HIGH-SPEED PHOTOGRAPHIC OBSERVATION OF PLASMA-LIMITER INTERACTIONS IN ISX-B*

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High-speed motion pictures confirm that arcing occurs during periods of plasma instability in ISX-B. Various types of plasma-limiter interactions are described and illustrated. Arcing and other visible phenomena are correlated to plasma paramèters.

1. INTRODUCTION

Limiters are mechanical devices used in tokamaks to protect walls and diagnostic devices from the hot central plasmas and to define the edge of the main plasma body. They are subject to intense bombardment by energetic plasma particles (hydrogen ions and electrons) and must absorb extremely high heat fluxes due to this bombardment. Limiter materials requirements are extremely severe. We are testing candidate limiter materials in ISX-B [1]. Sputtering, arcing, and vaporization all cause damage to limiters and result in impurities entering the plasma. The observations reported here are a part of our attempt to better understand the plasma-limiter interactions and the mechanisms which contribute to limiter performance.

The high-speed photographic observations were initiated especially to study the role of arcing in producing damage to coated limiters. The observations show arcing phenomena but are not limited to arcing and should stimulate interest and concern among those who design and use limiters.

Arcing may not only damage limiters but is a source of impurities in tokamak plasmas. Arc tracks are observed in all tokamaks and are especially severe on surfaces projecting close to the limiter radius and on the limiters themselves. We have previously shown by combined electrical and optical measurements that arcing occurs most frequently during periods of plasma instability [1]. This paper confirms previous observations and offers new insights into arcing and other interactions at the limiters. Typical interactions are illustrated using selected frames from the motion pictures.

2. TECHNIQUE

A Wallensak Fastax WF3 high-speed movie camera was set up to look at a split field image as shown schematically in Fig. 1. The port and mirrors are also used for fast infrared measurements of limiter temperatures. Both inner and outer limiters are seen as is shown in Fig. 2.

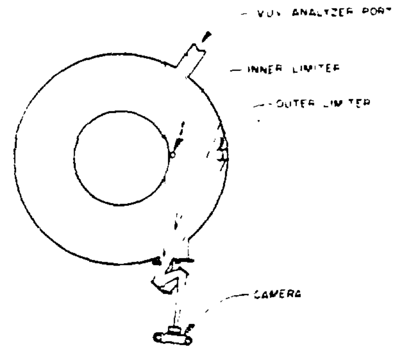

Fig. 1: Diagram of mirror system which gives a split field showing the inner and outer limiters in ISX-B.

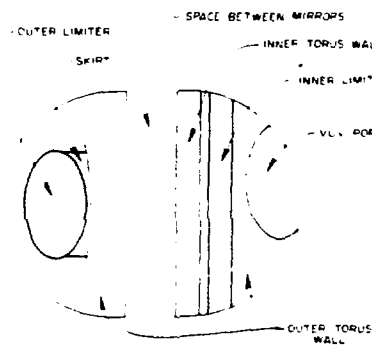

Fig. 2: Diagram of the view seen by the camera.

Note that the positions of the images are such that the main plasma is on the right side of the inner limiter and the left side of the outer limiter, <u>not</u> between them.

Images were recorded on Eastman Ektachrome video news film, high-speed 7250 tungsten (ASA400) at

*Research sponsored by the Office of Fusion Energy, U. S. Department of Energy under contract W-7405-eng-26 with the Union Carbide Corporation.

about 3000 frames per second. Timing marks were placed on the film at 8.33 ms intervals. A 50 mm lens was used at f-8 for most exposures. Plasma parameters and the voltage between the outer limiter and the plasma vessel were recorded by a computerized data collection system.

The inner limiter is a 3.2-cm-diam type 304L stainless steel bar grounded to the plasma chamber. The outer limiter was mushroom-shaped TiC-coated POCO graphite similar to the one described previously [2]. Its largest diameter is 13 cm and its thickness is about 3 cm. It is electrically isolated from the plasma chamber and floats electrically.

