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HIGH BRIGHTNESS IMMERSED SOURCE INJECTOR CHARACTERIZATION

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ABSTRACT

RADLAC II is a high current linear induction accelerator for electrons. The beam is produced in a field-immersed foilless diode injector. We report the first time-resolved characterization of a similar high-brightness immersed diode source using a time-gated, 2-D x-ray imaging technique. The experiments were performed on the 4-MeV IBEX accelerator and produced currents exceeding 40 kA in a 6-mm radius, thin annular beam with a measured thermal transverse velocity $v_\perp=\beta_\perp c\sim0.1c$. For currents of 30 kA, even brighter beams with $\beta_\perp=0.07$ were obtained. At lower currents, beams as small as 2 mm in radius were produced with a smaller cathode tip. In all cases, the measured parameters were consistent with 2-D PIC simulations. The experimental results will be discussed and compared to theory and simulations.

INTRODUCTION

The upgrade of RADLAC II to the 40-kA level imposes severe requirements on the injector. The field-immersed diode source, which produces an annular beam geometry, was chosen for RADLAC because it allows generation of higher currents than shielded sources.[1] In order to obtain the small equilibrium radius that is required for atmospheric pressure beam propagation experiments, a high brightness, (low transverse momentum) source is essential. This is because the

beam equilibrium radius in air is proportional to the emittance (including rotation) and the square root of the ratio of Alfven current to net current. In one previous experiment,[2] which used a 10 Tesla solenoidal field, an ultra-high brightness beam was generated in the field, but could not be extracted due to high canonical angular momentum, P_θ. In another experiment,[3] it was demonstrated that the immersed diode source could generate a beam of reasonable emittance, which could be extracted, but optimization of beam brightness or time-resolved measurements of beam emittance were not attempted.

Our recent experiments on the 4-MeV IBEX accelerator[4] have demonstrated operation of an immersed diode source at currents and brightness greater than the RADLAC-II upgrade requirements. A unique instrument, the 6-frame gated x-ray camera,[5] was used to study time-resolved beam generation in the source on a nanosecond time scale.

APPARATUS

Figure 1 shows the IBEX field-immersed foilless diode source schematically. Six-inch diameter pancake coils were used to provide a uniform solenoidal pulsed magnetic B_z field in the region of the annular stainless steel cathode tip. The B_z field could be varied up to >2 Tesla. The cathode radius and A-K gap spacing were also varied to optimize beam current and emittance.

The diode voltage was monitored with a D-dot monitor and Rogowski coils were used to measure the beam current generated by the source. A metallic witness plate or tantalum x-ray converter was used to image the beam at various distances from the cathode tip for analysis. The beam was characterized by imaging the x-ray converter with a time-gated, x-ray framing camera with 5-ns time resolution. The intensified images were recorded on polaroid film, which was scanned to provide beam intensity contours.

EXPERIMENTAL RESULTS

A thin annular beam was generated as seen in Fig. 2 for the optimized case of 2.2 Tesla with a 6.3-mm radius cathode and 2.0-cm A-K gap. The six plots result from scans through x-ray frames with a real time-separation of 5 ns. Figure 3 is the result of azimuthal averaging through the same data. In this form it can be seen that the annular beam radius and thickness do not vary significantly during the diode voltage pulse. An analysis of Larmor orbits as described in Ref. 6 shows that $\beta_\perp$ can be computed from the beam annular width w in centimeters by $\beta_\perp=(w-a)B/(3.4\ \gamma)$ where a is the annular thickness of the cathode tip in centimeters and B is in kilogauss. This analysis implies $\beta_\perp=0.07$ for the optimized case of Figs. 2 and 3 which produces a measured current of 30 kA with a mean radius of 6 mm. Again using the method of Ref. 6, we compute a beam brightness, $I/(\pi\varepsilon_b)^2$, of $3x10^{+4}$ and $5x10^{+2}$ $A/(rad\text{-}cm)^2$ for the magnetized and extracted beam, respectively, where ε_b is the normalized beam emittance. The extracted brightness which is of interest for beam propagation studies is much higher than the requirement for RADLAC-II beam propagation experiments.

Reducing the B_z field to 1.5 Tesla caused a considerable increase in the transverse velocity. The 6-frame x-ray camera revealed the presence of radial oscillations 5 cm beyond the cathode tip as shown in Fig. 4. Measurements at 50 cm beyond the tip showed a phase mixed beam with the radial oscillations converted to temperature.

To produce even higher brightness, experiments were conducted with very small cathode tips. A 3.2-mm radius tip with a 7-cm AK gap and 2.2 Tesla produced a 14-kA annular beam with 3-mm radius and a thermal $\beta_\perp \simeq 0.1$. Figure 5 displays a slice through the time integrated x-ray pinhole image produced by this beam with the tantalum converter 50 cm beyond the cathode. The smallest cathode tip studied was a 1.6-mm radius solid stainless steel rod. For this configuration the Larmor orbits were comparable to the beam size and a well smoothed Bennett-like 12-kA beam with a 2-mm radius was produced as seen in Fig. 6. For the smaller tips, the extracted beam brightness is two orders of magnitude higher than the RADLAC requirements.

Production of higher currents was also studied. With the 6.3-mm radius cathode, a peak current of 39 kA with $\beta_\perp = 0.12$, was obtained for a 1.0-cm AK gap at 2.4 Tesla. By increasing the cathode radius to 9.5 mm, currents exceeding 50 kA were obtained but the brightness was degraded due to the large radius.

COMPARISON TO SIMULATIONS

The 2-D fully electromagnetic PIC code MAGIC was used to simulate the high brightness immersed diodes. Table I summarizes the 27 cases that were run. In the table, d refers to the anode cathode gap while r_{tube} is the radius of the conducting transport tube which along with the cathode is immersed in the uniform solenoidal B_z field. The beam current that is produced and propagated by the diode is labelled I_{total} while I_{shank} refers to that fraction of the current which is formed on the sides of the cathode rather than on the face. Finally, $\beta_{\perp}$ is the RMS value of the transverse thermal velocity. The rotational velocity which will result if the beam is extracted from the magnetic field is an additional term not included in Table I.

