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LITHIUM FLUORIDE ION SOURCE EXPERIMENTS ON PBFA II*

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ABSTRACT

Lithium fluoride, field-enhanced ion source experiments are being performed on PBFA II. The source consists of a thin coating of LiF on a microscopically rough substrate. Diagnostics to measure ion beam energy, purity, and transport include electrical monitors, Faraday cups, nuclear activation, ion pinhole camera, Rutherford magnetic spectrograph, and shadowbox aperture array. With PBFA II operating at three-quarters energy, the source has produced 16 TW of ion power and 550 kJ of ion energy with 70% diode efficiency. Over 26 kJ of lithium beam energy has been focused to the diode center axis with a peak energy density of about 1.3 kJ/cm^2. PICDIAG simulations of the lithium focus indicate the intrinsic source divergence is about 45 mrad with a 20-μm-grade porous stainless steel substrate.

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INTRODUCTION

The Particle Beam Fusion Accelerator II (PBFA II) was designed to provide a 30 MV, 150 TW power pulse to an Applied-B ion diode, for the purpose of investigating the suitability of light ions for inertial confinement fusion (ICF).[1] Singly-ionized lithium is the desired ion for acceleration, since it has the proper range in ICF target materials at 30 MeV, is magnetically stiff (compared to protons), and should be obtainable in a single charge state, due to the large second ionization potential for lithium. For PBFA II, the lithium ion source should provide less than a few nanoseconds turn-on delay with respect to the arrival of the accelerating pulse and an ion current density of greater than 5 kA/cm^2 over an active anode area of up to 800 cm^2. A Li^+ beam purity of greater than 90% is required and it must operate in the PBFA II vacuum (10^{-5} Torr). To obtain a good focus, the intrinsic source divergence must be less than 10 mrad, and the ions must originate from a thin (< 1 mm) layer conformal to the anode surface.[2] A lithium fluoride field-enhanced ion source on PBFA II has satisfied several of these requirements.

EXPERIMENTAL

The field-enhanced source consists of a thin (1-3 μm) coating of LiF vacuum-deposited on a microscopically rough anode substrate. For most of these experiments, the substrate was a porous, "20-μm-grade" stainless steel frit (Mott Metallurgical Corp.). Two-dimensional JASON calculations of the LiF-coated frit protrusions indicate the anode electric field should be locally enhanced by about a factor of 3.5, sufficient to initiate a number of ion-producing processes.[3] These include dielectric breakdown, valence-to-conduction band electron tunneling, surface flashover, and explosive fragmentation of the LiF surface.

A flat, nonfocusing, cylindrical anode was used for these experiments. It had an inside radius of 15 cm. and an ion-emitting height which was varied from 6-9 cm. The PBFA II accelerator was operated at three-quarters energy, without a plasma opening switch. The ion diode configuration was as shown in Figure 1, with a 2-μm Mylar gas cell window separating the diode vacuum gap from the 1 Torr argon-filled transport region. Diode electrical behavior was monitored by conventional methods.[4] In addition to the nuclear activation diagnostics described previously,[5] diagnostics at large radius included a shadowbox aperture array[4] to observe lithium beam divergence and steering and filtered Faraday cups to measure beam current density and composition. The on-axis lithium beam energy spectrum and focused power density were measured with a time-resolved magnetic spectrometer[6] which observed ions Rutherford scattered from a 0.25-μm-thick gold foil located at the center of the diode. The spatially-resolved energy density of the focused beam was measured by a dE/dx multi-frame ion pinhole camera (IPC),[7] which also observed ions scattered from the on-axis gold foil. The camera was modified for lithium experiments to allow a large, 12 cm^2 field-of-view. Both of these latter instruments have a low energy cutoff of about 4 MeV for lithium, due primarily to energy loss in the gas cell and scattering foils.

RESULTS AND DISCUSSION

Previous experiments with the LiF ion source with PBFA II at one-half energy had produced over 9.2 TW of ion power and over 300 kJ of ion energy, with 80% ion current efficiency.[5] Electrical monitors and nuclear activation measurements at large radius had suggested the accelerated ion beam was primarily lithium (two-thirds, by energy), with a small (<15%) proton fraction. These experiments were performed with the diode magnetic field separatrix (zero stream function surface) conformal to the anode surface. This configuration prevented the Li^+ from reaching the diode centerline, due to stripping of Li^+ to Li^{+++} in the gas cell foil and the concomitant change in canonical angular momentum.[8] Attempts to bring the horizontal position of the focus on-axis for Li^+ by moving the separatrix towards the cathode resulted in poor diode efficiency and large electron loss in the power feeds.

