RPN6

Radiation Production Notes
Note 6

30 Dec 1968

The Production, Transport and Focussing of Electron Beams with a $\nu/\gamma < 1$

by

M. J. Goodman
Atomic Weapons Research Establishment

First Printed as SSWA/MJG/6812/106

1. Preface

1.1 This and the following three papers describe some of the work which has been performed at AWRE in the high voltage electron beam field over the last few years. Historically, the approach to the present position in the high current beam area has been made from the radiographic point of view. Cathode development in particular has been made with this in mind and hence, for reasons outlined later, the major proportion of the work has been with the so-called 'plasma' cathode in a nominally plane-parallel electrode geometry. However, it is recognised that this approach is not necessarily the best one for use in low impedance, high deposition energy density applications where orthogonal electron trajectories at the anode window may not necessarily be ideal. Fortunately the fundamentals of the 'plasma' cathode, once established, allow individual tailoring of electrode geometries to suit specific requirements. The attraction of this form of cathode lay in the ability to define more precisely than with previous divergent systems the entrance conditions for initial study of electron beam behaviour.

1.2 A brief introductory note on ν/γ is included here for reference purposes.

ν arises as a parameter in the analysis of electron trajectories in a cylindrically symmetric geometry in the presence of electric and magnetic fields, and is defined as:

$$\left.\begin{aligned} \nu &= N\,r_o = \frac{Ne^2}{m_o c^2} \quad (\text{c.g.s}) \\ \nu &= \frac{Ne^2}{4\pi\varepsilon_o m_o c^2} \quad (\text{MKS}) \end{aligned}\right) \qquad 1$$

where N is the no. of electrons per unit beam length

r_o is 'classical' electron radius

m_o is electron rest mass

e, c, ε_o have usual definitions.

γ is the conventional relativistic factor:

$$\gamma = \frac{1}{\sqrt{1 - \beta^2}} \qquad 2$$

for a particle velocity βc, and can be written for a particle with energy eV

$$\gamma = 1 + \theta \qquad 3$$

where $\theta = V/V_o$, $V_o = m_o c^2/e \sim 0.51$ MV, the equivalent rest energy of the electron. Hence, for V in megavolts,

$$\gamma = 1 + 2V_{MV} \qquad 4$$

ν/γ can be written in a more convenient form by using current I amps, where

$$I = Ne\ \beta c \qquad 5$$

so that 1 becomes:

$$\nu = \frac{I}{\beta}\frac{30}{V_o} \qquad 6$$

As $\beta = \frac{\sqrt{\theta^2 + 2\theta}}{1 + \theta}$ 3 and 6 give $\frac{\nu}{\gamma} \sim \frac{30I}{\beta\gamma V_o} \sim \frac{30I}{\theta V_o}\left(\frac{\theta}{2 + \theta}\right)^{1/2}$

and if the beam impedance $Z = \frac{V}{I}\ \Omega.$,

$$\frac{\nu}{\gamma} \sim \frac{30}{Z}\left(\frac{\theta}{2 + \theta}\right)^{1/2} \qquad 7$$

so that in the extreme relativistic limit, $\nu/\gamma \sim 30/Z$.

1.3 The parameter ν/γ and the condition $\nu/\gamma = 1$ may be interpreted in various ways.

(a) From an analysis of particle trajectories in an electrically neutral beam* injected with zero radial velocity into a drift region, for $\nu/\gamma << 1$ very slight convergence leads to a definite beam many diameters in length. When $\nu/\gamma > 1$. rapid convergence means that such a beam cannot exist under the postulated

---

*See, for example, J. D. LAWSON: J. ELECT. & CONTROL 3, 587 (1957) and 5, 146 (1958).

and very simplified conditions as well as invalidating the assumption that transverse particle velocities are very small compared with axial drift velocity. The condition $\nu/\gamma = 1$ hence represents a borderline case in which the beam achieves a focus in a length ~ the beam radius.

(b) For a fully neutralized beam in which ions are assummed to have only radial velocities and electrons have radial velocity component β_t c with axial drift velocity βC, then

$$\frac{\langle \beta_t{}^2 \rangle}{\beta^2} \sim \frac{\nu}{\gamma}$$

$\langle \beta_t{}^2 \rangle$ being the average over all β_t and radii; ie ν/γ expresses the ratio of the radial component of electron energy to the axial drift energy (strictly only for $\beta_t << \beta$).

(c) The instantaneous radius of curvature ρ of an electron with energy eV in a magnetic field H is given by:

$$H\rho = \frac{1}{\eta_o}\left(V^2 + 2VV_o\right)^{1/2} \quad \text{(M.K.S.)}$$

where $\eta_o = 120\ \pi$ is the free space wave impedance.

For V >> 1/2 MV,

$$H\rho \sim \frac{V}{\eta_o} \qquad 8$$

In a beam of radius r and current I,

$$H = \frac{I}{2\pi\gamma}$$

and hence

$$\frac{\rho}{\gamma} = \frac{2\pi}{\eta_o} \cdot \frac{V}{I} = 2\pi\ \frac{Z}{\eta_o}$$

Thus, the condition that $\nu/\gamma \sim 1$, or $Z \sim 30\ \Omega$ is equivalent to:

$$\frac{\rho}{r} \sim \frac{1}{2}$$

ie: the instantaneous radius of curvature of an electron orbit at radius r is one half the beam radius.

2. Introduction

This paper refers particularly to the studies performed on electron beams with the aid of the generator "MOGUL", it also alludes in passing to work done with "SMOG", "PLATO" and "PARIS". In all these cases the electrons had an initial energy of 2 MV or more and in this relativistic region the simple relationships

$$\nu = K \frac{I}{\beta}$$

and $\gamma = 1 + 2V \approx 2V$ (in megavolts) holds, thus $\nu/\gamma \approx 30/Z$ where Z is the impedance of the electron beam as viewed by the generator driving it. All the beams generated by the four machines referred to above had impedances ranging from 50 ohms to several hundreds of ohms. Hence they all operated in the regime where ν/γ was 0.5 or less and, in principle, at least were capable of transport at some gas pressures without catastrophic collapse phenomena occurring. ($\nu/\gamma = 1$ is roughly the region where the radius of curvature of the electron trajectories inside the beam is of the order of the beam diameter when it is fully gas neutralized).

The basic requirement for these studies was radiography and the aim was to transport the beam as efficiently as possible and then produce as small a spot on the target as was feasible with a reasonable paraxial beam trajectory. The work will be described in the three sections implied in the heading, viz:-
3 The Production of the beam including details of the generators and the cathodes employed.
4 The transport of the beam in a field free region with different geometries and gas pressures.
5 The Focussing of the beam onto a target and the problems of target blow up.

The intention is to describe the experimental problems involved and not to give a theoretical analysis of the situation which in many regions is still confused.

3. The Production of Electron Beams

3.1 The Generators

The basic parameters of the four generators used for these experiments are listed in Table I.

MACHINE	SMOG (A)	PARIS (B)	PLATO (C)	MOGUL (D)
Date when experiments performed	1965	1964	1966	1968
Pulse length (ns)	30	30	13	50
Rise time (ns)	12	8	5	12
Maximum and (normal) tube volts MV	4(3)	2.5(1.8)	2(1.7)	6(4)
Normal Beam Current KA	30	20	10	50
Generator Output Impedance Ω	30	30	80	30
Typical ν/γ	0.3	0.3	0.15	0.3
Typical Energy in Beam KJ	1.8	0.6	0.2	8
Pre Pulse Characteristic	*	*	*	⌿
Dose at 1 m. from small spot R.	2	0.5	0.3	50

TABLE 1

*Pre-pulse of both polarities lasting about 1 to 2 μsec. with amplitude less than a few KV.

⌿Pre-pulse of both polarities lasting 1 μsec. with amplitude up to 70 KV.

SMOG is a generator still in active use in a bomb chamber and one of its standard set ups employs a plasma cathode sending a beam through a window to converge onto a tantalum target producing a 3 mm spot.

PARIS was a smaller early version of SMOG and is now defunct but historically was the first machine used by us to produce a high current relativistic electron beam with some attempt at space charge neutralisation in a drifting section.

PLATO was a small test generator which is also now out of use but was employed in the development of Plasma Cathodes.

MOGUL is currently the largest generator actually in use by J. C. Martin's section and is now awaiting its removal to a bomb chamber for large scale radiography.

3.2 Diagnostics employed

The measurements performed on these electron beam studies varied with the systems employed, table 2 lists the various devices available with each machine, these were not necessarily used on all firings.