For all the cases which were compared to the experiment, good agreement to the measured values was obtained for I_{total}, $\beta_{\perp}$, and for the beam radius (r_b) and thickness. There are no free parameters in the code and the resulting beam parameters are predicted solely from the diode geometry, voltage, and magnetic field.

Figure 7 shows a particle plot resulting from run #17 simulating the optimum case with cathode radius r_k=0.63 cm, d=2.0 cm, B_z=24 kG, and V=3.5 MV. The simulation predicts a clean annular beam slightly thicker than the annular cathode with $\beta_{\perp}$=0.07. Again this is in excellent agreement with the experimental data.

Figure 8 resulting from run #7 shows that for a 0.95-cm radius cathode a 35-kA beam with $\beta_{\perp}$=0.09 can be produced with only 10 kG field. Figure 9 from run #9, shows the result of decreasing the field to 6 kG. The beam temperature increases to $\beta_{\perp}$=0.2, and zero frequency cyclotron waves are excited. This is the same effect that was observed experimentally when inadequate magnetic field was employed. It is possible to generate beams with adequate brightness for the RADLAC experiments using the .95-cm radius cathode but higher brightness can be achieved with smaller cathodes if 20 to 30-kG fields are available.

By going to larger gaps and smaller cathode radius r_k=3.2 mm, we obtain Runs 22-25 of Table I. The $\beta_\perp$ is larger, but this is more than compensated by the smaller r_b and final rotation after extraction. Note that a larger drift tube is used, so that these runs are near I_{SCL} = 17 kA.

Figure 10 shows the beam for a 1.6-mm radius solid-tip cathode (Run 27). The beam current is reduced (12 kA), but $\beta_\perp$ is not greatly increased, and the final rotational velocity will be about c/6 (max). Of course, such a small beam would have space-charge-limit problems in RADLAC, but if high brightness is the main concern, these small-cathode diodes may be the best approach.

CONCLUSION

Experimental and theoretical work have demonstrated that proper injector design results in the generation of very high brightness beams in a field-immersed foilless diode source which is suitable for use on RADLAC II. By dropping the current, even brighter beams can be obtained. The good agreement with PIC simulations should allow scaling to other applications, such as microwave sources and free electron lasers.

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Figure Captions

Fig. 1. Schematic of IBEX high brightness field immersed foilless diode source.

Fig. 2. X-ray framing data for 2.2-Tesla field with 5-ns frame spacing.

Fig. 3. Current density radial profile from angular averaging of x-ray frame data for 2.2 Tesla.

Fig. 4. Current density radial profile for 1.5-Tesla field showing radial oscillations.

Fig. 5. Current density radial profile from time integrated x-ray pinhole data for 3.2-mm radius cathode with 2.2-Tesla field..

Fig. 6. Current density radial profile for 1.6-mm radius solid cathode with 2.2-Tesla field.

Fig. 7. MAGIC simulations of IBEX high brightness immersed source with R_k=6.3 mm, d=2.0 cm and B_z=2.4 Tesla.

Fig. 8. MAGIC simulations of IBEX source with R_k=9.5 mm, d=2.0 cm and B_z=1.0 Tesla.

Fig. 9. MAGIC simulation of IBEX source with R_k=9.5 mm, d=2.0 cm and B_z=0.6 Tesla. Zero frequency cyclotron waves result from inadequate field.

Fig. 10. MAGIC simulation of IBEX source with R_k=1.6 mm, d=7 cm and B_z=2.2 Tesla.

Table I MAGIC Runs of IBEX foilless immersed diodes.

All cases used V = 3.5 MV except 12, 13 (4 MV).

run	r_k(cm)	d(cm)	r_{tube}(cm)	B_z(kG)	I_{tot}(kA)	I_{shank}(kA)	$\beta_\perp$	Comments
1	1.0	0.6	2.0	10	59	44	0.32	large radial oscill.
2	0.91	1.6	2.0	10	37	28	0.11	good beam
3	0.91	1.6	2.0	10	38	27	0.12	DZ/2 test
5	0.95	2.0	1.9	7	39	30	0.20	B_z too small
6	0.95	2.0	1.9	10	34	26	0.10	
7	0.95	2.0	1.73	10	35	26	0.09	varied r(tube)
8	0.95	5.0	1.73	10	22	17	0.06	big gap, better beam
9	0.95	2.0	1.73	6	42	33	0.2	12 kA loss
12	0.63	1.0	1.73	24	32	22	0.13	small δR
13	0.63	1.0	1.73	24	33	21	0.15	DZ/2 test
14	0.63	1.5	1.73	24	31	22	0.10	
15	0.63	1.0	1.73	24	40	28	0.14	near I_{SCL}
17	0.63	2.0	1.73	24	28	21	0.07	great beam
19	0.63	2.0	1.73	12	33	27	0.17	scrape limiter
18	0.32	1.0	0.87	12	40	33	0.18	28 kA loss
20	0.32	1.0	0.87	24	33	27	0.17	
22	0.32	5.0	3.0	22	15	11	0.13	r_b = 3.2 mm
23	0.32	5.0	3.0	16	16	13	0.19	r_b =4.0 mm; at I_{SCL}
24	0.32	10.0	3.0	16	15	12	0.13	r_b = 3.8 mm
25	0.32	10.0	3.0	22	14	11	0.09	r_b = 3.2 mm
27	0.16	7.0	3.0	22	12	11	0.17	r_b = 2.1 mm

