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BEAM SHAPING MEASUREMENTS ON THE 730 PULSER FACILITY

by L. Hatch

INTRODUCTION

It has become of great interest to test the feasibility of using multipole magnets in the electron beam to (1) distort the beam profile into an elliptical shape to more efficiently irradiate rectangular objects and (2) to be able with the use of two quadrupoles, focus the electron beam to small intense spots with the ultimate possibility of both controlling the beam intensity with a "knob" and improving the shot to shot reproducibility. A first step towards these goals was realized during a recent series of shots on the 730 pulser facility.

EXPERIMENT DETAILS

It is not at all obvious that the electrons in high intensity 50-100 kiloamp electron beams react to externally applied electric or magnetic fields as a single particle would. At low pressure < 0.5 torr in a field free region the electron stream pinches and externally applied fields do not effect the electrons in the usual single particle way. At pressures around 2 torr in a field free region conventional still photography of the electron beam (i.e., the recombination light) seems to imply that the electron trajectories are straight--the electrons do not affect their neighbor's trajectory and merely "drift." In the drifting mode the beam could be expected to react to the magnetic field in the conventional way.

It was decided to test the notion of using a multipole to distort the drifting beam by constructing a quadrupole from four permanent bar magnets. The figure below shows the magnets in place.

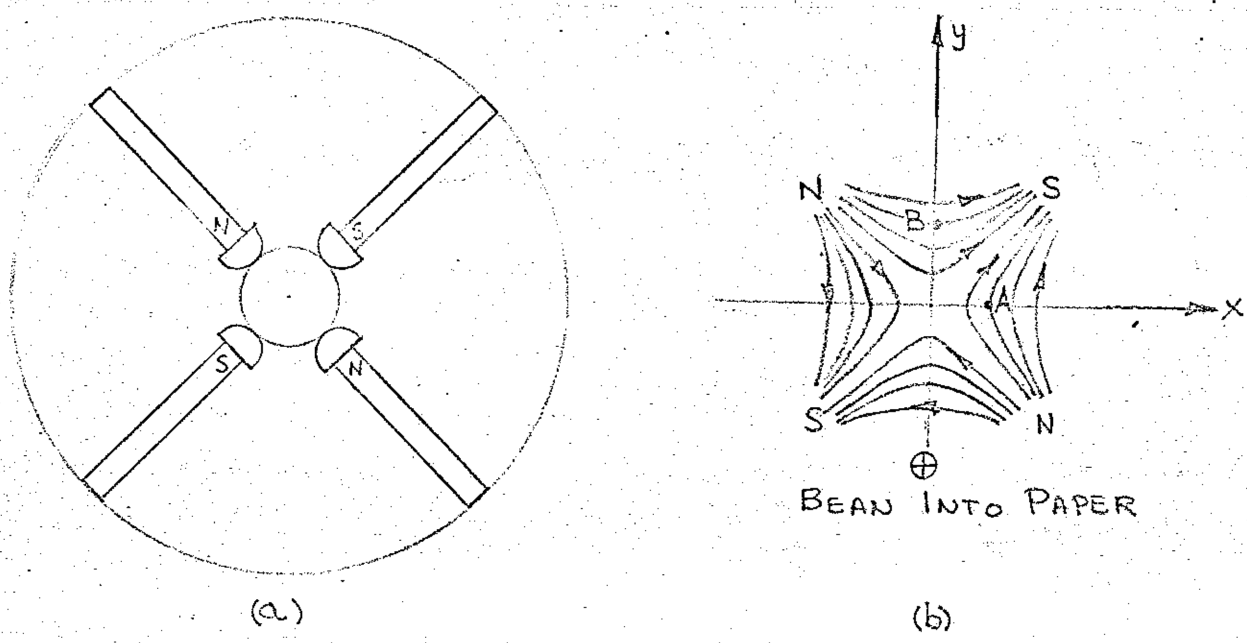


FIGURE 1. QUADRUPOLE CONSTRUCTION AND MAGNETIC FIELD CONFIGURATION

The theory of quadrupoles is described in detail in PIIR-26-67 by W. T. Link; however, the relevant features will be repeated here. The field configuration is shown in Figure 1(b). Pole tips of the same magnetic polarity are placed opposite one another producing zero field at the center of the aperture but a field measured in the x or y direction which varies linearly with displacement from the center. Particles that travel down the center experience no lateral forces. However, an electron which finds itself at point A would experience a force towards the origin $x = y = 0$. An electron at B would experience a force away from the origin. Hence the configuration given would produce a beam divergent in the vertical y direction and convergent in the horizontal x direction. The beam will actually come to a focus in the x direction if the incident trajectories are parallel and the electrons all have the same energy. This is the same as the thin lens case in light optics where parallel rays converge to a common focus because the amount of angular change in the incident ray is proportional to the distance from the center of the lens. However, the magnetic quadrupole is not axially symmetric in its treatment of electron trajectories so that one plane converges while the other diverges. Two quadrupoles in series rotated 90° with respect to one another would cause convergence in both planes and would act like a lens.