This difficulty was resolved by pushing more applied magnetic field flux towards the cathodes above the active anode region with the aid of anode feed coils.[9] This improvement, shown in Figure 2, gave efficient diode operation with the separatrix in a position to focus Li^+, thus permitting the use of on-axis particle diagnostics. Figure 3 shows electrical characteristics of a shot (2621) with the accelerator at 3/4 energy and the diode magnetic field as shown in Figure 2. With an anode-cathode (AK) gap of 1.6 cm. and an insulating applied field of 2 T, the diode was critically insulated for 10.3 MeV electrons. On this experiment, peak ion power was 16 TW, with 550 kJ of ion energy, and an ion current efficiency (ion current/diode current) of 70% at peak power. The time delay between the diode current and the onset of the ion current was 5 nsec. The voltage pulse decays rapidly approximately 15 nsec. after the onset of ion current. In proton diodes utilizing a surface flashover ion source, this voltage decay has been attributed to magnetic flux penetration of the anode plasma surface caused by ionization via charge exchange processes of fast neutrals which are freely expanding across the AK gap.[10,11] A similar mechanism is likely to pertain to the LiF source, with comparatively faster voltage decay due to the relatively smaller dynamic gap. The time-resolved measurement of the peak lithium beam energy, as determined by the on-axis magnetic spectrometer diagnostic, has shown good agreement with the electrical diode voltage monitors, indicating the beam is accelerated primarily as Li^+ and not in higher charge states.

Figure 4 shows the multi-frame ion pinhole camera images of the on-axis lithium focus with the improved diode magnetic field design. The beam is well-centered horizontally, but elongated vertically as a result of the flat, nonfocusing anode surface. The peak energy density on this experiment was 1.3 kJ/cm^2 for lithium ions above 5 MeV, with a total lithium beam energy on-axis of 26 kJ. This beam energy measurement has been confirmed by nuclear activation measurements with an ErD_2 target positioned immediately behind the Rutherford scattering foil. PICDIAG simulations[12] of the ion beam transport have predicted the on-axis lithium beam energy should be about a factor-of-three higher than the measured value. These simulations are performed assuming experimental applied B-field and electrical parameters, uniform ion emission from the active anode surface, 100% Li^+ purity, and complete current neutralization inside the gas cell. The simulations suggest that about 15% of the lithium ion beam energy is lost in the gas cell foil and approximately half of the beam strikes the cathodes with a flat, 7.5-cm-high anode surface. There are several possible explanations for the factor-of-three discrepancy between the experiments and the PICDIAG simulations, such as non-uniform anode emission, incomplete transport physics in the code (such as different or incomplete current neutralization inside the gas cell), or a lower beam purity than had been indicated on previous experiments, which had the separatrix on the anode.[5,13]

The horizontal full width at half-maximum of the lithium beam focal intensity, as measured by the IPC, was typically about 1.5 cm. for the LiF-coated, 20-μm-grade frit source, implying a total beam half-angle divergence of about 50 mrad. Of this, 25 mrad is attributable to non-constancy of the magnetic field stream function to the gas cell foil, flux penetration of the anode plasma, and multiple final charge states resulting from the low diode voltage and consequent incomplete stripping of Li^+ in the gas cell foil. Subtracting the beam transport-derived divergence in quadrature, the indicated intrinsic source divergence is 45 mrad.

Depending on the details of the ion-production mechanism, the beam divergence may be related to the source substrate topology. A simple analysis of an array of individual emitters of tip radius r_0 and spacing λ predicts a micro-divergence given by

$$\theta \sim \left\{ 2 \frac{E_s r_0}{V_0} \left[1 - \sqrt{\frac{2 r_0}{\lambda}} \right] \right\}^{1/2}$$

where V_0 is the gap applied voltage and E_s is the electric field stress necessary for ion emission. Analysis of the surface topology by profilometry, optical, and electron microscopy suggested that $\lambda \sim 150$ μm and $r_0 \sim 25$ μm for the 20-μm-grade frit. To obtain the indicated source divergence requires that $E_s = 5$ MV/cm for a 5 MV diode voltage. An experiment with a finer pore, 2-μm-grade frit ($\lambda \sim 70$ μm, $r_0 \sim 12$ μm) gave an IPC image FWHM of about 1.0 cm. and an inferred intrinsic divergence of about 25 mrad, in reasonable agreement with the prediction given above.

