Fermilab

Gun Anode Lens Effect on the Electron Beam Transverse Temperature

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Introduction

A review of the design constraints on the electron gun parameters that control the transverse temperature of the electron beam has shown that the magnetic guide field must be held above a threshold value, to achieve a low transverse temperature beam.

Kudelainen et al (1) have shown that the anode aperture in a Pierce design gun marks the end of the Pierce region ($E_r = 0$). The thick E-field defocusing lens here can produce transverse energies of 1 or 2% of the beam energy, if not magnetically optimized.

Because of the axial magnetic guide field, the electron beam generally sees a crossed electric and magnetic field configuration ($E_r \times B_z$), the radial electric fields arising from space charge, anode aperture lens or other voltage electrodes. The gun electron beam optics can then be characterized by the rotation around the gyro center and the gyro center drift velocity:

$$V_d = E_r \times B_z = V_\phi \qquad (1)$$

assuming other gyro center drift terms are negligible.

Heating in the Transverse Plane

An heuristic derivation of the lens heating effect for cylindrical symmetry begins by noting that an electron traveling with no transverse velocity

($V_r = V_\phi = 0$) along a constant axial magnetic field (B_z) is represented as the origin on the transverse velocity plane. All other points on this plane (V_r , V_ϕ) simply rotate around the origin with the cyclotron frequency:

$$\omega_c = \frac{e}{m} \cdot B_z \cdot \frac{1}{\gamma} \qquad (2)$$

where $1/\gamma = \sqrt{1 - \beta 2}$ is the time dilation correction.

If a radial electric field was suddenly turned on, the result seen in the V_r - V_ϕ plane is a change of the center of rotation of the velocity points from the origin to a point (0 , V_d), where

$$V_\phi = V_d = E_r/B_z = k \, . \, r/B_z \qquad (3)$$

Thus a particle originally on the origin (no transverse energy) upon entering an electric lens, sees itself now rotating in the velocity plane around the point (0,V_d) at the cyclotron frequency. Note that one point on this plane which represents all beam particle for a perfectly quiet beam, (0,0) will transform to a line assuming the gyro center drift velocity results from a linear lens action with the radial dependence shown in (3).

For an E-field lens of length L and radial electric field at the beam edge of $E_r(b)$ the heating in the transverse plane is represented by the motion along the circle shown in fig. (1) where $V_d = E_r(b)/B_z$ is the crossed field drift velocity and θ is the phase motion around the gyro center, i.e.,

$$\theta = \frac{L.2\pi}{\lambda} = \frac{e}{m} \cdot \frac{L.B_z}{v_z} \cdot \frac{1}{\gamma} \qquad (4)$$

and $\lambda = \frac{v_z . 2\pi}{\omega_c}$ is the gyro wavelength. The total transverse velocity is:

$$\overline{V}_1 = \overline{V}_\phi + \overline{V}_r \qquad (5)$$

where $V_\phi = V_d.(1-\cos(\theta)$

$V_r = V_d.\sin(\theta)$

and the transverse energy is:

$$E_t(B_z) = 2V_d^2 \cdot \left[1 - \cos\left(\frac{e.L.B_z}{m.\gamma.v_z}\right)\right]\frac{m}{2} \qquad (6)$$

This equation implies zero heating occurs when the effective length of the lens, L, is an integer number of gyro wavelengths. (Figure (2) is a plot of equation (6) for the SLAC gun parameters derived from the gun modelling program EGUN (2).) Note that for no guide field (B_z=0) the heating is:

$$E_t(o) = \left(E_{-r}\frac{(b).L.e}{v_z\ m}\right)^2\frac{m}{2} = 1400 \text{ ev}$$

for a 110 kv beam, in a flat cathode gun.

Space Charge Effects

The space charge radial field for a 10 amp. x 2 in. diameter beam at 110 kv is:

$$E_r(b) = \frac{I}{E_o 2\pi b.v_z} = 0.41 \text{ kv/cm at b=1 in.}$$

This field, about 10% of the anode lens field for the SLAC gun, yields a residual transverse energy that must remain after passage through the anode lens.