Generator	PARIS	PLATO	SMOG	MOGUL
A. Tube volts v. time	Yes	Yes	Yes	Yes
B. Tube current v. time	No	No	No	Yes
C. X-ray Int. v. time	Yes	Yes	Yes	Yes
D. Pinhole camera spot	Yes	Yes	Yes	Yes
E. Pinhole camera tube	No	No	No	Yes
F. Edge Projection	Yes	No	Yes	Yes
G. Calorimeter	No	Yes	No	Yes
H. Open Shutter Phot.	Yes	Yes	Yes	Yes
I. Tube & drift Tube Vac.	Yes	Yes	Yes	Yes
J. 4 Dose	Yes	Yes	Yes	Yes
K. Selected Dose	No	No	No	Yes
L. Polar Diagrams	No	Yes	Yes	Yes

TABLE 2

A. The tube voltage is monitored with a $Cu\ SO_4$ and/or a carbon resistor divider chain with a 20 KV signal level tap off applied to a high speed low sensitivity scope of our own manufacture.

B. The tube current was monitored with a small pick up loop situated near the feed point to the envelope and the signal applied to a Mk. IIc AWRE scope.

C. A Plastic phospher/ITT diode was used to feed the X-ray/ time relationship also into a Mk. IIc scope.

D. A Pinhole camera with a series of interchangeable tungsten plugs with different size holes in them ranging from 1.0 mm to 4.0 mm was used to view the anode and the X-rays were recorded with fast X-ray film. Minification factors around 2 or 3 to 1 were normally employed.

E. In the case of generators where the X-ray tube extends beyond the machine it is often salutary to view them (with a large hole, wide field of view pinhole camera) from a direction say at right angles to the normal axis. Any stray electrons hitting the rest of the system are very painfully obvious. It is advisable to filter the X-rays with some copper or similar material to avoid seeing very soft X-rays due to spurious electrons thrown around in the pre or post pulse phases.

F. The projection of high Z edges onto X-ray film is the best way of defining spot size for radiographic purposes and this system is usually employed as a reference standard.

G. The calorimeter is a single channel millivolt chart recorder monitoring the thermo-couple output connected to a carbon block - fairly standard but a useful check on voltage and current monitors.

H. A variety of cameras usually using Polaroid film record various aspects of the beam. Photographs looking at the cathode and at the electron beams are shown later in the text.

I. Standard Pirani, Penning, Ionisation and McLeod gauges are used to monitor the various gas pressures involved.

J. The X-ray dose is quoted at 1 metre from the target but measurements are made at all distances. The standard method is Li F T.L.D.'s using a CONRAD reader and quick measurements are also done using a quartz fibre pen dosimeter calibrated for high speed pulses. The T.L.D's are usually shielded with 0.030" Copper. Also X-ray film was calibrated with standard sources and the dose v density relationship employed.

K. A device like a pinhole camera but using a T.L.D. rather than X-ray film has proven very helpful in determining the dose coming from selected areas on the anode.

L. Polar diagrams of the x-rays are measured using T.L.D's and these give a valuable guide to the degree of divergence in the electron beam when they hit the target.

3.3 The Cathodes

When cathodes are employed for electron beam transport it helps if they usually attempt to meet several criteria such as:-

(i) a reasonably uniform current density preferably both on the cathode surface and the anode surface. This is to avoid blowing up material which can effect the work function, emission area and even send ions across the gap from the anode and start increasingly rapid runaway effects.

(ii) a near normal incidence onto the anode window. If the electrons pass through in a roughly paraxial trajectory they can be transported in an efficient manner, contrarily if they have a wide range of angles then they possess significant transverse energy and this will be conserved or get worse due to foil scatter etc. At higher energies the dose polar distribution is markedly peaky and electrons moving at significant angles to the central axis produce noticeably less dose on axis which is inefficient for several reasons. If the electrons are needed for energy deposition effects the energy depth curve can be shallower than expected and electrons can re-escape from the front surface with greater facility thus increasing the energy loss due to back scatter.

(iii) the ability to withstand some degree of mechanical damage which can result from exploding targets, windows, post pulse arcs etc. It is an unfortunate fact that the more sophisticated cathodes tend to be the most fragile and much effort is made to try to make them more robust.

(iv) are capable of withstanding or employing the effects of pre-pulse which in many generators is present to quite a large degree. This pre-pulse can lead to plasma blobs forming in the most inconvenient places before the main signal arrives and cause very erratic behaviour. Equally some cathodes can benefit from some pre-pulse which gives plasmas time to spread and establish before the high voltage pulse arrives.

The cathodes employed are all cold cathode so called field emission space charge limited type. The types used for electron beam transport with the generators above are shown in table 3 below.

TABLE 3

Generator	Cathode Type	Diagram in Fig.4	Operating Voltage MV	Current KA	$\frac{\nu}{\gamma}$ at window
PARIS Jan. 1964	Large gramophone needle	(i)	1.8	10	0.13
Sept. 1964	Rough Re-entrant surface	(ii)	2.0	10	0.15
SMOG Jan. 1967 to date	Lucite button Plasma Cathode	(iii)	3.0	30	0.30
PLATO Oct. 1966	Plasma Cathode (a) Single Spot (b) 4 spot (c) 55 spot (d) 10 Spot (e) Fibre in Epoxy	(iv) (a) (b) (c) (d) (e)	1.8	10	0.13
MOGUL Feb. 1968	Honeycomb Cathode Sharp Edged Cylinder	(v) (vi)	4.5	60	0.4

These cathodes can be split into 2 types (a) those which employ field distortion to produce higher fields than the surroundings and hence produce electrons from a sort of field emission effect, and (b) those which keep the field reasonably uniform but reduce the work function to the point where field emission still occurs.

The early cathodes were initially believed to be of type (a) but nowadays we tend to concentrate on type (b) which is the so called "Plasma Cathodes". It is suspected that both types of cathodes employ plasma blobs of some sort because the work function required to give the current densities observed in terms of the Fowler Nordheim equation tend to come out at 0.5 eV or so in both cases. The disadvantage of the field enhanced cathode is the fact that the electrons are produced in a rapidly divergent field and this makes it difficult to produce coherent beams. They are also somewhat suspect to pre-pulse because plasma blobs can form on the high field surfaces when as little as 30 KV or so is applied to the tube. Their main advantages are cheapness, ease of manufacture and robustness being reasonably impervious to flying debris.

This last reason is, of course, the disadvantage of the so called "Plasma" cathode. The idea behind these is to produce a plasma with a negligible work function over those areas you wish to emit electrons and prevent them from occurring elsewhere. If this can be achieved electrons can then be produced in uniform field conditions which results in parallel electron beams. The favoured method of producing the plasma is to put a layer of insulating material down on the cathode surface and then either oil the whole device if the pre-pulse allows or polish dry if not. The latest "honeycomb" material for instance uses Aluminium foil in a 3 mm diameter honeycomb array encapsulated in eposy, set into the cathode plate and then machined and polished flush with the surface. The argument runs that either (a) the field emission from the sharp edges of the Aluminium foil causes gas to occur from the local surface which is ionised and the plasma blobs then travel out from the Aluminium edges over the surface of the epoxy. This happens over most of the edges and hence causes the surface to cover with plasma. The Alternative argument (b) is that field emission from microscopic specks on the surface of the epoxy cause these points to move away in potential from their surrounding and if the local horizontal field exceeds 50 KV/cm or so then they can break down in a similar manner to an X-ray tube with a parallel envelope face which is very rapid and widespread. If this happens the surface is again covered in plasma and is connected locally with the Aluminium foil. Obviously this system is sensitive to the degree, magnitude and duration of any pre-pulse because these can establish plasma surfaces in advance of the main pulse.

The first attempts at a non divergent cathode were those mentioned in the table under PARIS Sept. 1964 when a re-entrant polished and oiled surface had a roughened area put in the centre and this worked surprisingly well giving a 2 mm spot at the focal centre of the system after passing through a 1 thou. Aluminium foil window. The impedance tended to drop by around 50% during the 20 ns pulse and the normalised dose performance was about 50% of the best available at the time but it did perform remarkably well really.

Most of the development of high impedance plane parallel plasma cathodes with the exception of honeycomb cathodes was done with PLATO.

Fig. 1 shows some of the pinhole pictures of the X-rays emitted from the beams coming from a variety of these cathode assemblies, it can be seen that a very good degree of correlation exists between the perspex disc distribution and the electron beams hitting the target. One of the problems with these cathodes is controlling the rate of change of the impedance during the pulse, it is not desirable to have changes of more than a factor of two and even this can be rather embarrassing for consistent operation. The smaller spot multi-element systems proved better here than the large single spot systems which also tended to have higher impedances per unit area as well suggesting plasma coverage was incomplete.

A similar cathode to the one developed on PLATO has been used occasionally on SMOG for the last three years at 3 MV and 30 KA for 30 ns and gives very good results in the form of a much better spot (3 mm) than the usual ball on ball cathode at the cost of half the dose (2 R at 1 mm).