CONCLUSIONS

The field-enhanced LiF ion source being tested in PBFA II satisfies several of the required lithium ion source criteria. It has proven to be a valuable tool for investigating lithium ion diode characteristics and beam transport and for lithium diagnostic development while more advanced sources are being developed.[2] With PBFA II in the three-quarters energy configuration and the diode magnetic field configured to focus Li^+, the source has produced 16 TW of ion power and 550 kJ of ion energy with 70% efficiency. 26 kJ of lithium beam energy has been focused to the diode centerline. This energy is a factor-of-three below that predicted by PICDIAG beam transport simulations. The discrepancy may be due to incomplete modeling of lithium beam transport physics, non-uniform ion emission, or lower ion beam purity. Experiments are being planned to resolve this issue. With 20-μm-grade frit as the ion source substrate, the inferred intrinsic source divergence is about 45 mrad. Experiments and modeling suggest this may be reduced to the required 10 mrad micro-divergence with a finer substrate topology. Additional improvements in the beam focus will result from increasing the diode voltage and proper shaping of the gas cell foil and anode surfaces.

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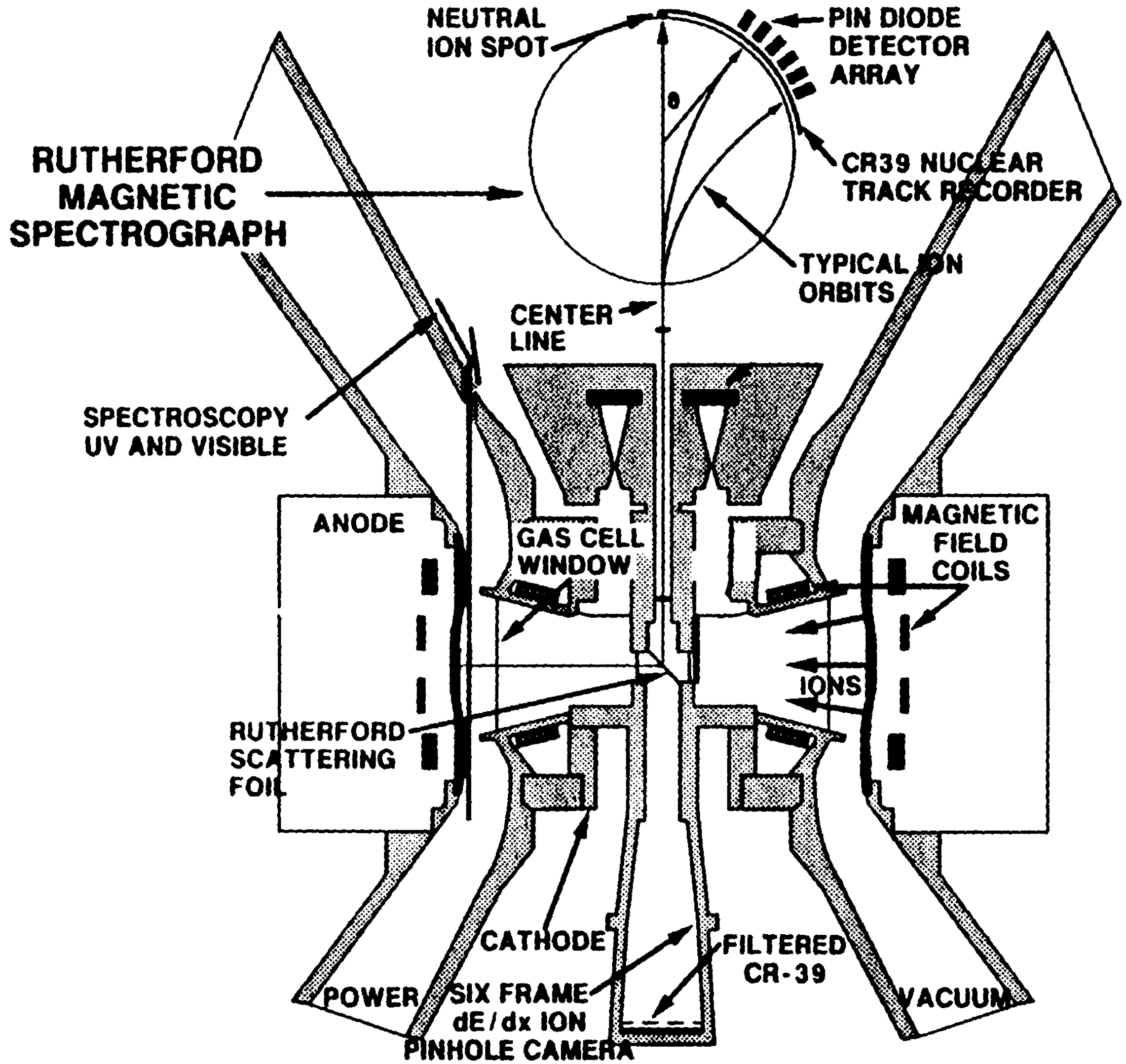
FIGURE CAPTIONS

