PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76-CHO-3073

PPPL-3018
UC-420,421,426

PPPL-3018

VERSATILE TV SYSTEM FOR PBX-M PLASMA CONTROL

BY

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NOVEMBER 1994

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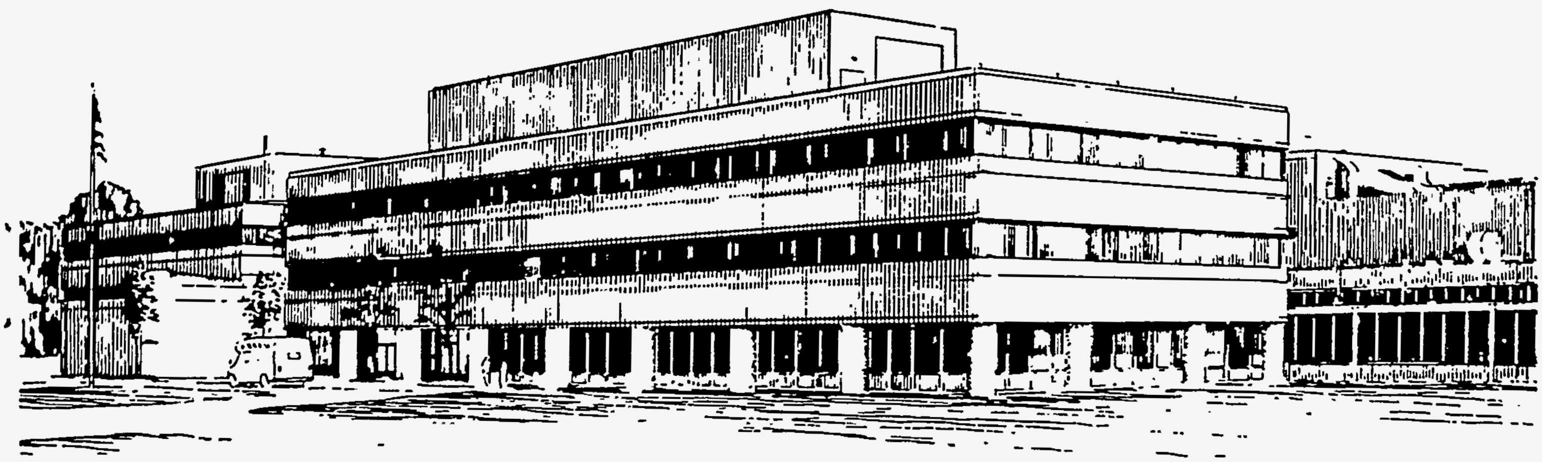

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VERSATILE TV SYSTEM FOR PBX-M PLASMA CONTROL

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Abstract

In advanced tokamak research involving complex magnetic geometries, midplane visible plasma TV images can indicate the need for tokamak control corrections not evident from other diagnostics. Suitable midplane viewports are often unavailable. The PBX-M plasma TV system uses four tangential midplane vacuum viewports. One tangential vacuum viewport is on a standard re-entrant midplane port flange. The other three vacuum viewports are tangentially-aligned along the inside vessel wall and connected to port flanges 40 cm from the midplane via 60 cm long re-entrant bellows. Fiber optic bundles transmit images from the re-entrant viewports through the off-midplane ports and out to TV cameras positioned beyond the TF coils. The VCR recorded images from each discharge were used to obtain information not available from other diagnostics.