Some results of the analysis of the trajectories of parallel beams of monoenergetic particles in quadrupoles are given below. If the field

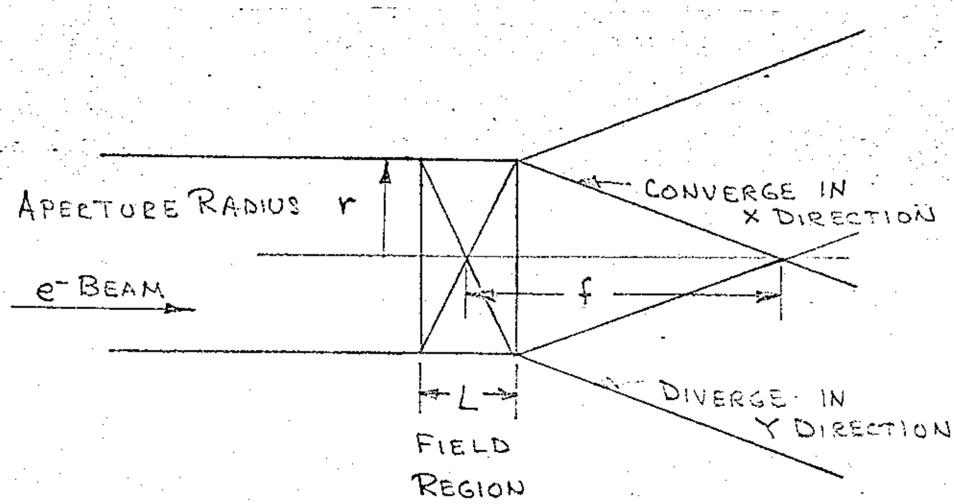


FIGURE 2. QUADRUPOLE MAGNET AS A LENS

gradient is k (K Gauss/cm), the momentum of a single charged particle P, the "effective" length of the magnet L then the focal distance is

$$f(\mathrm{cm}) = \frac{3.3\ P(\mathrm{MeV/c})}{k(\mathrm{KG/cm})\ L(\mathrm{cm})} .$$

For the ideal case of a monoenergetic 3-MeV parallel beam of electrons with the quadrupole used in this experiment when the aperture was 4 cm

$$f = \frac{3.3 \times 3}{0.40 \times 4.5} = 5.5 \text{ cm.}$$

The diagram below shows the experimental layout in the 730 pulser facility machine. The diameter of the electron beam passing into

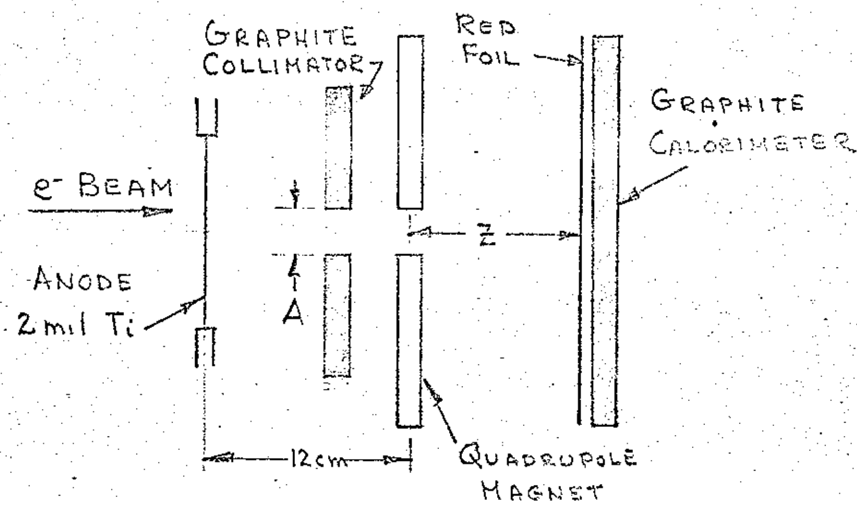


FIGURE 3. ARRANGEMENT OF EXPERIMENTAL APPARATUS

the quadrupole was determined by a 2-cm thick piece of graphite with a hole in it. The aperture of the magnet, i.e., the distance between opposing tips was made the same as the aperture size. For the first few shots this was 4 cm and was subsequently opened up to 5 and finally 9 cm.