At the time most of these pictures were taken the inner limiter had been exposed to more than 11,000 tokamak pulses (shots). The outer limiter was relatively new for some of the data presented here. It was put into ISX-B just prior to shot no. 36853. Shot numbers are indicated on most of the photographs.

The power deposited on the ISX-B limiter during steady operation with 2 MW of neutral beam injection is estimated to be >>10 kW/cm^2 and much higher during the brief time of disruptions.

3. GENERAL OBSERVATIONS

As expected, nearly all of the violent arcing occurred during unstable plasma conditions at the beginning or end of a plasma pulse or accompanying plasma disruptions.

In normal ohmically heated plasma pulses the initial plasma formation is usually accompanied by a small amount of weak arcing on the inner limiter. In a good plasma pulse the plasma then increases in strength (density and temperature) with a minimum of interaction with either limiter. When the amplitude of the magnetohydrodynamic (MHD) instabilities becomes large the H_α light due to plasma-limiter interactions at both limiters increases. When the plasma current is ramped down at the end of a shot, H_α light decreases. If the current is terminated abruptly arcs often flash intensely, but briefly on the inner limiter. As plasma power is increased and neutral beams come on, the outer limiter begins to heat, small incandescent spots form first (probably at protrusions or inhomogeneities in the TiC coating) and if the heating is long and intense enough the whole center of the limiter surface becomes incandescent.

Sometimes, especially in high power shots, the discharge space next to the limiter emits a blue glow which is more intense than the H_α light. This blue glow may cover large areas of the outer limiter and must be the result of impurities getting into the plasma from the limiter. This emission of limiter material into the plasma may be caused by sputtering, electrical phenomena, or thermal processes. In any event, the increased light emission often precedes a violent disruption accompanied by arcing and dumping of power and plasma particles on the limiter at extremely high rates — H_α light, impurity light and thermal light all increase precipitously and a wake is frequently visible in the plasma on the downstream (ion drift) side of the limiter. These observations are categorized, discussed, and illustrated below in more detail.

4. SPECIFIC OBSERVATIONS ON THE INNER LIMITER

Large Current Multiple Cathode Spot Arcs

Figure 3 shows cathode spots on the inner limiter during a disruption caused by abruptly terminating a plasma pulse after the plasma current had been ramped down to about 10 kA. If each spot is carrying 60—100 A the total current in this arc was 900—1500 A [4]. The streamer to the left from the arc is along magnetic field lines. The cathode spots persist for several frames (more than a millisecond) and although the number of spots change, their positions are relatively stationary. Electrons leaving the limiter and flowing to the left are moving in the direction of electron drift in the normal tokamak plasma. These arcs melt and vaporize material from the stainless steel limiter. Although current disruptions at the end of the discharge produced the largest and most persistent arcs we observed, arcs of this nature may occur whenever there are current disruptions no matter whether it is in the beginning, middle, or end of the plasma pulse.

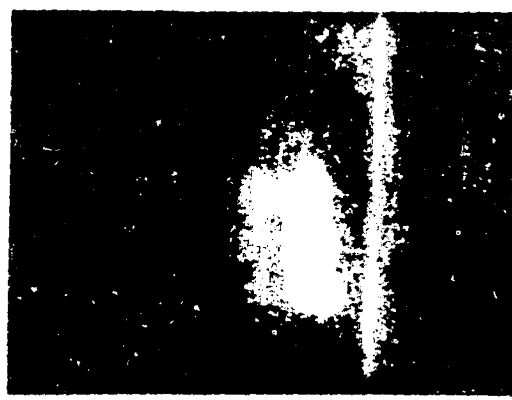

Fig. 3: Inner limiter arc showing multiple cathode spots and impurities streaming into the plasma edge region to the left along magnetic field lines. These arcs can be relatively stationary because the arc is along field lines. Cathode spots can persist for several frames (i.e., a millisecond or more).