I. INTRODUCTION

Midplane visible plasma TV systems have been used extensively for high temperature plasma control, diagnostic analysis, and device maintenance [1-3]. Increasingly, in advanced tokamak research involving complex magnetic geometries, midplane visible plasma TV systems have become a required diagnostic tool for operating high power, high-β, plasmas with auxiliary heating, profile control, and various RF antenna, limiter, and probe interactions with the edge plasma. Visible plasma TV images can indicate the need for control corrections not evident from other diagnostics. In addition, plasma TV systems can be used for vessel inspection during maintenance periods and for studying unforeseen edge plasma phenomena. These diverse uses require optical systems with adequate fields-of-view and a wide dynamic range. The TV viewport locations that provide the most useful fields-of-view are at tangential-viewing vacuum windows on the midplane. However, other hardware requiring midplane port access can impose significant constraints on the design of plasma TV systems. The use of off-axis ports usually places fewer constraints on toroidal location at the expense of more complex optical transport systems which must also accommodate the need for a wide dynamic range. At least one plasma view of high optical quality is desirable to provide the principal plasma shape and location information. Other plasma views, such as those used to monitor the plasma edge at the location of antennas and probes can be of lower optical quality and still provide the desired diagnostic information. In this paper, we describe the design and performance of the PBX-M plasma TV system which uses only one direct tangential-view midplane viewport and 3 off-midplane ports with simple fiber optic bundles to provide information for the operation of relatively complex diverted plasmas.

II. EXPERIMENTAL CONDITIONS

Recent PBX-M advanced tokamak, high-β, profile modification experiments for accessing the near second stability regime have been discussed previously [4]. The vessel internal hardware includes a passive plate stabilization system, internal coils, poloidal limiters, and internal buses and shields for passive plate biasing experiments. The experimental program requires the use of complex magnetic geometries and encounters a wide range of plasma shapes, conditions, heating and profile modification methods. PBX-M plasmas are started as low current circular plasmas at the outboard major radius and are evolved to diverted, highly indented, high triangularity, high-β plasmas. The resulting plasma control requirements demand precise corrections in shape and position to optimize plasma conditions and minimize edge interactions with nearby passive plate structure, IBW antennas, and LHCD couplers. In this complex plasma environment, the resolution of the magnetic flux loop systems is not sufficient to allow for avoidance of deleterious edge plasma interactions without occasional operator assistance using visible edge plasma imaging systems. During PBX-M plasma operations, two or more, plasma TV views are video taped simultaneously using standard VCR's. Each recorded frame includes discharge number and lapsed-time into the discharge. The recorded plasma views are inspected by operators after each discharge to determine possible control corrections.

III. DESIGN AND PERFORMANCE

Fig. 1 gives a partial schematic plan view of PBX-M showing the locations of the 4 TV vacuum viewports and fields-of-view, 4 neutral beam injection (NBI) systems, 2 Ion Bernstein Wave (IBW) heating antennas, 2 Lower Hybrid Current Drive (LHCD) couplers, the UCLA Fast Probe, and a solid target boronization (STB) probe. The PBX-M visible plasma TV system uses one midplane viewport (TV-1) with a color TV, to obtain the primary information on plasma shape and position, and three off-midplane viewports (TV-2,-3,-4) using black and white TV's to monitor edge plasma interactions with the IBW Southwest antenna, the two LHCD couplers, and the solid target boronization probe. Fig. 2 (a) gives a partial schematic diagram showing a plan view of the re-entrant tangential viewport (TV-1) on a midplane perpendicular port and (b) an elevation view of re-entrant tangential viewports (TV-2,-3,-4) using off-midplane ports about 40 cm above or below the midplane. The main re-entrant vacuum interface is a high vacuum quality, 46 cm long by 3.8 cm I.D., stainless steel hose, consisting of a thin-walled bellows covered with flexible stainless steel braid. The hose has rotatable metal seal flanges at each end that couple to transition spool pieces. The window is BK7 glass to provide high thermal and shock resistance. The window of the re-entrant assembly can be placed at the outer vessel wall near midplane ports or in the usually ample space available opposite TF coils. A standard 50 mm TV lens is positioned behind the window and aimed and focused at objects about 3 m distant. The lens is coupled to a 1.2 m long, 8 mm x 10 mm bundle of 10 micron fiber optics clad in a flexible stainless steel braid. The fiber optic transports the image to a standard CCD TV camera outside the TF coil region. This allows the camera to be easily accessed for maintenance and aperture adjustments to accommodate different experiments (*e.g.*, with optical filters) and for inspections using the vessel illumination sources. The outside face of the vessel flange was designed so that if an air leak should occur, a vacuum pump could be attached for evacuation and isolation without opening the vessel.