The honeycomb cathode, much used in the MOGUL system was initially developed in MINI B (see Paper SSWA/THS/6812/107)[1] and has been described already. It has been used in two forms on MOGUL, both as discs, one flat and the other slightly convex and both have given excellent results. The situation regarding oiling has been different in this case from our previous experience and here we have found it advantageous not to oil the supporting surfaces which tend to emit more current if oiled (fig. 2). The high voltage (> 2 MV) high impedance systems are in many ways more difficult to operate than the low voltage high current devices because it is difficult to prevent significant current being emitted from the supporting structures in the high fields that exist and the low currents being drawn from the cathode are correspondingly shunted and do not produce enough magnetic field to self trap the electrons emitted back along the shank. (In fact as a rough guide to self trapping the A-K impedance should be less than the impedance of the transmission line of the stem and the envelope feeding it). The oiling technique is thus more critical and the higher pre-pulse levels on MOGUL probably caused their undoing. Thus acting on the principle that if you can't beat 'em you join them the cathode support stem on MOGUL was made small in diameter (1") to put the transmission line impedance up to several hundred ohms and the 90 ohm optimum match lead of the cathode was enough to self trap the electrons which are inevitably emitted due to the high field on the shank. The cathode is then put on a large bulb on the end of the shank and this is highly polished to reduce electron emission to a minimum.

3.4 Electrical Characteristics of Cathodes

In theory the impedance of a space charge limited plane parallel diode should go as

$Z = K(V)\,\dfrac{S^2}{r^2\,V^{1/2}}$ ohms where K(V) is a function of the

---

[1] Radiation Production Note 5

applied voltage given in fig. 3, S is the A-K separation in cms, r is the cathode radius in cms. and V is in Megavolts. Table 4 lists the measured values of K for various cathodes employed in these beam studies.

TABLE 4

Generator	CATHODE see fig. 4	THEORETICAL K	MEASURED K
PARIS	(ii)	180	150
SMOG	(iii)	190	10
PLATO	(iv) (a)	170	(a) 20
	(b)		) 120
	(c)		)
	(d)		)
	(e)		)
MOGUL	(v)	200	120

The low voltage high current cathodes (Paper SSWA/THS/6812/107)[2] follow the above relationship very well but the high voltage low current cathodes tend to be less related. The perveance tends to be too high for virtually all cathodes, i.e. they pass more current than one would expect often by a factor of up to ten more than the Child Langmuir relation would predict. Even assuming full positive ion space charge limited current flowing from the anode this is still not adequate to explain the actual current passed. The reason why the MOGUL results tend to be more in agreement is probably fortuitious because the emission area assumed is larger than the central area emitting. There is strong evidence which suggests the current does not increase at the same rate as the area if a plasma cathode is extended in size in one piece. It only increases at the right rate if the area is increased by making more small spots rather than one large one. In the case of MOGUL one large spot is employed. It is thought that the reason the current is higher than space charge formulae would predict could be due to partial gas neutralization near the cathode surface where the electrons are slow enough to have large collision cross sections and the gas pressure can rise high enough due to cathode surface gas emission to produce the ionic concentration required. At the gas pressures normally employed (1 μ or less) it is difficult to see how ionisation in the main gap can account for the large increase in current unless the gap pressure locally was raised by several orders of magnitude.

---

2. Radiation Production Note 5

Another point of interest is the minimum distance which the anode cathode gap can maintain a significant impedance for the full pulse, this is some function of the pre-pulse, the cathode geometry, anode material, gas pressure, pulse length and voltage applied amongst others. Typical distances are 8 mm for PARIS and 11 mm for SMOG at 2 and 3 MV respectively.

3.5 Dynamic Characteristics

When the electrons are emitted from the cathode they travel in a region where the gas pressure is not really well known and may be changing dramatically and locally during the pulse. Many cathodes produce beams which are affected by this and the self magnetic fields can produce a bewildering range of instabilities in the trajectories if the current densities or gas pressures rise too high. For instance shot 555 in figure (1) shows the way in which a beam has gone into a series of flutes producing a cartwheel effect when it hits the anode. An example which uses this effect is cathode (vi) in fig. 4 from MOGUL which produces a fine spot on the anode from a large annular razor edge, this is a direct result of beam collapse in the main gap. The difficulty with this system as a beam launcher is the problem of handling the trajectories and damage the high current density does to the window. This particular cathode is quite sensitive to tube pressure and starts to cut the pulse off altogether at 1 μ or so. This problem of beam collapse is not too severe with $\nu/\gamma < 1$ but is very difficult for high ν/γ beams (see Paper SSWA/THS/6812/107).[3] The effect of gas pressure on pulse length i.e. the time for which the impedance holds up to a reasonable level is shown for a typical cathode geometry in fig. (5).

4. The Transport of Electron Beams

4.1 The question may well be asked, why bother to transport the beams at all? There are at least four reasons which apply at some time or other:-

4.1.1 Protection of the X-ray tube When the beam hits a target if it has been concentrated at all it will cause the target to explode and the resulting debris will cause severe degradation of the envelope and cathode structure to the point where they have to be thoroughly cleaned between shots and for some cathodes even rebuilt. If the target is moved to the far end of a drift tube and possibly angled as well the resulting debris can be kept almost completely clear of the tube and at the worst the cathode will need lightly cleaning.

4.1.2. Protection of the Generator For high speed radiography involving explosives the generator needs to be kept on the far side of a reasonably thick protective wall and it is an obvious advantage if the beam can be transported some distance down a drift tube before it hits the target, this section can

---

[3] Radiation Production Note 5

then be made small and expendable if necessary and the dose required could be less because the source is closer to the object and the film. This then requires a good spot of course but this is always desirable for radiography anyway.

4.1.3. Manipulation of the beam There are several reasons why the electron beam could be manipulated.

(i) several beams either from one generator or several generators can be fed together to irradiate an object from one side or from several directions at once.

(ii) The beam at the anode surface usually has a fine structure and if the energy deposition requirement is for good uniformity then it pays to drift the beam for a while and it then emerges with all the fine structure removed and good uniformity assuming the correct drift conditions have been met.

(iii) A study of the beam in its own right. The physics of relativistic high current electron beams has been considered theoretically over the last 30 years or so, but only in the last few years have the beams been available for experimental measurements.

4.2 Effects of Gas Pressure on Beam

There are four basic gas pressures to consider when looking at their effects on a drifting relativistic electron beam. These pressures are:-

(I) around 1 μ or less.
(II) around 10^{-1} τ
(III) around 1 τ
(IV) near atmospheric.

The forces acting on an electron at the surface of a beam in a good vacuum are twofold:-

(a) the electric repulsive force F_e, and
(b) the magnetic attractive force F_m.

In the case of pressure (I) the net effect is a repulsive force $F = F_e + F_m$ where $-F_m\beta^2 = F_e$, ($\beta = v/c$) hence $F = F_e \cdot (1 - \beta^2)$. For example at 2 MV $F = .04\ F_e$ thus the force is quite small for relativistic beams but still repulsive. Hence at pressures in the 1 μ level a reasonably parallel uniform beam of electrons will tend to diverge.

When the pressure is raised to 10^{-1} τ or so the situation is changed and the beam pinches down to a few mm's diameter as Ion Physics and Physics International have shown. This is caused by gas ionisation occurring in the beam in the first few nsecs and the slow electrons are repelled out leaving a surplus of positive ions present. When this happens the electric repulsive force is partially reduced and the magnetic attractive force dominates. Remember the difference between these forces at 2 MV is only 4% anyway so a little neutralisation goes a long way and at 0.1 τ the electro static forces are almost completely neutralised.

Now if the pressure is raised to a few τ the situation changes again and the beam will travel in a state of near equilibrium neither growing or shrinking and will transmit energy quite efficiently down the drift tube. The position here is that the slow electrons produced by the gas ionisation are attracted back to the anode plate by the electric field caused by the entry of the beam into the chamber. This return current of slow electrons is now large enough to cancel most of the magnetic field produced by the fast electrons. Now both electrostatic and magnetic forces are nearly cancelled and the beam drifts along with no force on it.

Finally when the pressure is raised to atmospheric the beam again pinches and then blows up, this is caused by the electron scattering being so great as to first prevent slow electron return drift hence F_m is not cancelled and beam collapse occurs and then the electrons in the mean beam get increasingly scattered and finally cease to be a beam at all.

We have looked at all four cases but the two of prime interest are II and III, i.e. gas pressures of 0.1 τ and 1 τ. Table 5 lists some of the drift systems employed with the four generators already mentioned, the operating conditions are mentioned in table 1.

