EMITTANCE DETERMINATION OF ELECTRON GUNS BY ANALYSIS OF BEAM PROFILE MEASUREMENTS

B. Strongin and A. Salop
Varian Associates Inc., 611 Hansen Way,
Palo Alto, CA 94303

Abstract

A method of analyzing beam profile data is used to determine the transverse emittance of electron guns used in microwave tubes and medical linacs. The emittance is obtained by fitting measured transverse beam profile data to a theoretical model which includes contributions from both emittance and space charge. The beam analyzer used for the measurements consists of a Faraday cup mounted on an XYZ translational stage, and allows both vertical and horizontal beam profiles to be measured as a function of the distance from the gun's anode. The data are then fit to a polynomial, and vertical and horizontal emittances are calculated.

Introduction

Knowledge of the gun emittance is important for optimizing accelerator performance as well as for realistic simulation of accelerators. Gun emittance measurements are usually accomplished by splitting the beam into many small "beamlets" with either pepper-pot targets or slits, and analyzing the angular divergence of the individual beamlets. In this paper we present a different method for the gun emittance measurements based on analyzing beam propagation in free space.

Method

Consider an electron beam propagating along the z-axis in a field-free drift region. The evolution of the beam envelope R as a function of z is described by the following differential equation[1]:

$$R''(z) = \frac{\varepsilon^2}{R^3(z)} + \frac{K}{R(z)}, \qquad (1)$$

where the derivative is with respect to z, ε is the transverse emittance, and K is the generalized perveance

$$K = \frac{I}{I_0}\frac{2}{\beta^3\gamma^3}. \qquad (2)$$

Here I is the beam current, I_0 is the critical current (I_0 = 17 kA for electrons), and β and γ are the usual relativistic parameters.

After one integration over z Eq. 1 becomes

$$R'(z) = [(R_0')^2 + 2K \ln\frac{R(z)}{R_0} + \varepsilon^2(\frac{1}{R_0^2} - \frac{1}{R(z)^2})]^{1/2} \qquad (3)$$

where $R_0 = R(z_0)$ and $R'_0 = R'(z_0)$ are the initial conditions at $z = z_0$. To simplify Eq. 3 one may choose z_0 to be the location of the beam waist in which case $R_0' = 0$. Then one obtains the following expression for the emittance:

$$\varepsilon^2(z) = \frac{(R'(z))^2 - 2K \ln\frac{R(z)}{R_0}}{\frac{1}{R_0^2} - \frac{1}{R^2(z)}} \qquad (4)$$

A second integration yields the following implicit relationship between R and z:

$$z - z_0 = \int_{R_0}^{R} [(R_0')^2 + \varepsilon^2(\frac{1}{R_0^2} - \frac{1}{R^2}) + 2K \ln\frac{R}{R_0}]^{-1/2}\, dR \qquad (5)$$

To obtain emittance values from Eq. 4 a polynomial function was fit to the experimental values R(z). This allowed R'(z) and R_0, and finally $\varepsilon(z)$ to be determined.

In the second approach a least squares minimization procedure was used to find the emittance value which gave the best fit of the theoretical relation of Eq. 5 to a polynomial function representing the beam profile data R(z). In both approaches the vertical and horizontal emittances were determined separately.

The beam profile data used in this analysis were provided to us by the Varian Microwave Tube Division[2]. The beam current was measured by a beam analyzer consisting of a Faraday cup mounted on an X-Y-Z translational stage. The cup diameter as well as positioning accuracy of the stages was about 0.05 mm. The system was evacuated to 10^{-8} Torr, and no magnetic field was present.

To derive the effective beam size from the current profile data $J(\xi,z)$ we used the following definition[1,3]:

$$R^2(z) = 4\frac{\int \xi^2 J(\xi,z)d\xi}{\int J(\xi,z)d\xi} \qquad (6)$$

Here ξ is either the horizontal or the vertical coordinate. This definition of R(z) is consistent with the definition of effective emittance being four times the r.m.s. emittance.