Fig.s 3 a, -b, -c, and -d show cross-section views of a 250 kA diverted, highly indented PBX-M plasma using camera system TV-1 positioned directly at a midplane, re-entrant tangential vacuum viewport. During the 1.3 MW NBI heated discharge, with solid target boronization in progress, the plasma transitioned to the H-mode from 456 ms to 568 ms. In Fig. 3a, at 68 ms, the ohmic plasma was initially circular and relatively outboard. At 201 ms (Fig. 3b), the plasma was becoming elongated, mildly indented, moved radially inward, and exhibited an intense plasma light at the inner midplane limiter. As the discharge progressed, the plasma elongation increased, the interaction at the midplane limiter decreased, and a separatrix became visible. At 503 ms (Fig. 3c), the plasma had transitioned into the H-mode and exhibited a sharply defined edge. At 602 ms (Fig. 3d), the plasma had transitioned out of the H-mode, the edge became more diffused, the plasma was moving radially outward, the interaction with the IBW East-antenna increased significantly, and the discharge disrupted at 680 ms. This visible record of the discharge sequence allowed the position, shape, and edge interactions to be monitored as the plasma proceeded from ohmic heated circular plasma to a diverted, highly indented, NBI heated plasma with an H-mode transition and asymmetric edge phenomena. This information allowed subsequent control corrections to optimize plasma performance.

LHCD has been applied to significantly modify PBX-M current density profiles in the presence of the closely-coupled passive plate stabilization system [4]. Fiber optic camera system TV-2 was used to monitor the LHCD couplers. Fig 4a shows the top and bottom LHCD couplers during normal operation. The brighter side of the coupler faced the incident ion direction (in Fig. 4, from the right). The upper outer passive plate structure is visible in the background. Fig. 4b shows the LHCD couplers during an arcing event such as occurs during high neutral density edge conditions and during high power reflection conditions. The visual record of the edge plasma interaction with the coupler aided in evaluating coupler design performance and in positioning the plasma edge during LHCD profile modification experiments.

IBW has been applied to significantly modify PBX-M pressure profiles and provide localized bulk ion heating in the presence of the closely-coupled passive plate system [5]. The front face of the IBW Southwest antenna was clad with a developmental boron nitride shield to reduce heavy metal sputtering into the plasma. Fiber optic camera system TV-3 was used to monitor and record the performance of this design. Fig. 5a shows the IBW-Southwest antenna at 41 ms into a discharge when the plasma was positioned too outboard, and Fig. 5b shows the antenna at 108 ms into the discharge when the plasma had been moved radially inward. In Fig. 5, the ions were incident from the right. The upper and lower outer passive plate structure is visible in the background. The record of the antenna performance aided in evaluating the performance of the boron nitride shield during a wide range of edge plasma conditions and in positioning the plasma edge during IBW profile modification experiments.

Real-time boronization has been applied routinely to PBX-M using the plasma ablation of solid target probes [6]. During insertion of a probe into the edge plasma, its incandescence was viewed and recorded using fiber optic camera system TV-4. Fig. 6a shows a solid target boronization probe exhibiting undesirable spallation and Fig. 6b shows probe incandescence during a more ideal steady evaporation. The incandescence illuminates part of the outer vessel structure in the background. The record of the incandescence behavior helped the operators to achieve relatively steady evaporation rates and avoid the spallation that can occur when probes are inserted too deep. The visible light intensity emitted by a solid target boronization probe was detected by the same TV system and integrated using a fast photodetector to give a waveform exhibiting a rise time characteristic of an approximately constant incident power density and an exponential-like decay. The incandescence of the probe was observable for at least 4 sec after the start of the 1 sec discharge and was used to monitor the effectiveness of the applied heating.