TABLE 5

Generator	K	Distance of Drift	Pressure Ranges	Energy Deposited	Target Spot Size mm.
PARIS	(i)	7 cm	I	500 J	2 cm & 3 MM
	(ii)	2 cm	I	400 J	2 mm
SMOG	(iii)	2 cm	I	2 KJ	3 mm
PLATO	(iv)	100 cm	II III IV	200 J	2 cm
MOGUL	(v)	140 cm	I II III	8 KJ	8 mm
	(vi)	6 cm	I	3 KJ	1 cm

Figure 6 shows some diagrams of the type of cathode, window and drift tube systems employed on MOGUL. Fig. 7 shows some open shutter photographs of the beams drifting in pressure ranges II and III with varying degrees of aperture at the end of coned sections as shown diagrammatically in 6. The first photograph of the set in Fig. 7b shows the result of passing the beam through a section at 1 τ and then via a second 1 thou. Titanium window into a section at 0.1 τ which causes it to collapse onto an angled target. Fig. 7b also shows the instability which can occur in the beam. In a later design this angled target is pointed at a re-entrant catcher section and this collects the exploding debris and prevents it returning through the windows into the tube. This particular system was developed for radiographic use and has the virtue of high beam current carrying efficiency in section 1 which enables the generator to be sited on the far side of a protective wall. The later section then produces the small spot required for radiography whilst keeping the lossy 0.1 τ pinch beam section down to a minimum length.

All the pictures and results shown refer to air in the drift sections, other gases have been tried on a limited scale but the results are not listed.

4.3 Beam Transfer Efficiencies

This has only been considered on MOGUL and here studies have been made of the energy loss factors in moving beams along drift tubes in the pressure ranges approximately centred around 1 μ, 0.1 τ and 1 τ. Table 6 gives a rough guide to the absorption factors observed, the distances quoted are roughly the lengths involved in reducing the beam intensity by a factor of e(2.72). These energies are measured with a carbon block calorimeter and are only approximate of course. The shape of the drift tube has an effect on the transfer efficiencies, for instance, in the E and B neutralized mode (pressure around 1 τ) the beam should not be affected by the walls and should pass straight into them but in practice it is observed that gently tapering sections joining tubes of different diameter is much more efficient than sharp edged junctions. Similarly the gently tapered cones as shown in fig. 5 and fig. 6 do tend to concentrate the beam of a 1 τ pressure beam into a smaller diameter quite efficiently if the reduction aimed at is not more than a factor of about 3 to 1. After this it gets very lossy at this pressure. A beam at 0.1 τ should reflect from metal walls at a glancing angle to the beam axis and this is observed. In a converging cone of metal (or gauze) the beam at 0.1 τ can be held central and will impinge on a perpendicular target quite consistently.

TABLE 6

Pressure Range	e-folding length cms.
1 μ	9
0.1 τ	120
1.0 τ	270

For optimum beam transfer the beam should enter the drift section centrally and along the axis, if it is off axis or pointing to one side it will bounce or absorb into the walls and be very lossy and inconsistent in hitting a target. Such things as good planar windows and cathodes are invaluable here and again the effects of pre pulse have to be watched to prevent erratic emission. The thickness and material of the windows contribute to beam scatter and hence loss but at the voltage employed in this work 1 or 2 thou. titanium or aluminium foil appear to be acceptable with only a few percent loss. The titanium foil has survived 4 MV, 50 ns, 50 KA beams 6 cm. in diameter for up to 6 shots before perforating, this is only obtainable with a fairly high degree of uniformity in the beam.

The transfer efficiencies are such that a 1 cm hole can be regularly blown in a 30 thou. Tantalum target 150 cms from the cathode with a 3.2 MV 35 KA 50 ns beam.

5. Focussing of Electron Beams

For radiography spots of less than 1 cm diameter are normally required. Similarly, for irradiation studies it may be desirable to reduce the beam diameter by a large or small factor, depending on the energy density and area of irradiation required. There are several reasons for producing a fairly large, low energy density beam to start with. One is to save the window through which the beam passes to avoid damaging the cathode with exploding debris. At voltages around 3 MV the current loading for titanium foil seems to be around 1 kA/sq. cm for 50 ns pulses from a plasma cathode: this compares with around 5 kA/sq. cm which one would expect from a uniform energy deposition. Another reason for keeping the current density low is that it helps to prevent beam collapse phenomena occurring in the A-K gap and thus disturbing the beam before it starts its travels.

As mentioned in the previous section, changes in gas pressure from a few torr down to 0.1 torr can result in changes in beam diameter from 5 cm to 5 mm in very short distances, certainly less than 10 cm, probably less than 5 cm. This is a fairly lossy process and at high voltages the peaky X-ray distribution means that the on-axis dose is diminished by making the electrons describe such large angle deviations. This remains at the moment our best system for producing small spots after drifting beams some distance. An alternative, or possibly an addition, to gas focussing is a large impressed external magnetic field. This has been planned but not tried to date. A large pulsed magnetic field near the anode cathode gap was tried in the past and caused serious breakdown troubles due to the pre-ionisation of the background gas, caused by the rapid rising magnetic field. This would not be a problem if the field is some distance down a drift tube.

The other scheme for diameter compression is reducing the drift wall diameter; again as mentioned before, the beam at 1 τ can be reduced by a factor of 3 to 1 this way without much loss, but at 0.1 τ the central core is not affected in diameter but can be located on the system axis until it starts to hit the wall, then it breaks up when the tube diameter is about 1 cm or so.

Mogul has produced 50 R at 1 metre from a 1 cm spot after drifting 140 cm using the two pressure system and this dose is better than 80% of the total dose recorded at the 1 metre position, i.e. the dose from scattered and stray electrons is less than 10 R extra.

No form of pre-ionization of the gas prior to the main beam entry has been tried or has appeared to be necessary.

6. Conclusions and Acknowledgments

It can be stated that very high beam transfer efficiencies can be achieved with low ν/γ beams in the multi-megavolt range. A suitable manipulation of the gas pressure in the drift tube section can carry large fractions of the beam for metres and also reduce the beam diameter to less than 1 cm.

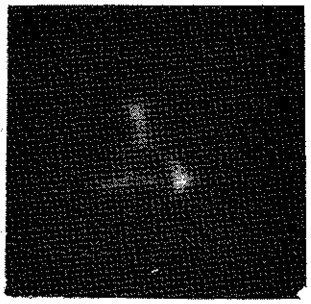
A plasma cathode producing electron beams with well defined trajectories for establishing good entry conditions is also realisable, although possibly with some difficulty.

It also showed that reduction of cathode emission area to target area by a factor of 75 to 1 was possible with 75% efficiency.

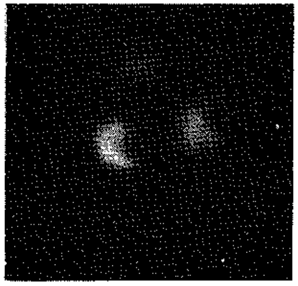
The authors would like to pay tribute to Mr. J. C. Martin and the remaining members of this section for their inspiration and hard work which lies behind this brief review.

Pinhole X-Ray Pictures of Different Cathodes Used With PLATO.

(Magnification 0.9:1)

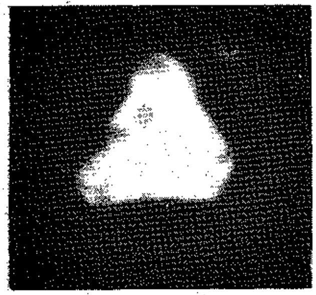


F555 3 Spot Cathode
Unoiled. $p \sim 1\mu$

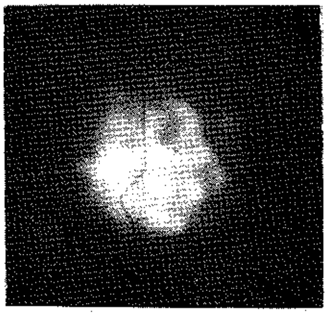


F556 3 Spot Cathode
Oiled All Over. $p \sim 1\mu$

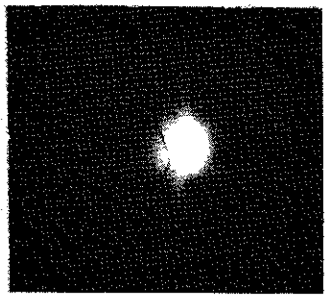
[All Pictures V_{A-K} 1.8 MV. A-K Gap ~ 2 cm.]



F659 27 Spot Triangular Array
with Bottom Right Hand
Spot Missing.
$p \sim 1\mu$. Oiled.



