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THE LOS ALAMOS PHOTOINJECTOR PROGRAM*

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Free-electron lasers (FELS) require electron beams of high peak brightness. In this presentation, we describe the design of a compact high-brightness electron source for driving short-wavelength FELs. The experiment uses a laser-illuminated Cs_3Sb photoemitter located in the first rf cavity of an injector linac. The photocathode source and associated hardware are described. The doubled YAG laser (532 nm), which is used to drive the photocathode, produces 75-ps micropulses at 108-MHz repetition rate and peak powers of approximately 300 kW. Diagnostics include a pepper-pot emittance analyzer, a magnetic spectrometer, and a 4-ps resolution streak camera. Present experiments give the following results: micropulse current amplitudes of 100 mA to 400 A, beam emittances ranging from 10 π·mm·mrad to 40 π·mm·mrad, an energy spread of ±3%, and peak current densities of 600 A/cm^2.

The experiment's design has now been changed to include a separately phased rf cavity immediately following the first cavity. This modification enables us to study the effects of phasing with the possibility of improving the injector performance. Also, this change will improve the vacuum conditions in the photoelectron source with a consequent improvement in lifetime performance. A brief discussion on the possible applications of this very bright and compact electron source is presented.

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1. Introduction

An FEL oscillator, driven by an rf linac, requires a train of low-emittance, high-current electron bunches delivered to an undulator. A conventional electron source consists of a dc electron gun, subharmonic bunchers to increase the peak current, and matching optics to conserve the beam brightness after introduction into the accelerator. The decrease in beam quality is not acceptable for advanced high-power and/or short-wavelength FELs. A new type of accelerator electron source has been demonstrated that uses a laser-illuminated photoemitter. The approach eliminates a conventional buncher system and thereby avoids the usual large loss in brightness that occurs in bunchers.

In 1985, the achievement of high-peak currents from a Cs_3Sb photocathode was reported [1]. More recently, it has been shown that the laser-driven photocathode produces an intrinsically bright beam [2]. It remains to be demonstrated that short bunches can be accelerated to relativistic energies without loss of brightness. With suitably short laser pulses incident on a photocathode that has a high quantum efficiency, it would appear to be a straightforward matter to create a high-brightness, optically chopped beam, accelerate it in several rf cavities, and then deliver it to the main rf linac.

A laser-illuminated photocathode can readily produce the electron bunch train that is required by rf linac-driven FEL oscillators. The emittance-growth problem associated with high space-charge density in short bunches can be alleviated by choosing an injector design that retains the requisite high-average current but accelerates, initially, a relatively long bunch. The longer bunch is best accelerated in a lower frequency linac operated at a subharmonic of the main linac frequency. After acceleration to several million electron volts, a magnetic phase compressor shortens the bunch.

A laser-illuminated photocathode can be used in a dc-gun configuration in much the same way that it is employed in the laser-klystron [3] or lasertron [4]. In an rf cavity, on the other hand, a more rapid acceleration rate can be achieved than in a dc gun. The rf gun forms the heart of an experimental program [5] at the Los Alamos National Laboratory to develop an intrinsically bright electron source for linacs. A similar program based on a dc gun is under way at Stanford University [6].

2 Electron-Source Brightness

The normalized peak brightness is defined as

$$B_n = I/(\varepsilon_x \varepsilon_y) \qquad [\text{units: } A/(m^2 \cdot rad^2)] \ ,$$

where I is the peak current and ε_x and ε_y are the normalized transverse emittances of the beam [7]. In accelerator discussions, it is constructive to use the rms emittance formulation, defined as

$$\varepsilon_x = 4\,\pi[<x^2><x'^2> - <xx'>^2]^{1/2} \ ,$$

where x and x' are the particle's transverse coordinate and angle of divergence from the optic axis, respectively, and < > means an average over the electron distribution. In this formulation, the rms emittance is equal to the total phase-space area for a Kapchinskii-Vladimirskii distribution [8]. The normalized emittance is then

$$\varepsilon_n = \gamma\beta\varepsilon \quad ,$$

where for an azimuthally symmetric beam $\varepsilon = \varepsilon_x = \varepsilon_y$.