The magnets were blocks of ALNICO V with dimensions 1/2 in. x 1 in. x 6 in. To help shape the field near the tips small blocks were glued to the ends of the magnets (Figure 1a). The field strength near the tips was about 1000 Gauss when the magnets were arranged in the quadrupole configuration. Plots of the field as measured with a Hall probe guassmeter at two different radii for the 2-cm radius aperture are shown in Figure 4. From these graphs one obtains the effective length L of the quadrupole. The tip length was 2.5 cm but the effective length is longer because of the large fringing fields. The length L was determined by making the product B_{max} x L equal the total area under the curve. At the two radii measured the effective length L = 4.5 cm. If the effective length is a function of the aperture then it appears L = Tip length + Aperture radius = 2.5 + 2 = 4.5 cm. At the largest aperture (9 cm diameter) the field had an effective length L = 5.5 cm = Tip length + 0.67 x Aperture radius.

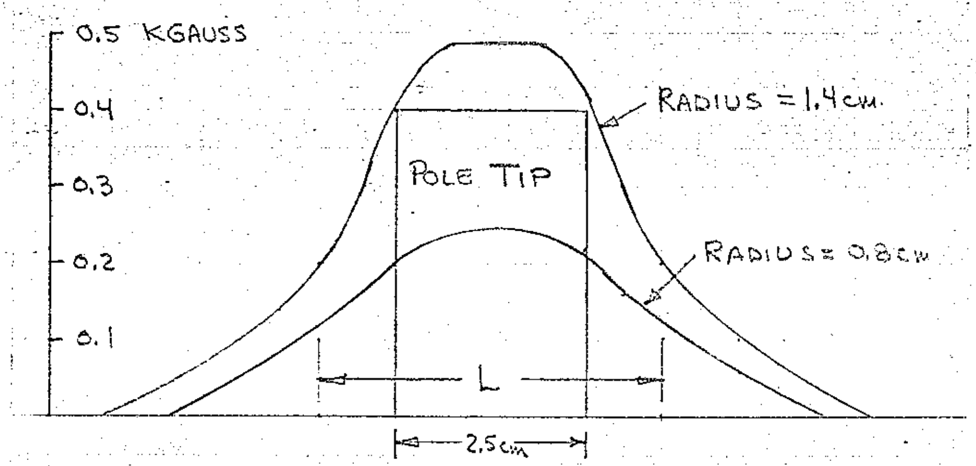


FIGURE 4. MAGNETIC FIELD IN QUADRUPOLE GAP

The focal length for a monoenergetic parallel beam with momentum = 3 MeV/c is computed for each aperture size and listed in the table below with the other physical parameters for each shot. These parameters are defined in Figure 3.

The shape of this beam was measured with a single sheet of red foil placed in front of the large ten inch square 5 x 5 graphite calorimeter. The red foil was read to produce contour plots of intensity. Normalization was made using the total calories measured in the graphite calorimeter. The amount of current passing through the quadrupole was estimated assuming 70 kiloamps produces 1500 calories in the calorimeter.

Shot	z	k	A	L	f	Focal length for P = 3 MeV/c
7218	10 cm	0.40 KG/cm	4 cm	4.5 cm	5.5 cm	
7219	10 cm	0.40 KG/cm	4 cm	4.5 cm	5.5 cm	
7220	10 cm	0.40 KG/cm	4 cm	4.5 cm	5.5 cm	
7221	10 cm	0.40 KG/cm	4 cm	4.5 cm	5.5 cm	
7222	10 cm	0.24 KG/cm	5 cm	5.0 cm	8.3 cm	
7223	10 cm	0.24 KG/cm	5 cm	5.0 cm	8.3 cm	
7224	15 cm	0.06 KG/cm	9 cm	5.5 cm	2.5 cm	
7225	7 cm	0.40 KG/cm	4 cm	4.5 cm	5.5 cm	