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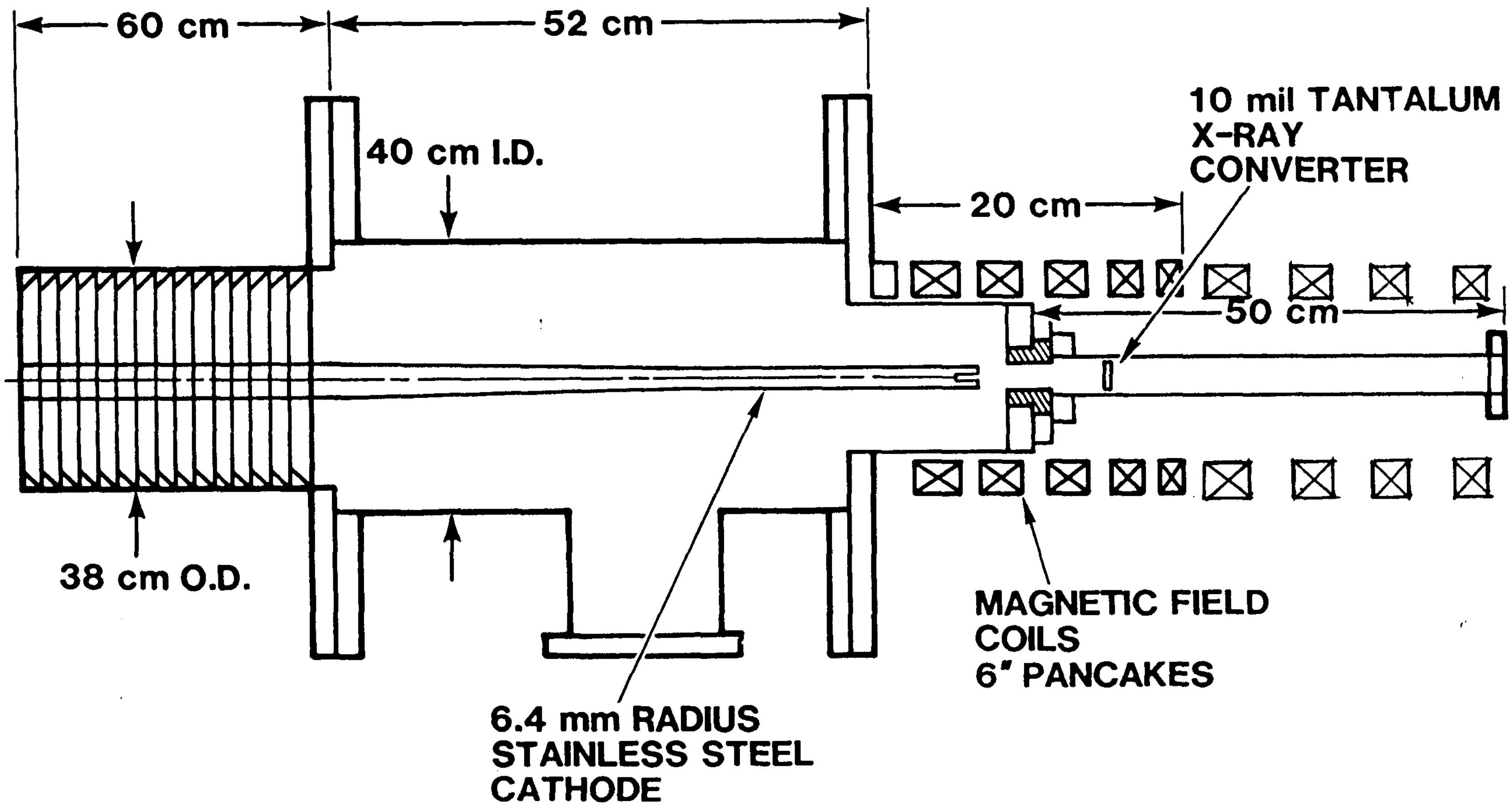
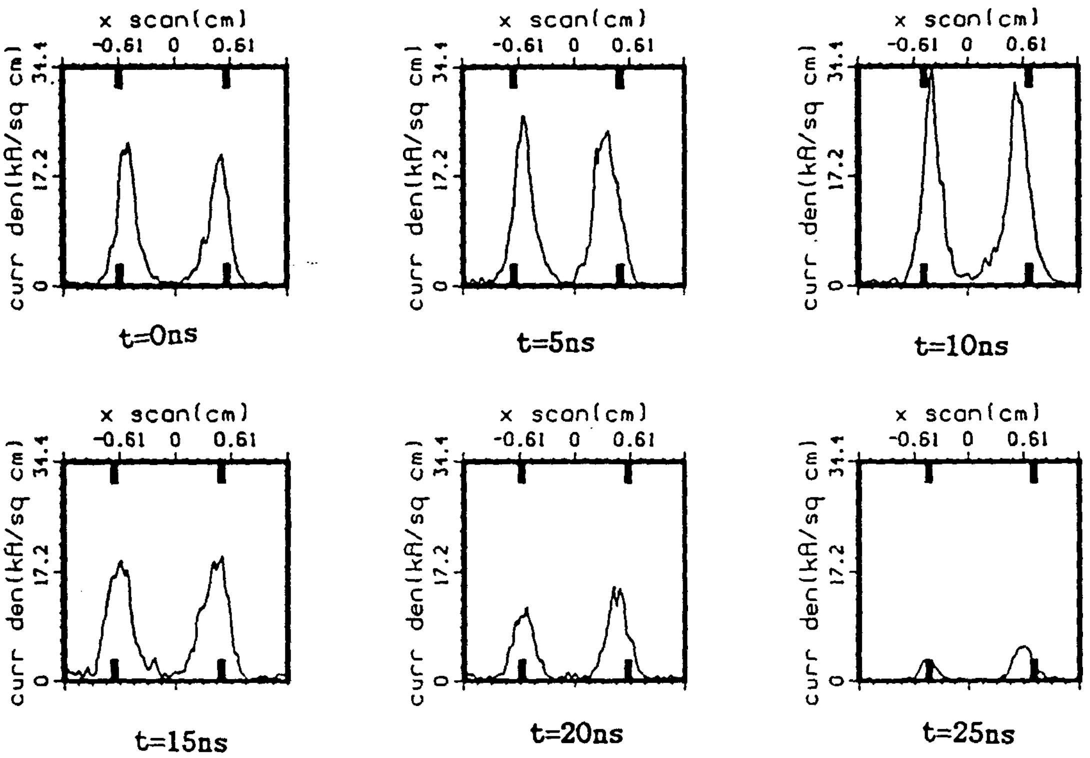
IBEX IMMERSED DIODE