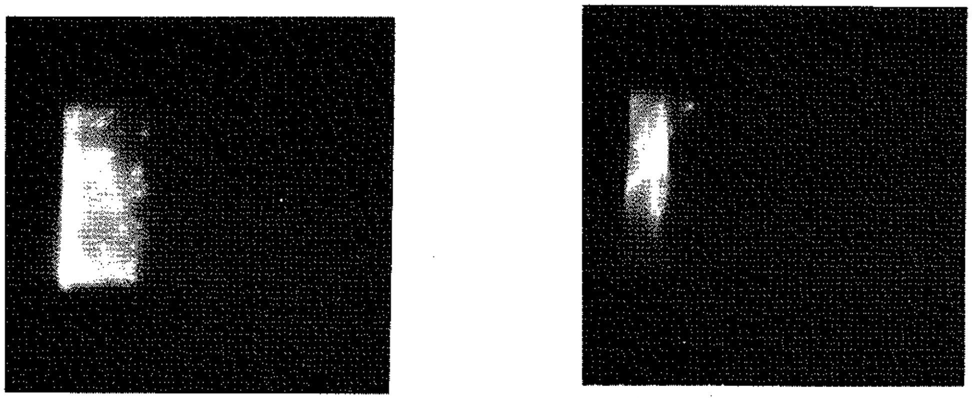
F647 55 Spot Cathode
$p \sim 1\mu$. Oiled.



F654 55 Spot Cathode
$p \sim 0.03\ \tau$. Oiled.

FIG. 1.

THE EFFECT OF OIL ON CATHODE SURFACES IN MOGUL.



F294
WITH OIL
Z_{TUBE} 90Ω

TUBE VOLTAGE 2MV

F296
WITHOUT OIL
Z_{TUBE} 400Ω

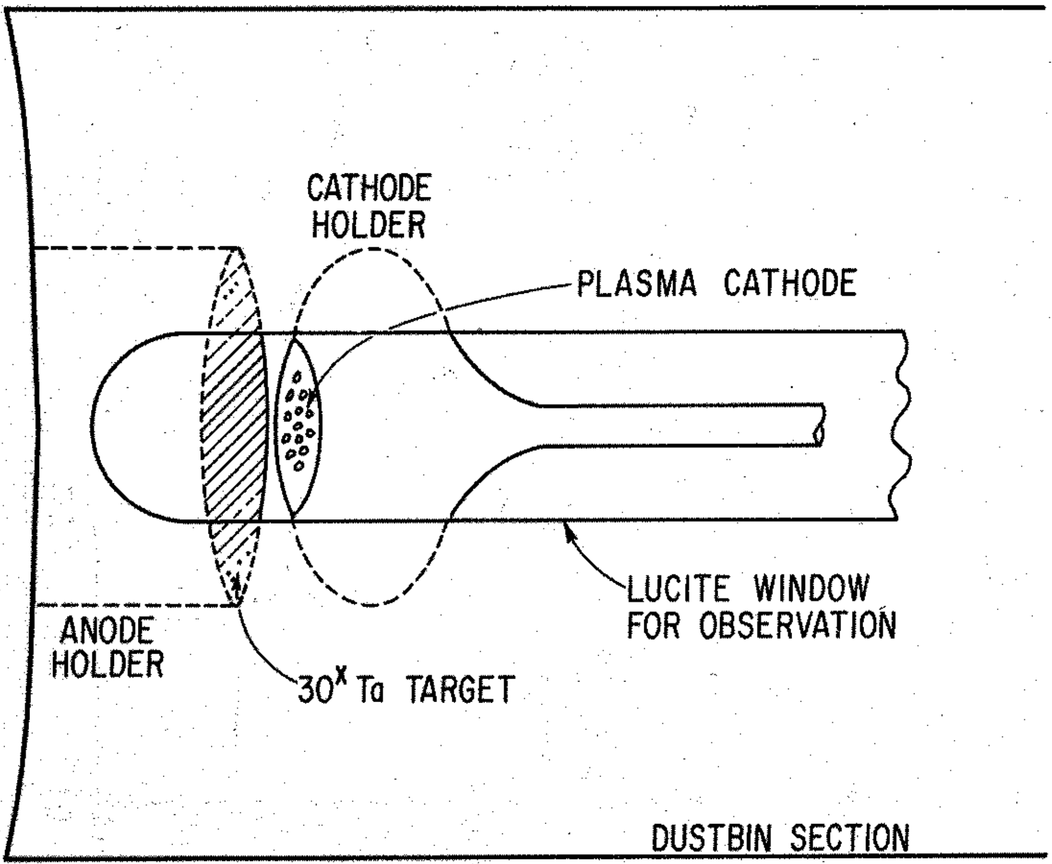
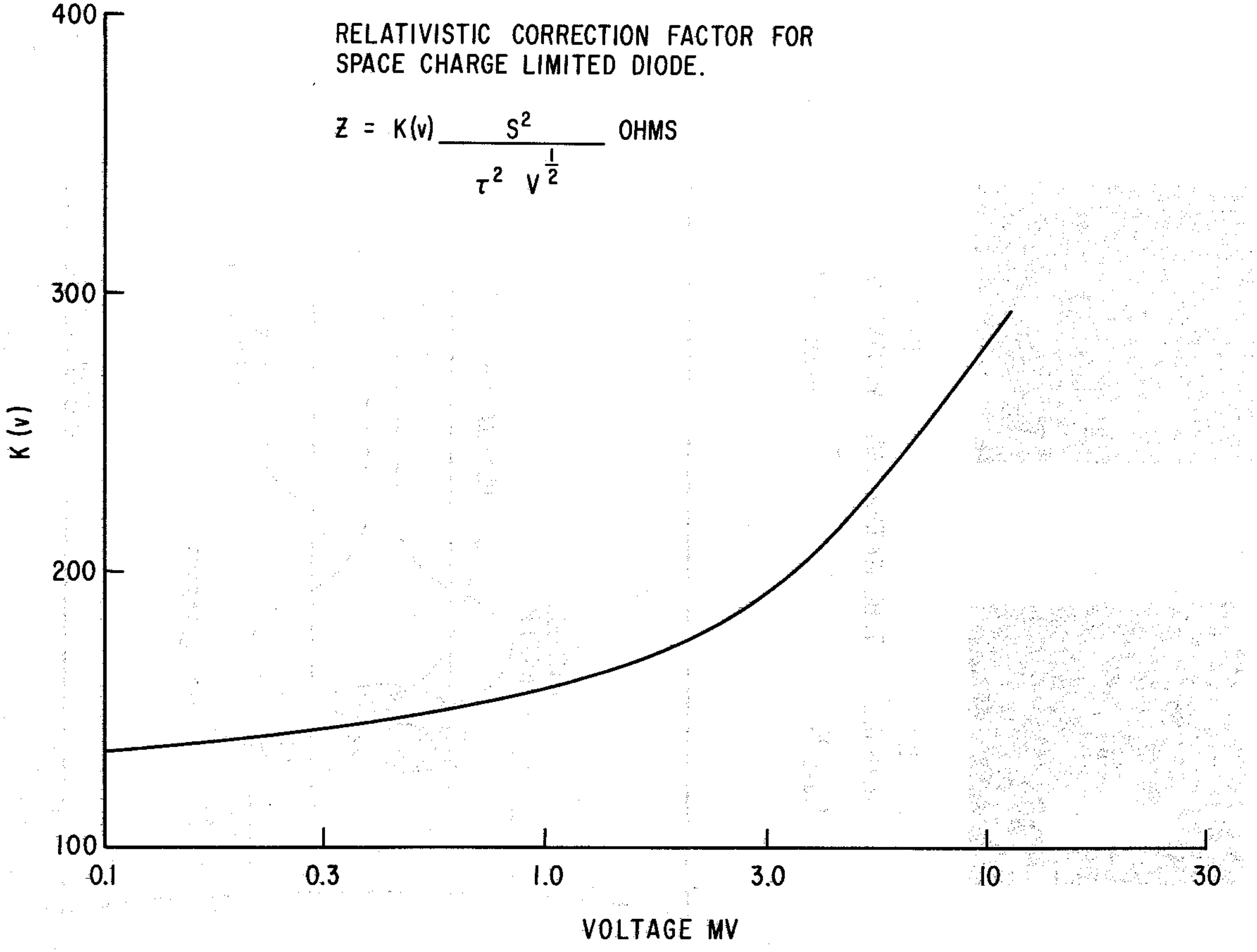


