKASTAR-2.

The probe tip used in the preliminary experiment was in a square shape with $5 \text{ mm} \times 5 \text{ mm}$. In the measurements, a smaller probe tip is proper considering the space resolution of the flux surface measurement and then the probe current would be smaller. If the obtained current was insufficient for a smaller probe tip, improvement of the electron gun, for example changing the tungsten filament to thoriated tungsten filament, would be required.

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