Figure 1. PBFA II Applied-B Ion Diode and Diagnostic Layout for LiF Ion Source Experiments.

Figure 2. Diode Magnetic Field Topology Configured to Focus Li+, Including Anode Feed Coils.

Figure 3. Diode Electrical Behavior for PBFA II Shot #2621, with Magnetic Field Topology Shown in Figure 2.

Figure 4. Ion Pinhole Camera Images of Lithium Focus with Diode Magnetic Field Topology Shown in Figure 2.



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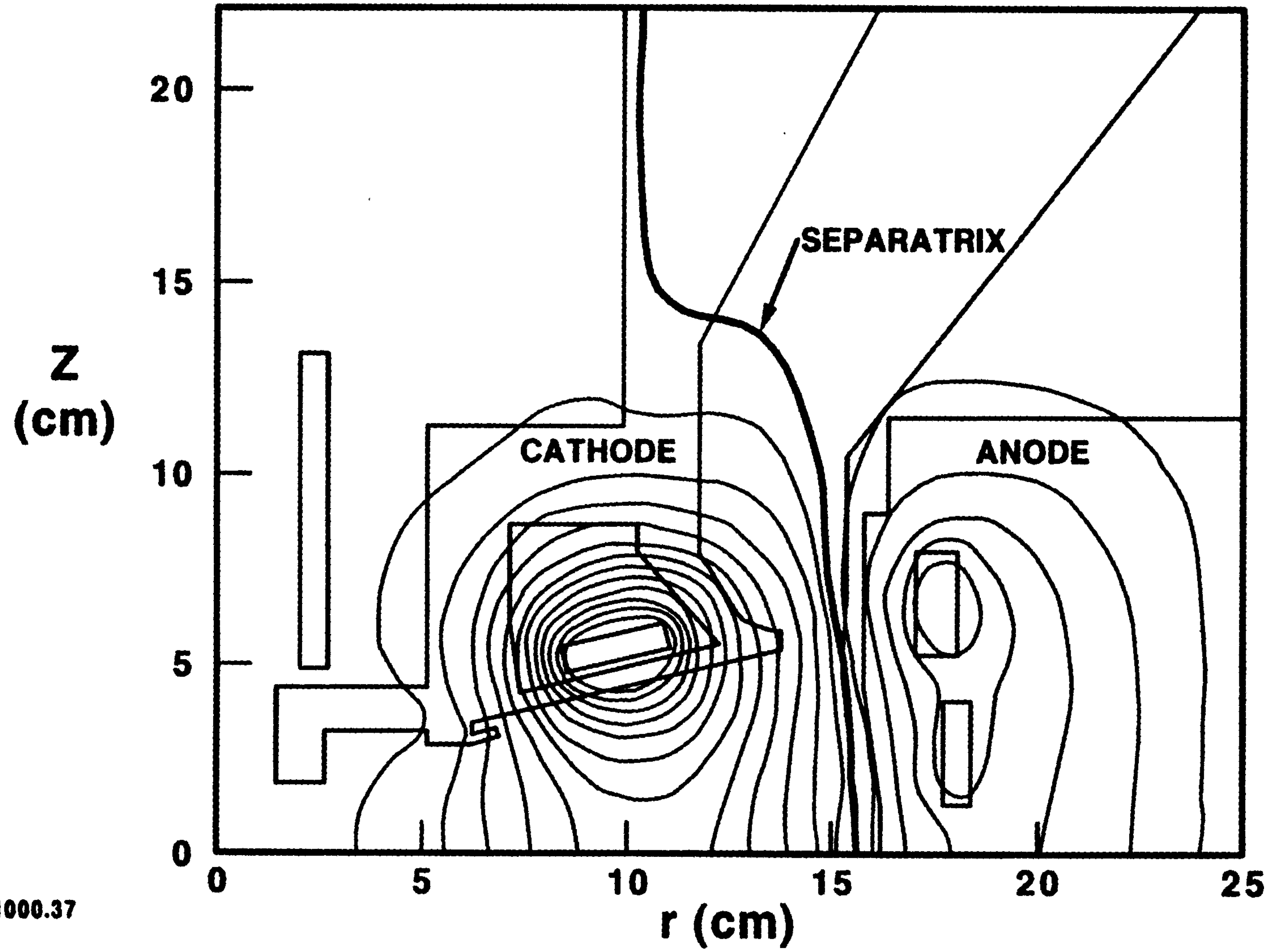
DIODE MAGNETIC FIELD PROFILES