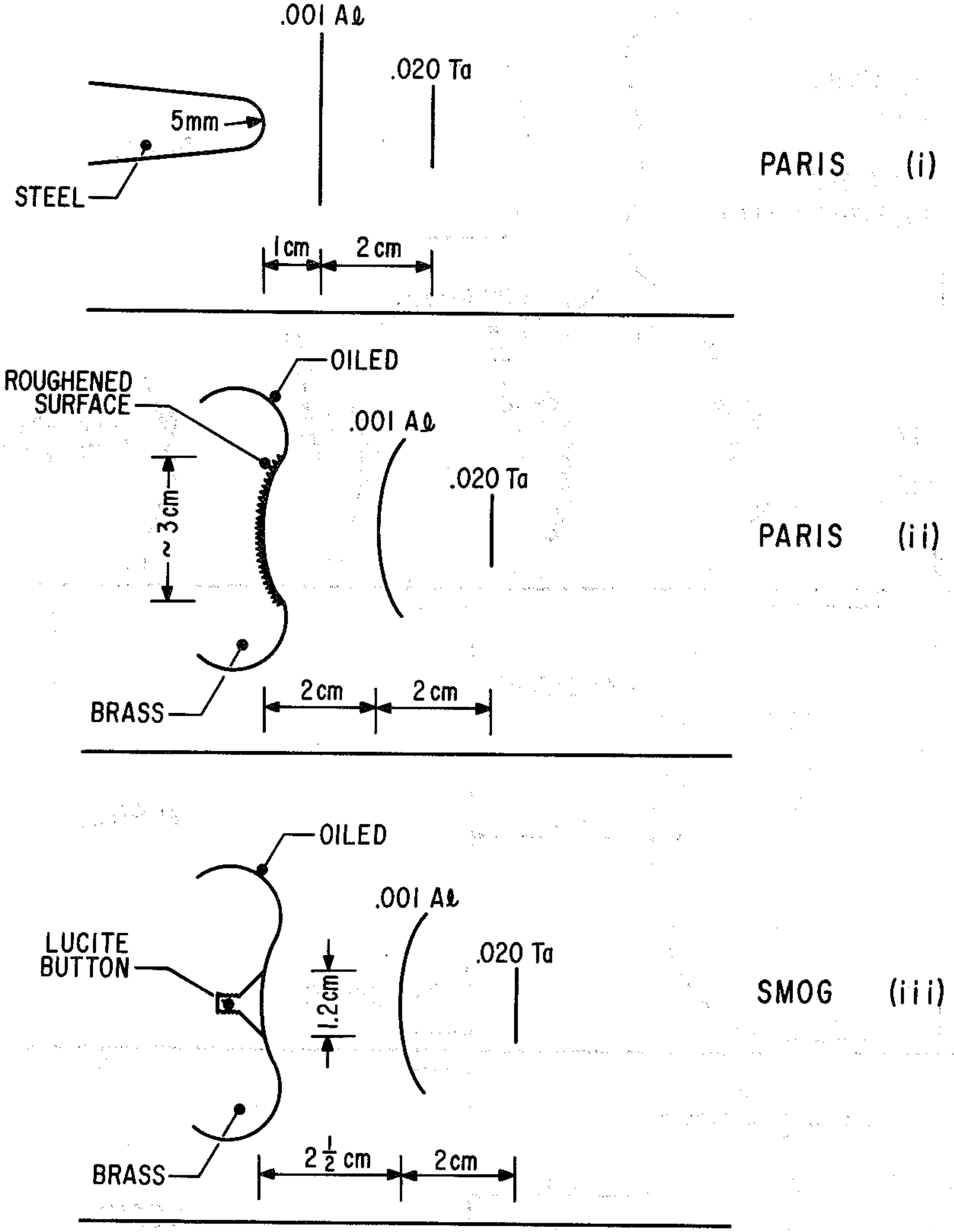
FIGURE 2



RELATIVISTIC CORRECTION FACTOR FOR
SPACE CHARGE LIMITED DIODE.