Flickering Luminous Curtains

These may cover large areas of the limiter with fairly intense light and exhibit fast moving, relatively sharp edges as shown in Fig. 4. The light is usually red (probably H_α). It is possible that what appears on the film is the trace of a very fast-moving arc front or a glow discharge perhaps supported by gas or vapor from the limiter. It is also possible that it represents a trace left by limiter interaction with an instability in the plasma edge. Often the brightest area in one frame is very dark in the next frame as though gas emission from an area was depleted by the previous intense activity. This phenomenon may occur at any part of the plasma pulse, but is often more intense just before disruptions. It is easiest to see on the inner limiter, but can also be observed on the outer limiter.

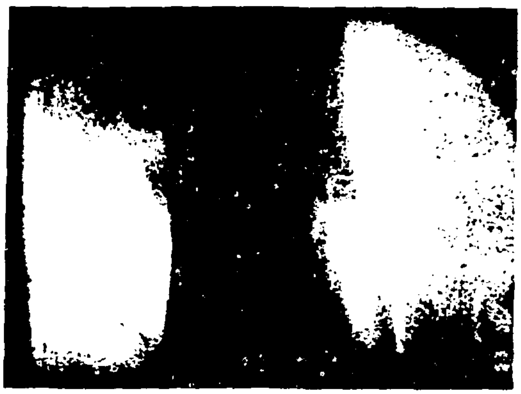

Fig. 4: Inner and outer limiter images just before a disruption. The outer limiter is very bright with both H_α and light apparently from luminescent vapors emitted from the limiter. The inner limiter is partially covered by a flickering curtain and also shows a luminous sheath. A "wake" is visible to the left of the outer limiter.

Luminous Sheath

This may or may not be related to the flickering curtains. It is also seen in Fig. 4 along with the flickering curtain, but is described separately since the sheath often persists for very long times. The sheath of light may be uniform or discontinuous on both inner and outer circumferences of the inner limiter and the outer limiter rim also. The light is often very bright and seems to extend from the very surface of the limiter into the plasma for several millimeters or more. The absence of a dark space between the limiter and the glow suggests that either the plasma density is very high or that this is not an electrical discharge phenomena (where mean free paths for excitation might be expected to be several millimeters or more).

5. SPECIFIC OBSERVATIONS ON THE OUTER LIMITER

Fast Unipolar Arcs

These features are distinguished by the very bright curved traces left by fast moving cathode spots as seen in Figs. 5(a) and (6). Individual traces are usually on only one frame although several arcs may appear on that frame and on preceding or succeeding frames. The tracks left by these arcs can be seen on fresh limiters and always move in the -JXB direction. The behavior of these arcs is consistent with earlier observations on small probes in ISX-A and as described in the literature [1,3].

Figure 7 shows the plasma current trace for shot no. 37099 and indicates the times at which Figs. 5 and 6 were obtained. Each arcing sequence seems to preceed the current disruption occurring at the indicated time but this does not necessarily imply that the arcing caused the disruption.

Repetitive Arcs

Arcs may occur repeatedly from the same arc initiation site and follow approximately the same path each time, creating a set of tracks with the appearance of a comet with the arc initiation site at its head.

Another type of repeating arc has been seen to initiate over and over from a linear feature such as a crack and produce an image which appears as a kind of curtain lasting for several milliseconds. Each curtain must consist of a long series of arcs in rapid succession moving in parallel paths but with the points of origin displaced along the crack for each individual arc. Figure 8 shows this kind of arc.

Eruptions and Particle Emission

Vapor and incandescent particles (probably limiter fragments or small molten droplets) are seen to be ejected from arc craters. Occasionally violent large eruptions with many particles and much vapor are observed on the outer limiter. Figure 5(a), (b), (c), and (d) shows one such eruption, while Fig. 9 shows a much larger one. The plasma survived the eruption in Fig. 5 as seen at time "a" in Fig. 7, but not the one in Fig. 9. Vapor clouds and particle showers may have initial velocities of several hundred meters per second, while some particles move more slowly and frequently are ejected several frames (~1 ms) after the arc.

