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Field-Emission Arrays — A Potentially Bright Source

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Field-Emission arrays are potentially a compact and bright electron source. Unlike a laser photocathode, external laser systems are not required. It is possible to have spatial control of the cathode emission. Temporal modulation up to 10 GHz may be possible. We estimate the emittance and brightness based on a reasonable FEA design. Since the FEAs are at an early stage of development for accelerator applications, many technical problems need to be addressed before they can become useful cathodes.

At the Naval Research Laboratory (NRL), we are developing the field-effect controlled (FEC) vacuum field-emission cathode, which is designed to improve the performance of field-emission arrays and to enable the success of envisioned applications of these vacuum field-emitters.

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I. Introduction

Free electron lasers (FELs) place very stringent requirements on the quality of the electron beam, i.e., low emittance, high current density and small energy spread. If the beam transport is properly designed, emittance is determined by the cathode. Recent efforts in improving the beam quality of the cathode have concentrated on the approach of the laser photocathode, which has high emission current density and good emittance. Field-emission arrays (FEAs) are emerging as a competitive cathode. In the past, developments of FEAs concentrated on applications for flat panel displays, electronics and CRTs. Researchers are beginning to address the physical issues of applying the FEAs to accelerators. Vacuum field-emitters such as the FEAs are versatile electron sources with the potential of producing bright beams in a compact system.

Vacuum field-emitters come in a wide range of configurations: cones[1-5], ridges[5], edges[5], etc. They are fabricated by a wide range of methods also. There are gated and ungated cathodes. The emission process of gated field-emission cathodes can be turned on and off by a low voltage. Figure 1 is a schematic of one type of gated FEA. A control (or grid) electrode is positioned very close to the emitting cone. The field at the tip of the cone is enhanced to cause the electrons to emit. The emission process usually can be described by the Fowler-Nordheim cold field-emission model.[6] The emitted electrons are then accelerated to the anode by the applied anode voltage. Ungated FEAs[4] do not have the control electrode. Thus, a large anode voltage is required to provide a necessary electric field at the emitter tip for emission. For many accelerators, gated FEAs may have more potential applications.

The most advanced and successful of the vacuum field-emitters is the metal (molybdenum) cone type FEAs pioneered by C. A. Spindt, et al.[1,3] These types of FEAs are also commonly called the "Spindt" cathodes, or thin film field-emission cathodes. In order to enable low control voltage for extraction, the control electrode is positioned approximately 0.5 μm from the emitting tip. FEAs with tip separation as close as 2 μm have been fabricated and have emitted. Emission current of up to 100 μA per tip was achieved. Current density of 1 kA/cm^2 has been demonstrated on small area arrays. This is the highest measured current density among all vacuum field-emitters.

Silicon cones are also beginning to produce good results.[2] Emission current of up to 50

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μA per tip has been measured. The control (or grid) electrode is positioned approximately 1 μm from the emitting surface and the tip separation is 4 μm.

Research efforts for cathode applications of FEAs in accelerators are beginning to be addressed. Methods of fabricating FEAs capable of modulating (or gating) the electron beam emission up to 10 GHz are being investigated by many institutions, such as SRI International, Naval Research Laboratory, MCNC Center for Microelectronics, Raytheon, etc. This paper will address the beam brightness calculations and methods to improve the quality of emission and will point out issues that are currently under investigation. Serious research efforts in applying the FEAs for accelerators, FELs and gyrotrons are also being performed at the Japan Atomic Energy Research Institute (JAERI).[7]

II. Emittance Calculation

In order to evaluate the beam quality of FEAs, one needs to understand the emission process. Cold field–emission by electron tunnelling through a 1–dimensional work function in an electric field was analyzed by Fowler and Nordheim quantum mechanically.[6] The resultant Fowler–Nordheim equation is

$$J = AE^2 \exp(-B\phi^{3/2}/E), \tag{1}$$

where $J(\mathrm{A/cm^2})$ is the current density, $E(\mathrm{V/cm})$ is the electric field at the surface, $\phi(\mathrm{V})$ is the work function of the surface, and A and B are constants related to the material properties. Fowler–Nordheim emission turns on sharply and the current rises sharply. The Fowler–Nordheim emission model has been incorporated into various field solver codes such as EGUN2,[8] MAGIC[9,10] and FEAT.[11]

