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PIIR-157
Radiation Physics Group

November 16, 1966

PROGRESS REPORT 50-077 INTERACTION OF ELECTRON BEAMS WITH BACKGROUND GAS

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I. SUMMARY

The interaction phenomena of a 2×10^{11} watt pulsed relativistic electron beam injected into a background gas in a region free from externally applied electric fields have been investigated. The electron beam parameters are 3 - 4 MeV, 50,000 A, 3×10^{-8} sec pulse width. The background gas (air) in the chamber was varied in pressure from 10^{-4} Torr to 760 Torr. The electron beam was extracted from the cathode-anode region of a Physics International 5 MeV pulsed power system through a 0.001 in. Al window into field free drift chambers of varying radii. Calorimetry and optical photography were used to diagnose the beam phenomena. Spatial beam variation as a function of gas pressure, the effects of current image forces, and the interaction of the beam with an applied magnetic field are discussed.

II. EXPERIMENTAL APPARATUS

The basic components of the Physics International Company high-voltage, high-current generator used in the external electron-beam experiments are shown in Figure 1.

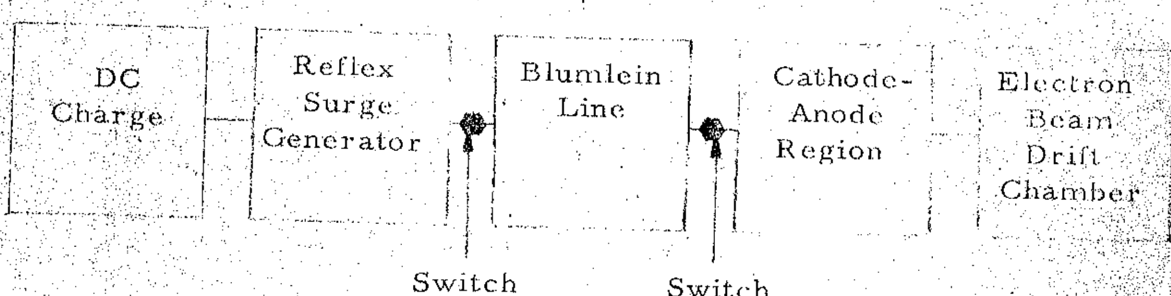


FIGURE 1. BLOCK DIAGRAM OF EXPERIMENTAL APPARATUS

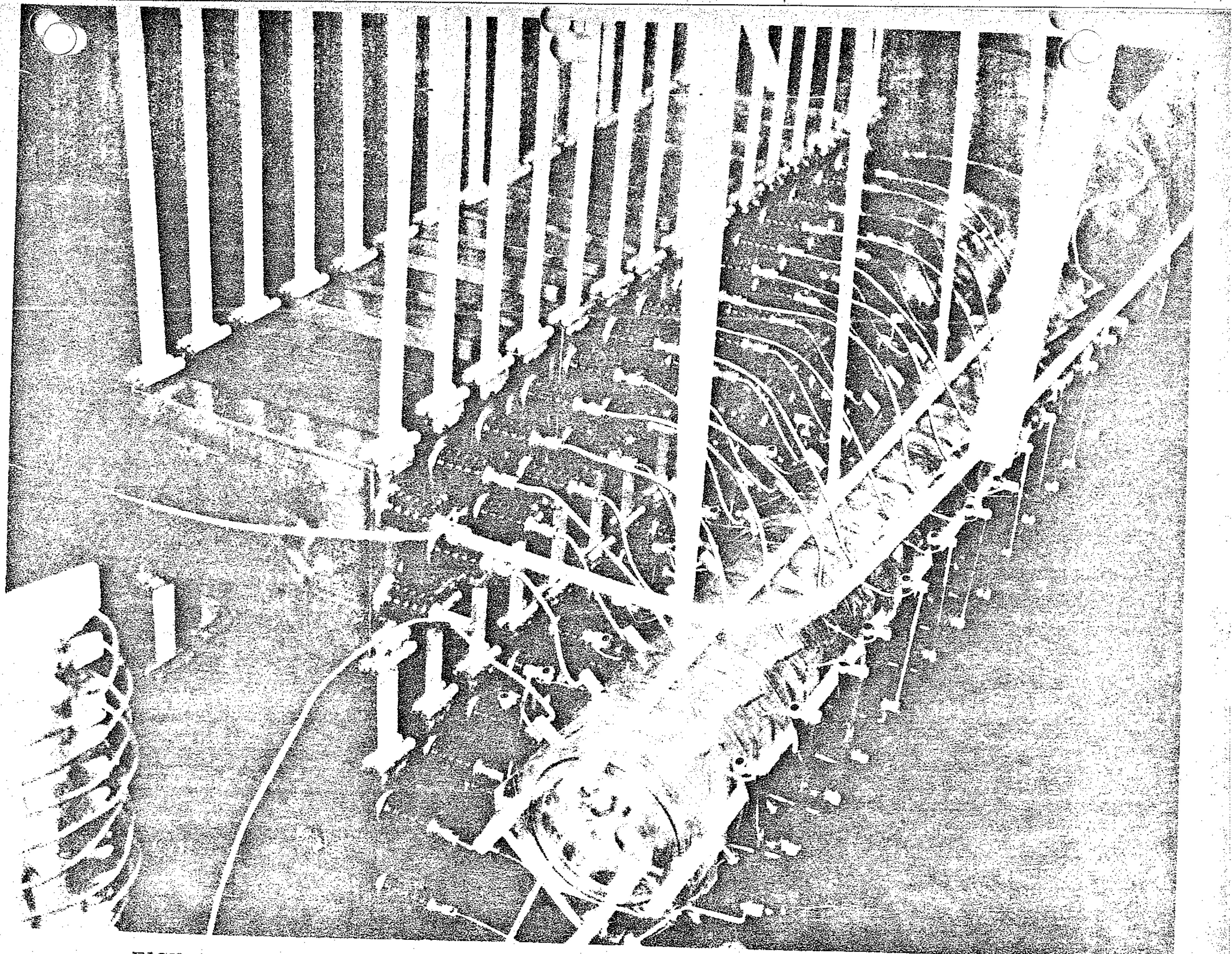


FIGURE 2. TYPICAL SURGE GENERATOR AND COAXIAL BLUMLEIN LINE

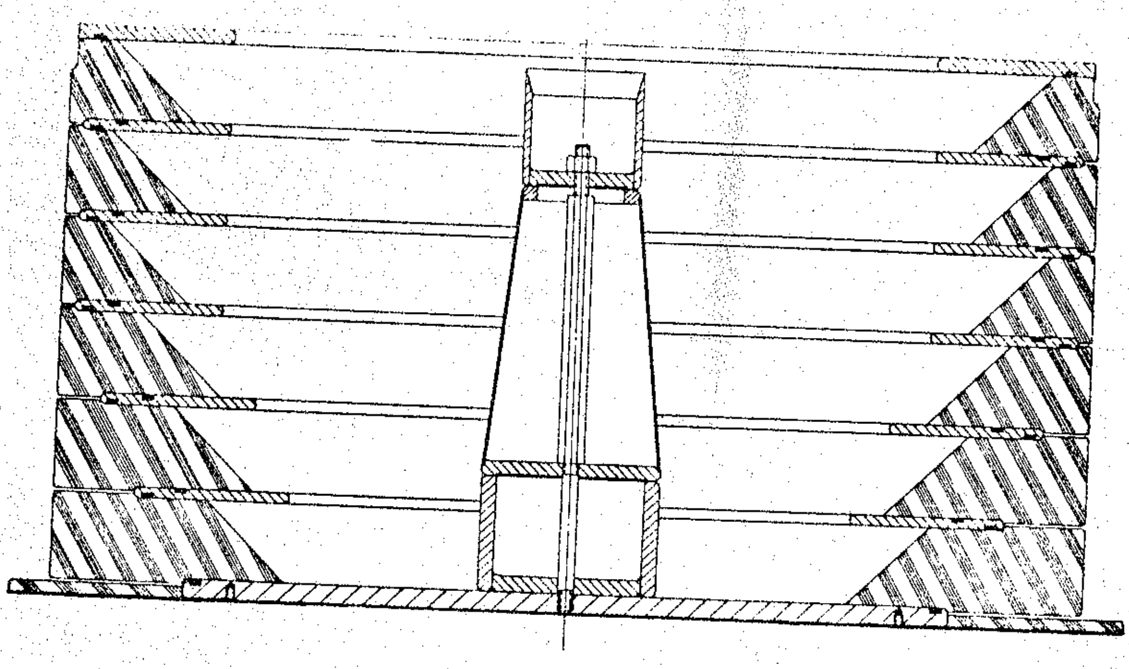


FIGURE 3. PULSED POWER GENERATOR CATHODE-ANODE REGION

The electron beam is extracted through a 0.001 in. Al window into the drift chamber region.