Typically, for a 1 kg. guide field this energy appears in the form of the rigid rotor motion as:

$$V_{rigid} = E_{sp.ch.}/B_z = \frac{0.41 \times 10^5}{0.1} = 4.1 \times 10^5 \text{m/s}$$

or a residual T.E. of:

$$E_t = \frac{mc^2}{2} \left(\frac{4.1 \times 10^5}{3.0 \times 10^8}\right)^2 = 0.45 \text{ ev (10 amp)}$$

for a 30 amp beam $E_t \approx 4.0$ ev.

The SLAC Gun Modelling

The gun modelling program EGUN has been used to calculate the anode lens parameters for the SLAC spherical cathode geometry gun. The results were:

$$L_{eff} = 7.28 \text{ cm}$$

$$E_r(\text{lin.}) = 3 \times 10^5 \text{ v/meter}$$

for a cathode-anode voltage drop of 110 kv. Further investigations of the magnetic field dependence of the lens heating effect for this gun is shown in figure (3). The anode region sees only 60% of the final field magnitude, because of the spherical geometry which required a tapered field; the first minimum ($L = 1.\lambda$) occurs for a guide field value around 1200 gauss. Figure (4) shows the plot of the field taper designed for the SLAC gun to match the trajectories evolving from the spherical cathode.

Transverse Energy Damping

The SLAC gun design chooses to damp out the residual anode lens transverse energy by means of electrostatic doublet lens pairs created across voltage gaps. It can be shown that such a doublet of axial length n x gyro wavelength simply translates all (V_r-V_ϕ) phase points along the V_ϕ axis by $4.V_d$. Thus a phase point at $(0, 4.E_r/B_z)$ would be damped down to the origin by such a gap, assuming a radial field of E_r at the particle radius.

In general two such gaps phased in quadrature, i.e., spaced an odd number of quarter wavelengths apart, would suffice to damp out transverse energies of order:

$$E_t = \left(\frac{4.E_r}{B_z}\right)^2 \cdot \frac{m}{2} = 40 \text{ ev}$$

for E_r = 1 kv/cm

B_z = 1 kg

Conclusions

A low temperature e-gun source (E_t = 1 ev) can be achieved by:

1. making the gun anode lens length one gyro-wavelength in axial extent.
2. using damping electrodes whose lens doublets are one gryo-wavelength long, with quadrature phasing.