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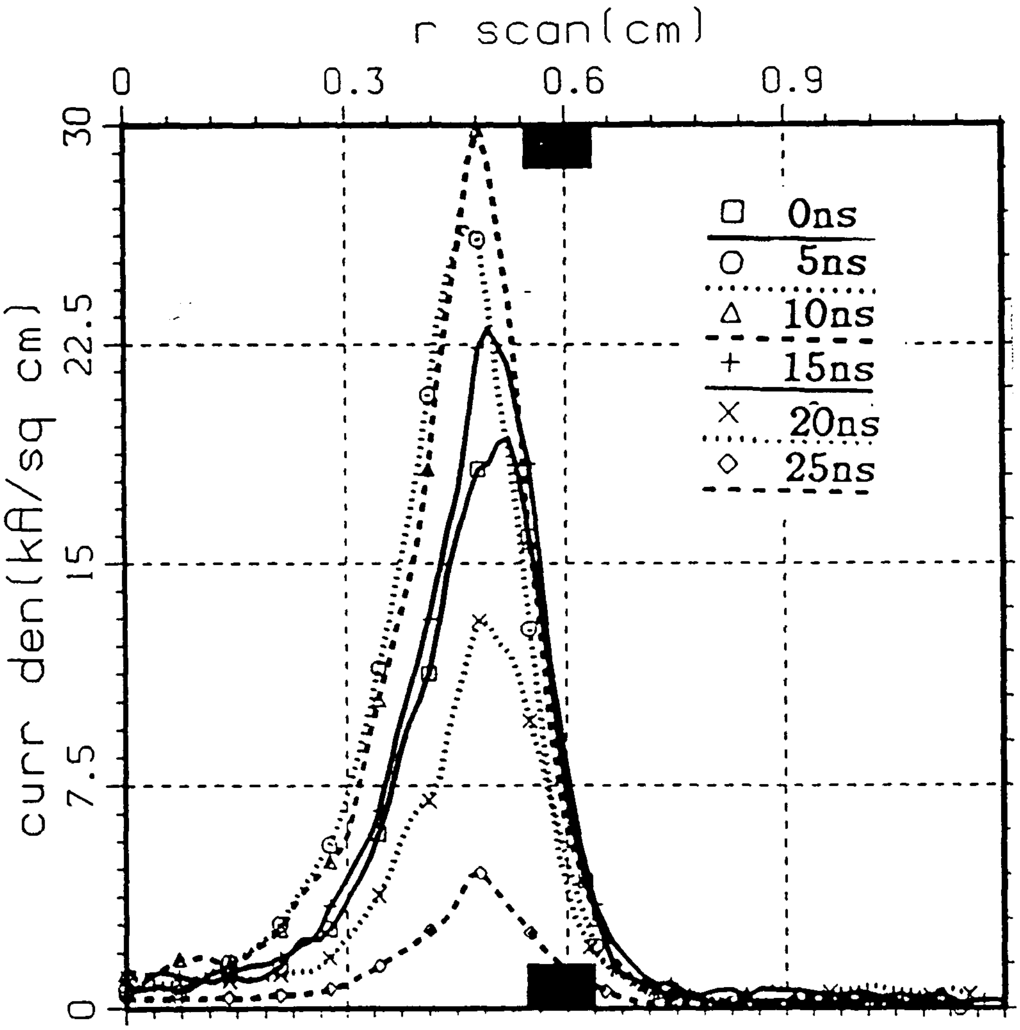
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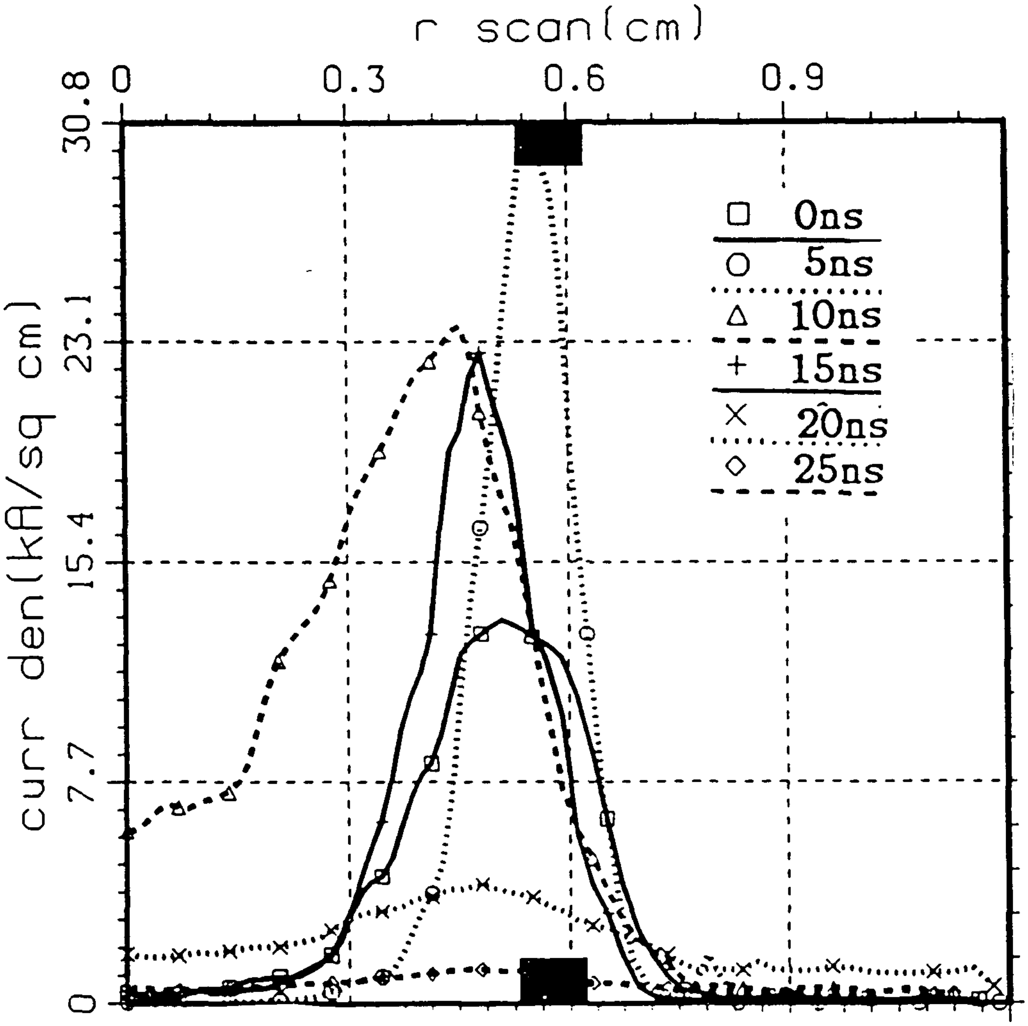
25ns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25ns