The lower limit of the beam's normalized emittance from a thermionic electron source is governed by the emitter size and by the transverse component of the thermal motion of the electrons. The thermal limit of the normalized rms emittance of a beam from a thermionic emitter of radius r_c at a uniform absolute temperature T is [9]

$$\varepsilon_n = 2\,\pi\, r_c[kT/m_0c^2]^{1/2} \qquad \text{(units: m}\cdot\text{rad)}$$

because $<xx'> = 0$ at the cathode. For a typical thermionic emitter at 1160 K, the average transverse energy of emitted electrons is 0.1 eV. For a uniform current density J, the total current is $I = \pi\, r_c^2 J$ and the lower limit on the rms emittance is

$$\varepsilon_n = 5.0 \times 10^{-6}\, \pi (I/J)^{1/2} \qquad \text{with J in A/cm}^2 \; .$$

The corresponding normalized peak brightness is limited to

$$B_n = I/\varepsilon_n^2 = 4.1 \times 10^9 J \; .$$

The current density from a dispenser cathode is typically not more than 10 A/cm^2; therefore, for an emitting area of 1 cm^2, the ratio I/J is of the order unity. Semiconductor photoemitters, on the other hand, are capable of delivering[5] over 500 A/cm^2, and their effective temperature[2] is low enough to produce beams an order of magnitude brighter than those from thermionic cathodes.

3. The Los Alamos Photoinjector Program

The Los Alamos program is based on an rf cavity with a photocathode electron source. The initial rf gun experiments were carried out at a frequency of 1300 MHz because a powerful klystron was available. A schematic diagram of the single cavity Los Alamos injector experiment is shown in fig. 1.

3.1. Photocathode Design

In recent years, photocathodes for polarized electron sources have been made from wafers of GaAs [10, 11]. Current densities as high as 180 A/cm^2 have been reported [11]. Photoemitters of Cs_3Sb are less demanding of system cleanliness [12] than are those of GaAs. An additional advantage of a positive electron affinity semiconductor like Cs_3Sb lies in the rapid emission of the photoelectrons [12]. By contrast, the intrinsic emission-time uncertainty of GaAs has been measured in the range from 8 to 71 ps for active layers between 50 nm and 2 μm in thickness [13].

A Cs_3Sb photocathode was chosen for its ease of preparation within the vacuum environment of the linac and for its relative tolerance of vacuum conditions in the injector linac [12]. A photoinjector linac must be bakeable in its entirety to about 200°C and be capable of maintaining a pressure below 10^{-9} torr, preferably 10^{-10} torr. If a Cs_3Sb photocathode is damaged in use, the damage can be erased by heating to 400°C, then a new one prepared *in situ*.

The spectral response [14] of Cs_3Sb extends from a quantum energy of 1.8 eV (λ = 690 nm) to energies greater than 3.8 eV (λ < 320 nm). Therefore, a Cs_3Sb photocathode can be used with a Nd:YAG laser with frequency doubled (λ = 532 nm) or tripled (λ = 355 nm). A Nd:YAG laser can readily be mode locked to deliver trains of 70-ps pulses at a microscopic repetition rate in a range from 50 to 120 MHz.

3.2. RF Gun Design

The thermal energy of the electrons as they leave the surface of the photoemitter is low. However, the transient forces to which an intense bunch is subjected as it emerges into a strong accelerating field are large and are comparable to the space-charge force.

Jones and Peter [15] have shown the importance of nonlinear forces in detailed simulation calculations of the transport of very short electron bunches in dc and rf fields. Emittance growth is minimized if at least two conditions are met: (1) the current density in the bunch is uniform and therefore the space-charge force is linear in the radial direction and (2) the cavity field (in the absence of space charge) is radially linear. The latter condition is satisfied if the cavity wall shape is given by

$$\rho^2 = 2[(\psi - \zeta)(1 - 2\mu) + \zeta^3/3 - \mu\zeta^2]/(\zeta - \mu) \; ,$$

where $\rho = r/z_0$, $\zeta = z/z_0$ $\psi = -\phi/E_0 z_0$, and ϕ is the electric potential; E_0 is the (axial) electric field at the origin ($r = 0$, $z = 0$). The radial electric field is given by $E_\rho = \rho(\zeta - \mu)$. The position at which the axial electric field vanishes for r =

0 is denoted by z_0, and μ is an arbitrary focusing parameter. For $0 < \mu < 0.5$, the radial electric field exerts a focusing force in the region $0 < z < \mu z_0$.

