Ultrahigh-Brightness Microbeams: Considerations for Their Generation and Relevance to FEL

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Abstract

Field-emission tips have ever been the brightest electron source, but the current of focused beams from them has been very low. A substantial improvement in beam intensity and brightness is expected with the use of a microfabricated gated-emitter which produces a parallel beam near the emitter. A high-gradient accelerating field suppresses large displacement of electrons from the beam axis and thus reduces the emittance growth due to aberration. The emission is typically 100 μA per tip, while higher currents are generated by tightly-packed arrays of the gated-emitters. The attainable normalized brightness is estimated to exceed 10^{13} A/m^{2}rad^2, and such beams have unique uses for extending the laser wavelength to the X-ray region at moderate beam energies.

INTRODUCTION

The free-electron laser (FEL) performance is remarkably affected by the characteristics of driving beams. The radiation wavelength is fundamentally limited by the beam emittance by the relationship $\lambda \geq \pi\varepsilon$, and the growth rate is an increasing function of the beam brightness. The requirements for good beam quality are especially stringent with compact FELs, that employ low-energy electron beams and short-period wigglers [1,2]. The beam quality deteriorates with propagation, and therefore the high source brightness is one of the key issues in obtaining a bright beam. So far the major effort has been directed to the development of photocathode combined with RF linac, and brightness of 8 x 10^{11}A/m^{2}rad^2 has been reached [3].

With regard to current density, field emission is superior to the photoemission by orders of magnitude. Due to their high brightness, field emission tips have been commonly used in electron microscopy and electron-beam lithography. On the other hand the microfabrication technology has been applied to produce a gated field-emitter tip structure with submicrometer dimensions. Techniques for fabricating arrays of such emitters have also been established. Emission current densities of up to 1 kA/cm^2 have been demonstrated on small area arrays.

Those microemitters have been developed to meet the requirements of vacuum microelectronics: cold emission, low voltage operation, high current density, small size, high-frequency response and uniformity of emission. Application of microemitters to FEL has recently been proposed [5,6] in the light of their advantages.

FIELD-EMISSION SOURCES

The electron emission from a tip is characterized by a high current density, small emitting area and large divergence angle (≈ 0.3 rad). The curent density given by the Fowler-Nordheim equation well exceeds 10^7 A/cm^2 for an electrtic field of 10^8 V /cm at the surface and a work function of 4 eV. The average thermal energy of emitted electrons is calculated to be 0.6 eV for the same parameters. The emitting area is of the order of 10 nm in radius when drawing 10 - 100 μA. The normalized intrinsic emittance and source brightness are then of the order of 10^{-11} m rad and $10^{14\text{-}15}$ A/m^{2}rad^2, respectively, though the details of the emission from a fine tip has not been clarified yet [7]. For conventional microbeams, up to 1 mA can be emitted from a single tip but the current at a focal spot is typically of the order of 10 nA. The reasons for this reduction are: 1) the beam spreads out quickly due to the initial angle, 2) the diversion is enhanced by the space-charge and 3) the beam is scraped by apertures placed in the lens system. The aperture system is designed to minimize the focal spot size, discarding electrons with high angular divergence or electrons with high displacement. In order to increase the current of a focused beam, therefore, one must keep the beam paraxial all through the system that includes the source and accelerator. The strategy is discussed in the next sectoin.

ACCELERATION OF A MICROBEAM FROM A GATED FIELD-EMITSSION TIP

High-Gradient Acceleration

The basic features of beam behavior are described by a paraxial envelope equation for the K-V distribution [8]

$$a'' + \frac{\gamma' a'}{\beta^2\gamma} + \left(\frac{\gamma''}{2\beta^2\gamma} + \frac{\Omega_L^2}{\beta^2 c^2}\right) a - \frac{K}{a} - \frac{\varepsilon_n^2}{\beta^2\gamma^2}\frac{1}{a^3} = 0 \qquad (1)$$

where a is the beam radius, ' indicates the derivative with respect to axial position z, β and γ are conventional relativistic notations, c is the speed of light, Ω_L the relativistic Larmor frequency, ε_n the normalized emittance, and $K = 2I / \beta^3\gamma^3 I_0$ represents the space-charge of the beam current I in terms of I_0 =17 kA. Equation (1) shows that the acceleration γ' has a focusing effect on a diverging beam. This effect is specially important at the early stage of acceleratin where β is small and the space-charge causes the main problem. With conventional field-emitters the electric field is strong only on

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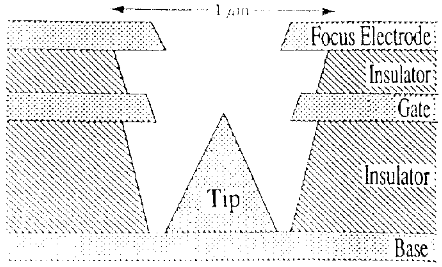

Fig. 1. Microemitter with a focusing electrode.

and around the tip. In gated microemitters as shown in Fig. 1, a gate (grid) is located close to the tip and provides a boundary beyond which an intense electric field can be present. In the following we assume a uniform accelerating field ($\gamma'' = 0$) of up to 4 MV/m, which is practical even in d c mode.

