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AUTHOR(S) Ronald A. Riley, Jr.
Ralph H. Lovberg
Jack S. Shlachter
David W. Scudder

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Optical Diagnostics on Dense Z-Pinch Plasmas

R. A. RILEY, R. H. LOVBERG, J. S. SHLACHTER, and D. W. SCUDDER
MS E-526, Los Alamos National Laboratory, Los Alamos, NM 87545

A novel "point-diffraction" interferometer has been implemented on the Los Alamos Solid Fiber Z-Pinch experiment. The laser beam is split into two legs after passing through the plasma. The reference leg is filtered with a pin-hole aperture and recombined with the other leg to form an interferogram. This allows compact mounting of the optics and relative ease of alignment. The Z-Pinch experiment employs a pulsed-power generator that delivers up to 700 KA with a 100ns rise-time through a fiber of deuterium or deuterated polyethylene (CD_2) that is 5-cm long and initially solid with radius $r \approx 15 \mu m$. The interferometer, using a $\Delta t \approx 200ps$ pulse from a Nd:YAG laser frequency doubled to $\lambda = 532nm$, measures the electron line density and, assuming azimuthal symmetry, the density as a function of radial and axial position. Calculations predict Faraday rotations of order $\pi/2$ for plasma and current densities that this experiment was designed to produce. The resulting periodic loss of fringes would provide the current density distribution.

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I. INTRODUCTION

In 1985, the ZEBRA project at Los Alamos National Laboratory began forcing high currents through initially cryogenic ($T \approx 18$Kelvin), solid ($n \approx 5 \times 10^{22} cm^{-3}$) deuterium fibers[1]. Fibers of radius $r \approx 15 \mu m$ continuously extrude into a vacuum chamber between electrodes $L=5cm$ apart[2]. We recently have begun using deuterated polyethylene (CD_2) fibers as well.

The current flowing along the Z axis of the fiber quickly ionizes and ohmically heats it. This current creates a magnetic field in the θ direction that presses the plasma toward its axis. The current was designed to increase in time according to the "Haines-Hammel curve"[3,4] to heat the plasma to fusion temperatures ($T \approx 10$KeV) despite Bremsstrahlung cooling, while retaining near solid density by balancing thermal plasma pressure with magnetic field pressure. This requires the experiment to apply a voltage that rises to $V \approx 2$MV in $t \approx 15$ns, and to drive a current that rises to $I \approx 1$MA in $t \approx 100$ns.

The data from the shots taken so far show that the plasma develops "m=0" sausage instabilities[5] and expands rapidly. These instabilities develop as the magnetic field squeezes into the plasma at some points along the Z axis until it "necks off" giving the plasma the appearance of a string of ink sausages. The current thrust of the experiment is toward understanding and explaining the development of the instabilities and how they drive the expansion of the plasma.

II. UTILITY OF AN INTERFEROMETER

The plasma exists in a very inhospitable environment for a very short time and expands radially by three orders of magnitude. This puts constraints on how we can collect data from the plasma. The high electric field strengths ($E \approx 400$ KV/cm) limit our diagnostics of the plasma to Bremsstrahlung and fusion product emissions and optical probing.

We chose an interferometer to measure the plasma density at different times during the evolution of the plasma. For simultaneously high currents and high densities, this diagnostic would also provide a measure of the magnetic field and current density distributions via Faraday Rotation.

The short duration of the plasma ($t \approx 100$ns) requires that the interferometer use a very short laser pulse ($t \ll 1$ns) to prevent smearing of the image by the motion of the plasma. Our laser delivers a 200ps pulse of green light ($\lambda = 532$nm) with a plasma cutoff density of $n_c = 4 \times 10^{21} cm^{-3}$. This means the light can penetrate the plasma as soon as the electron density decreases by a factor of 10 from solid deuterium.

III. POINT-DIFFRACTION INTERFEROMETER

The point-diffraction interferometer (Fig. 1) has long been used for testing optical components. Recently it has been applied to imaging large wind tunnel flow fields[6]. It can be employed in a number of other applications as well.