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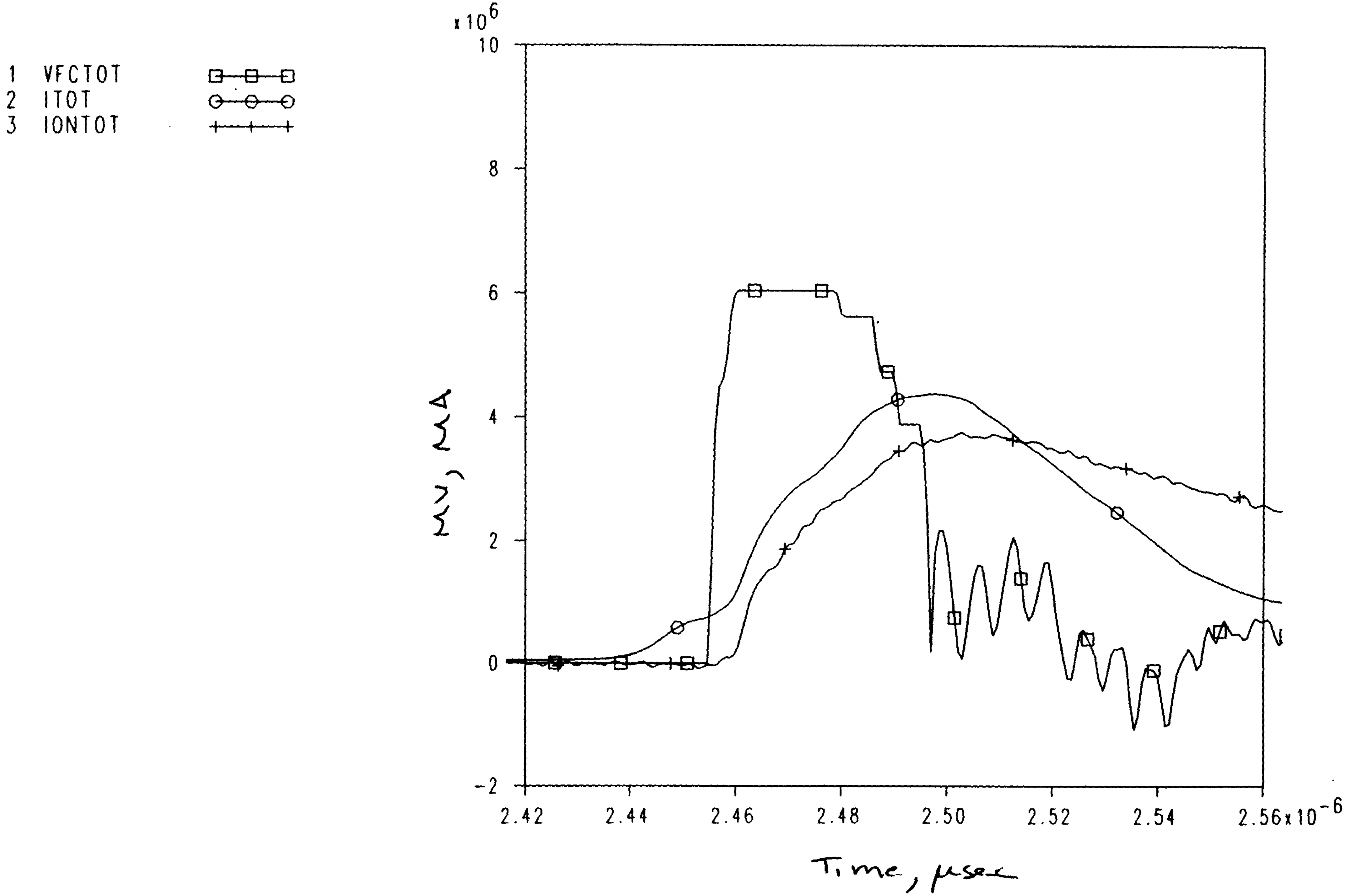

