Fatal Damages due to Breakdown on a Diagnostic Mirror Located outside the Vacuum Vessel in JT-60U*)

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Some discharge phenomena seriously damaged the secondary mirror for Thomson scattering diagnostics, which was located outside the vacuum vessel. In this paper, the surface damages recorded on the mirror are observed in detail with an optical microscope. Many fine trails were found on the surface. The trails could be categorized into two different types with respect to the trail width. The mechanisms to lead the damages were discussed based on the observation. This study issues warning on the components to be installed in future fusion devices both inside and outside the vacuum vessel.

Keywords: diagnostic mirror, breakdown, arcing, surface discharge

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1. Introduction

In fusion devices, the initiation of arcing has been an important plasma surface interaction issue, because it could cause damages on divertor and first wall materials and deteriorate the plasma performance consequently [1,2]. Recently, an enhancement of the initiation of arcing on divertor surfaces has been pointed out due to the surface morphology change and transient heat loads, such as ELMs and disruptions [3–5]. Because the pulsed heat load of the ELMs and morphology changes caused by helium irradiation could be more serious in future fusion devices like ITER and DEMO compared to the situations in present tokamaks, further investigation is required to understand the mechanism of arcing and find the way to suppress the initiation.

Arcing and breakdown phenomena have been observed not only on the divertor plate and first wall, but also on an in-vessel mirror [6], heating antenna [7], and so on. Shown in Figs. 1 (a) and (b) are arc trails recorded on corner cube retroreflector (CCR) and optical shutter in JT-60U, respectively. They were equipped inside the vacuum vessel. The CCR was composed of Zerodur and the surface was coated with gold, and the optical shutter was made of stainless steel. It is worth noting that the CCR was located on the upper diagnostic base of JT-60 and was several meters away from the plasma. It seems that the arcing has been frequently observed inside the vacuum vessel. However, arcing or breakdown phenomena take place not only inside the vessel, but also outside the vessel.

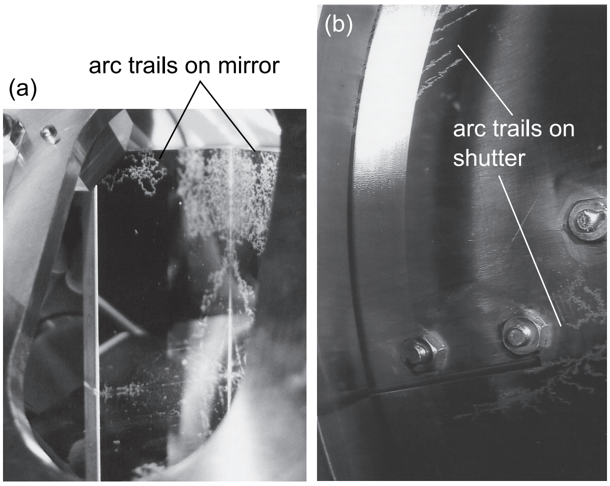

Fig. 1 Pictures of arc trails recorded (a) corner cube retroreflector for interferometer measurement in JT-60U and (b) optical shutter for Thomson scattering system in JT-60U.

In this study, we will report the breakdown phenomena occurred on a diagnostic mirror in JT-60U, which was located outside the vacuum vessel. Because the damages were so fatal that the mirror had to be replaced after the breakdown. In this study, details of the characteristics of the damage are revealed from the observation of the trails. Furthermore, the mechanism to cause the damages will be discussed based on the observation.

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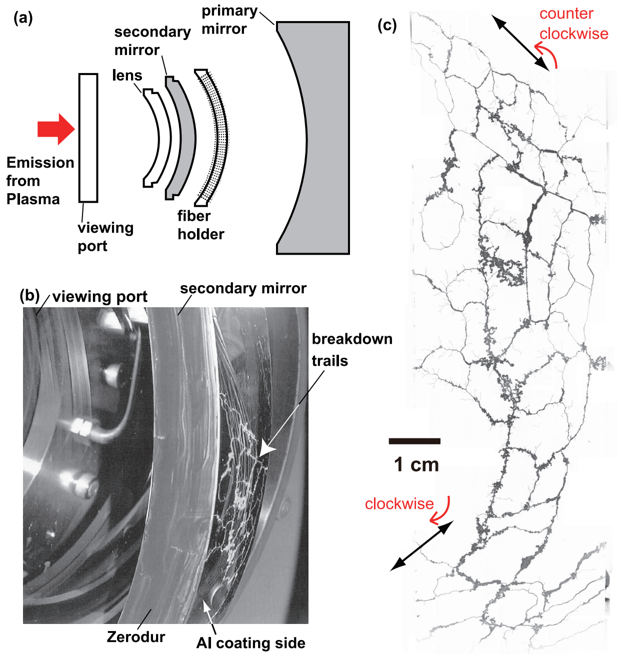

Fig. 2 (a) shows a schematic of the collection optics for Thomson scattering system in JT-60U. (b) shows a picture of the damaged secondary mirror. (c) The whole image of the surface damage observed with an optical microscope.