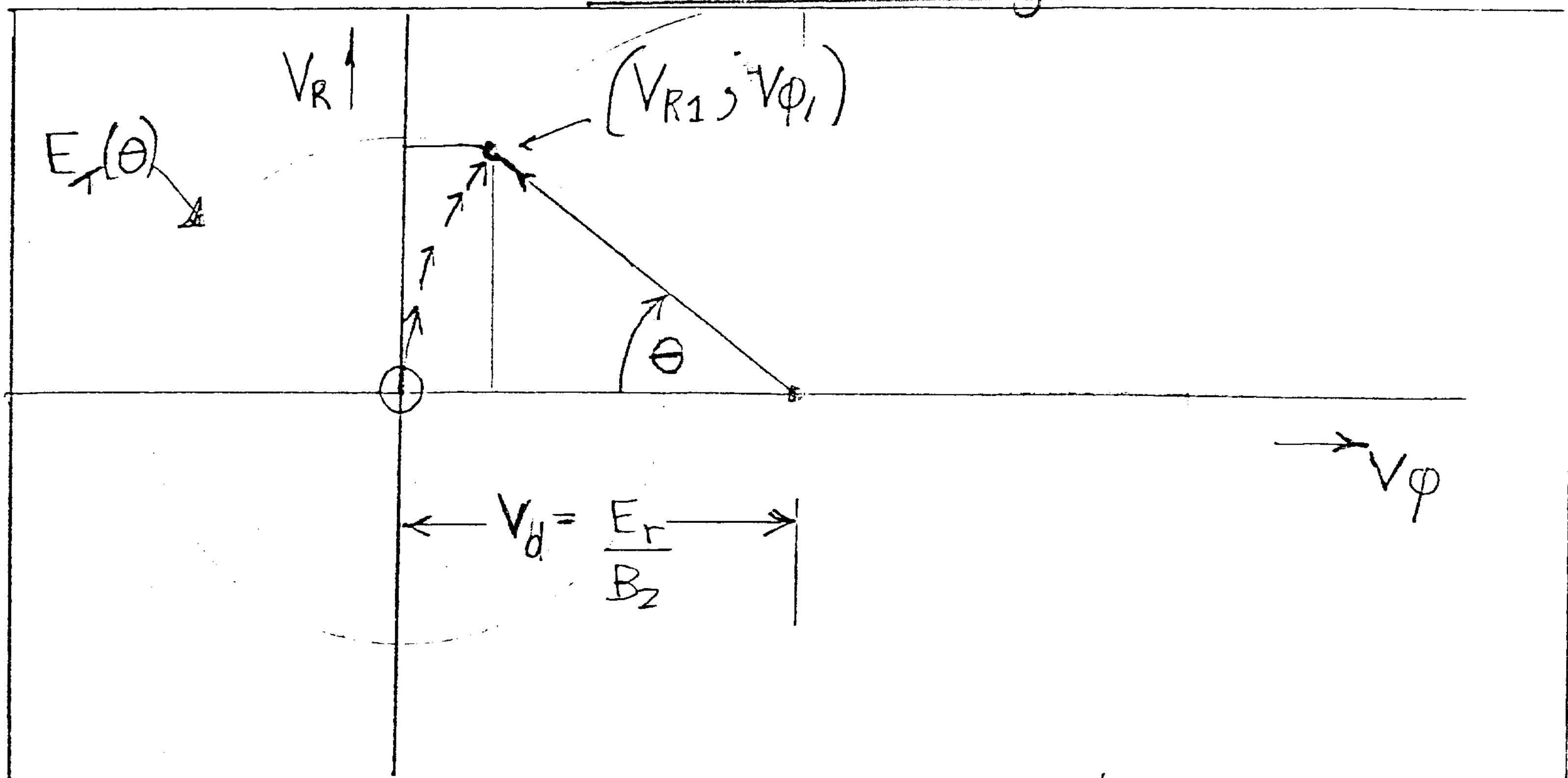
The European approach ahs been to achieve condition (1) with a long multi-electrode anode structure, which simultaneously yields low radial fields and a low magnetic field threshold. The SLAC gun configuration requires a compromise, since (1) and (2) are somehwat orthogonal in this design because of aperture restrictions. However, if condition (1) is achieved for the flat cathode SLAC gun design, useful tunes of the damping electrodes are predicted for gap voltages of 25-35 kv for beam E_t = 1 ev.

References

1. V. I. Kudelainen, I. N. Meshkov and R. A. Salimov, Soviet Physics, Technical Physics, Vol. 16, No. 11, May 1972, p. 1821.

2. W. B. Herrmannsheldt, "Electron Trajectory Program," SLAC - Report 226 November 1979.

Transverse heating from an E-lens in an Axial magnetic field.