The drift chamber is shown in Figure 4. Two cameras are mounted 90° from one another on glass ports to view the beams in a stereoscopic manner. Vacuum feed-through ports allow for the extraction of thermocouple leads which are integral parts of the graphite calorimeter used to monitor the high energy beam.

III. ELECTRON BEAM PHENOMENOLOGY

For an electron beam in a region of hard vacuum, the radial electric field and the aximuthal magnetic fields are given (in Gaussian units) by

$$E = \frac{2Ner}{r_o^2} \qquad B = \frac{2Ne\beta r}{r_o^2}$$

where
E = radial electric field
B = azimuthal magnetic field
N = number of electrons per unit length
e = electronic charge
β = v/c
v = $\frac{dz}{dt}$ = electron velocity
Z = axial distance in the drift region
c = velocity of light
r_o = beam radius
r = radius at which E and B are observed ($r \leq r_o$)

The electrons in the beam experience an outward force due to the electric field of the space charge and an inward force due to the magnetic field.

The force on an electron at the edge of the beam ($r = r_o$) is:

$$F = e\left(E + \frac{v \times B}{c}\right)$$
$$F = \frac{2Ne^2}{r_o}(1 - \beta^2) \tag{1}$$

If the electron beam experimental chamber is filled with a low-pressure gas, the self-forces in the beam may be strongly modified. The high-energy electrons ionize the gas,

If the electron beam experimental chamber is filled with a low-pressure gas, the self-forces in the beam may be strongly modified. The high-energy electrons ionize the gas, and the released electrons are then repelled by the large radial electric fields. The remaining positive ions tend to electrically neutralize the electron beam.

The rapid rise of magnetic field when the electron beam passes through the experimental chamber may induce large back currents that reduce the magnetic field of the primary electron beam.

If the electric field is reduced by the factor f_e and the magnetic field by the factor f_m, Equation (1) becomes

$$F = \frac{2Ne^2}{r_o}\left[1 - f_e - \beta^2 (1 - f_m)\right] \qquad (2)$$

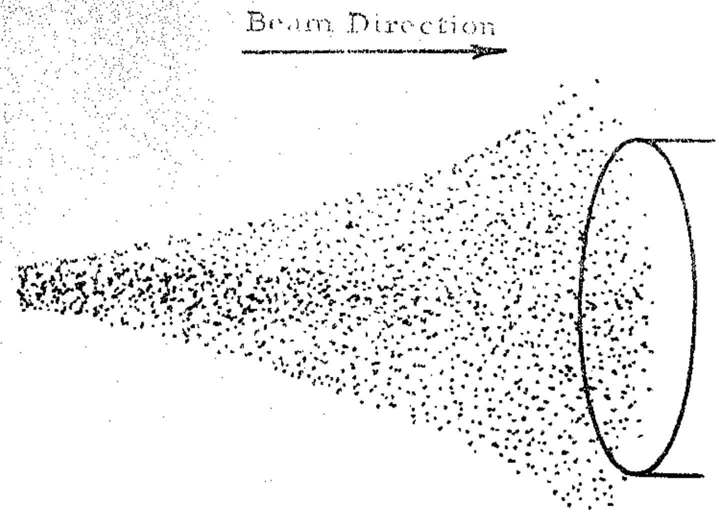
For a wide range of gas pressures f_e is nearly unity, and the force experienced by high-energy electrons is due primarily to the magnetic effect and becomes negative, or directed toward the beam axis. This is the condition for a self-pinch of the beam.

At air pressures from 0.01 Torr to 1 Torr, the beam is observed in a variety of pinched modes, one of which is indicated in Figure 5b. Figures 5b, 5c, and 5d are examples of self-photographs of the light in the wake of the electron beam.

As the air pressure rises above 1 Torr, the induced conductivity of the air increases, beam-induced back currents become large, and the factor f_m approaches unity. In this case the beam is both electrically and magnetically neutralized, and beam self-forces are greatly reduced. The beam drifts through the experimental chamber expanding with its own initial angle of divergence, as illustrated in Figure 5c. If the air pressure is raised further, the back currents decrease, and the beam again pinches, as in Figure 5d. Figure 6 presents several photographs of the beam passing through the drift chamber at a wide range of pressures. This mode of operation was slightly different from the previous photographs.

A. Image Forces

The existence of large beam self-forces suggests the possibility of large forces resulting from image charges and image currents in metallic surfaces.