The PBX-M plasma TV system can be expanded without perturbing existing midplane hardware by making use of available off-midplane ports and the ample space on the inner vessel wall opposite the TF coils. This system provides useful information on plasma performance and control corrections that are not evident from other diagnostics.

ACKNOWLEDGMENTS

We wish to acknowledge the helpful discussions and technical contributions of R. Bell, S. Bernabei, D. Krause, M. Okabayashi, M. Ono, and R. Palladino. This work was supported by US DOE Contract No. DE-AC02-76-CHO-3073.

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FIGURE CAPTIONS

Fig. 1. Partial Schematic plan view of PBX-M showing TV viewports, fields-of-view, and edge hardware locations.

Fig. 2. Partial schematic showing (a) a plan view of re-entrant midplane viewport (TV-1) and (b) an elevation view of typical off-midplane re-entrant TV viewport (TV-2,-3,-4).

Fig. 3. Cross-section views using plasma camera system TV-1 at the re-entrant midplane tangential-viewport showing the evolution of a PBX-M plasma during solid target boronization from (a) 68 ms, initially ohmic heated circular outboard, (b) 201 ms, mildly indented and elongated, (c) 503 ms, NBI heated diverted highly indented and elongated, H-mode plasma, d) 602 ms, plasma had transitioned out of H-mode and moved outward toward IBW antenna.

Fig. 4. Fiber optic camera system TV-2 views showing (a) the top and bottom LHCD couplers during normal operation and (b) during an arcing event.

Fig. 5. Fiber optic camera system TV-3 showing (a) the boron nitride face of IBW Southwest antenna at 41 ms into a discharge when the plasma was positioned too outboard, and (b) at 108 ms into the discharge when the plasma was moved radially inward.

Fig. 6. Fiber optic camera system TV-4 showing (a) spallation of a solid target boronization probe, and (b) the same view under constant conditions.