drift velocity $V_D = E_r/B_z$

$$V_{R1} = V_d \sin\theta$$

$$V_{\varphi 1} = V_d (1-\cos\theta)$$

$$\theta = \frac{e}{m} \cdot \frac{L \cdot B_z}{V_z} \cdot \frac{1}{\gamma}$$

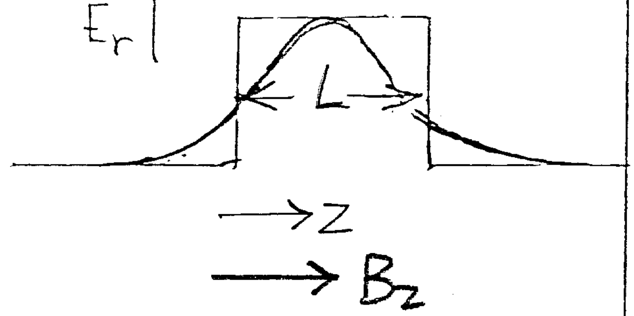
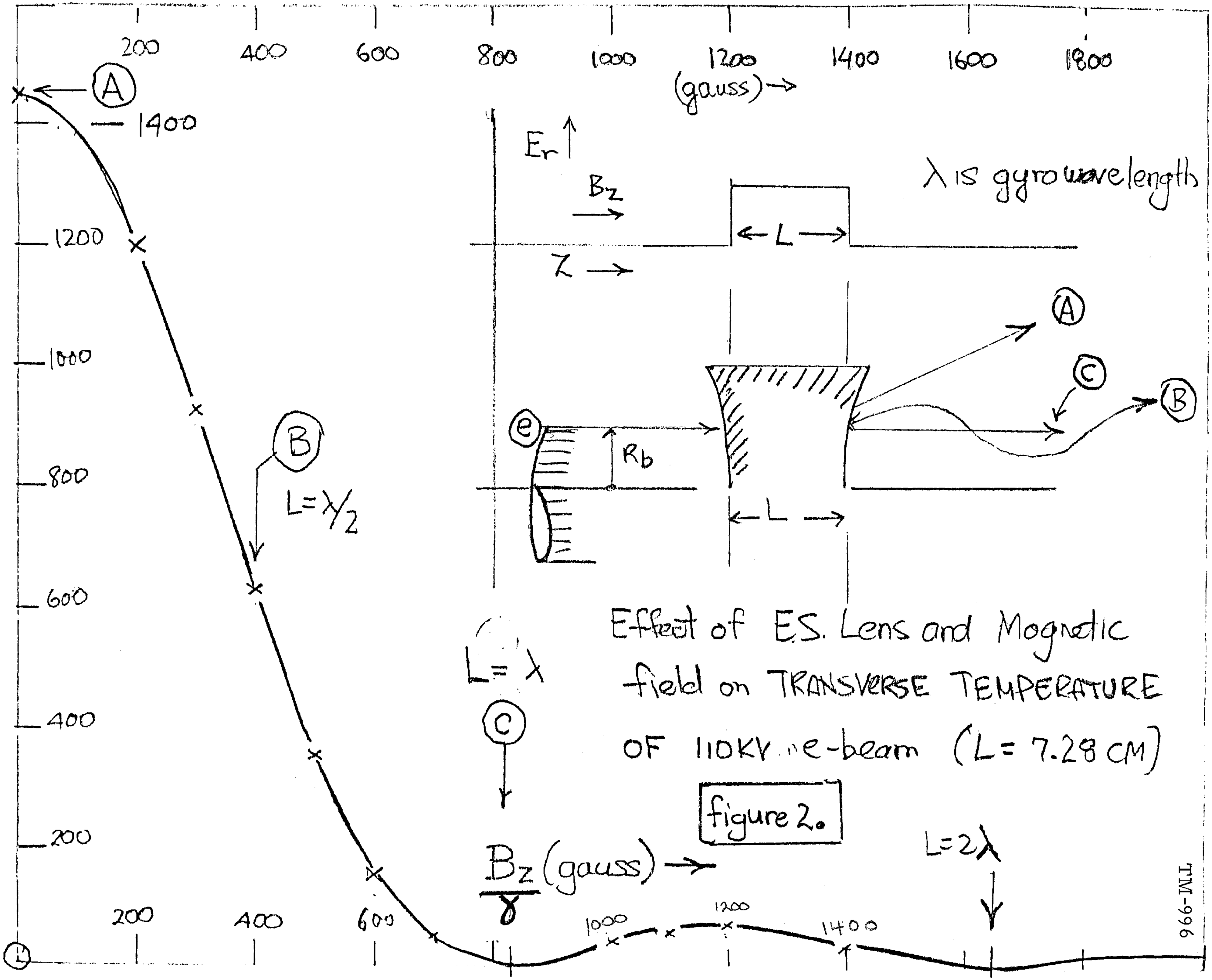


figure 1.



Effect of E.S. Lens and Magnetic field on TRANSVERSE TEMPERATURE OF 110KV e-beam (L = 7.28 CM)

figure 2.