RESULTS

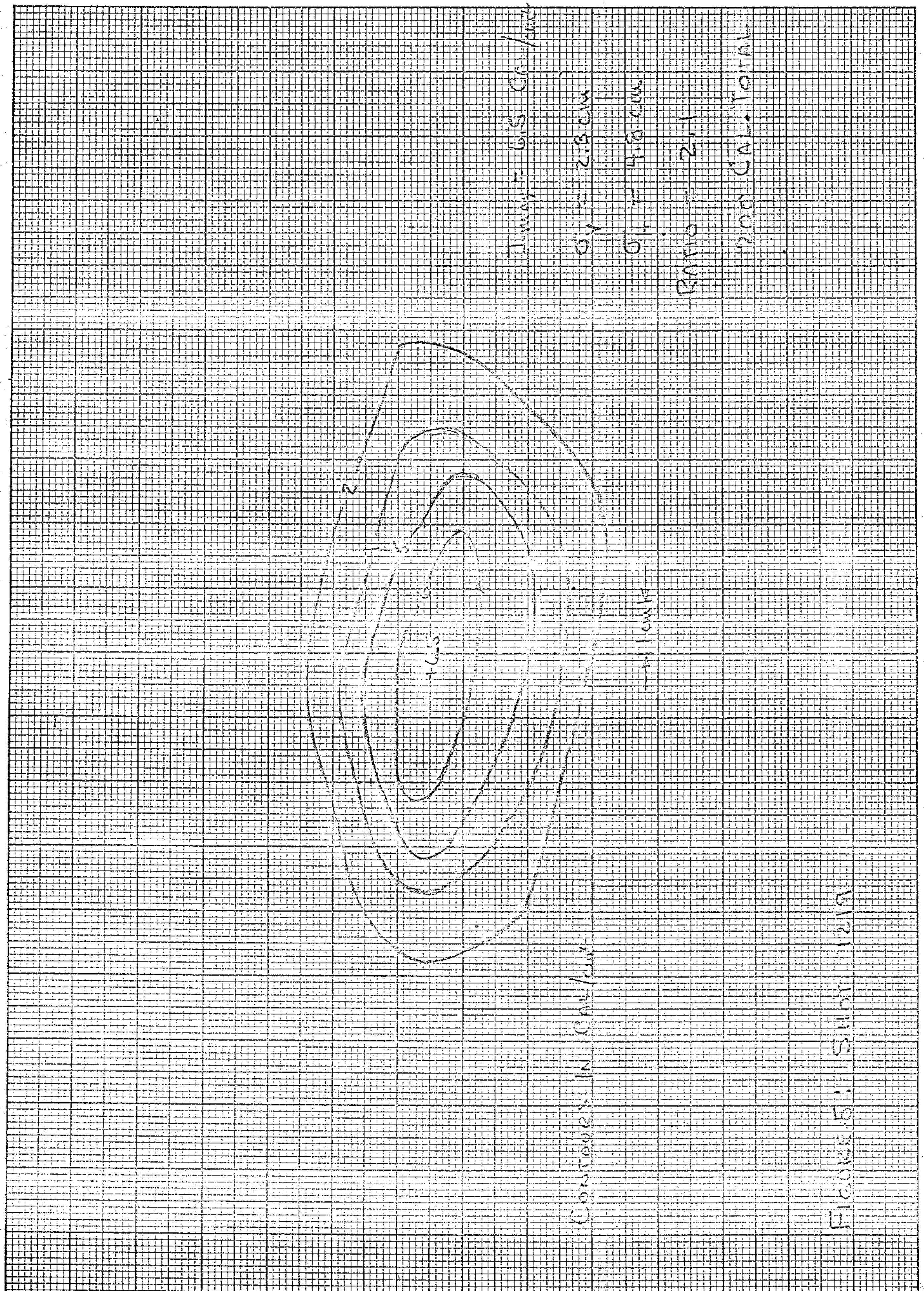
The first result is that the electron beam when in the drifting mode can be distorted using a quadrupole magnet. The electron beam has a significant spread in both energy and entrance angle into the quadrupole. The quadrupole used in this experiment does not act like a thin lens since its effective length is comparable to the focal length for the mean electron energy. All of these characteristics tend to smear out the focal point so that the distortion ratio of the beam shape (major axis/minor axis of elliptical beam) is in fact much less than that estimated for monoenergetic parallel electron trajectories. Also for the small aperture shots beam misalignment tended to distort the results because the entrance aperture of the quadrupole was assymetrically populated by electron trajectories.

The table below tabulates the parameters of the elliptical beam analyzed at the distance z from the quadrupole.