Flicker Arcs

The outer limiter coating was largely removed from the center of the limiter during the first week of operation (~200 shots). After the "hole" in the coating appeared, arcing often appeared in that area in the form of bright flickering which became more and more frequent

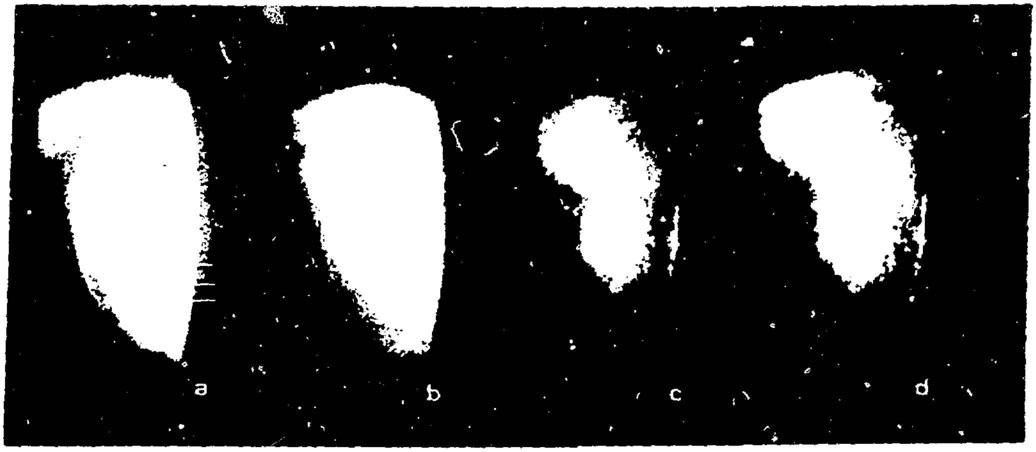

Fig. 5: Multiple arcing during shot 37099. This sequence shows the outer limiter at the beginning of a disruption at 162 ms followed by an eruptive discharge of particles and vapors into the plasma. The arrow indicates one of the arc traces. The frames a,b,c,d are sequential at 0.00033 s intervals. Particle velocities are greater than 100 ms.

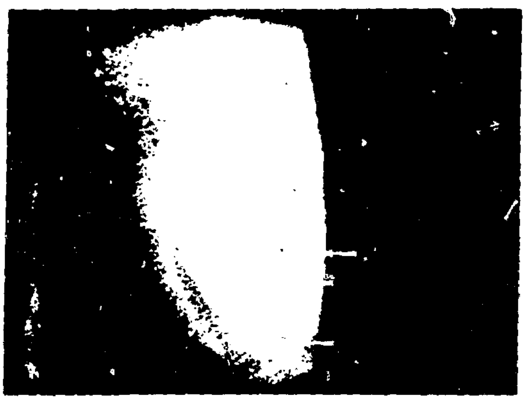

Fig. 6: Multiple arcing on the TiC coated outer limiter at 176 ms into shot number 37099.

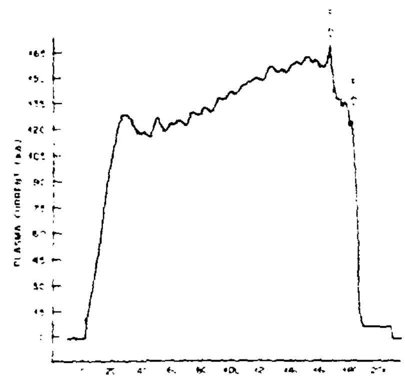

Fig. 7: Plasma current, as a function of time for discharge 37099. Figure 6 was taken during the time of the final disruption, while Fig. 5(a), (b), (c), (d) were obtained at the time of the disruption at 162 ms.

until it was almost continuous during high power (>2 MW) neutral beam injection. These arcs seemed to be confined to a central region of a few centimeters in diameter. At the time this phenomena became common, unipolar arcing such as described above decreased noticeably. A typical flicker arc is shown in Fig. 10.