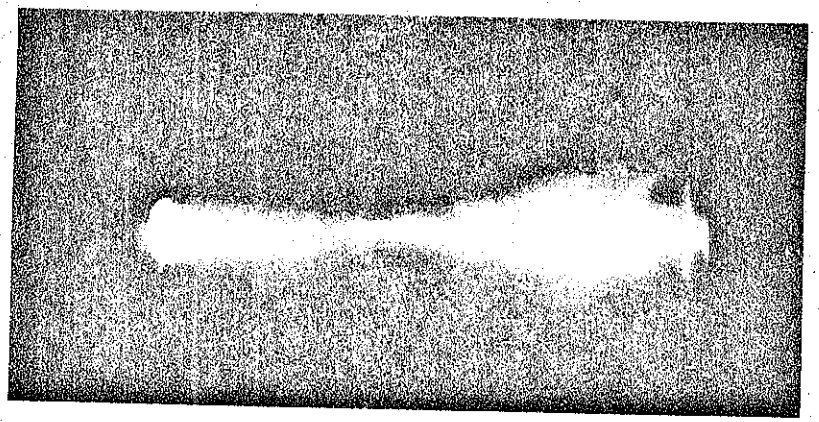


(a)

Pressure = 0

$f_e = f_m = 0$

F is large and positive



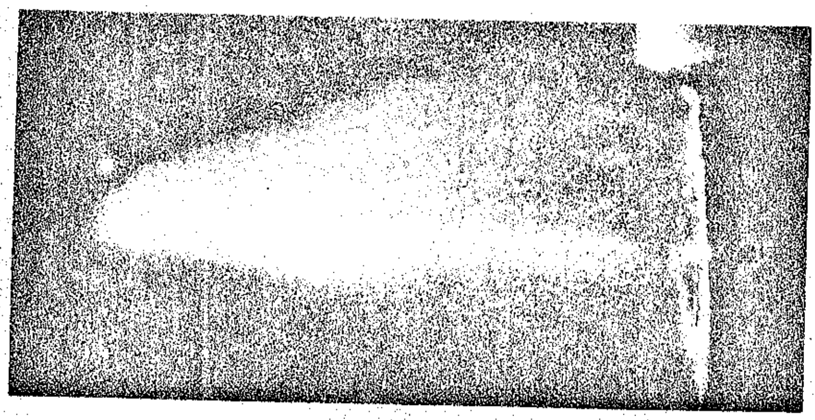
(b)

Pressure = 0.1 Torr

$f_e \approx 1$

f_m small

F is large and negative



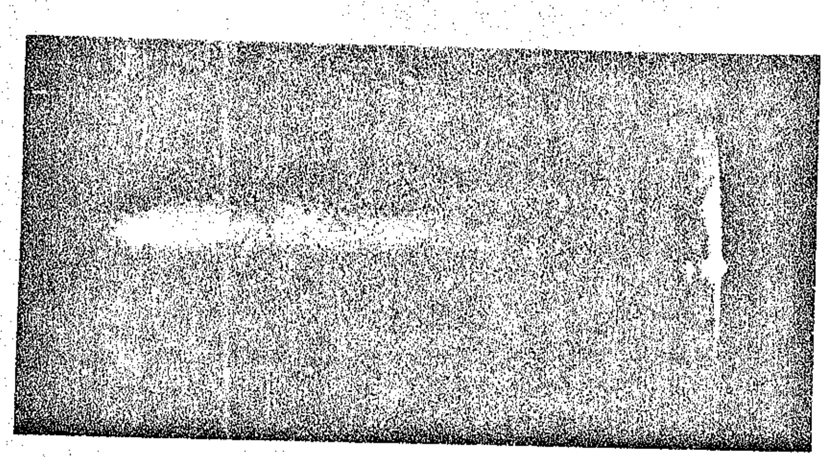
(c)

Pressure = 5 Torr

$f_e \approx 1$

$f_m \approx 1$

F is small



(d)

Pressure = 20 Torr

$f_e \approx 1$

$f_m < 1$

F is negative

FIGURE 5. SELF-PHOTOGRAPHS OF THE ELECTRON BEAM AT VARIOUS AIR PRESSURES

The electric charge in the beam induces opposite image charges in a metallic surface, while the time-varying magnetic fields of the beam induce eddy currents in a metallic surface that are equivalent to a single, oppositely directed image current. This is illustrated in Figure 7.