In a bunch of finite length, the electrons in the leading- and trailing-edge regions are acted upon by the large, nonlinear, transient longitudinal forces arising from the large rate of change in the total current. These forces lead to emittance growth that is reduced by using long pulses in which the hot end regions form a smaller fraction of the whole. The cavity walls near the beam axis are shaped according to the above equation for ρ^2. The focusing parameter μ was chosen to be 0.15, a value that gives minimum emittance growth [16], and the scaling parameter $z_0 = 4.0$ cm was used. The outer part of the rf gun cavity was shaped to maximize the cavity quality factor Q. Fig. 2 shows the rf gun cavity designed for an operating frequency of 1300 MHz. Plots of the radial electric field for different Z values obtained from the code SUPERFISH for a conventional high Q cavity and linear field cavity are shown in figs. 3 and 4, respectively. The specially designed cavity is much more linear than the corresponding fields in a more conventional rf cavity optimized for high shunt impedance.

3.3. Single-Cavity Experimental Results

Initial observation of the accelerated electron beam from the rf gun was obtained with the wall-current monitor shown in Fig. 1. With a fast oscilloscope, the largest pulse trains repeatedly observed had peak amplitudes of 4.4 V with 40 dB of attenuation in place. The measured bunch charge, obtained from the integrated pulse profiles, was 27 nC, giving an average current in the pulse train of 2.9 A. Assuming that the temporal profile was Gaussian (see below), the peak current was 390 A. The probable error in these measurements is ±20%.

The minimum laser pulse width observed was 53 ± 1 ps FWHM; on the same streak-camera sweep, the electron bunch widths were the same to within the experimental error when allowance was made for the observed 6% energy spread. We conclude, therefore, that for the present experimental conditions, the pulse broadening introduced by the Cs_3Sb photoemission is less than 2 ps.

The emittance of space-charge-dominated beams was measured with peak currents ranging from 100 to 150 A. Three measurement sets were made under various combinations of peak current and focusing strength in the first solenoid (table 1). The normalized emittance for 130 A peak was 20 π·mm·mrad. The corresponding normalized peak brightness was $\sim 4 \times 10^{10}$ A/(m^2·rad^2), and the average macropulse current was ~1.0 A. The estimated probable error on all these measurements is ±20%. No corrections have been made for space-charge effects. The beam energy measured on the double-focusing spectrometer agreed within 10% of the predicted value, 1.1 MeV. The measured energy spread was ±3%.

4. Two-Cavity Experiment

The second phase of this experimental program is to improve the vacuum conditions in the injector photocathode region and to study the effects of relative phasing using two rf cavities on the electron beam emittance. The new experimental configuration is shown in fig. 5. A new vacuum photocathode preparation unit and direct vacuum pumping on the rf cavities have been added. Also a second rf cavity, designed with linear radial electric fields, immediately follows the first cavity.

5. Conclusions

The photoinjector experiment demonstrated the predicted performance in yield and temporal response and exceeded expectations in current density and brightness. The temporal profile measurements prove that the emission time uncertainty is less than 10 ps. The two-cavity experiment has been assembled and is now being tested.

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Figure Captions

Fig. 1. Plan view of the photoinjector experiment.

Fig. 2. Profile of the linear-field rf gun cavity. The inner walls of the cavity (radius < 2 cm) are given by eq. (1) with $\psi = 0$ or 0.8, shown by dashed lines at large radii. The bore radius is 1.7 cm.