Point-diffraction has some advantages over the commonly used Mach-Zehnder interferometer. All of the optics in the interferometer can be mounted on one small rigid platform. This allows the optics to be better protected from mechanical damage and de-steering. The alignment is easier since all of the adjustments are near each other. It is also easier to adjust the lengths for the two legs to be equal for laser pulses with short coherence lengths. Since only one beam passes through the experiment, the ports can be made smaller or the beam larger.

This interferometer works well for our application. But, if the object occupies too much of the input laser beam, then much of the light will be filtered out of the reference leg and the fringe contrast will be poor. It is possible to compensate to some extent by putting more neutral density in the image leg if the filtered intensity is predictable.

IV. LINE DENSITY MEASUREMENT

Light traveling through plasma will have its phase advanced by

$$m = \frac{1}{\lambda}\int dx(1-n_r) \approx \frac{\lambda r_e}{2\pi}\int dx\, n_e \qquad (1)$$

where λ=532nm is the wave length of the light, n_r is the index of refraction of the plasma, n_e is the electron density, r_e is the classical electron radius, and the integral is along the path of the light ray. When this light interferes with the reference leg there will be shifts in the fringes proportional to the amount of plasma the light has gone through. Line density can then be computed by integrating the fringe shifts along a line on the image normal to the Z axis.

$$N_e(z) = \int_{-\infty}^{\infty} dy \int_{-\infty}^{\infty} dx\, n_e = \frac{2\pi}{\lambda\, r_e}\int_{-\infty}^{\infty} dy\, m \qquad (2)$$

In practice, the reference leg can be tilted slightly to produce background fringes perpendicular to the Z axis. A reference image (Fig. 2) is taken to record these background fringes, shortly before applying voltage to the fiber. The reference image also provides the initial position of CD_2 fibers. (Cryogenic deuterium fibers "wiggle" quite a bit while extruding.) The fringe shifts in the plasma interferogram (Fig. 3) relative to this reference are then counted along lines normal to the axis and integrated to compute the line density. This interferogram can only provide a lower bound on line density since most of the plasma is above the critical density of the light.

V. ABEL INVERSION

The integral defining the fringe shifts in polar coordinates

$$m = \frac{\lambda r_e}{2\pi} \int dx\, n_e = \frac{\lambda r_e}{4\pi} \int_y^{r_0} \frac{dr\, r\, n_e}{\sqrt{r^2 - y^2}} \tag{3}$$

can be inverted by a transform called "Abel inversion"[7]

$$g(y) = \int_y^{r_0} \frac{dr\, r\, f(r)}{\sqrt{r^2 - y^2}} \quad \rightarrow \quad f(r) = -\frac{2}{\pi} \int_r^{r_0} \frac{dy\, \dot{g}(y)}{\sqrt{y^2 - r^2}} \tag{4}$$

if we assume azimuthal (θ) symmetry, to produce the electron density as a function of radial (r) and axial (z) position.

$$n_e(r, z) = -\frac{2\pi^2}{\lambda r_e} \int_r^{r_0} \frac{dy\, \dot{m}(y)}{\sqrt{y^2 - r^2}} \tag{5}$$

The interferograms we have taken so far are symmetric enough about the axis of the pinch to assume azimuthal symmetry. Fringe shift data taken along a line normal to the Z axis is fit by a function of y. The partial derivative of this function is then integrated to provide the density as a function of r and z.

VI. - ADAY ROTATION

Should we attain high current at high plasma densities, there would be an opportunity to extract more data. This diagnostic also can provide the magnetic field and current density distributions. The two circularly polarized components of our linearly polarized light experience a different refractive index for the plasma in the presence of a magnetic field parallel to its propagation

$$n_{\pm} = \sqrt{1 - \frac{4\pi r_e n_e / \kappa^2}{1 \pm \frac{eB_{\parallel}}{m_e c \kappa}}} \tag{6}$$

This results in a rotation of the angle of polarization of the light termed Faraday Rotation. This rotation should be visible on the interferogram as a periodic loss of interference fringes as the rotation reaches odd multiples of $\pi/2$.

