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TITLE: "END-ON SOFT X-RAY IMAGING OF FIELD-REVERSED CONFIGURATIONS (FRCs) ON THE FIELD-REVERSAL-C(FRX-C)/LARGE SCALE MODIFICATION (LSM) EXPERIMENT"

AUTHOR(S): DANIEL P. TAGGART, RITA J. GRIBBLE, ANDREW D. BAILEY III, AND SATOSHI SUGIMOTO

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Los Alamos National Laboratory
Los Alamos, New Mexico 87545

End on Soft X-ray Imaging of FRCs on the FRX-C/LSM Experiment *

D.P.Taggart, R.J.Gribble, A.D.Bailey III[1], and S.Sugimoto[2]

Los Alamos National Laboratory

Introduction

Recently [1], a prototype soft X-ray pinhole camera was fielded on FRX-C/LSM at Los Alamos and TRX at Spectra Technology. The soft X-ray FRC images obtained using this camera stand out in high contrast to their surroundings (unlike the images from visible light framing cameras which are often obscured by light emission from sources outside the FRC). It was particularly useful for studying the FRC during and shortly after formation when, at certain operating conditions, flute-like structures at the edge and internal structures of the FRC were observed which other diagnostics could not resolve.

Building on this early experience, a new soft X-ray pinhole camera has been installed on FRX-C/LSM, which permits more rapid data acquisition and briefer exposures. It will be used to continue studying FRC formation and to look for internal structure later in time which could be a signature of instability. This paper summarizes the initial operation of this camera.

As of this writing, the camera has been used primarily in conjunction with measurements of external magnetic field asymmetries of FRCs. Some of the images obtained during the bias and pressure scans of this series of measurements are included to indicate the effect of varying source conditions on formation. Additionally, a series of shots at optimum operating conditions was taken to document the appearance of the best FRCs which we can form on FRX-C/LSM and to establish analysis procedures which would be applied to all of the data at various pressures and biases. Preliminary analysis of this data shows good agreement between the FRC radius determined from the X-ray image and the excluded flux array. It also indicates that relative density values (maximum density vs. density in "hole") inferred from the data are reasonable.

Experimental Apparatus and Procedure

A diagram of the new soft X-ray pinhole camera is shown in Figure 1. The camera uses a vacuum flange mounted Galileo 3075-FM Chevron MCP with a phosphor/fiberoptic output. The vacuum flange mounting allows the image recording medium (film or CID camera) to be outside the vacuum chamber, which eliminates the prototype camera requirement of vacuum openings between shots to retrieve exposed film. A 0.25-μ Be foil blocks visible and UV light. This plus a 300-nm CsI coating on the input side of the MCP should ensure that the camera's response is peaked near 10 nm. The input side of the MCP is gated once per discharge with a flat-top pulse of 1 μs duration (the prototype camera had an exposure time of 2 μs). The output of the MCP is at ground and the phosphor bias is typically +2.5 kV. For this first series of experiments, images were recorded as contact prints on Polaroid Type 52 sheet film. These images were subsequently digitized and analyzed using a G.E. 4TN2507A CID surveillance camera and Imaging Technology FG-100-AT image processing board with the ITEX 100 library of image processing subroutines (both PC based). Pinhole diameters of 0.5-1.0 mm were used, permitting spatial resolution at the plasma on the order of 0.8-1.6 cm. This resolution plus the short (~1 μs) exposures allows us to detect fine scale features at the plasmas edge (Fig. 2).