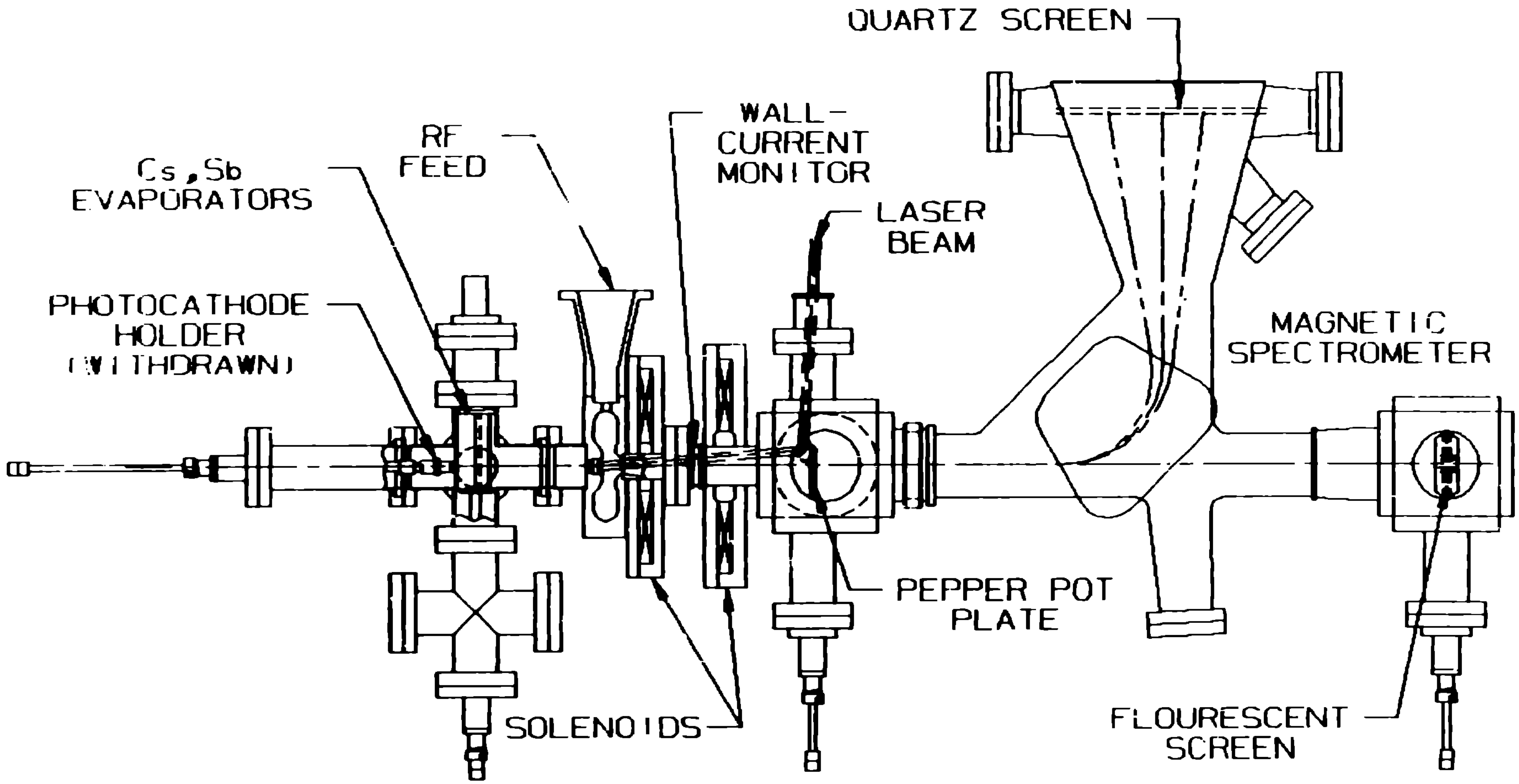
Fig. 3. The radial electric fields near the axis of a conventional rf accelerator cavity optimized for high shunt impedance (within the cross-hatched area of the insert.

Fig. 4. The radial fields near the axis of the rf gun cavity (within the cross-hatched area in the insert). The bore radius is 1.3 cm.

Fig. 5. Plan view of two-cavity photoinjector experiment.