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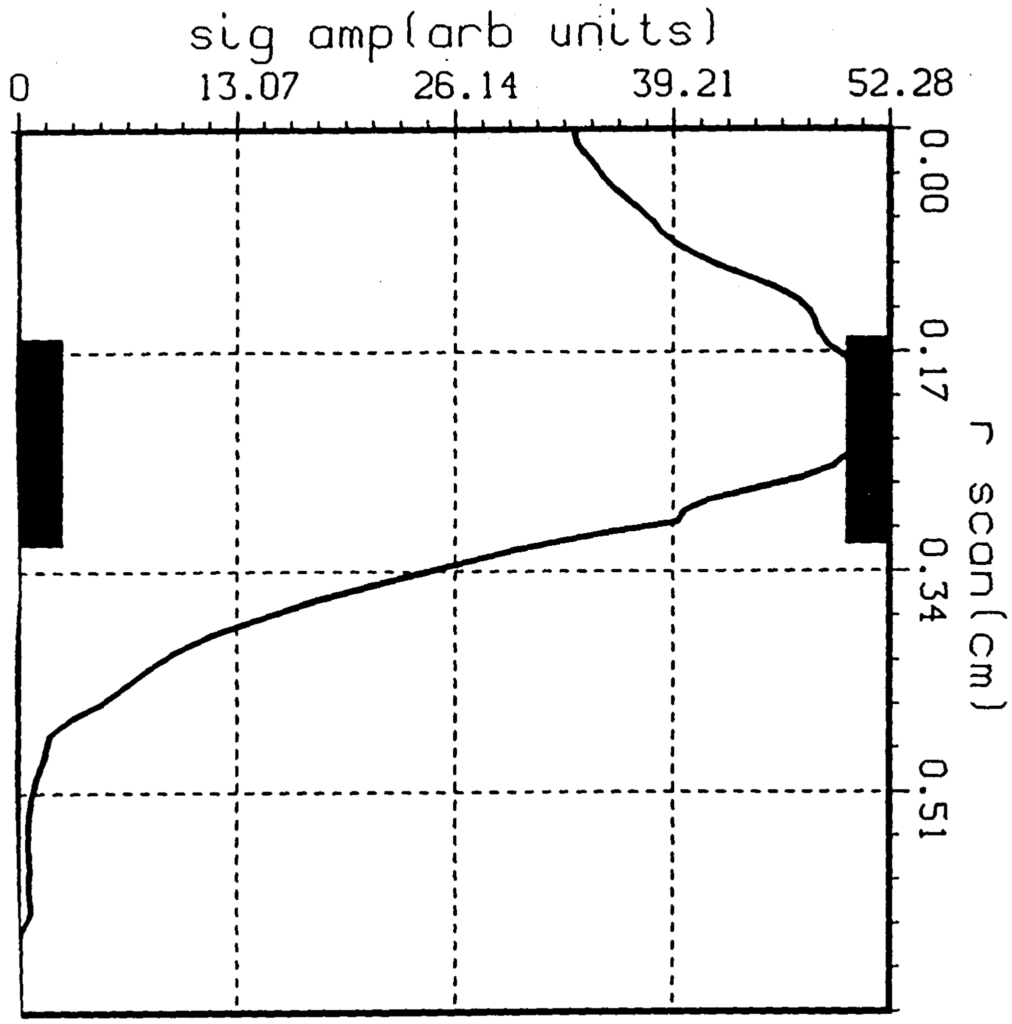
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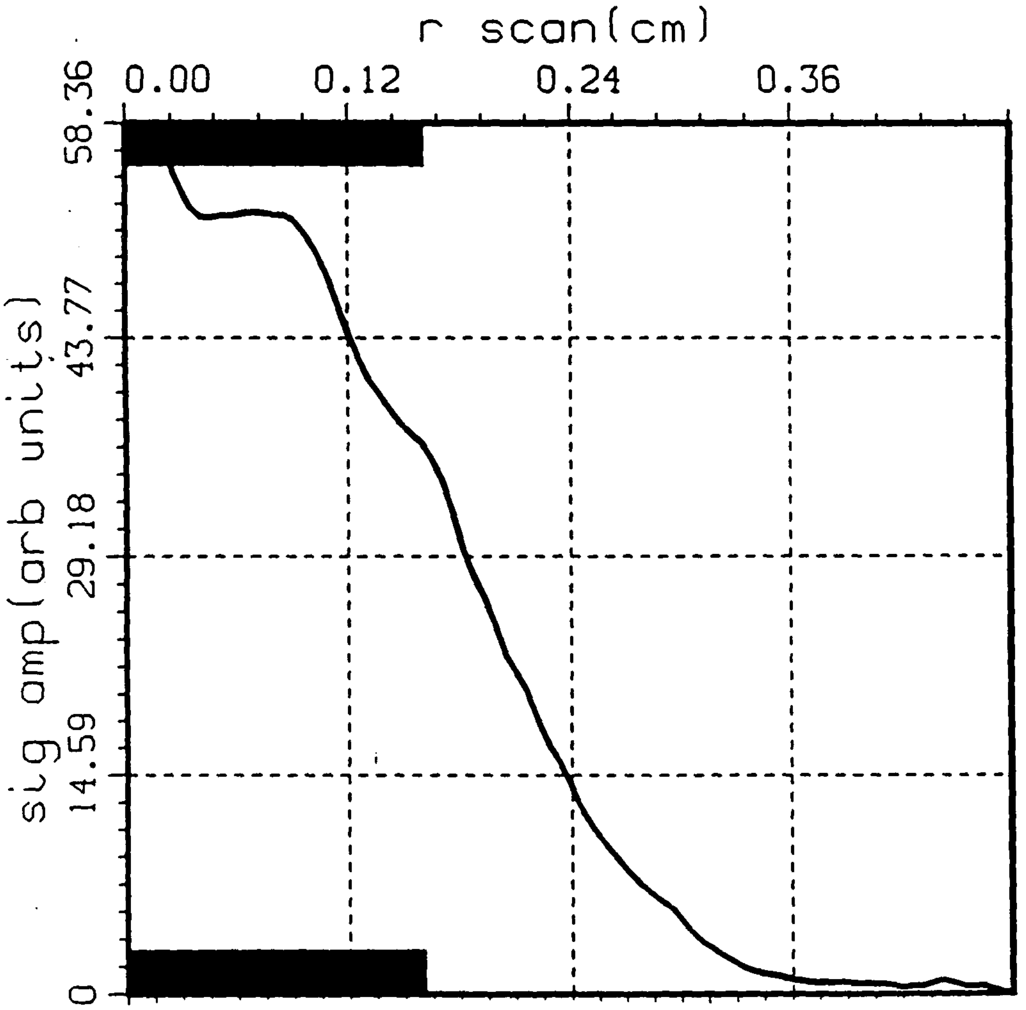
0.51
r scan(cm)