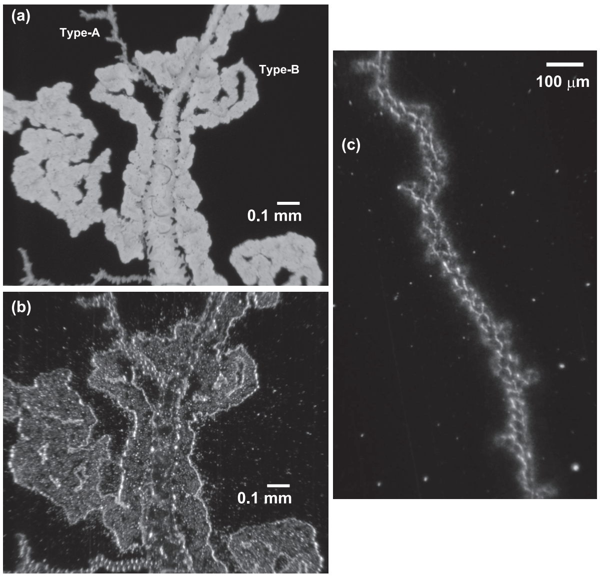

Fig. 3 Detailed pictures of the trail. The object was illuminated from the backside in (a), while it was illuminated from the front side in (b). (c) an enlarged images of type-A trail.

2. Observation of Trails

Figure 2 (a) shows a schematic of the collection optics for Thomson scattering system in JT-60U [8, 9]. In Fig. 2 (a), scattered photons, which come from the left hand side, pass through a viewing port and lens, and they are transferred with primary and secondary mirrors and collected with optical fibers equipped on a holder. The optics is located in between the toroidal coils, where a strong magnetic field should exist during discharges. Figure 2 (b) shows a picture of the damaged secondary mirror, which was installed in 1991. The picture was taken from the primary mirror side, and the plasma existing area is over the viewing port seen in the left part in Fig. 2 (b). The damage on the surface was found in November 1999, and the mirror was replaced in the next year. It is highly possible that the damage was formed within several months before the finding, because detailed checks of the optics had been conducted constantly. The base material of the secondary mirror was Zerodur, which is a glass-ceramic made by Schott AG. One of the advantages of Zerodur is low (nearly zero) thermal expansion around the room temperature. The surface was covered with a protection coating in addition to an aluminum coating on Zerodur. Because the protection coating layer was an insulator, it was likely that the aluminum layer was not connected anywhere electrically.

The surface of the damaged secondary mirror was observed by an optical micrograph (VCR800, Omron Co.). Figure 2 (c) shows a whole image of the surface damage. For the observation using an optical micrograph, it was technically important how to illuminate the object. In Fig. 2 (c), the object was illuminated from the backside in a dark room. Because Zerodur is optically transparent and aluminum reflects light, the damaged part, where aluminum coating was removed, can be clearly identified by illuminating from the backside. It is seen that many lines run up and down and bridges between the longitudinal lines are formed; moreover, bifurcations occur frequently. From the shape of bifurcated trails, the phenomena could be categorized to electrical treeing.

Figures 3 (a) and (b) show detailed pictures of the trail, where the mirror was illuminated from the front side. It is identified that there exist two different types of trail with respect to the trail width. They are called as type-A and type-B in this paper: type-A with the trail width of ~30–40 μm and type-B with the width of ~60–70 μm. Short bifurcated trails correspond to type-A, while major trails seem to be composed of type-A and type-B. Figure 3 (c) is an enlarged image of the type-A trail. It is identified that the trail is composed of many small footprints. The characteristics are similar to arc trails. Usually, for arcing, trail is formed in the process of repetitive re-ignition of arc spot [10]. It is thought that type-A trails were formed by the motion of spots.

Figure 4 (a) shows a micrograph of the trail on the surface. From the direction of the treeing, we can determine the direction of the motion of the spot. For the case of Fig. 4 (a), the spot would have been moved from left to right, because the treeing grew toward the right direction. In Fig. 4 (b), the direction of the motion identified from the direction of treeing are presented as arrows. The directions are not unique, but rather random. Moreover, at location A

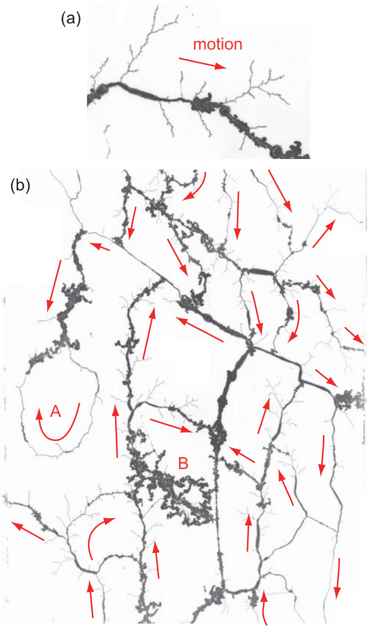

Fig. 4 Optical microscope images of the trail on the surface. The directions of the motion is depicted as arrows.

in Fig. 4 (b), the spot turned around clockwise. At location B in Fig. 4 (b), the trail shows fractal-like feature, indicating that the spot seemed to move very randomly. Although variation of fractality in a trail has been observed recently at the terminal point of an arc spot [11], the fractality of an arc trail is basically determined by the magnetic field strength. In Fig. 4 (b), on the other hand, the trail is mainly composed of sharp lines with treeing, and sometimes fractal-like feature appears on the trail. Such a mixed feature cannot be usually seen on a trail of arcing.