$$Z = K(v) \frac{S^2}{\tau^2 V^{\frac{1}{2}}} \text{ OHMS}$$

FIGURE 3



DIAGRAMATIC DISPLAY OF CATHODES EMPLOYED IN ELECTRON BEAM EXPERIMENTS

FIGURE 4

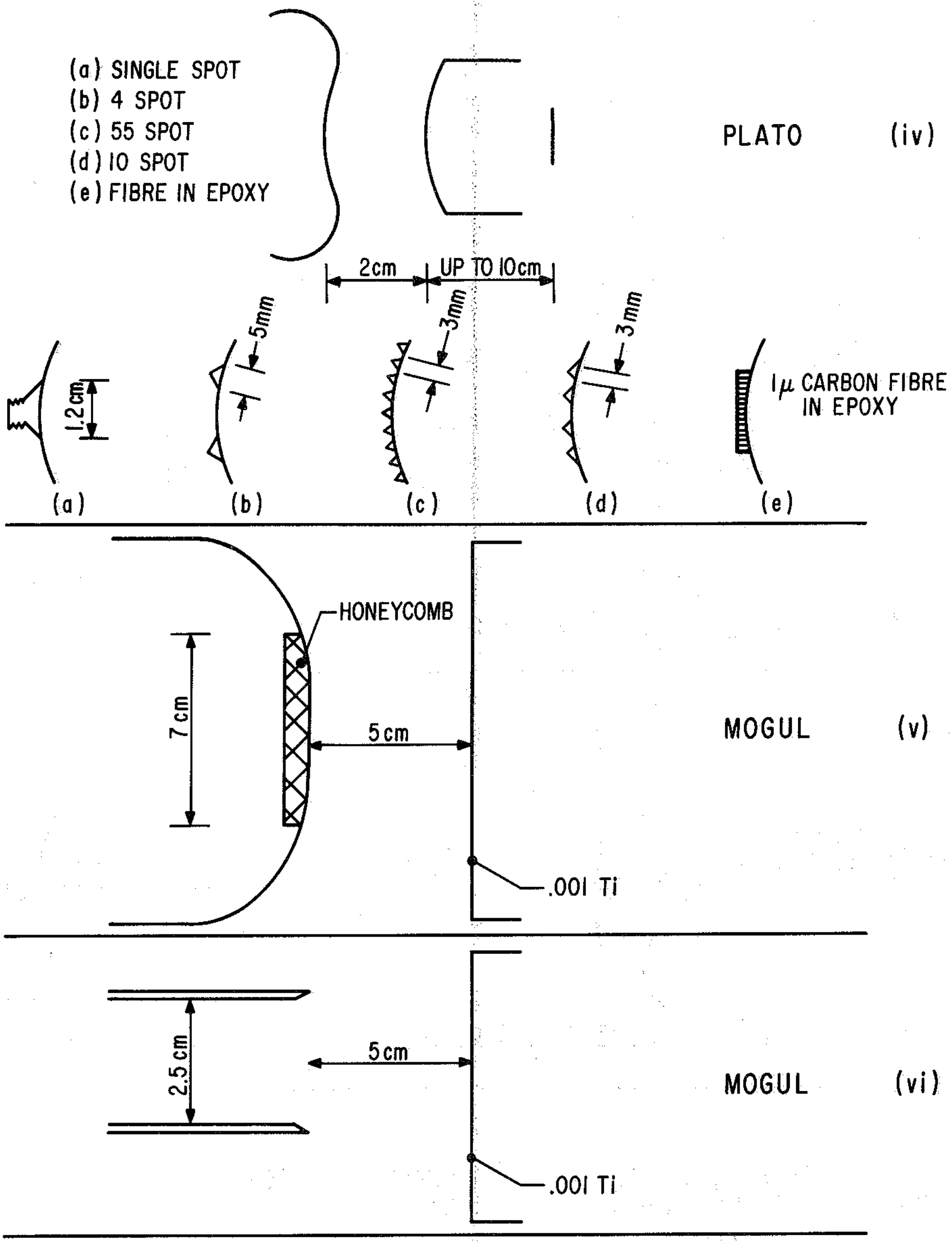
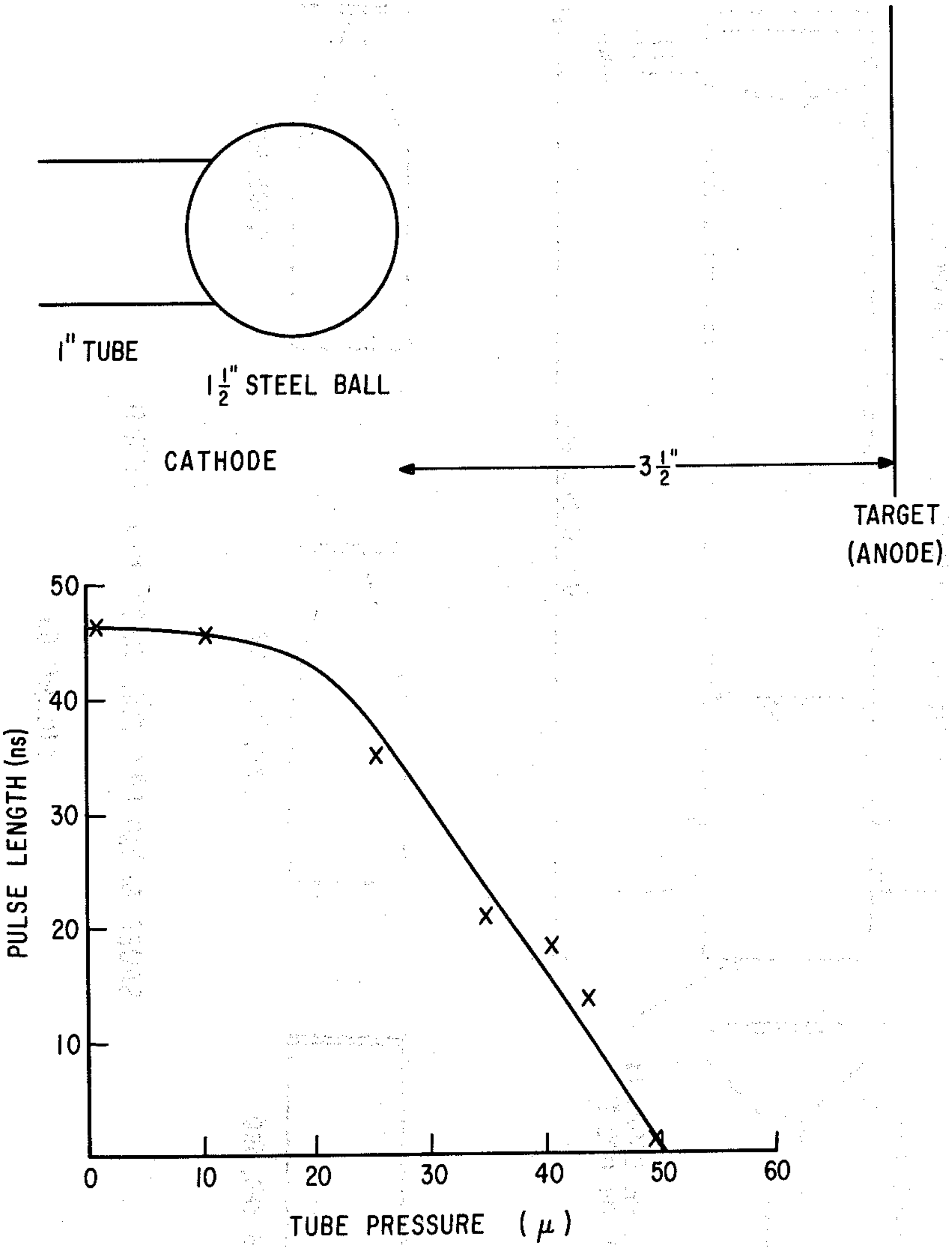
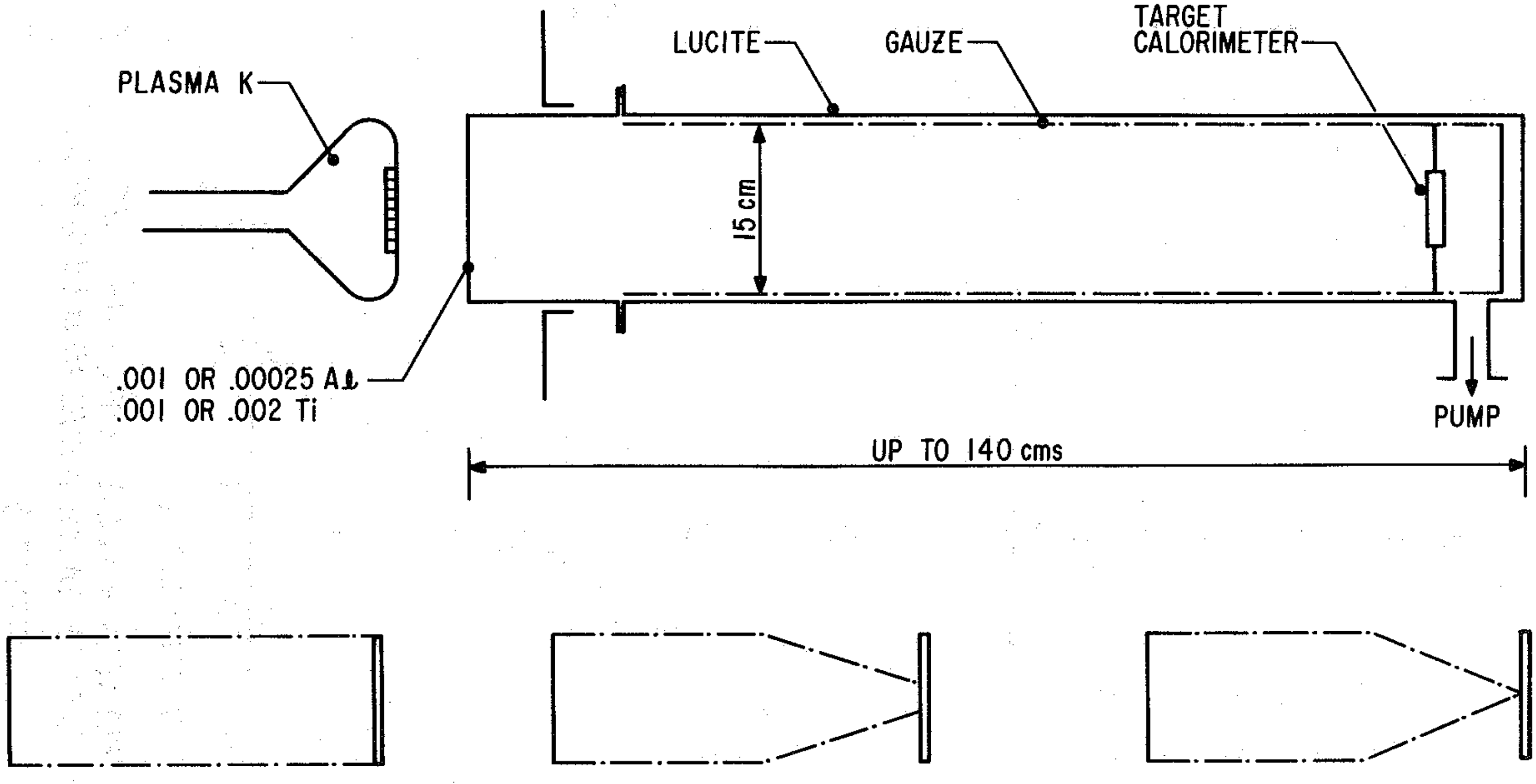


FIGURE 4 CONT.



RELATIONSHIP BETWEEN γ PULSE LENGTH AND TUBE PRESSURE FOR CATHODE SHOWN ABOVE AS USED IN MOGUL

FIGURE 5



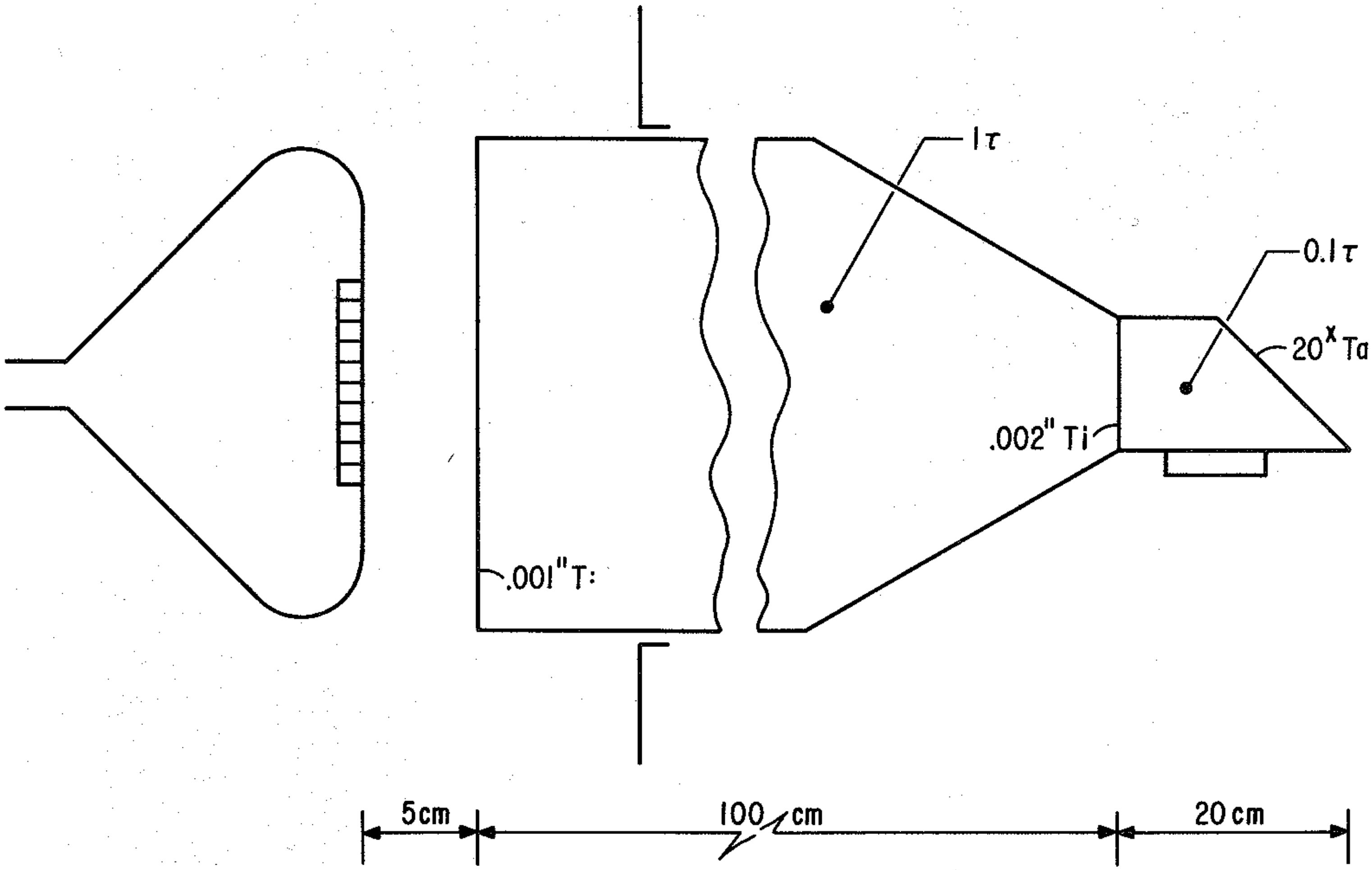
F, 383, 389, 390.