6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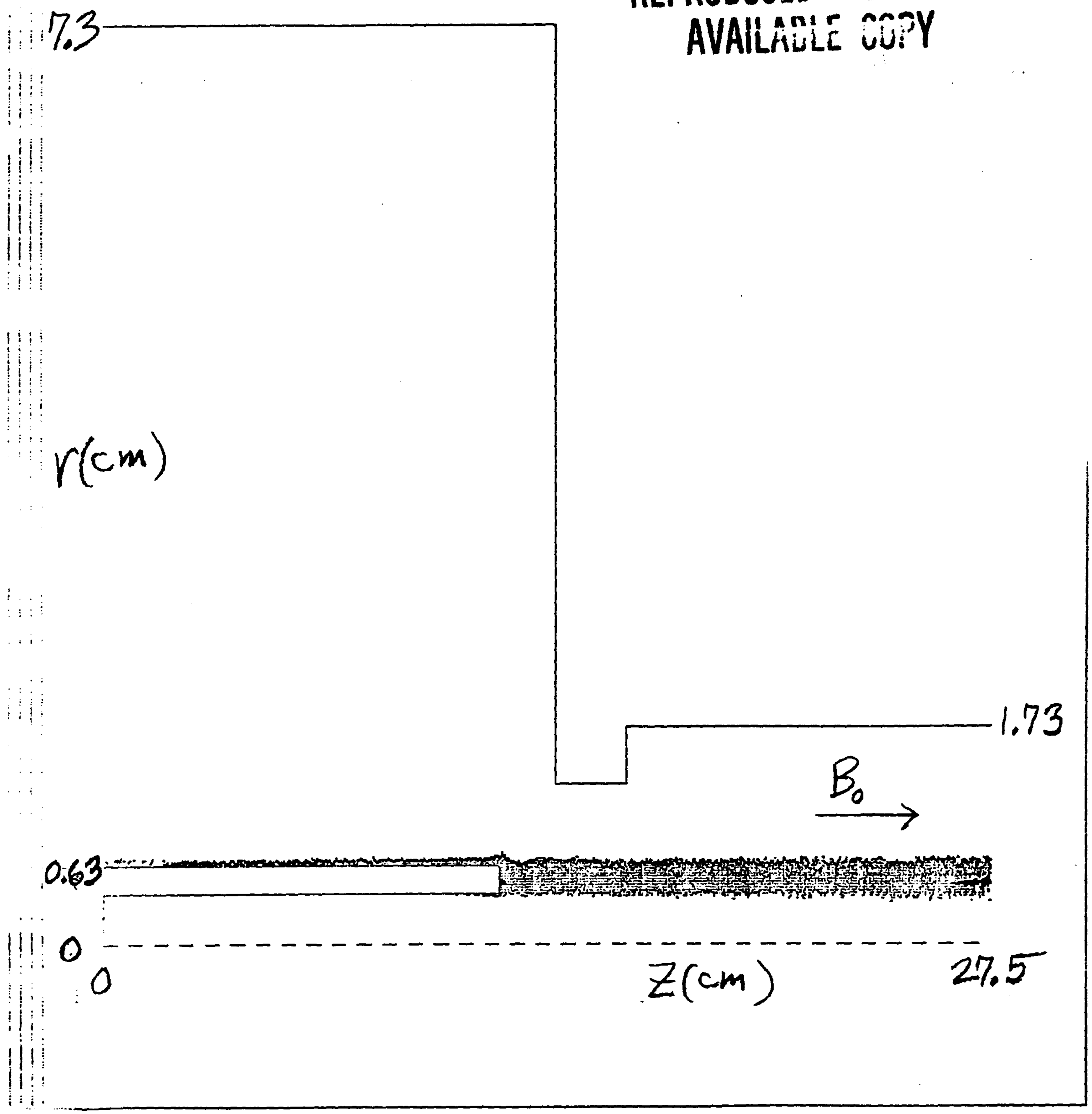
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B_0
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0
Z(cm)