Results

The emittances of two different guns were determined using the two approaches described above: one is a diode gun for microwave tubes, and the other is a gridded gun for medical accelerators. The two guns were tested under different operating conditions: the anode voltage for the diode gun was 20 kV with the cathode current of 127 mA; the voltage of the gridded gun was 6 kV, and the cathode current was 93 mA. In both cases we found that the Debye length $\lambda_D = (\varepsilon_0 kT/e^2 n)^{1/2} << R_{beam}$, and therefore the space charge effects are important. Figs. 1 and 2 show beam radii for the diode and the gridded gun respectively, points with errors represent data, and the smooth lines represent the fit polynomials. Fig. 3 and 4 show horizontal (unnormalized) emittances for the diode and the gridded gun respectively as functions of z, these emittances were calculated using Eq. 4. Fig. 5 shows the best fit of the theoretical relation of Eq. 5 to the polynomial representation of the beam radius data for the diode gun and lists the value of ε corresponding to the best fit. The two other curves show the deviations of the theory from the polynomial representation for an emittance value 20% higher and 20% smaller than the best fit value. Fig. 6 is a similar presentation for the gridded gun. These figures give an indication of the resolution of the matching technique.

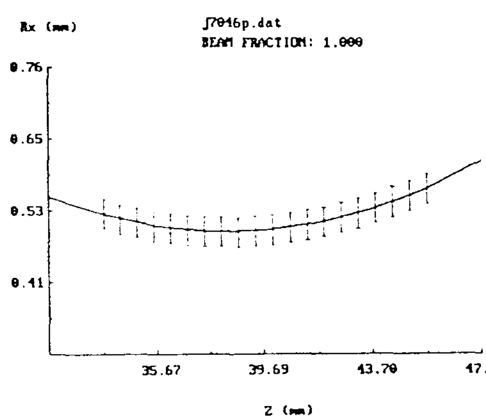

Fig. 1. Beam profiles for the diode gun. Points with error bars represent data, the solid line is the fit polynomial.

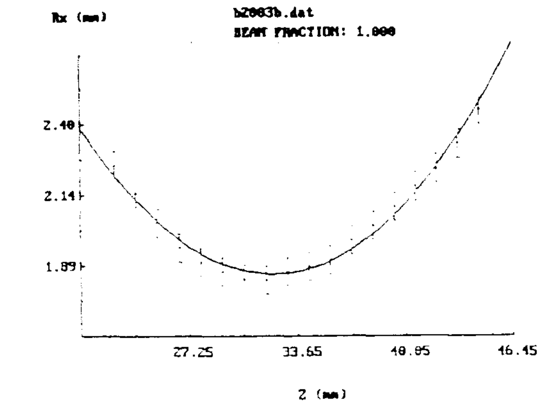

Fig. 2. Beam profiles for the gridded gun. Points with error bars represent data, the solid line is the fit polynomial.

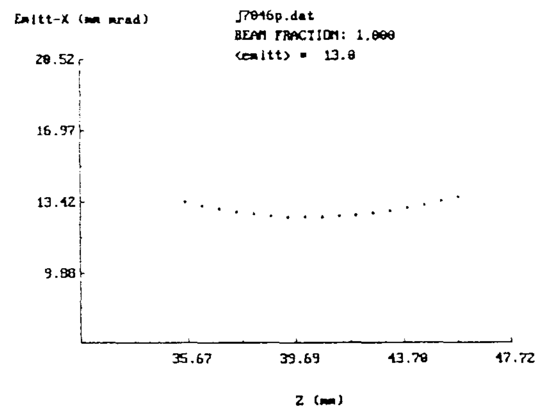

Fig. 3. Emittance of the diode gun as a function of z.

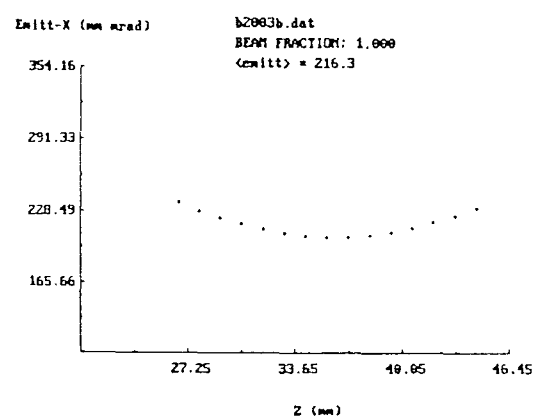

Fig. 4. Emittance of the gridded gun as a function of z.