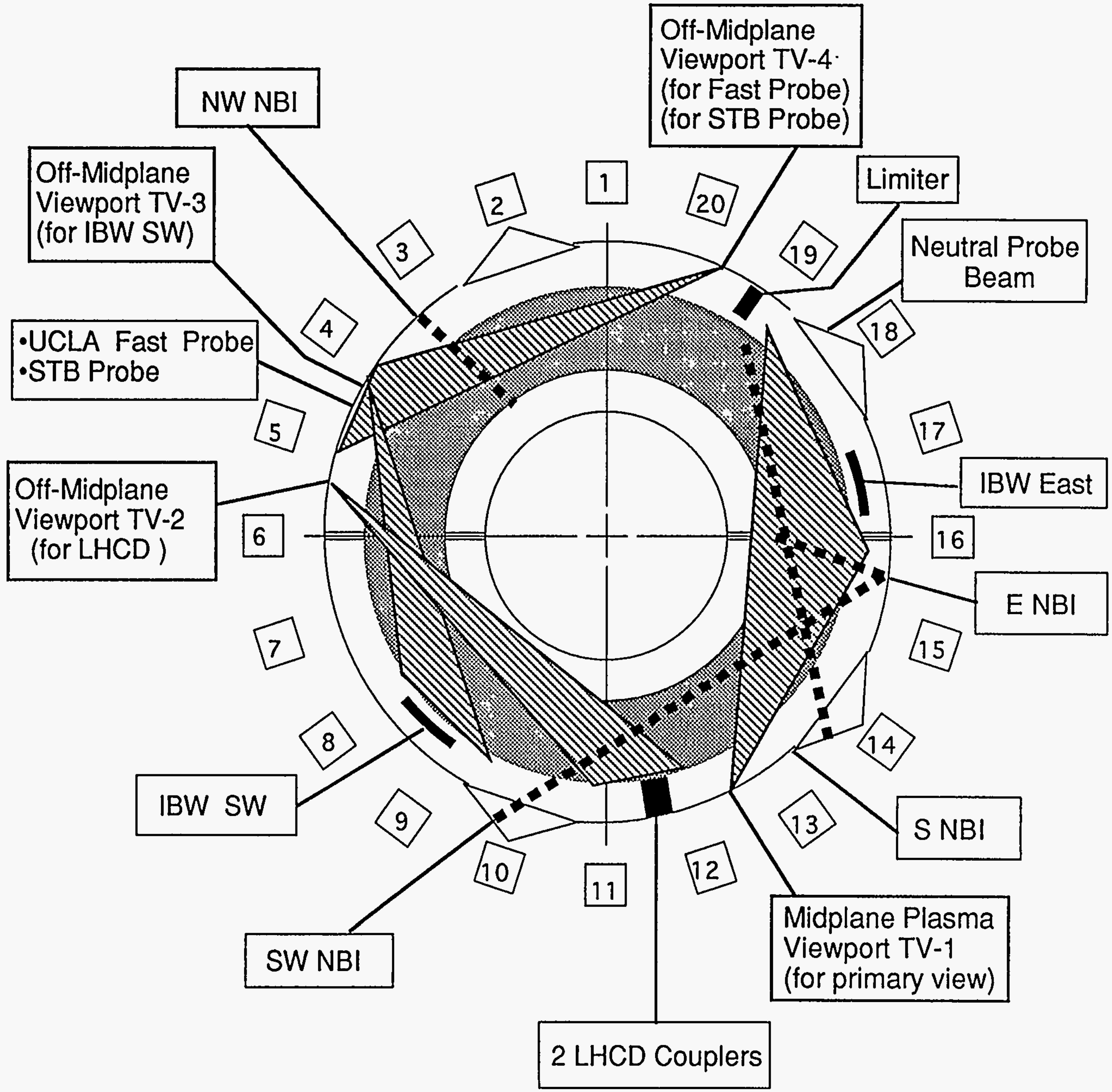
NW NBI
Off-Midplane
Viewport TV-4
(for Fast Probe)
(for STB Probe)
Off-Midplane
Viewport TV-3
(for IBW SW)
Limiter
Neutral Probe
Beam
•UCLA Fast Probe
•STB Probe
Off-Midplane
Viewport TV-2