Discussion of Results

To document the appearance of the FRC in our optimum operating regime, a time series of photos was taken at a fill pressure of 3 mTorr with a 570 gauss bias. The outstanding characteristic of these FRCs (up to their n=2 instability at about 80 μs) is their nearly circular, smooth edge profile. These images have been used to compare the radius determined from the excluded flux array with the radius determined from the X-ray image. The radius of the plasma in the X-ray image is taken to be the point at which the density drops to $n_{max}/2$. The density is assumed to be related to the reflected light intensity from the contact print image of the FRC by $I_R \propto (n^2)^\gamma$, where I_R is the reflected light intensity from the contact print image and γ is the slope of the characteristic curve of the film (γ for our film is 1.35). The results (Fig. 3) show that from about 10 μs after formation begins to the onset of the n=2 instability, the two methods agree to within 4%. At earlier times the plasma is too dynamic and at later times the plasma is too deformed to expect good agreement. Because of point and line defects (bright spots) in the images as well as moire' type patterns cutting across the field of view, not much effort has been devoted to trying to quantify internal structures seen within the separatrix. Nevertheless, a crude analysis of how n_{hole}/n_{max} varies with x_{sep} has been made. Restricting the analysis to shots with exposure levels which should be in the most linear region of that curve, the correct trend is seen in the data (Fig.4) when compared to a rigid rotor model, but with considerable scatter. Using the same scaling, a contour plot is shown for a shot with a particularly deep center hole (Fig.5).

As Fig. 1 shows, not all FRCs are as symmetric as our optimized 3 mTorr shots are. As an example of one trend which is evident in our data, Fig.6 shows how, at constant bias, FRC symmetry deteriorates as fill pressure increases.

Summary and Future Plans

In summary, a new soft X-ray pinhole camera has been constructed and used successfully. Image processing software has been developed to analyze the resulting images. We are continuing to analyze our data to:

i) determine if the azimuthal asymmetries seen at high fill pressures during formation can be explained by consideration of the radial dynamics[2] of the plasma,

ii) correlate the measured shifts of the plasma away from the geometric axis with magnetic field asymmetries measured at the wall,

iii) develop software to analyze images for evidence of asymmetries inside the plasma separatrix.

We have completed preparations to eliminate the use of film all together and record the image directly using the CID camera. Finally, a 4-frame system is being built (in collaboration with Spectra Technology,Inc.) for use early next year.

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1-Caltech
2-Osaka University

References:

[1] E.Crawford,Proceedings 9th U.S. Compact Toroid Symposium (Union, WA, 1989),pp.138-141
[2] A.Sgro,*ibid.*,pp.91-94