However, the Fowler–Nordheim relation is only valid for blunt tips. Field–emission from very fine tips, on the order of a few Å, is completely different.[12] Emission physics from tips of intermediate tip sizes may also require correction factors to the Fowler–Nordheim equation.[13] Currently, only the Fowler–Nordheim emission model is available for implementation in a field solver code. All the above codes are currently under modification to include more of the physics. They might not give us the exact solutions, but they are good zeroth order estimates.

Since the FEA structures are very small, precise measurements of the structure parameters are either very difficult or nonexistent for the structures described here. Available measurements of tip radius, tip height, cone angle, etc., are approximate. For low and intermediate current density emissions, Zaidman[9] was able to match the experimentally measured current, obtained by Phillips[14] from a thousand tip FEA produced by Spindt, to currents calculated from the MAGIC code by making small variations of configuration parameters about the approximate measured configuration. They found that space charge is not as important a factor for the emission process as expected. For low and intermediate current density emission, a numerical code with Fowler–Nordheim field–emission model provides a zeroth order approximation.

For very high current emissions, however, it was not possible to obtain the correct current from the computer code using a Fowler–Nordheim emission model with the approximate measured parameters unless whiskers (or bumps) with radii of a few Å were introduced.[8] The small whiskers model may not be appropriate for high current emission from the "Spindt" cathodes. Instead, it may be necessary to consider the correction factors[13] to the Fowler–Nordheim model for tips with radii of curvature on the order of 100 Å. The emission process from small (few Å radius) whiskers[12] is also completely different from that of the Fowler–Nordheim model. In addition, no existing code can handle more than one whisker on axis on the emitter cone.

For this paper we will consider low to intermediate emissions from tips with 150–200 Å radius of curvature using the code EGUN2. We benchmark the EGUN2 code with that of the published results of the MAGIC code.[9] For the examples compared, the emission current from EGUN2 is about a factor of 2 larger than that in Ref. 9. This is not a very large discrepancy because the Fowler–Nordheim emission is extremely sensitive to the numerically obtained electric field. Slightly different expressions for A and B in Eq. (1) are used by the two codes. For EGUN2, they are: $A = (1.5 \times 10^{-6}/\phi)e^{(10.4/\sqrt{\phi})}$ and $B = 6.44 \times 10^{-7}$. Another main difference is the boundary conditions chosen for the outer radial wall, which is taken to be a field line in EGUN2. The variation in emittance is much less than the variation in emission current for similar configurations. This concept is verified by a range of examples simulated on EGUN2.

We present the configuration with tip radius of 150 Å, tip height of 1.25 μm, grid hole radius of 0.55 μm, tip half-angle of 15°, work function ϕ of 4.35 Volts, grid thickness of 0.3 μm, applied grid voltage of 140 Volts and anode voltage of 155 Volts at about 4 μm from the grid. The electron trajectories are shown in Fig. 2. The emission current I_1 is 10 μA and 90% of the emitted current are represented by the 11 center rays.

Normalized emittance ϵ_n for a single emitting tip can be calculated, where x is the transverse electron position and $\theta \simeq v_x/v_z$ is the angle of the electron trajectory with the axis in radians. In the paraxial limit, $\pi\epsilon_n$ is defined as the phase space area occupied by $(\beta\gamma\theta, x)$. The paraxial limit can be obtained when the electrons are propagated further in a uniform accelerating field. The emittance diagram for axially symmetric emitter tips generally looks like Fig. 3. The shape of the curved boundary is a function of tip geometry. In this case, we analytically propagated the electrons for 1 mm with 3636 Volts giving $\beta\gamma = 0.124$. The analytical propagation gives: $\beta\gamma\theta = 0.0154$ rad and $x = 220$ μm for the 90% ray.