(for LHCD)
IBW East
E NBI
IBW SW
S NBI
SW NBI
Midplane Plasma
Viewport TV-1
(for primary view)
2 LHCD Couplers
1
2
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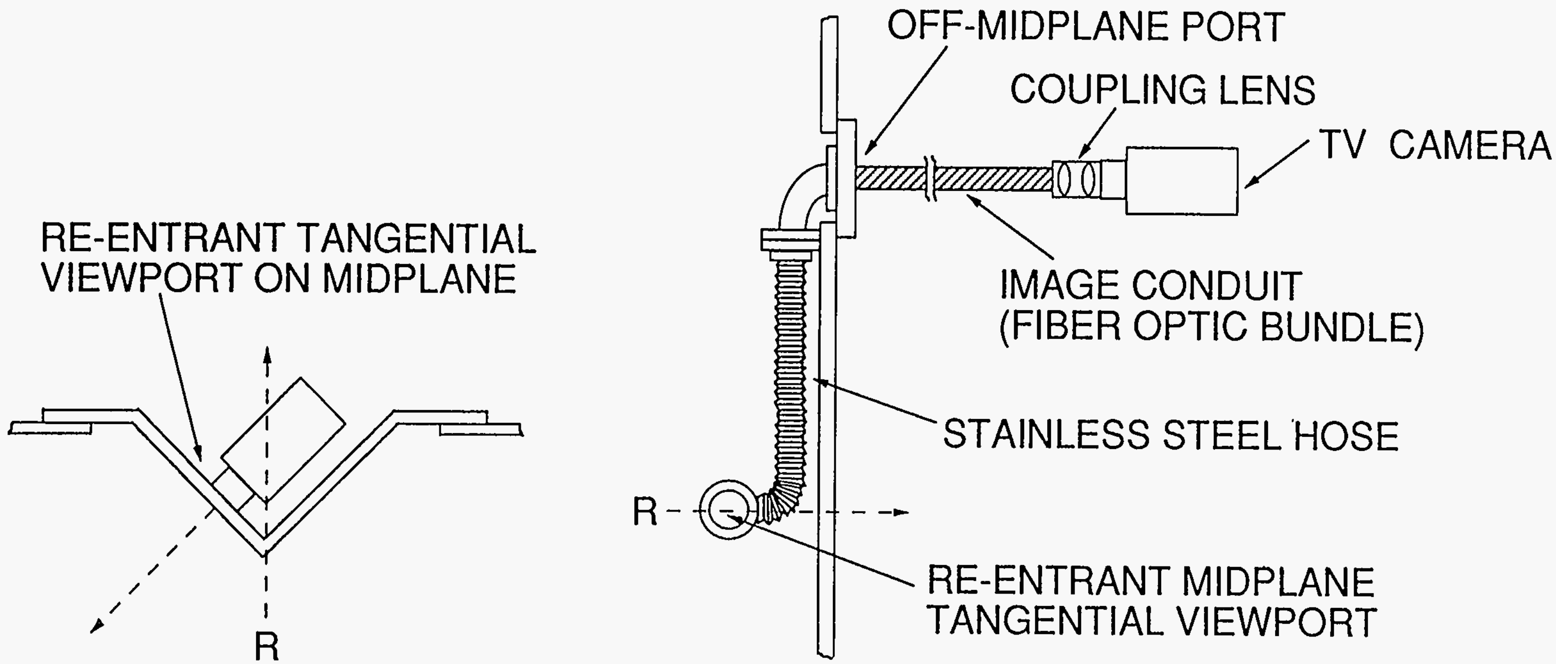
Fig. 1