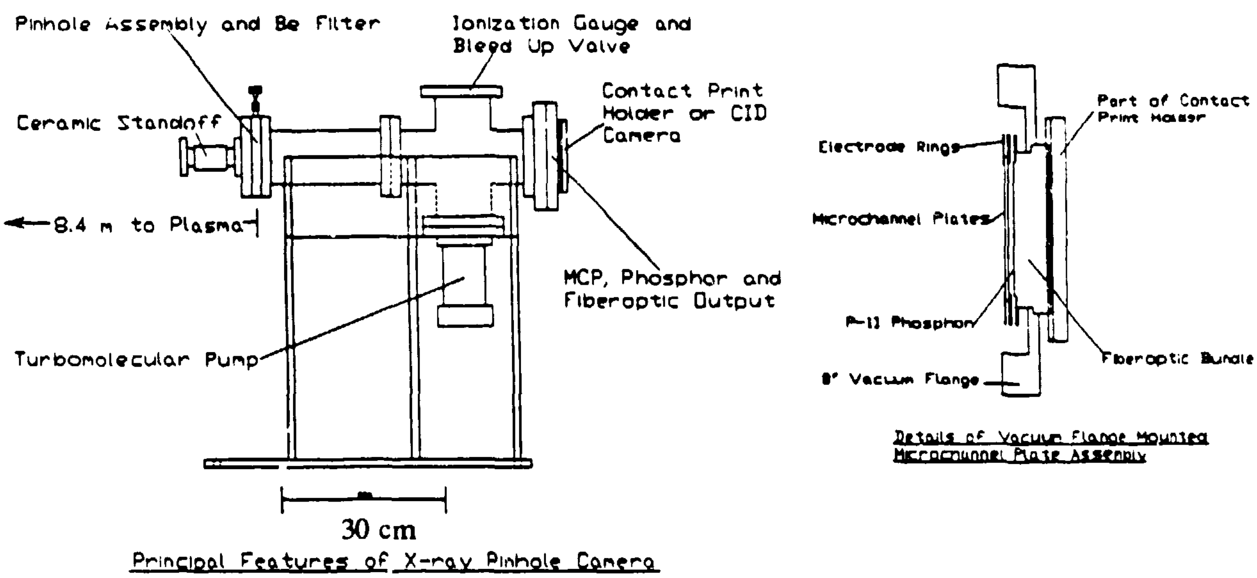


Figure 1-Schematic Diagram of New Soft X-ray Pinhole Camera

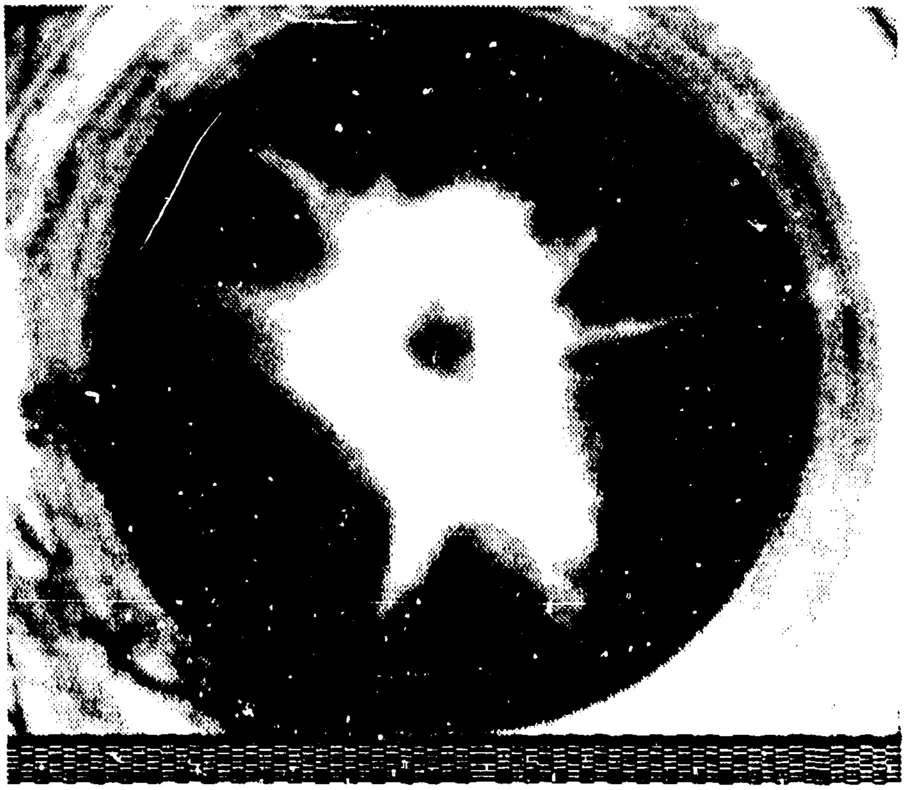
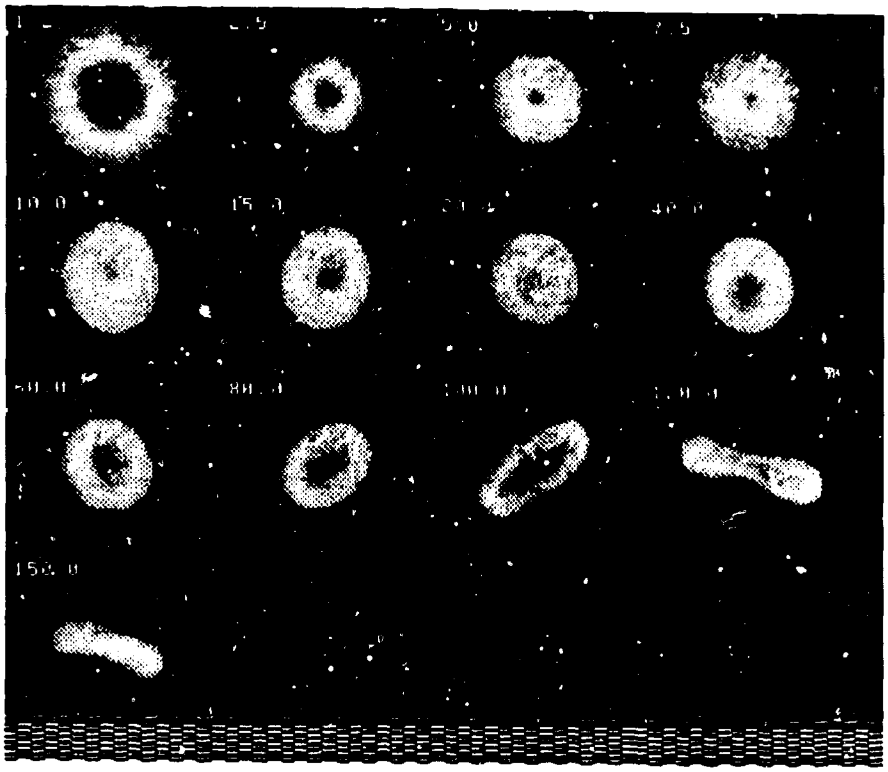