Modelled Anode lens transverse plane heating vs. Bz

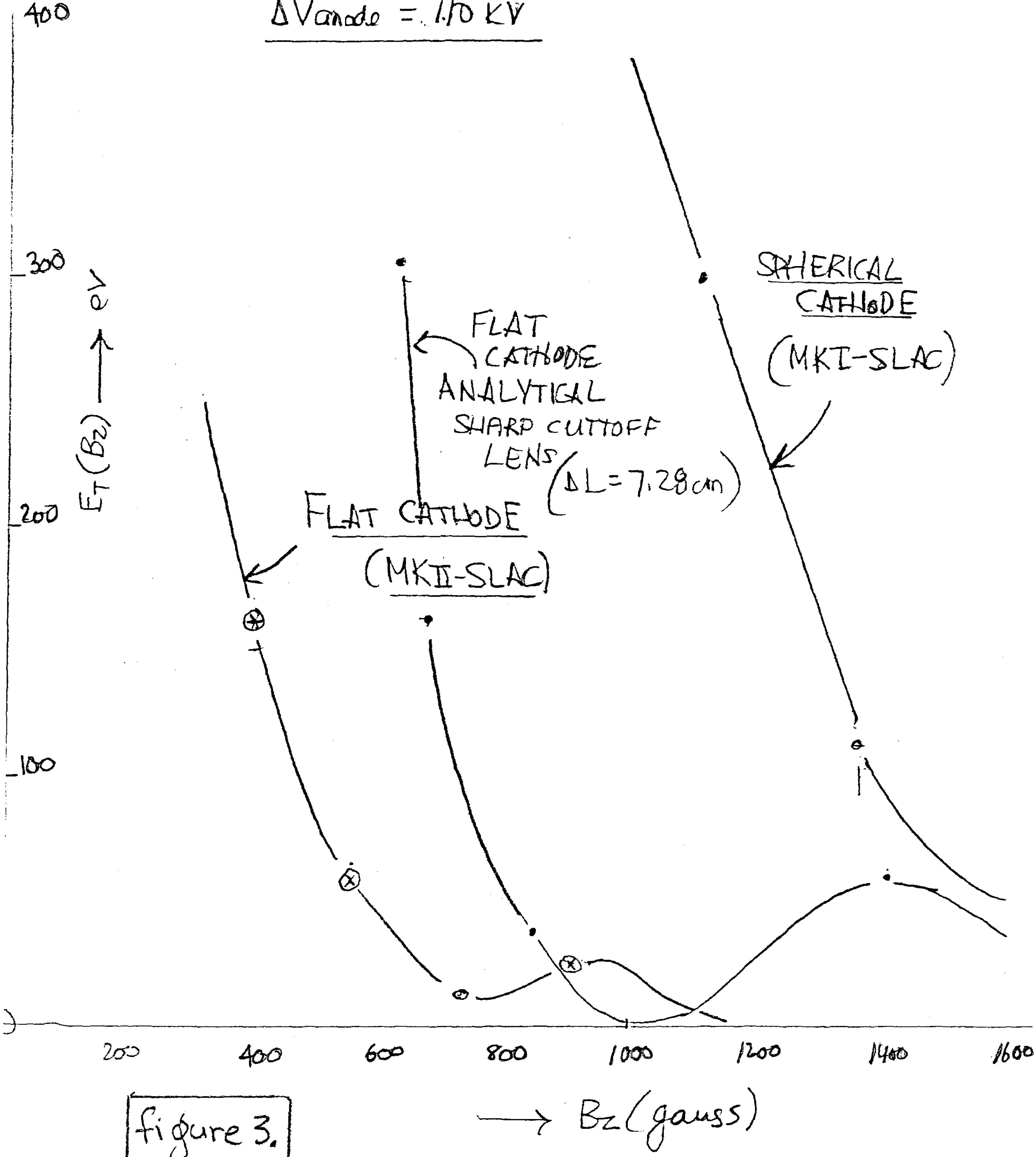


figure 3.