The emittance from a single tip is excellent, but the current is too small for accelerator applications. Arrays of tips are necessary. A packing density of up to 1.5×10^7 tips/cm^2 has been achieved. The emittance diagram at the cathode for a $m \times m$ array is shown in Fig. 4. The total emittance in the shaded area is conserved. The practical definition of emittance in applications, however, is the area within the dashed curve, which is also a conserved quantity when space charge effects are absent.

Here, we derive the evolution of the effective emittance without focusing or space charge effects. We allow the electrons to accelerate in an axial uniform electric field:

$$\frac{dp_x}{dt} = 0, \tag{2a}$$

and

$$\frac{dp_z}{dt} = e\frac{d\varphi}{dz}, \tag{2b}$$

where p_x and p_z are the transverse and axial momenta, φ is the axial accelerating potential and e is the charge. We obtain

$$\beta\gamma\theta = \frac{C_0}{c}\left(\frac{2\Phi + \Phi^2}{2\Phi + \Phi^2 + D_0}\right)^{1/2}, \tag{3}$$

$$\Delta x = x - x_0 = \frac{C_0}{c}\int_{z_0}^{z}\left[2\Phi + \Phi^2 + D_0\right]^{-1/2} dz', \tag{4}$$

where $\Phi = (e/m_0c^2)\varphi(z)$, c is the speed of light, $C_0 = \gamma_0 v_{x,0}$, $D_0 = (\gamma_0 v_{z,0})^2$, x_0, $v_{x,0}$ $v_{z,0}$ and γ_0 are the initial conditions for x, v_x, v_z and γ at z_0 and c is the speed of light. Since

$D_0/(2\Phi + \Phi^2) << 1$ is true soon after leaving the cathode,

$$\beta\gamma\theta \simeq \gamma_0 v_{x,0}/c. \tag{5}$$

However, the x position of the particle continues to increase. Thus, the shape of the effective emittance in Fig. 4 becomes stretched more and more in the x–direction as axial distance increases. However, the effective area in the phase space diagram remains constant and the normalized emittance without space charge effects is

$$\epsilon_n \simeq (m\delta x)(2\Theta)/\pi, \tag{6}$$

where δx is the tip separation and $\Theta = \gamma_0 v_{x,0}/c|_{90\%}$ is a constant.

The normalized emittance can be reduced by improving the parameter Θ with the incorporation of electrostatic lenses near the tip of the emitter.[8] One such lens is shown in Fig. 5, where the design of the lens has not been optimized. There is already an approximate improvement of a factor of 5 for the emission angle Θ. However, the application of electrostatic lenses might reduce the emission current.

As the beamlet mix, the shaded area in Fig. 4 becomes distorted due to space charge effects. In addition, space charge effects cause distortion of the dashed curve in Fig. 4 and emittance growth. The application of electrostatic and/or magnetic focusing will be necessary to prevent emittance growth. The application of focusing should start as close to the cathode as possible.

A common measure of beam quality is the normalized brightness

$$B_n = 2I/\pi^2\epsilon_n^2. \tag{7}$$

For the $m \times m$ array, the current $I = m^2 I_1$, where I_1 is the current per tip. Brightness can be rewritten as

$$B_n \simeq I_1/2(\delta x\Theta)^2. \tag{8}$$

For the non–optimized example given by the parameters associated with Fig. 2, the beam brightness is 3.2×10^9 A/(m–rad)^2. Since current density about a magnitude larger has been observed, beam brightness can at least be $B_n \simeq 3.2 \times 10^{10}$ A/(m–rad)^2. Assuming focusing lenses can be fabricated at the emitter, the brightness, without current loss, can be as large as $B_n \simeq 8 \times 10^{11}$ A/(m–rad)^2.