Figure 2- The severely deformed FRC shown above was photographed 5 μs after firing the theta pinch. It was formed at a bias magnetic field of 290 gauss and a deuterium fill pressure of 12.7 mTorr. It is not a typical FRC but demonstrates the capabilities of the soft X-ray imaging system. The FRC stands out in high contrast to its surroundings. The bright circular area at the perimeter of the photo is the quartz tube in the compressor (40 cm dia., 6.4 m from pinhole). The pinhole diameter for this photo was 0.5 mm, giving spatial resolution of 0.8 cm at the FRC, which is 8.4 m from the pinhole.



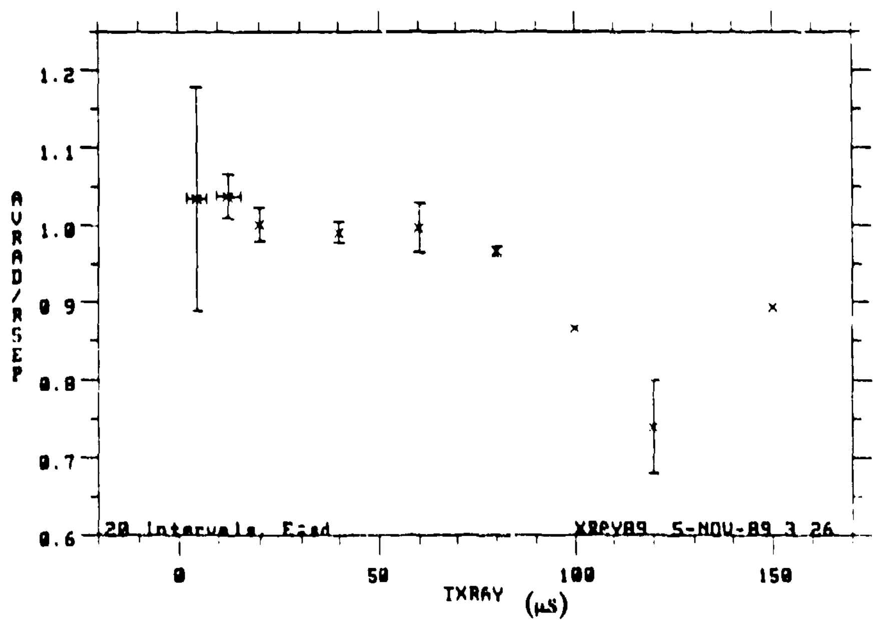


Figure 3- The time sequence of photos above is typical of FRCs formed at the optimum operating regime (fill pressure= 3 mTorr deuterium, bias field= 570 gauss, B_{wall}=4 kG, τ_ϕ= 270 (+/- 70) µs). The time of the photo (in µs) is listed in the upper left hand corner of each frame and there is one exposure per discharge. The plot below compares the plasma radius determined from the X-ray image (AVRAD) with the radius determined from the excluded flux array (RSEP) at various times.