3. Discussion

3.1 Initiation source

To initiate the breakdown, charged particles, i.e. electrons, are necessary to be formed in the first place. They could be an initiation source if they were accelerated by the electric field somehow formed near the surface. Formation of damages by breakdown phenomena also occurs on a solar array in space [12, 13]. On the panels, the electron bombardment to the surface in space leads to secondary electron emission, which leaves positive charges on the surface. However, in our case, such a particle bombardment does not take place. The materials are only exposed to the ultraviolet and gamma ray radiations from the plasma. Even for dielectric material, photoelectric effect and Compton effect could occur and electrons might be released from the surface. For e.g., it might be possible that runaway electrons were produced during disruption and massive amount of gamma ray was released when they were bombarded to the wall. Around 1999, many high performance discharges and disruption experiments that produced runaway electrons were conducted in JT-60U. The neutron yield in 1999 was the second highest in the deuterium discharge experiment term from 1991 to 2008. From the end of May to the end of October, there were approximately 60 discharges only for the experiments of runaway electrons. Although no direct evidence has been found to support the mechanism, the discharge operation in this period might be related with the formation of initiation source.

3.2 Initiation and expansion of breakdown

After electrons are produced from the surface, an electric field is required to initiate the breakdown. Moreover, to explain the expanded trail in the whole area of the mirror, it is necessary to introduce some other mechanisms. It is thought that there are two types of candidate discharges: an arcing or a flashover discharge. If the direction of the formed electric field was normal to the surface, the dishcarge would be categorized to arcing, while it would be categorized to the flashover discharge if the direction was parallel to the surface.

From the trail observed in Fig. 3 (c), it seems that the part of the trail is formed by the re-ignition process of an arc spot. It is noted that since no material that can be another electrode existed near the mirror, the arcing corresponds to unipolar arc, in which a plate plays roles of both cathode and anode. Once a plasma is formed on the surface, unipolar arc can be sustained by forming a current loop locally, as described in Schwirzke's model [14]. In that sense, it might be possible that the plasma had two different footprints, namely, cathodic and anodic footprints. It is suspected that the type-A and type-B trails shown in Fig. 3 correspond to the cathodic and anodic footprints, respectively. However, it is unknown whether and why the electric field to initiate unipolar arcing was formed.

The motion of arc spots in the existence of magnetic field might extend the trail area. For arcing, an arc spot moves randomly without magnetic field; it moves retrograde ($-\boldsymbol{j} \times \boldsymbol{B}$) for parallel magnetic field to the surface [15] in vacuum and is reversed when the pressure is sufficiently high, such as in air atmosphere [16]. If the magnetic field lines cross the surface obliquely, the spots tends to drift in the direction of the opening of the acute angle between the magnetic field line and its projection on the cathode surface [15, 17]. As shown in Fig. 2 (c), the direction of many lines seems to be rotated at the upper and lower part of the trail. At the upper part, the line rotates counterclockwise, while it rotates clockwise at the lower part. At the upper and lower parts of the mirror, magnetic field crosses the surface, and acute angle rule might be introduced.

During disruption, in which great tokamak current is terminated in a short time period, say 1-100 ms, strong magnetic and electric fields can be formed in the current quench phase. It was likely that Eddy current flowed in the aluminum coating. A non-uniform electric field might be formed if the aluminum coating had non-negligible electric resistance. If the strength of the electric field exceeded the creepage resistance, the flashover discharge could be initiated. Considering the fact that the trail had various directionalities, a complicated structure, and loops, as shown in Fig. 4 (b), it was thought that the induced current might play roles to initiate flashover discharge.

4. Conclusions

The trails recorded on the secondary mirror for Thomson scattering diagnostics in JT-60U were observed and the mechanisms to form the damages were discussed. From the trail, it was thought the damages can be attributed to a breakdown phenomena. Some trails are composed of small footprints similar as arcing. Also, the trails have various directionality and complicated structure such as loops and fractal features. Considering the fact that the mirror was electrically floating and located in air atmosphere, it is highly likely that some abnormal events like disruption are related with the breakdown phenomena.

Concerning the breakdown mechanism, the electron release from the material by photoelectric effect and Compton effect may be the initiation sources. Unipolar arcing and flashover discharge are the possible candidate to expand the damages to the whole area of the mirror. Although the mechanism to arise the electric field to initiate the breakdown is yet to be understood, Eddy current in response to the disruption may play role to form the electric field. To investigate the phenomena further, since it is difficult to simulate the similar situation, finding similar damages around tokamks will provide clues to reveal the mechanism and the influences in future fusion devices.

Acknowledgments

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