Now we compare the laser photocathode to the field–emission arrays. The laser photocathode is at a fairly advanced stage of development. Beam brightness at the cathode of 2×10^{12} A/(m–rad)^2 was calculated.[15] The temporal structure of the drive laser is flexible. For example, pico–second laser pulses with the appropriate rf frequency to match the rf accelerator parameters have been used. The disadvantages of the laser photocathode are i) the requirement of a drive laser system and ii) the inability to have complete control of the transverse current profile from the surface of the cathode, such as a step current density profile.

The FEAs probably will not be as bright as the laser photocathode and are still at an early stage of development for accelerator applications. However, they can be compact and do not require a drive laser. It is possible to introduce spatial control. Step function, Gaussian or other transverse current density profiles from the FEA may be produced. Research on temporal modulation up to 10 GHz is currently being conducted.

At NRL, we propose to improve the performance of the field-emitters.[16] The primary advantages of this type of gated cathodes are: i) the current from the emitting tips can be limited to prevent breakdown, ii) the current can be modulated, iii) the gate control voltage is approximately one Volt, iv) external modulation frequency can be high, v) emission is made uniform via current saturation of the emitting tips and vi) spatial modulation of the beam profile.

III. Summary

Free electron lasers are progressing towards compact accelerators with high brightness. The field–emission arrays have the potential of satisfying both the compactness and the high brightness criteria. The FEC cathodes under development at NRL are designed to improve the performance of the gated FEAs.

An additional major accelerator issue requiring research is the prevention of arcing in a high voltage environment. Fabrication techniques are being evaluated for this purpose. For low emission current and low acceleration voltage, lifetime tests have shown FEAs to last for more than one and a half years.

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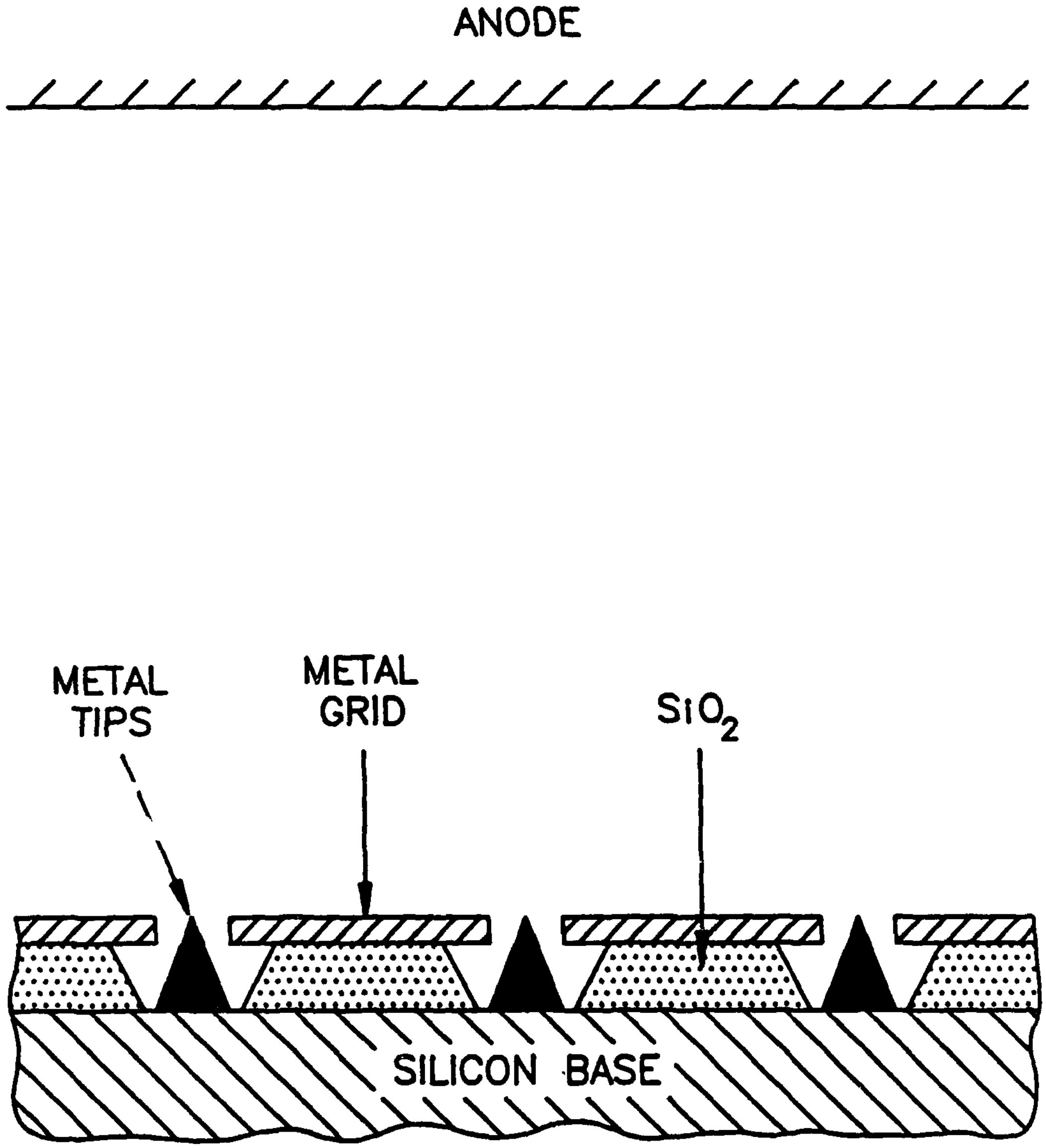