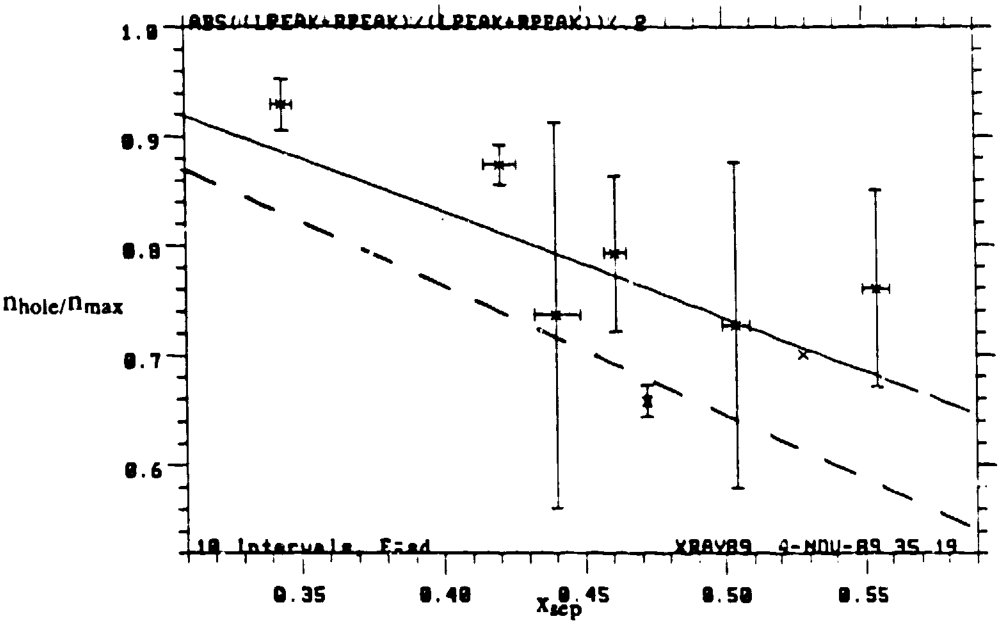


Figure 4- In the figure above the ordinate n_{hole}/n_{max} is the ratio of the density at the "hole" of the FRC (central density minimum) to the maximum density (which occurs somewhere between the hole and the FRC edge). The relative density values are inferred from the reflected light intensity using the same relationship which was used to determine the FRC radius from the soft X-ray images. The abscissa x_{sep} is the excluded flux radius normalized to the radius of the field coils. The solid line is a linear least squares fit to the experimental data and the dashed line is what one would expect for a rigid rotor.