Shot	z	σ_V	σ_H	Ratio	Aperture	Orientation	Calories	Current Ampere
7218	10	Not Measured			4 cm	↔	~200	10,000
7219	10	4.8 cm	2.3 cm	2.1	4 cm	↕	~200	10,000
7220	10	2.4 cm	1.0 cm	2.4	4 cm	↕	~500	20,000
7221	10	2.3 cm	1.3 cm	1.8	4 cm	↕	~500	20,000
7222	10	5.0 cm	2.8 cm	1.8	5 cm	↕	~900	40,000
7223	10	3.3 cm	5.5 cm	1.7	5 cm	↔	~900	40,000
7224	15	2.8 cm	5.0 cm	1.8	9 cm	↔	~1500	70,000
7225	7	3.2 cm	1.4 cm	2.3	4 cm	↕	~500	20,000

Shot 7218 was not analyzed because the beam alignment was very poor and the dose levels in the red foil were too low to read. The "orientation" symbol indicates which plane should defocus by the sense of the double ended arrow, the beam focuses in the other plane. The sigma's have been measured off the contours and reflect the widths of the intensity profiles along the two axis.

Figures 5-7 are intensity contours. Figure 5 contains only about 200 calories because of poor beam alignment. Figure 6 shows a beautifully distorted elliptical beam with 500 calories or 20,000 amps. Finally, Figure 7 contains the contours for the full 70,000 amp beam passing through a 3-1/2 in. aperture. The distortion is considerably reduced in this case because the magnetic field strength was very low.


Imax = 6.5 Cal/cm²
σy = 2.3 cm
σx = 4.8 cm
Ratio = 2.1
2000 Cal. Total
2
1 cm
Contours in Cal/cm²
Figure 5: Shot