RE-ENTRANT TANGENTIAL VIEWPORT ON MIDPLANE
R
OFF-MIDPLANE PORT
COUPLING LENS
TV CAMERA
IMAGE CONDUIT (FIBER OPTIC BUNDLE)
STAINLESS STEEL HOSE
R
RE-ENTRANT MIDPLANE TANGENTIAL VIEWPORT

(A) (B)

Fig. 2

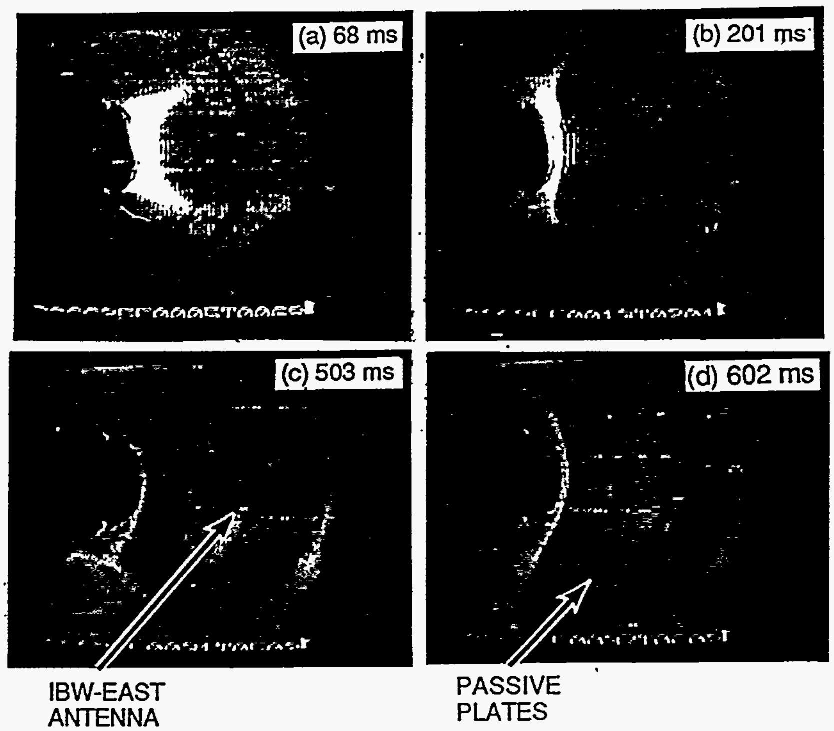

(a) 68 ms
(b) 201 ms
(c) 503 ms
(d) 602 ms
IBW-EAST ANTENNA
PASSIVE PLATES

Fig. 3

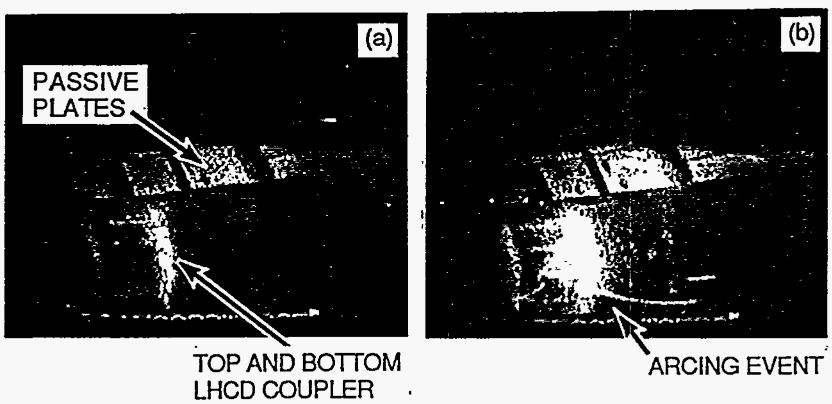


Fig. 4

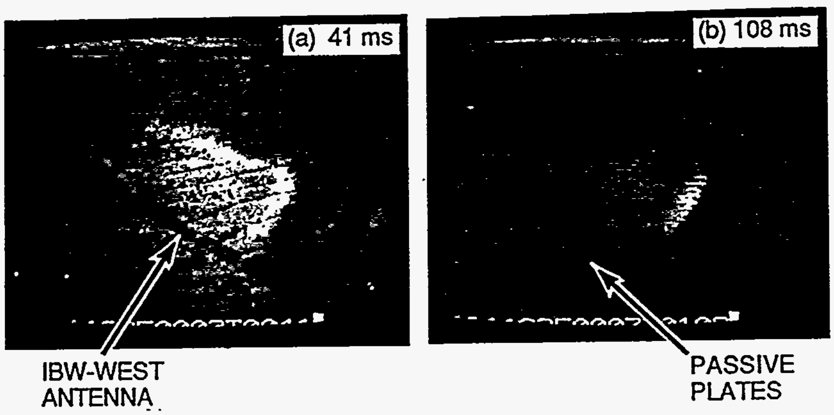


Fig. 5

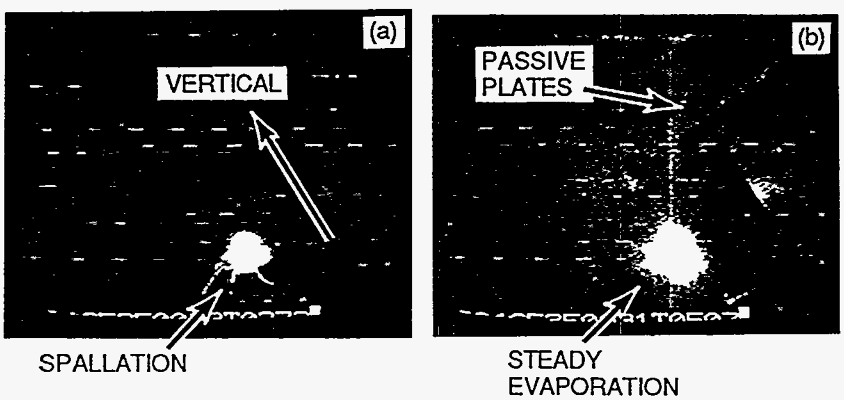

(a)
VERTICAL
SPALLATION
(b)
PASSIVE
PLATES
STEADY
EVAPORATION

Fig. 6

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