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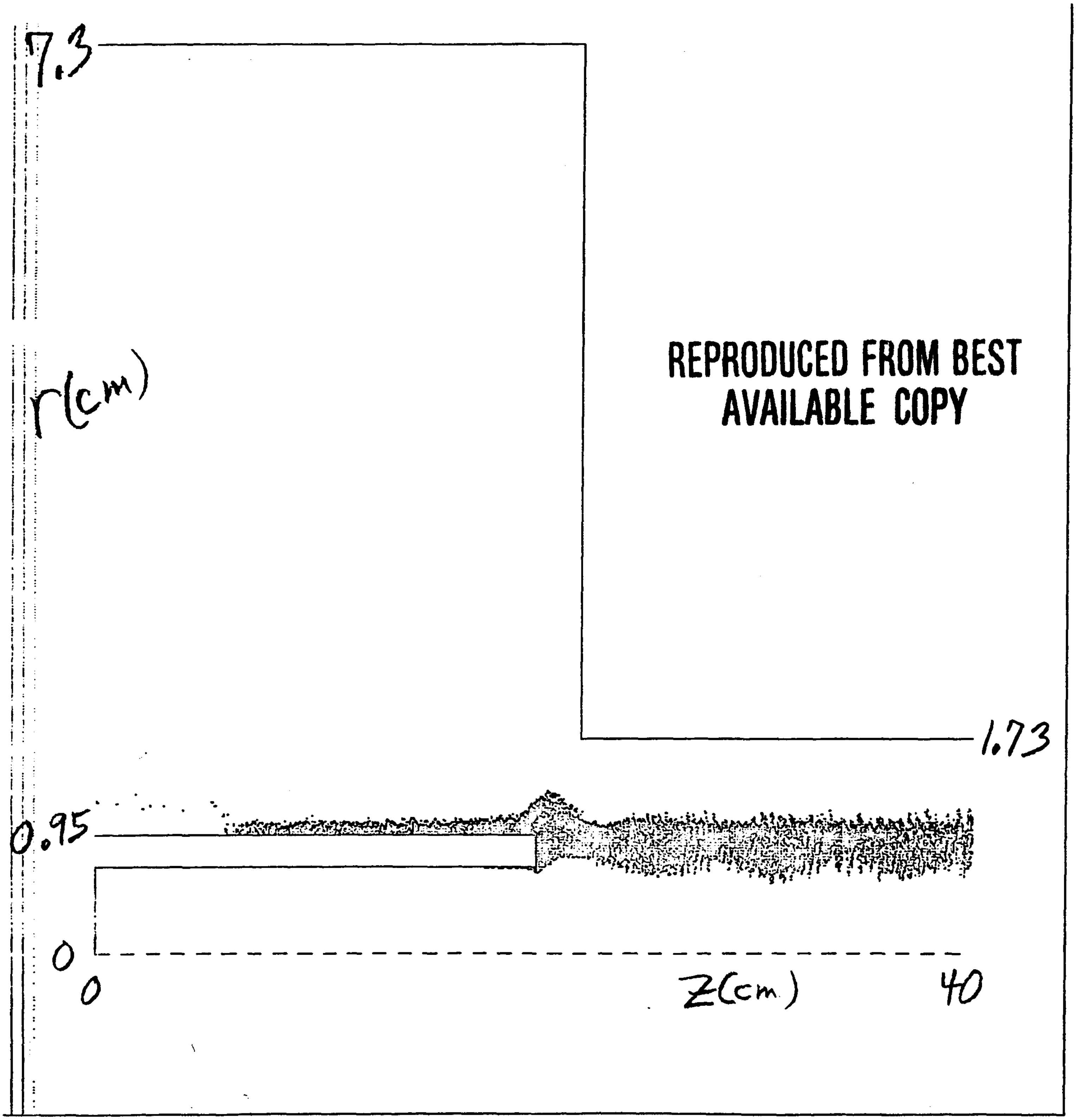
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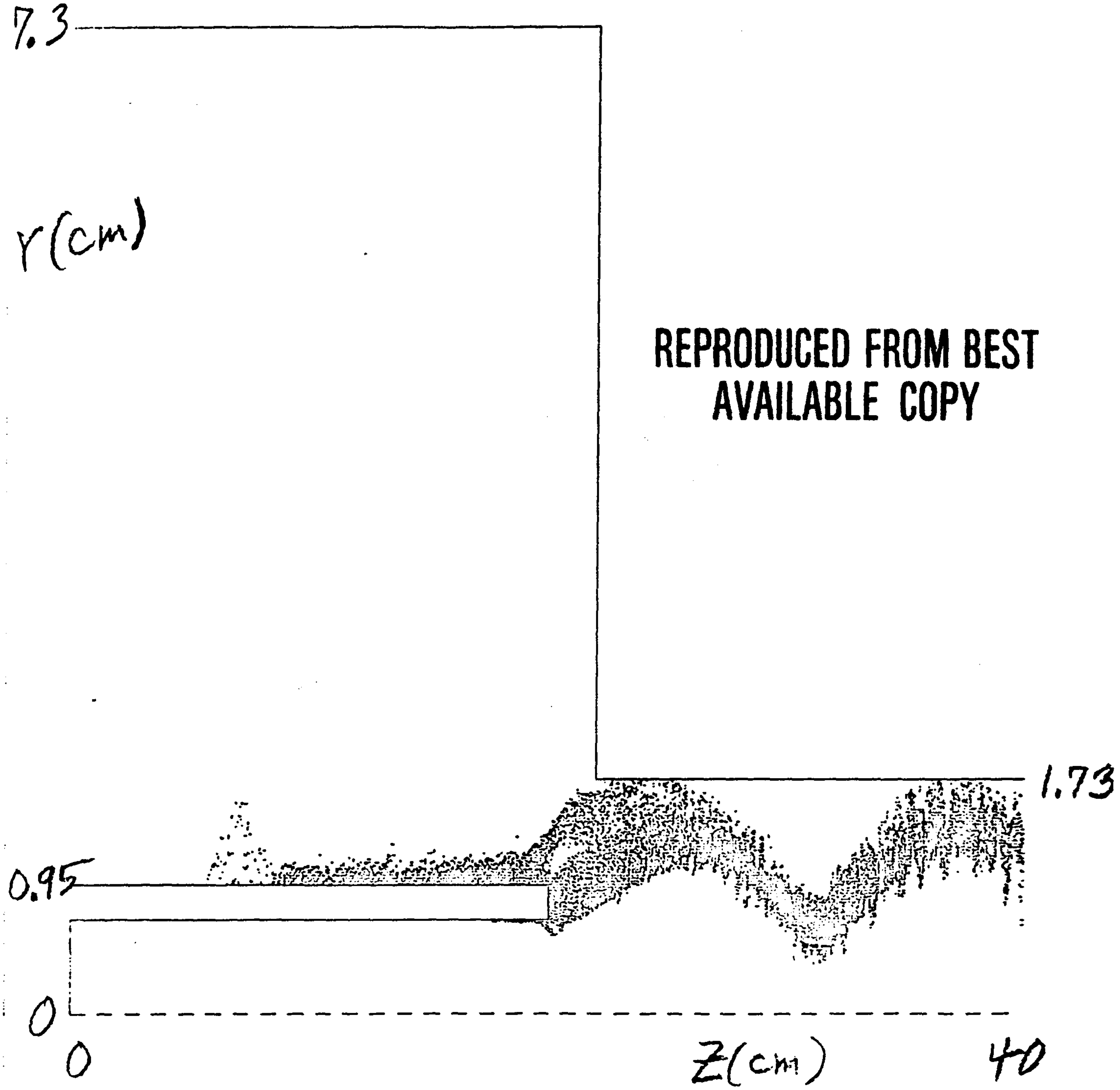
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Z(cm)