Plasma Wake

This phenomenon is commonly observed just before and during disruptions. Figure 4 shows such a wake extending to the left from the outer limiter as a dark band created as the limiter intercepts plasma streaming past the limiter. Usually the limiter becomes quite bright and streamers of light may appear to flow from the limiter along the magnetic field in the normal ion drift direction in much the manner of a bow wave from a boat. "Wakes" or shadows sometimes appear to extend up or down from the limiter as well as along the magnetic field. The cause of the vertical features is unknown.

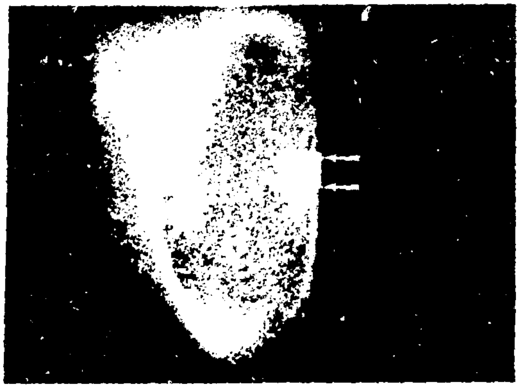

Fig. 8: A repetitive arc along the base of the outer limiter. The arc appears as a curtain extending from the cracklike bright feature to the right. Shot 37099. The cracklike feature is also visible without arcing in Figs. 5, 6, and 9.

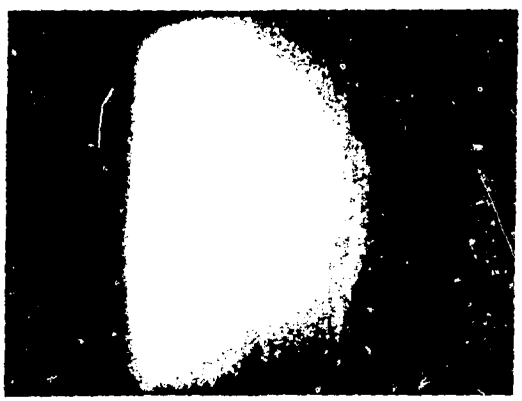

Fig. 9: A large eruption with both particles and a luminous gas cloud ejected at high velocity into the plasma. This eruption caused an immediate final disruption ending plasma shot no. 37121.

6. CONCLUSIONS

A variety of plasma limiter phenomena have been described. Some are clearly unipolar arcs. Others are cloudlike glows, diffuse arcs or simply intense H_α light which may accompany or cause particles and vapors to be emitted into the edge region of tokamak plasmas. In some cases these latter phenomena seem to evolve or lead to the formation of cathode spot and true arcs. Other phenomena are due mainly to thermal effects and still other observations await explanation. The very great importance of plasma-limiter interactions justifies this attempt to describe and classify the observations even though the mechanisms involved are in several cases not obvious.

Fig. 10: Small arcs flicker continuously on the eroded central area of the limiter during high power neutral beam heated discharges. This discharge, no. 37663, was heated with >2 MW of neutral hydrogen beam injection and was smooth and without major disruptions. The incandescent points surrounding the central region are on the TiC coating. They are stationary; it is not known if they are caused by defects or hot spots in the coating or by some discharge phenomena.

Our observations are being extended to a larger range of plasma conditions and other limiter materials. They will also be coupled with other types of measurements from both the plasma and the limiter to provide a better understanding of plasma-limiter interactions. This understanding and the empirical testing of materials will assist the development of materials, designs, and techniques to minimize erosion or other arcing damage to limiters and other surfaces and the resulting plasma contamination.

ACKNOWLEDGMENTS

The authors wish to point out that these studies complement a cooperative limiter development program with Sandia Albuquerque Laboratory which supplied the TiC coated limiters. C. Bush of ORNL was kind enough to allow us to use the infrared camera optical path, mirrors and windows on ISX for these observations and Phil Edmonds, Alex Gabard, and Steve Bates all provide' direct assistance in the setup and operation of the necessarily complicated apparatus. Finally, our thanks to all of the helpful and patient members of the ISX-B staff who allowed their experiments to be interrupted frequently for reloading film and related camera support work.

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