Table 1
Emittance Measurements

Set	Peak Current (A)	Lens 1 Current (A)	Bunch Charge (nC)	x_m (mm)	x'_{m} (mrad)	Normalized Emittance ($\beta\gamma = 3.0$) (π·mm·mrad)	Normalized Brightness (A/(m^2·rad^2))
1	100	235	8	3.9	1.7	20	[illegible].5 × 10^{10}
2	150	310	12	7.5	1.4	32	1.4 × 10^{10}
3	130	314	10	3.9	1.5	18	4 × 10^{10}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SPECTROMETER
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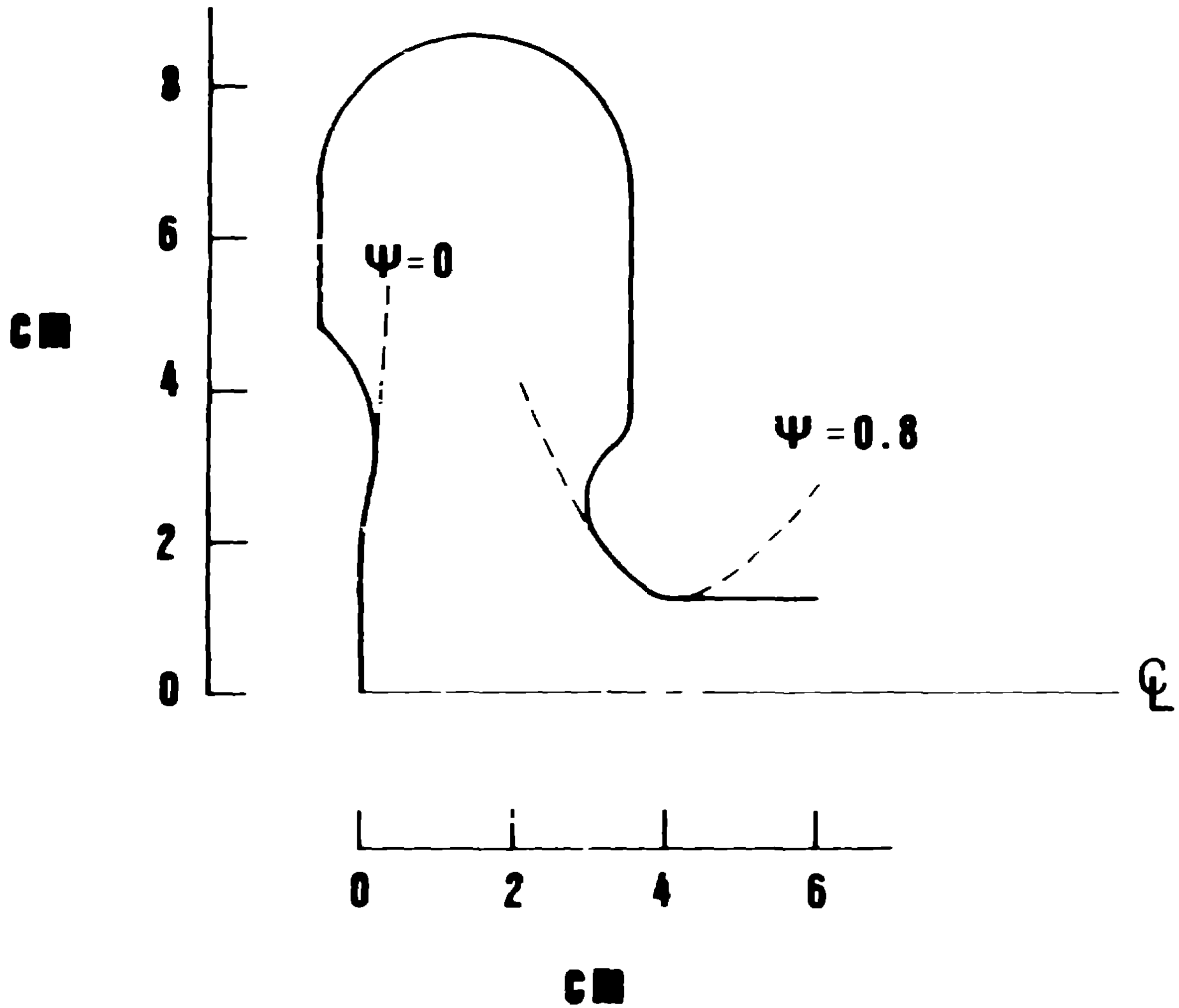
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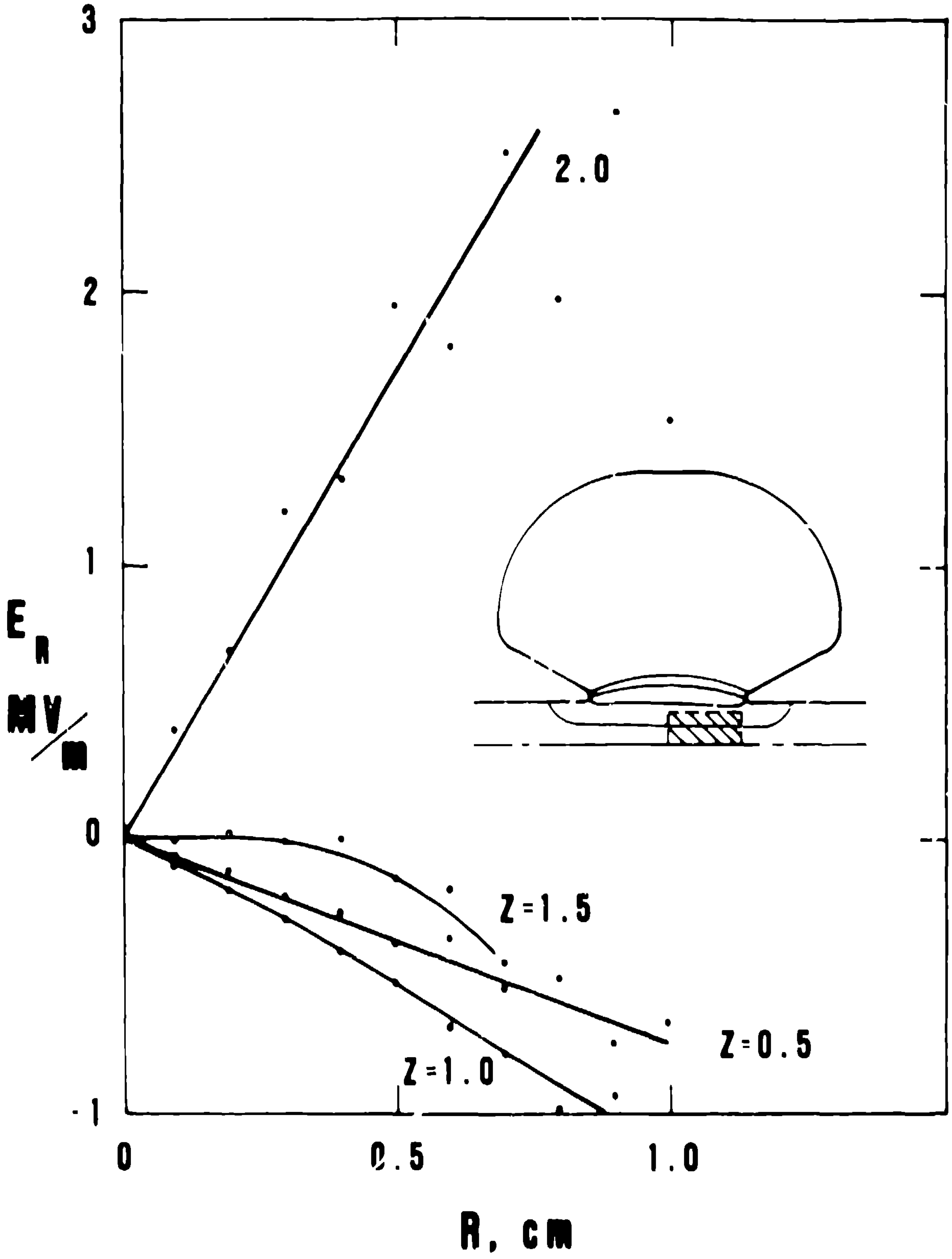