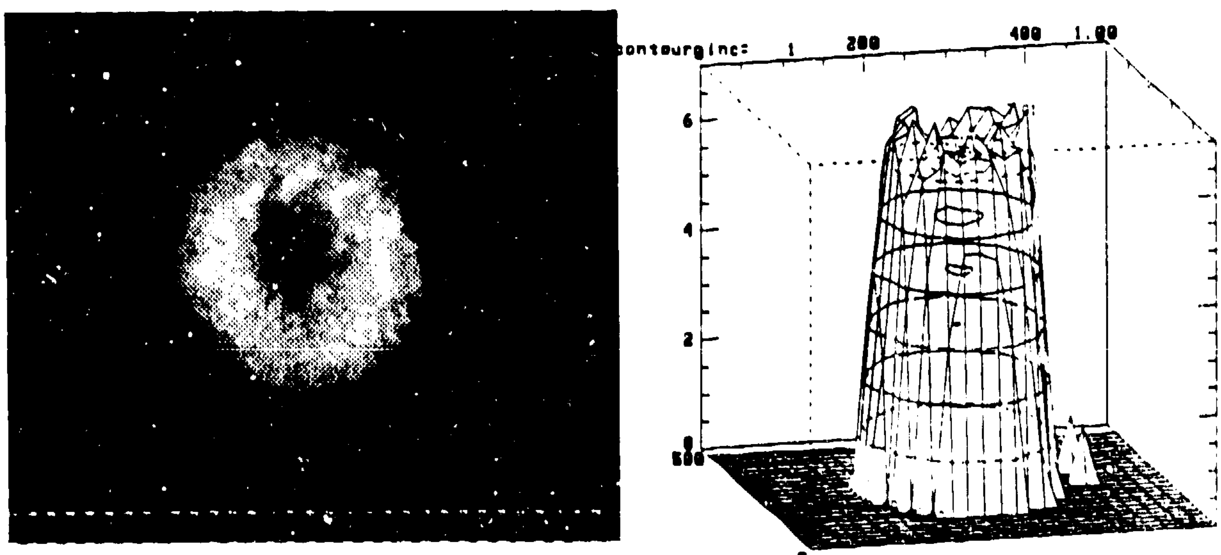


Figure 5- The above photo of an optimized 3 mTorr FRC was taken 60 μs after firing the theta pinch coil. Because it is very symmetric and has a particularly deep hole, it was chosen as an interesting example of how the density as a function of position can be unfolded from the photos. Using the same relationship between reflected light intensity and density mentioned above, the contour plot at the right was obtained. The vertical axis represents the density and the horizontal axes position.

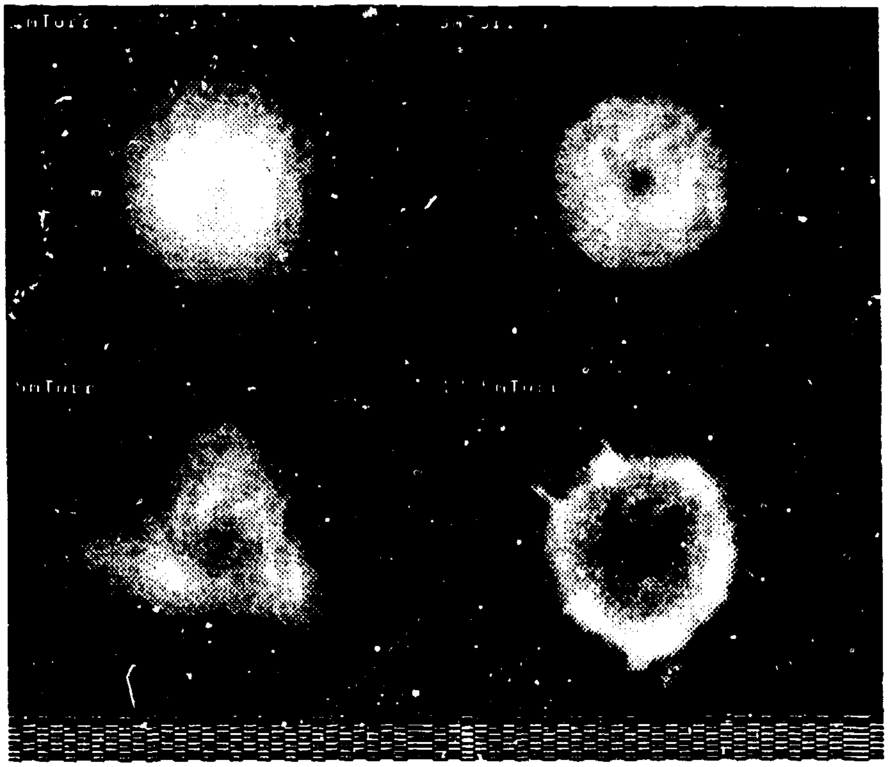


Figure 6- The figure above demonstrates how, at constant bias, FRC symmetry and confinement deteriorates as we increase fill pressure. Each of the photos above was taken 5 μs after firing the theta pinch at a bias field of 570 gauss. The fill pressure is listed in the upper left hand corner of each frame. The flux confinement times for these shots are listed below.

Fill Pressure (mTorr)	Flux Confinement Time τ_ϕ (μs)
2	168
3	470
5	14
12.5	17