Fig. 1. A schematic of a cone type of gated field-emitter.

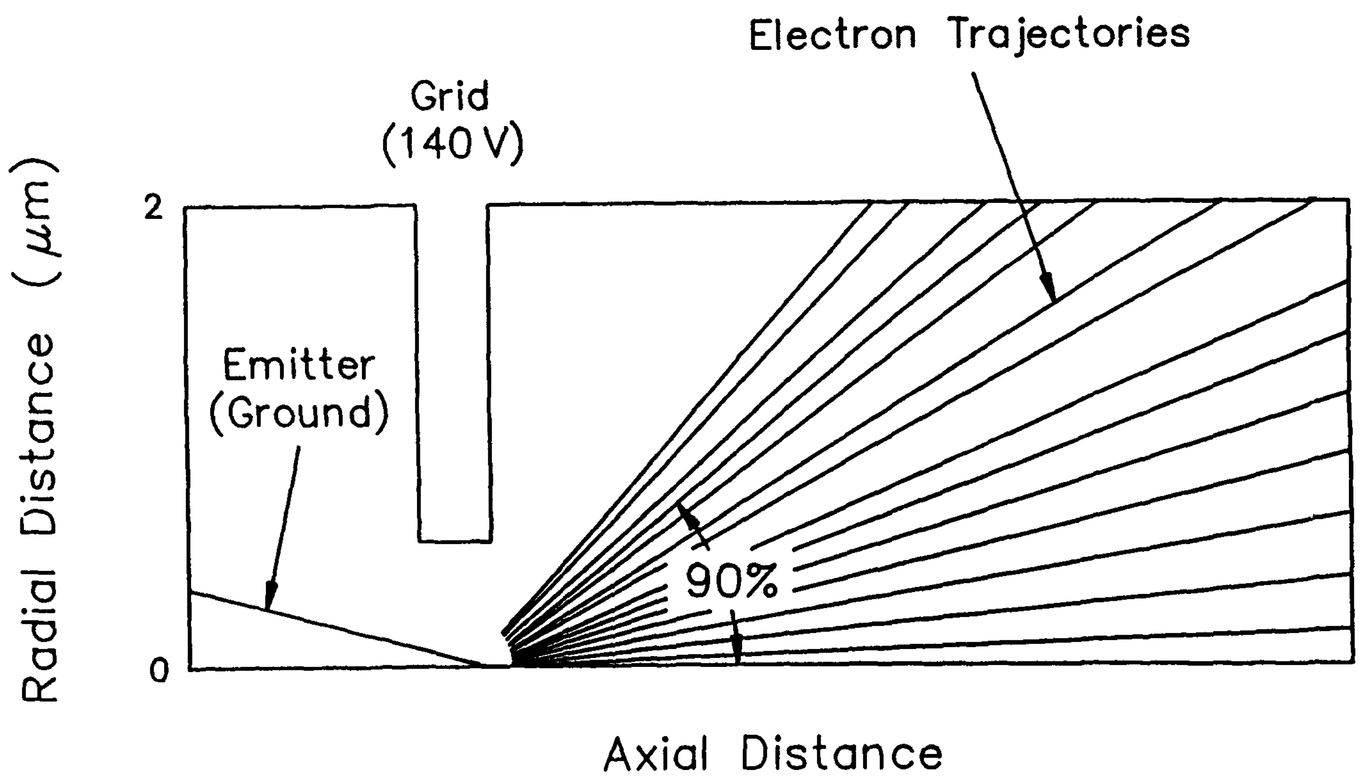

Fig. 2. Electron trajectories from a cone type of gated field-emitter.