Figure 4 shows a simulated interferogram with Faraday effects. The simulated plasma has a gaussian distribution of current and density of radius $s=100\mu m$ corresponding to an initial solid fiber of radius $r_0=15\mu m$. The simulated current is I=200KA. Notice the fading of the fringes at

$r \approx 60 \mu m$. Actual unfolding of the magnetic field distribution and current density may be difficult with less than ideal lighting.

FIGURE CAPTIONS:

FIG. 1. Point-diffraction interferometer: A collimated laser beam illuminates a refractive object and a lens collects the light. The light is then split into two legs. One leg is spatially filtered with a pin-hole aperture and becomes the reference of the interferometer. The other leg has some neutral density filtering to limit its brightness to that of the reference leg for better fringe contrast. The two legs are then recombined to form an interference pattern which is imaged by a camera.

FIG. 2. Reference shot of undisturbed fringes with solid CD_2 fiber ($r=19\mu m$).

FIG. 3. Interferogram of plasma about 20ns into the current rise. Much of the plasma has an electron density greater than the critical density of the laser.

FIG. 4. Simulated interferogram with Faraday rotation.

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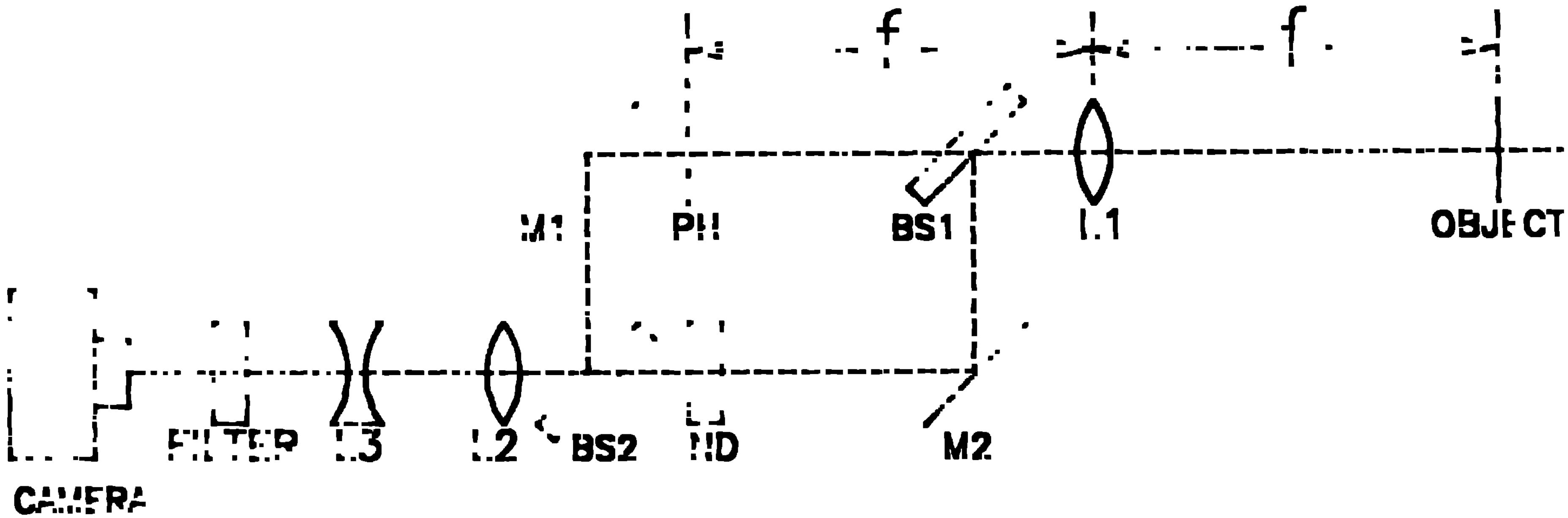
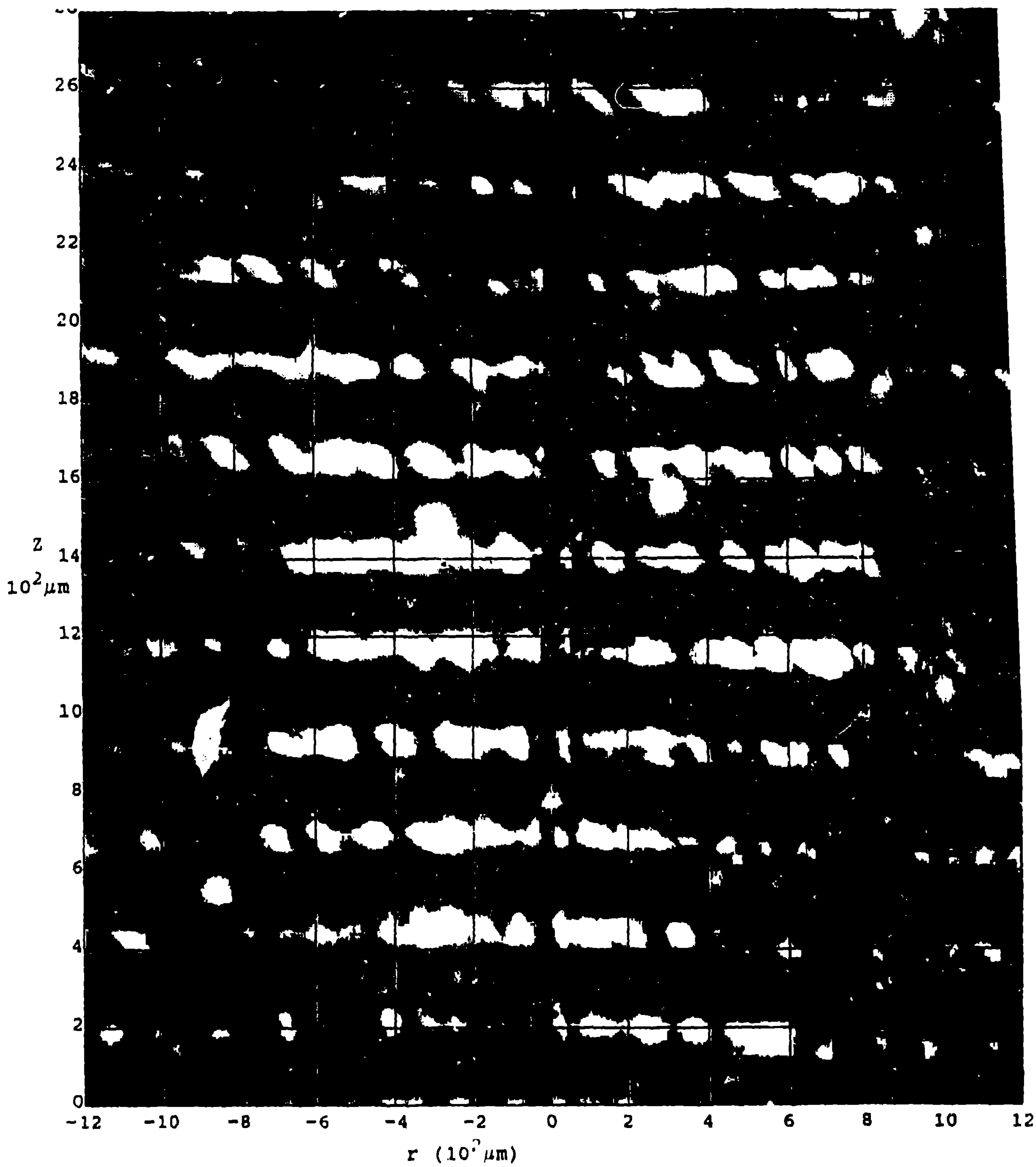