The results obtained with the point-to-point calculation based on Eq.4, and the fit results from Eq. 5 are summarized in Table 1 which shows normalized emittances $\varepsilon_{norm} = \varepsilon\beta\gamma$ for both guns. For the point-to-point technique the average values are quoted. Also included in Table 1 are the calculated values of the normalized thermal emittance for each gun given by $\varepsilon_{therm} = 2R_c\sqrt{\frac{kT}{m_0c^2}}$, where R_c is the cathode radius, and T is the temperature.

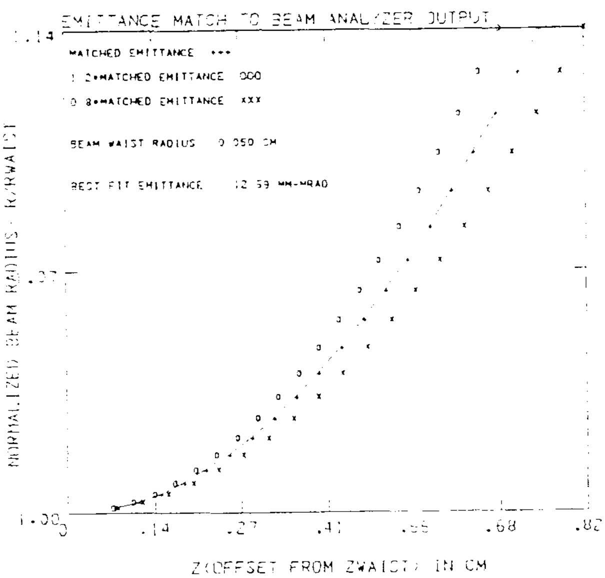

Fig. 5. Emittance determination by a match of theoretical relation (Eq. 5) to a polynomial representation of beam radius data (continuous curve) for the diode gun.

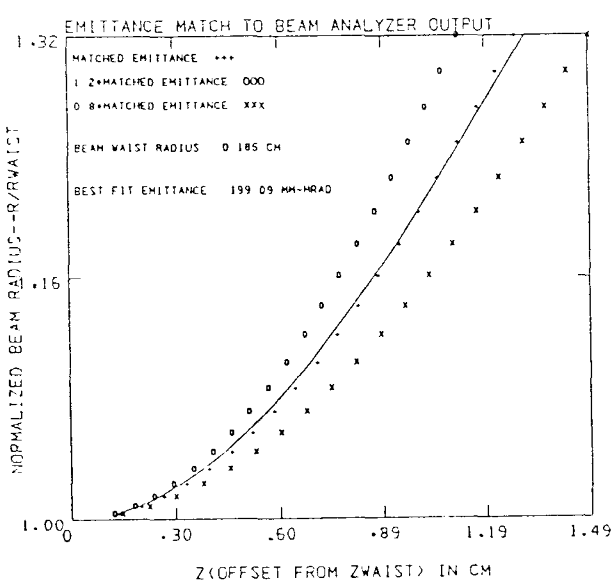

Fig.6. Emittance determination by a match of theoretical relation (Eq.5) to a polynomial representation of beam radius data (continuous curve) for the gridded gun.

TABLE 1.

Normalized emittance values.

	Diode Gun (mm mrad)		Gridded (mm mrad)	
	point	integr.	point	integr.
$<\varepsilon_x>$	3.67	3.56	33.24	30.40
$<\varepsilon_y>$	3.93	3.83	34.75	32.23
ε_{therm}	2.42		4.85	

These results suggest that the emittance of the diode gun is close to its theoretical lower limit, indicating a relatively small emittance growth in the beam as it traverses the drift region after the anode. In contrast the emittance of the gridded gun appears to be about a factor of six or seven larger than the thermal emittance, which may be attributed to the field inhomogeneities and scattering effects introduced by the grid.

Conclusions

The method presented here allows relatively quick and easy measurements of electron gun emittance using existing conventional beam analyzers without any additional hardware.

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3. P.M. Lapostolle, IEEE Trans. Nucl. Sci. NS-18, 1101 (1971).