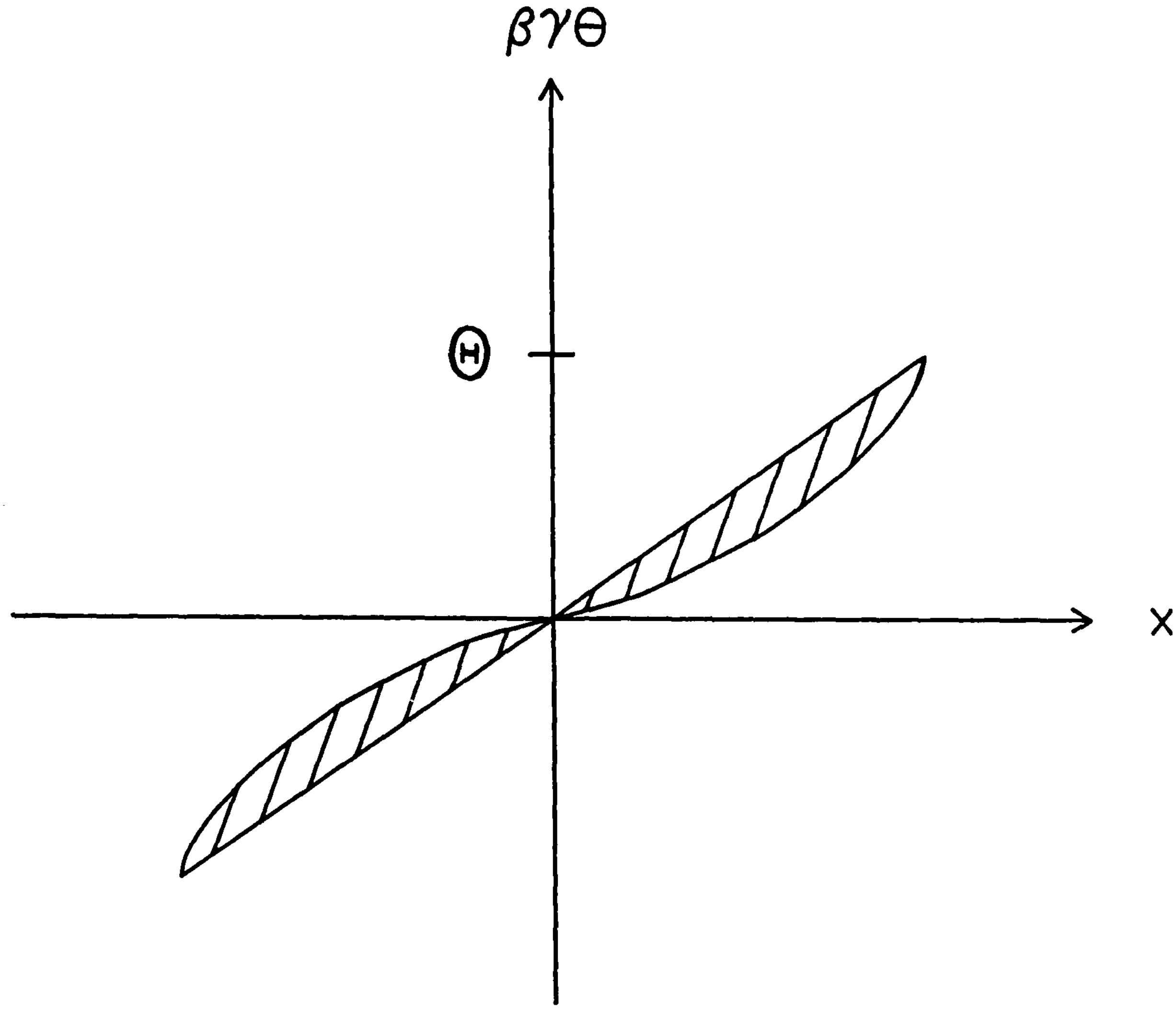

Fig. 3. Emittance diagram associated with emission from a single emitter tip.