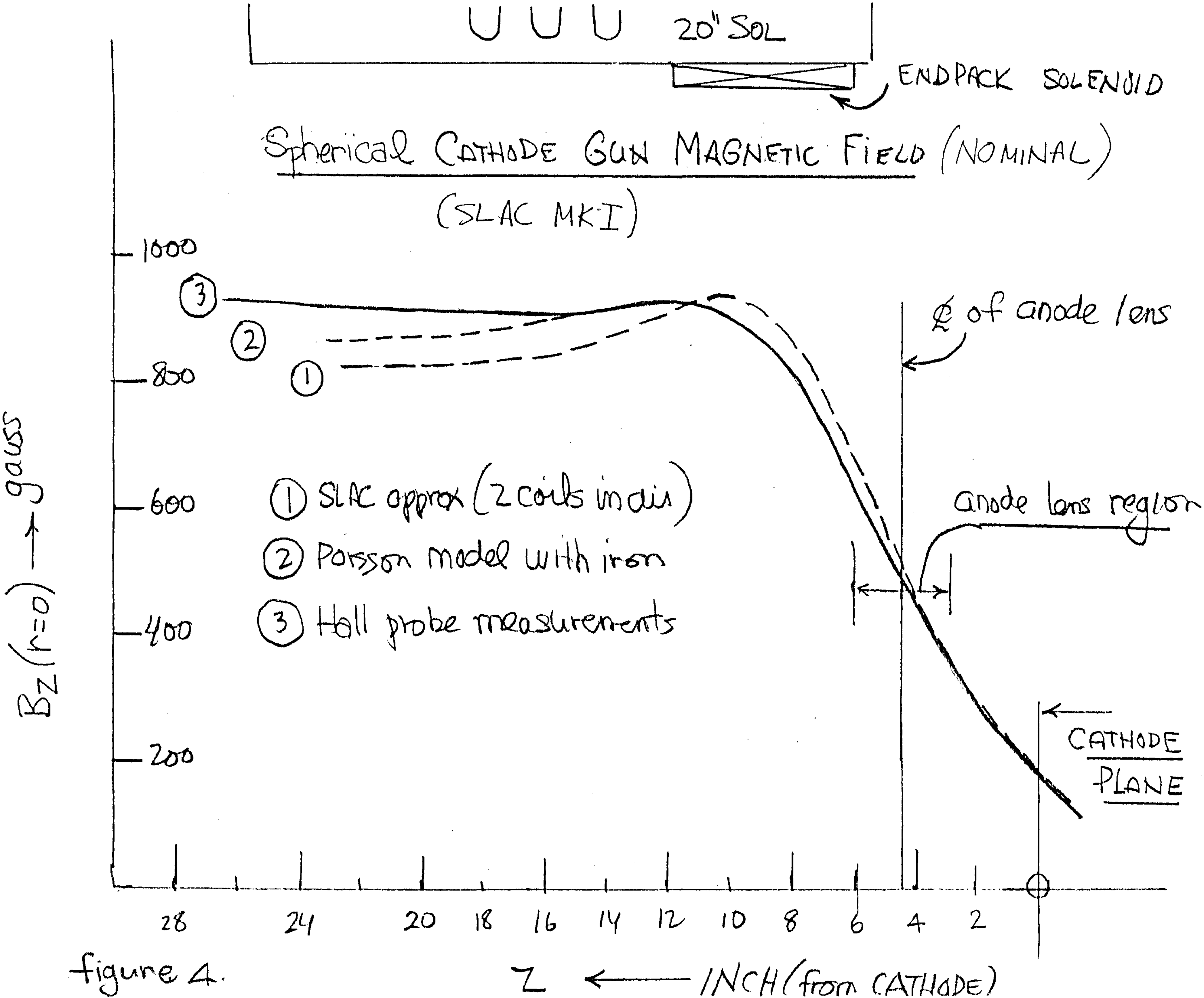

20" SOL
ENDPACK SOLENOID
Spherical CATHODE GUN MAGNETIC FIELD (NOMINAL)
(SLAC MKI)
$B_Z(r=0)$ → gauss
1000
800
600
400
200
③
②
①
① SLAC approx (2 coils in air)
② Poisson model with iron
③ Hall probe measurements
℄ of anode lens
anode lens region
CATHODE PLANE
28
24
20
18
16
14
12
10
8
6
4
2
Z ← INCH (from CATHODE)

figure 4.