POINT DIFFRACTION INTERFEROMETER

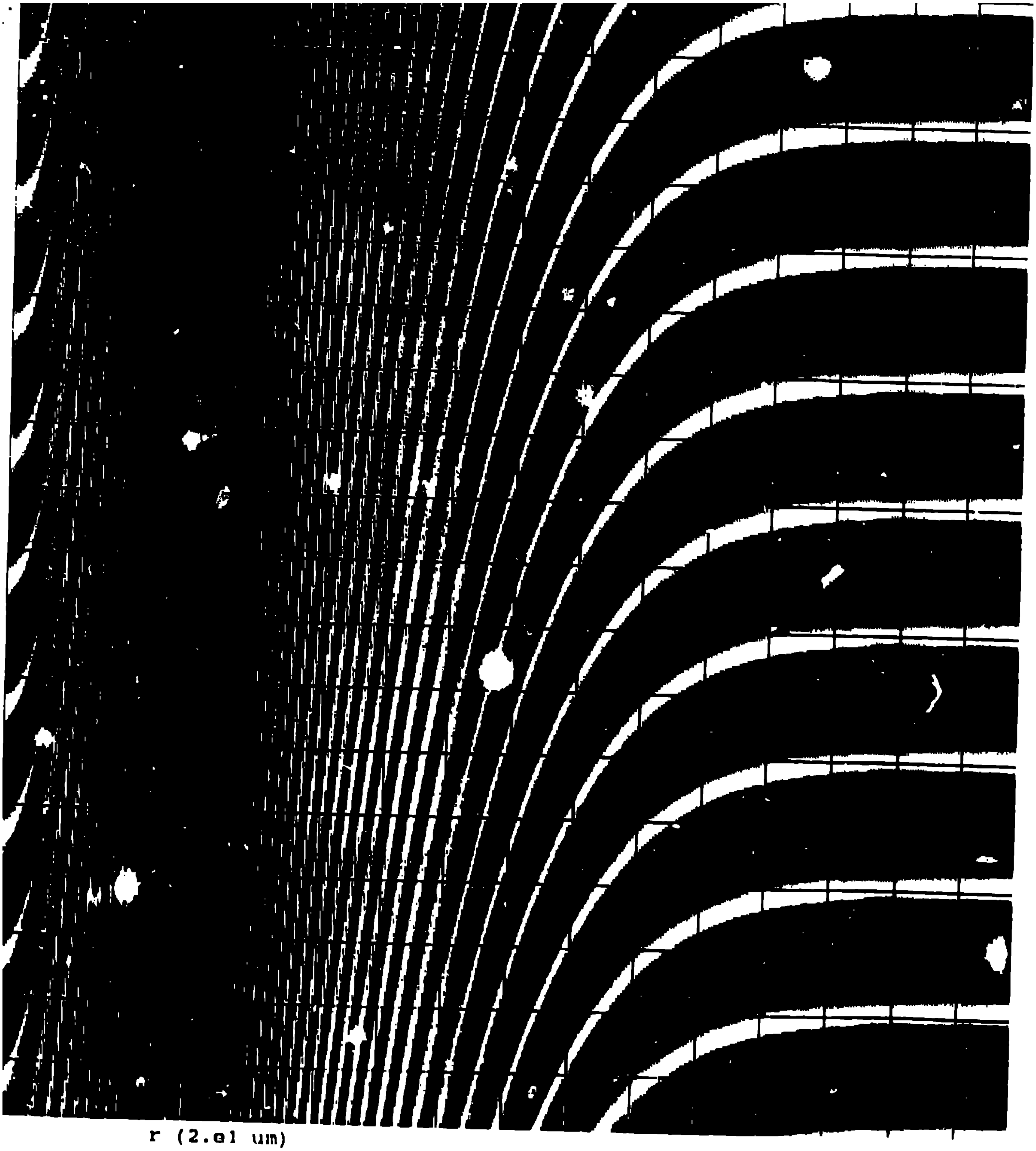


Reference shot: Solid CD2 fiber diameter = 38 μm

Shot 32?

t ≈ 20 ns into a current that peaks at 600 kA with 100 ns rise time.

shot 321



r0=15.0 um, s 100.0 um, I=2.00e+002 kA