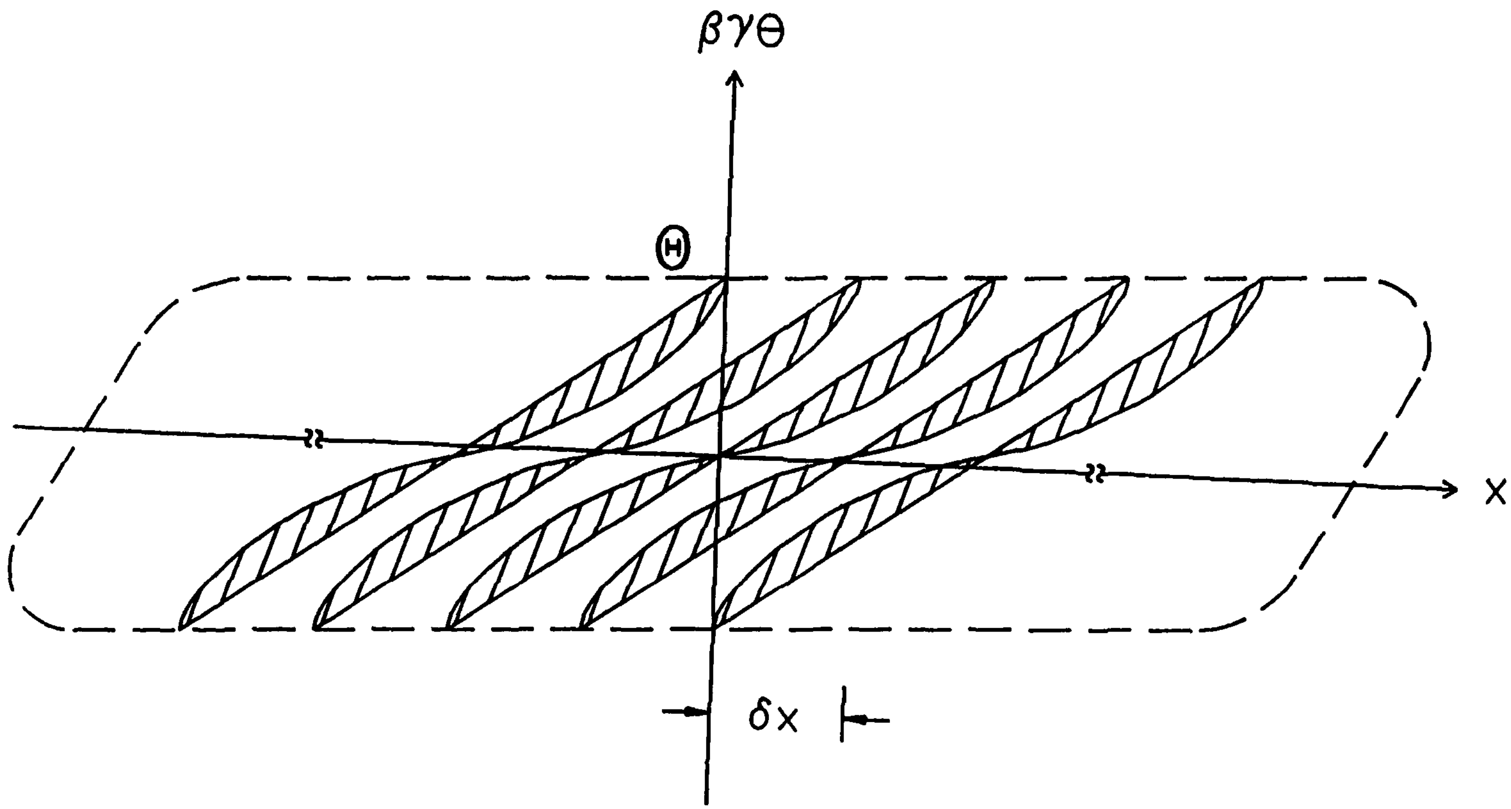

Fig. 4. Emittance diagram associated with emission from an array of emitters. The effective emittance is enclosed by the dashed curve.