MkII SLAC Gun Anode Radial Field Distribution

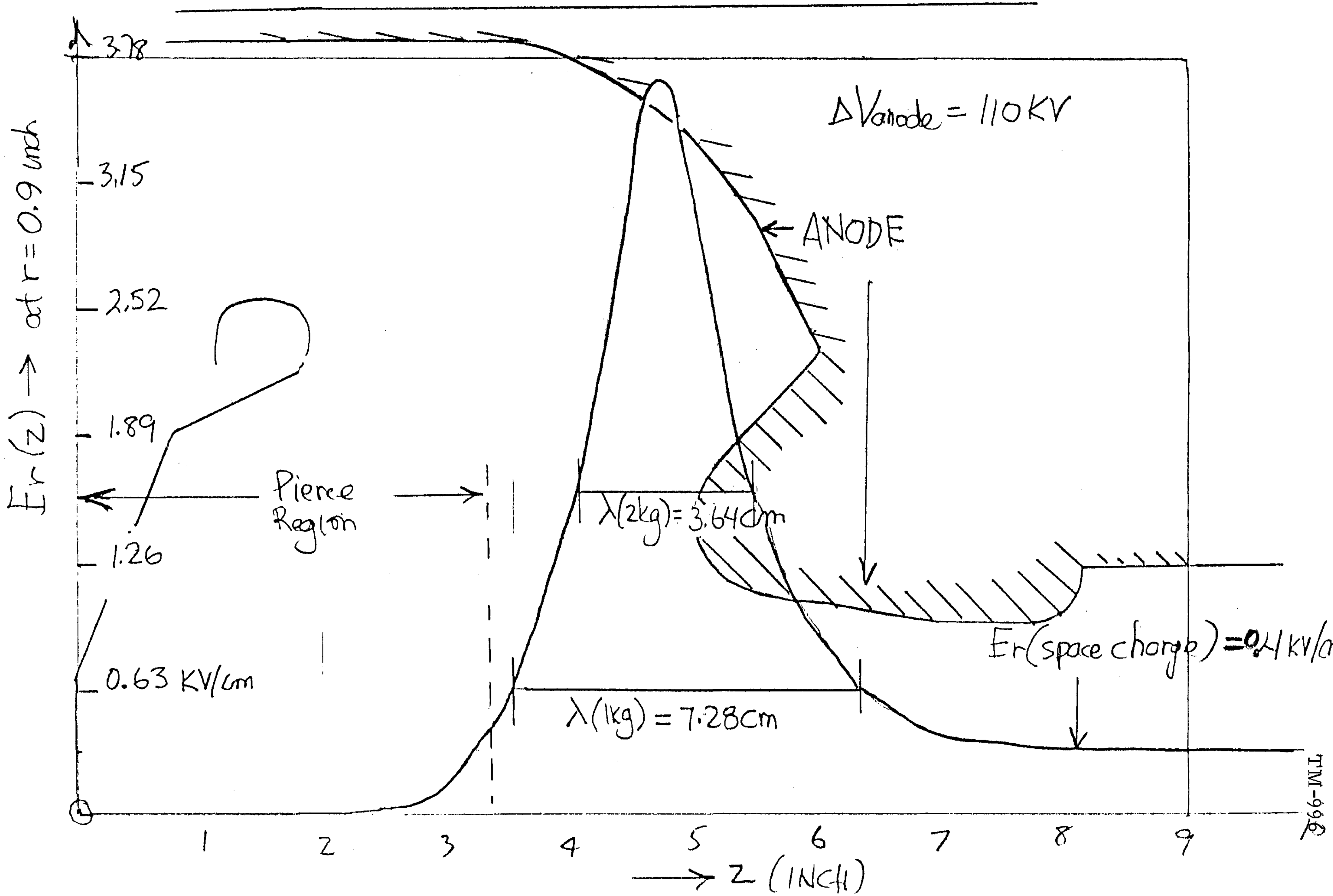


figure 5.