F, 391, 392, 394.

F, 395, 396.

GAUZE GEOMETRY FOR SHOT N^{os} SHOWN

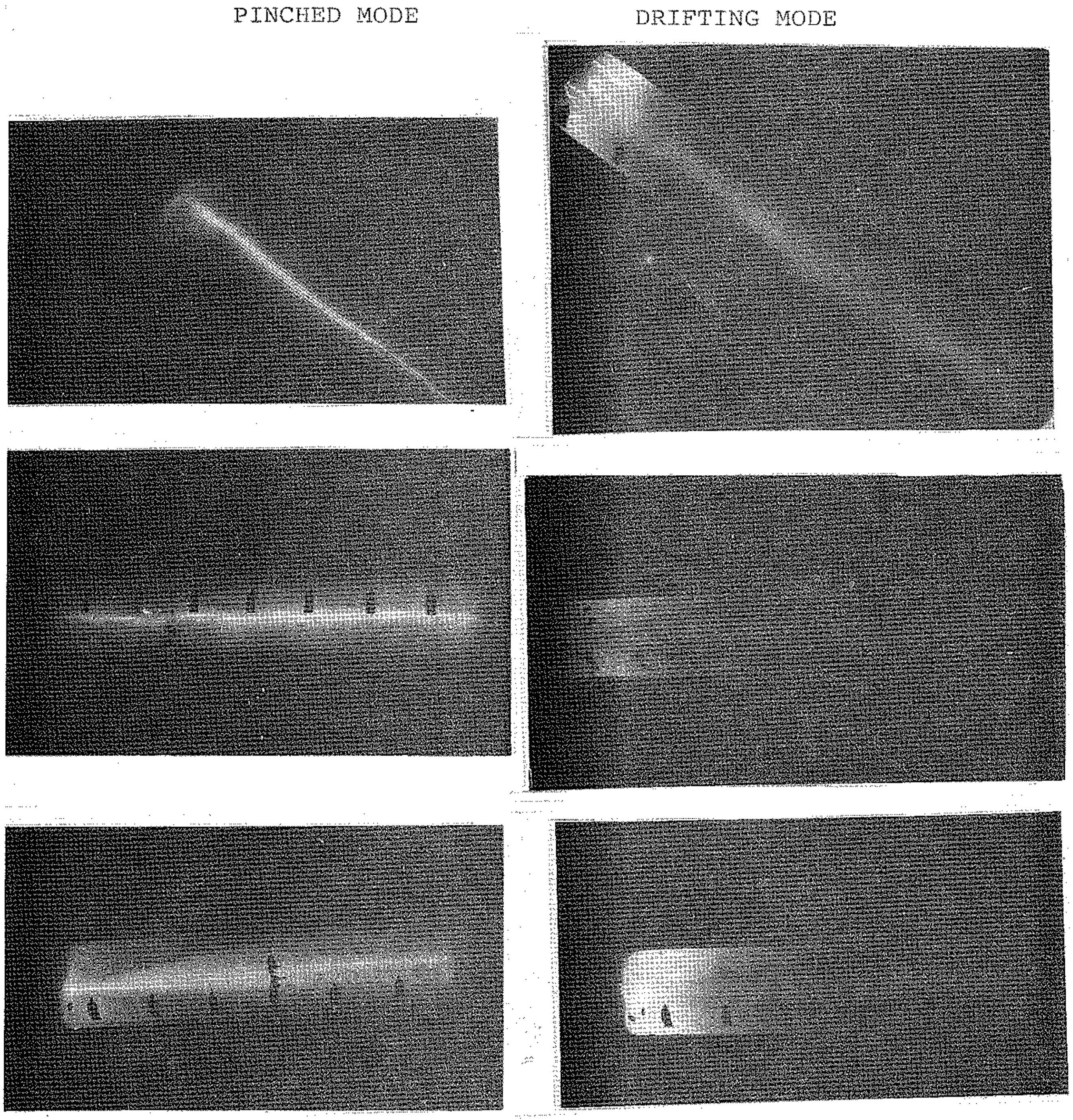
FIGURE 6a



SET UP FOR F397

FIGURE 6b

Open Shutter Photographs of Electron Beams Drifting in
Copper Gauze Tubes as Shown in Fig. 6a.
Pressure Ranges 0.1 τ and a few τ. Film Speed 75 A.S.A.


PINCHED MODE

DRIFTING MODE

p 0.1 τ f11 F395

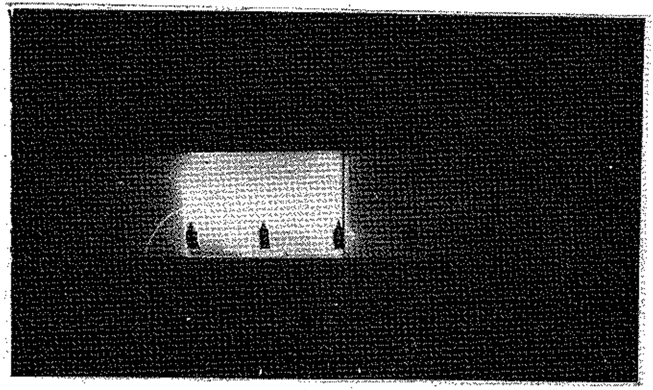
p 5 τ f5.6 F396

beam direction ←

FIG. 7a.

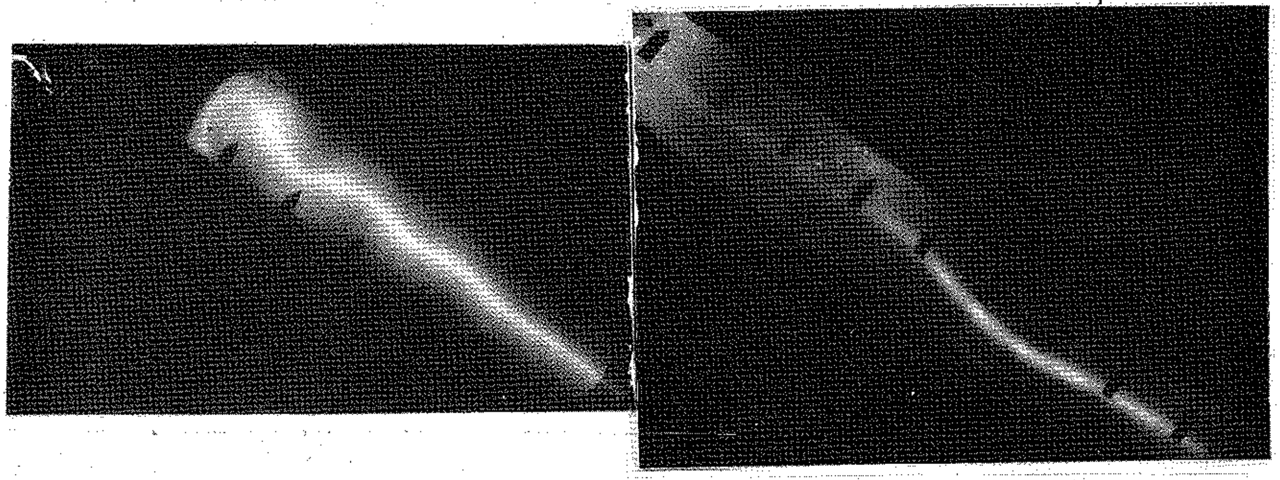
Open Shutter Photographs of Drifting Electron Beams in Configurations as Shown in Fig. 6.

Film Speed 75 A.S.A.   Black Markers 10 cms Apart.



f8 p_1 0.2 τ p_2 4 τ F397

(See Fig. 6b)



f19 p 0.1 τ F389

f8 p 1 τ F391

beam direction

←

FIG. 7b.