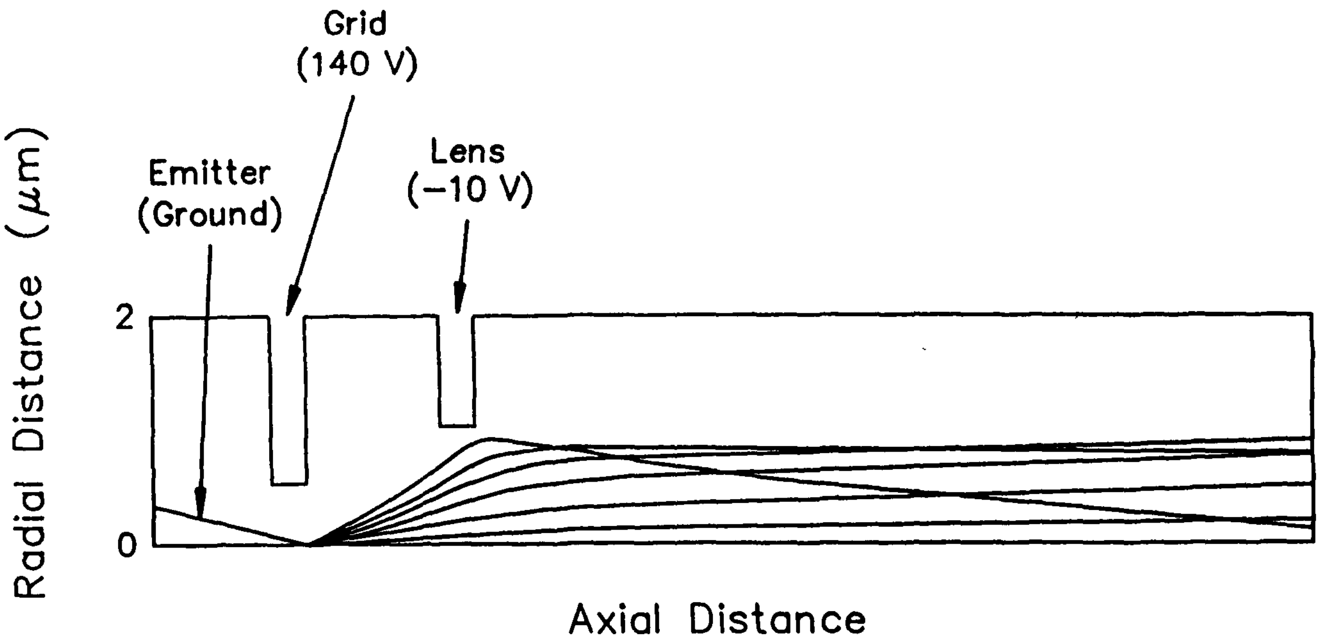

Fig. 5. Electron trajectories from a cone type of gated field–emitter with an electrostatic lens at the emitter tip.