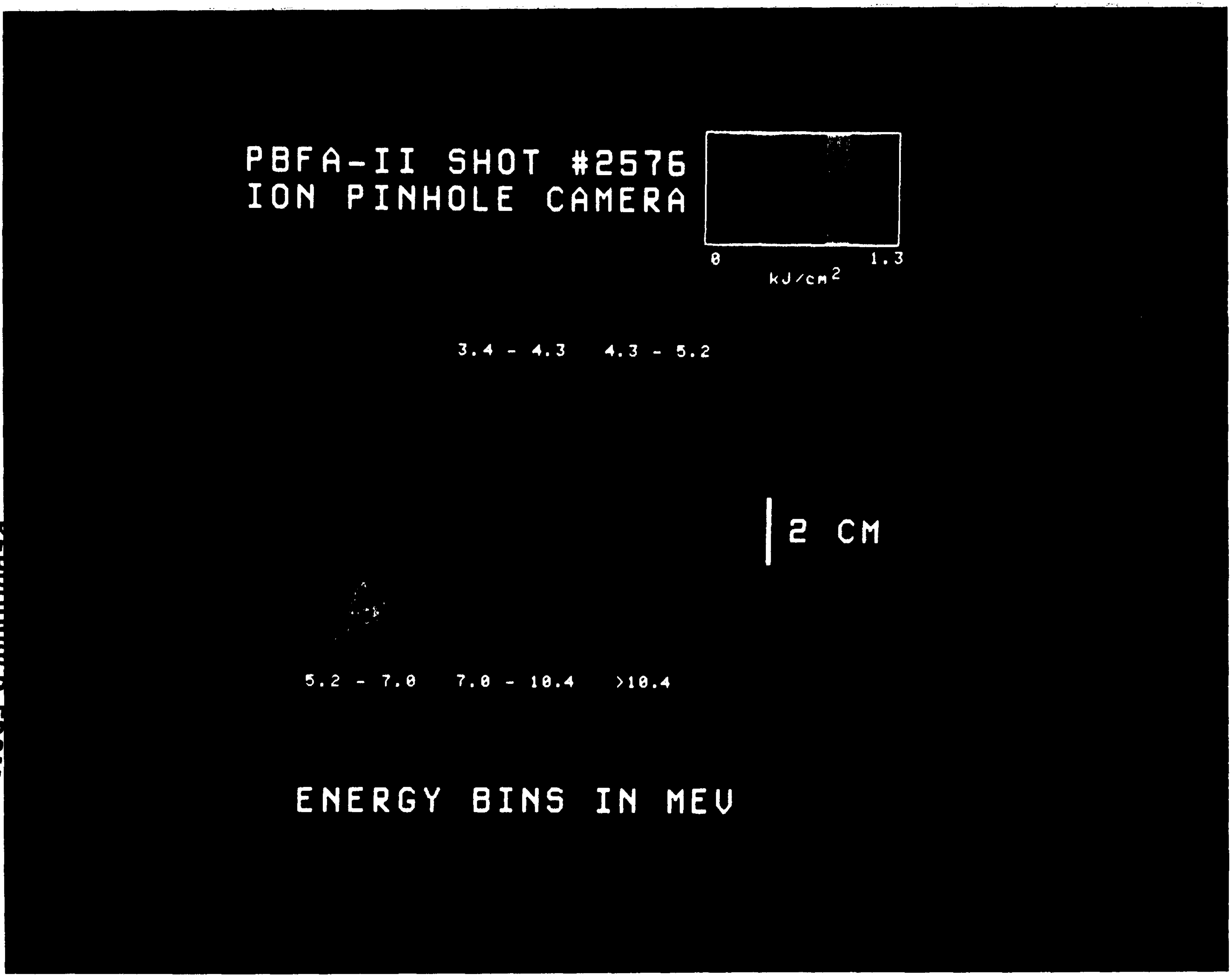
PBFA-II SHOT #2576
ION PINHOLE CAMERA
0
1.3
kJ/cm2
3.4 - 4.3
4.3 - 5.2
2 CM
5.2 - 7.0
7.0 - 10.4
>10.4
ENERGY BINS IN MEV