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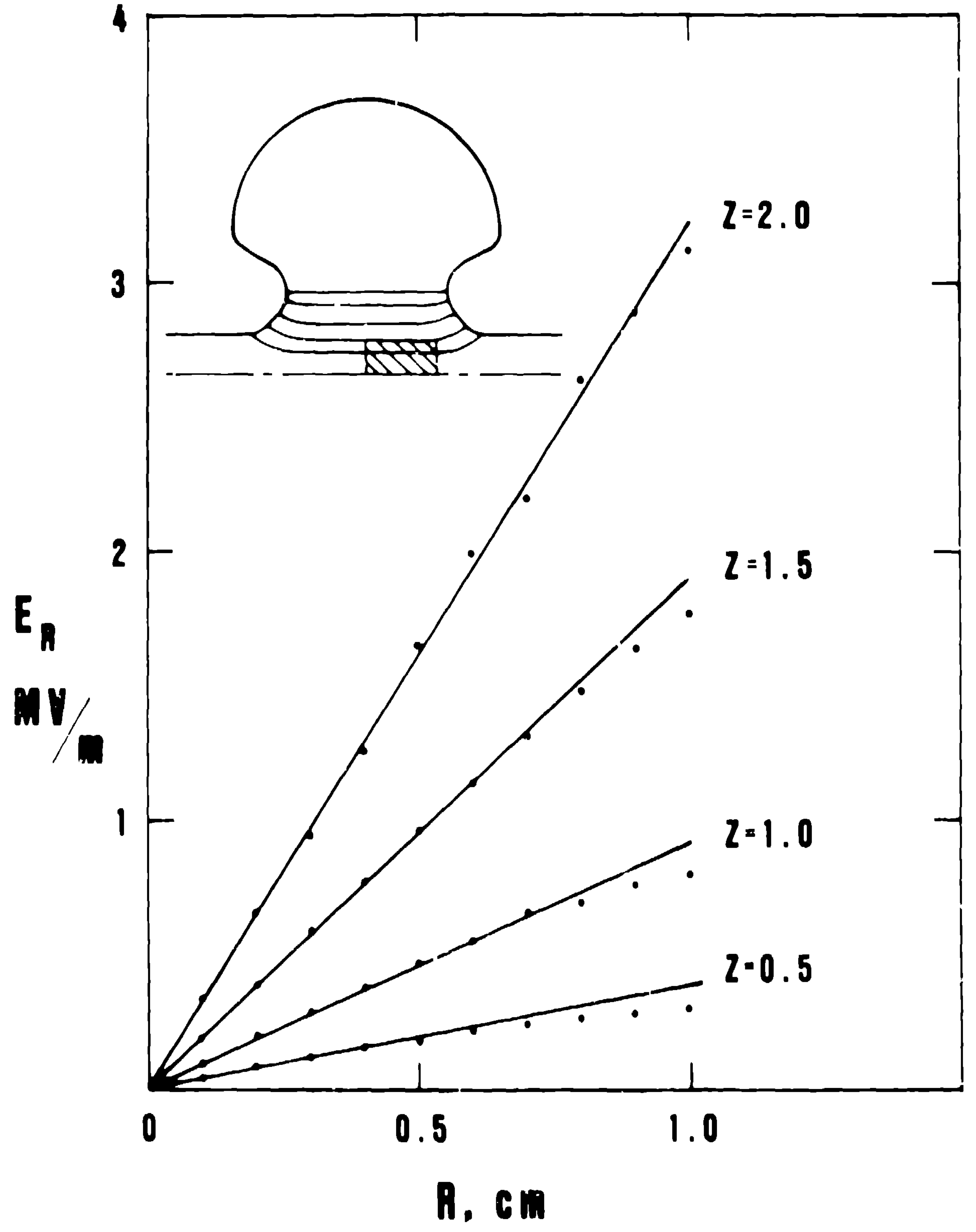
R, cm



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PHOTOINJECTOR TWO CAVITY EXPERIMENT