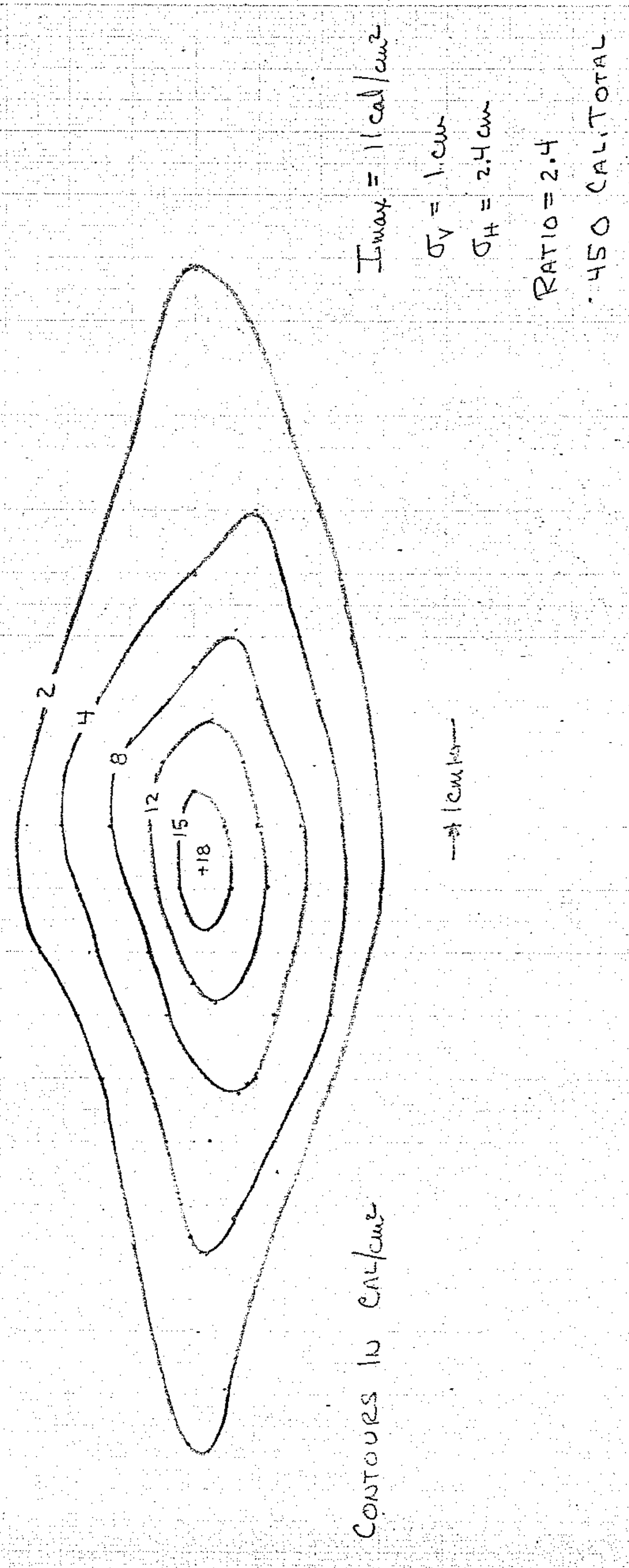
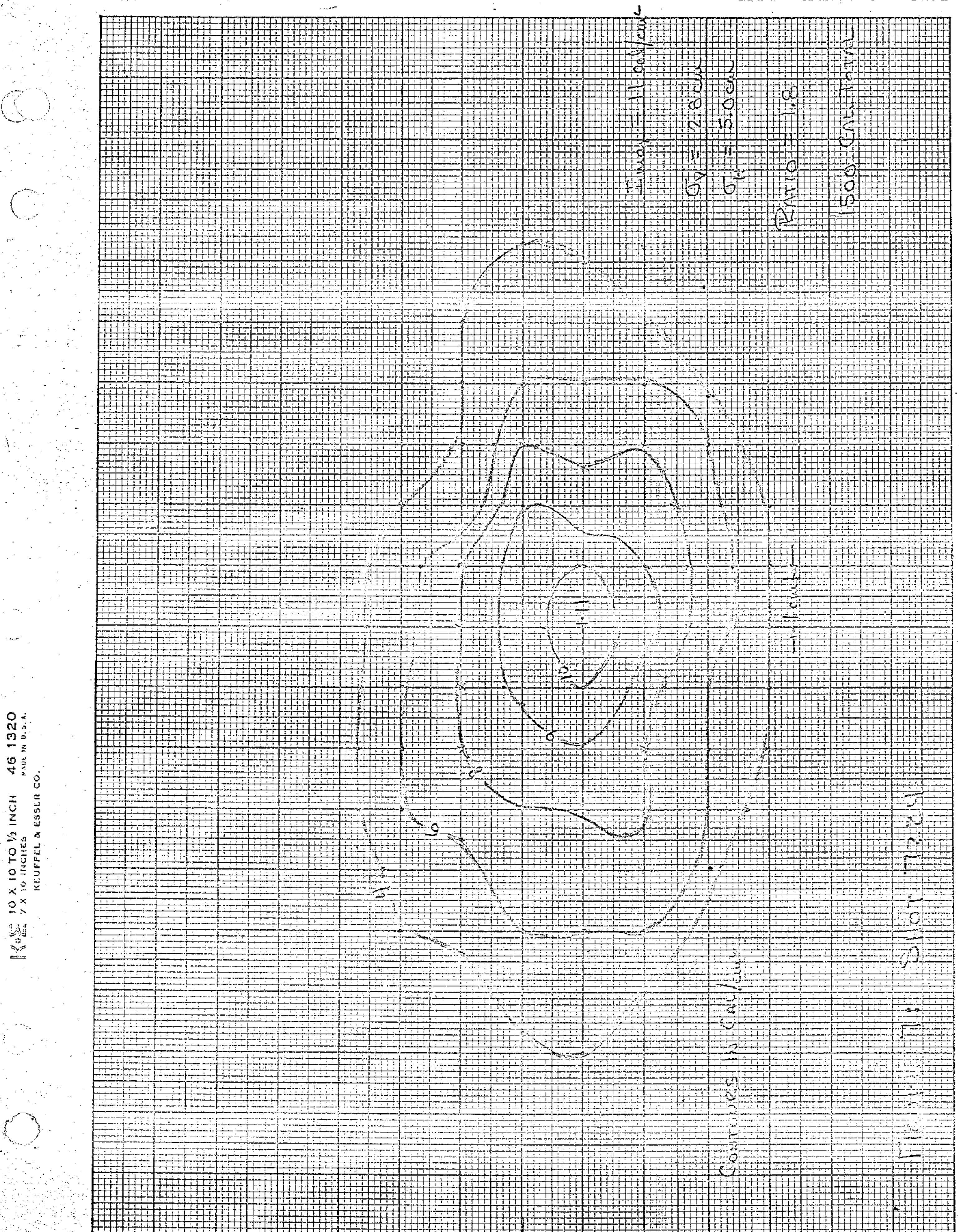


Figure 6: Shot 7220


Imax = 11 cal/cm²
σV = 2.8cm
σH = 5.0cm
Ratio = 1.8
1500 cal Total
Contours in cal/cm²
— 1 cm —
11
10
9
8
6
4
10 X 10 TO ½ INCH 46 1320
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.