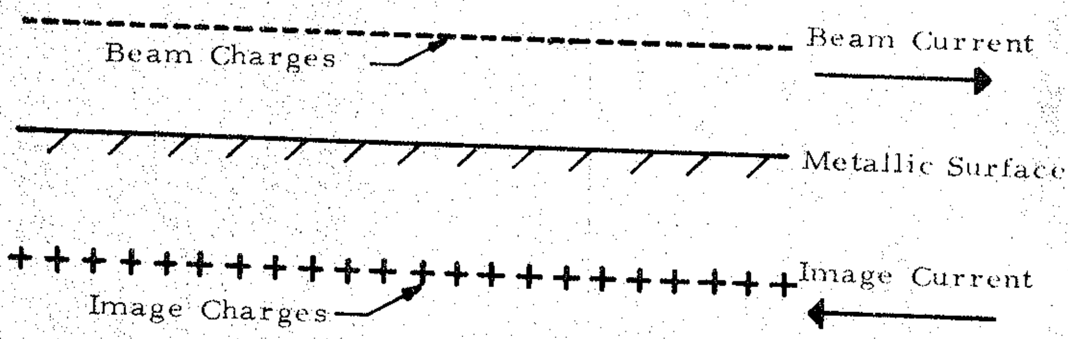


FIGURE 7. IMAGE CHARGES AND CURRENTS

The force between charge and image charge is attractive, and the force between current and image current is repulsive. If electric neutralization is nearly complete ($f_e \sim 1$ in. Equation 2), the repulsive force predominates. Figure 8 is a self-photograph of an actual 50,000 amp, 3-MeV electron beam that has been fired into a metallic channel. The beam reflects from surface to surface in the channel much as light would reflect in a light guide. In this case the channel was too sharply curved to allows the electron beam to completely follow it.

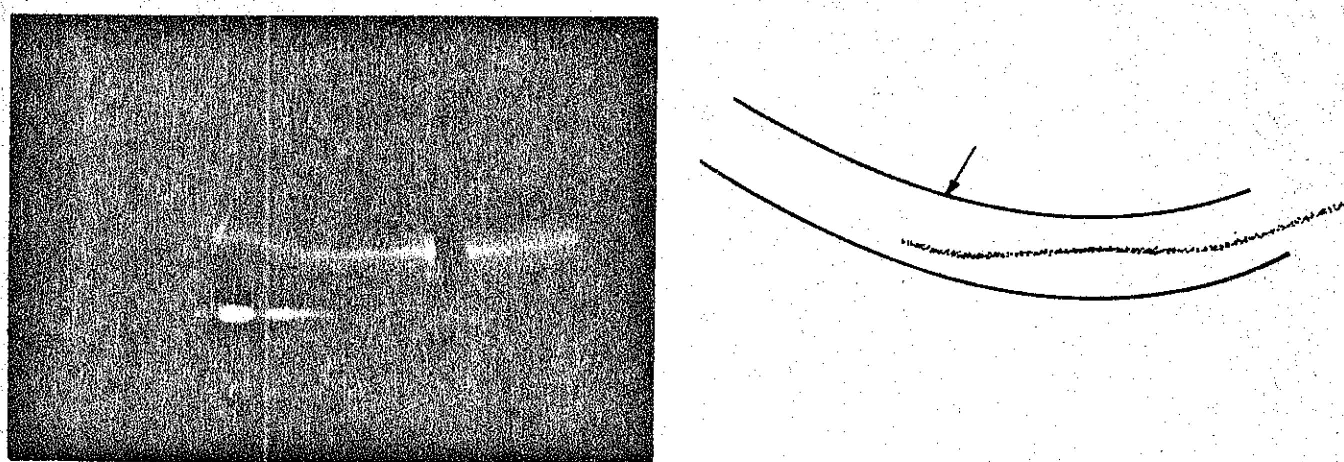


FIGURE 8. SELF-PHOTOGRAPH OF THE ELECTRON BEAM IN A METALLIC CHANNEL

B. Magnetic Field Interactions

The electron beam can and has been bent by a magnetic field (~2000 gauss) even when fully pinched. The internal self-forces of the beam make impossible the measurement of momentum distribution in a moderate magnetic field for the total beam. A portion of the beam sufficiently small to nearly eliminate the self-forces can, however, be magnetically analyzed in the usual way.

C. Beam Divergence Angular Deviation and Intensity

In twenty consecutive test shots at a pressure of 2.0 Torr the rms angular deviation of the electron beam from the experimental chamber axis was 3 deg with a half angle of 0.1 radian.

In a recent series of 40 test shots, the intensity per unit area was varied from 10 cal/cm^2 to 120 cal/cm^2 by changing the target-to-anode distance for each test. The predicted and measured values of intensity were in agreement to within 8 per cent. Attainable intensities vary from less than 1 cal/cm^2 over large areas (7100 cm^2) to 500 cal/cm^2 over 1/4 cm^2.