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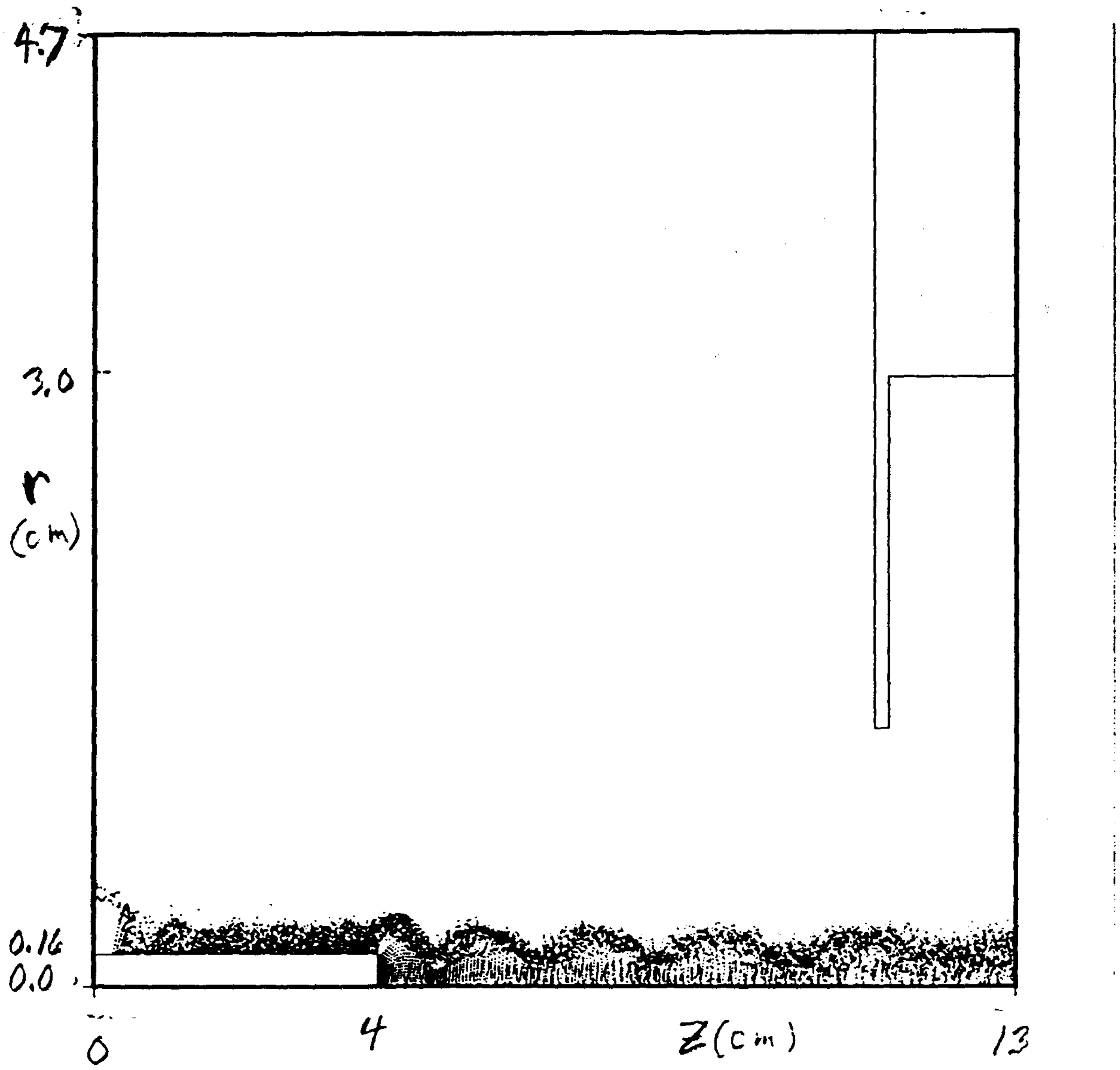
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0.0
0
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Z(cm)
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