Electrostatic Pre-Focusing at the Source

As proposed by Spindt [7], additon of a focusing electrode to the emiter enables the formation of a parallel beam near the tip. Computer simulation has demonstrated that the radius and divergence angle at 1 keV energy can be as small as 3 μm and 5 mrad, respectively, in the presence of an accelerating field of 4 MV/m [9]. The phase plot is distorted due to the spherical aberration of the lens, but the effective normalized emittance is evaluated to be a few times 10^{-10}m rad for a 10 μA beam.

After leaving the source the beam radius increases with axial distance. Solving eq. (1) numerically for $\gamma'' = \Omega_L = 0$, we plot in Fig. 2 the beam radius at 10 keV vs the beam current. The initial values (at 1 keV) of a and a' are 3 μm and 5 mrad, respectively, and the axial electric field and normalized emittance are the parameters. The focusing effect of the axial electric field is clearly seen. The six curves in each group are, from the bottom to the top, for $\varepsilon_n = 0$ to 10^{-9} m rad at an interval of 2 x 10^{-10} m rad. Note that the beam radius is insensitive to both the emittance and the beam current when E_z is high; a $\leq$ 10 μm for $I_b \leq 100$ μA and $E_z \geq 4$ MV/m.

Magnetic Pre-Focusing near the Source

A magnetic field can be utilized, instead of the electrostatic lens, to suppress the divergence of microbeams. An immersed cathode has already been a practical option for enhancing the brightness of microbeams in the submicroampere range [10]. In the presence of a strong accelerating field, much higher currents can be confined by the axial magnetic field.

A field-emission tip is assumed to be located at z = o in a magnetic field given by a vector potential

$$A_\theta = \frac{r}{2} B_0 \left(1 - \frac{1}{8}\frac{r^2}{z_b^2}\right) \exp(-z/z_b) - \frac{r}{2} B_1 \qquad (2)$$

where r is the radial variable. In Fig. 3a is shown the on-axis field B_z for $B_0 = 3$ kG, $B_1 = 1$ kG and $z_b = 4$ cm. The equations of motion, including the self-field term of uniform beam, were solved for electrons leaving the tip of 10 nm radius under the following conditions at 100 eV energy: beam radius 500 nm, divergence 0.3 rad, and the spread in transverse energy 0.6 eV. Formation of a nearly parallel beam is shown in Fig. 3b for a 10 μA beam and $E_z = 4$ MV/m (the electron energy is 400 keV at z = 10 cm). When increasing the current to 100 μA, the maximum radius becomes slightly larger than 0.1 mm.

The initial value of the canonical angular momentum is small because of smallness of the source. If the magnetic field is not reversed as in Fig. 3a, the beam converges to a spot and crossover appears. The magnetic cusp was introduced to avoid this and produce a Brillouin-like flow. The emittance diagram computed at different axial positions did not show significant distortions due to the spherical aberration.

Emittance Preservation during acceleration

The pre-focused beams are accelerated to higher energies by a uniform electric field. In Fig. 4 are plotted the radius and divergence angle as functions of axial position z. Here 10 μA and 100 μA beams from the emitter with a focusing electrode are accelerated to 10 MeV. No lens is assumed outside the emitter, and so γ'' and Ω_L are put to 0 in eq. (1). The effect of emittance on the beam dynamics is negligibly small. In the accelerator the the emittance is preserved because the space

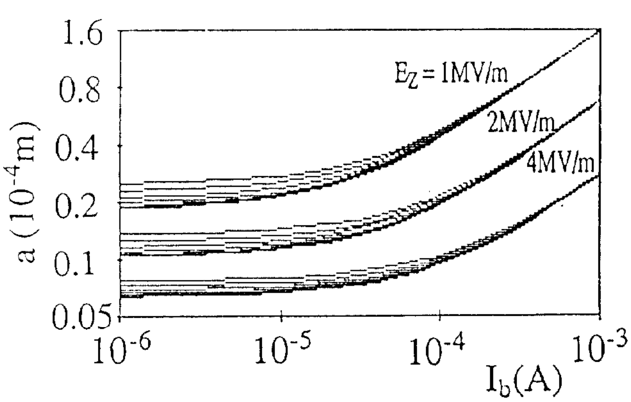

Fig. 2. Beam radius at 10 keV vs current. Beams from emitters with a focusing electrode and accelerated in uniform electric field E_z. ε_n = 0, 2, 4, 6, 8, 10 x 10^{-10} m rad.

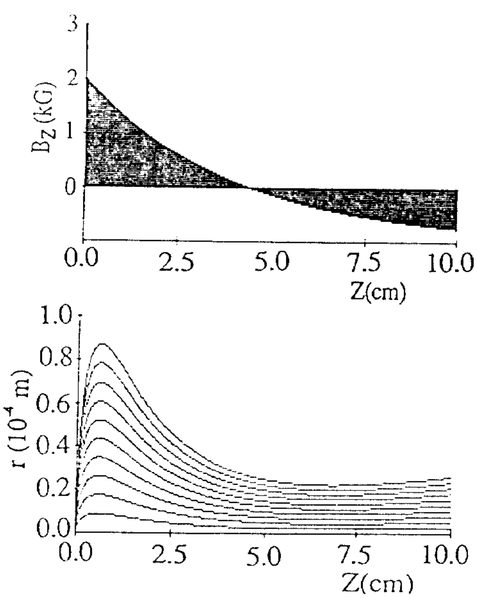

Fig. 3. Magnetic pre-focusing. (a) Magnetic field vs z. (b) Radial position vs z in a 10 μA beam. Ez = 4 MV/m.

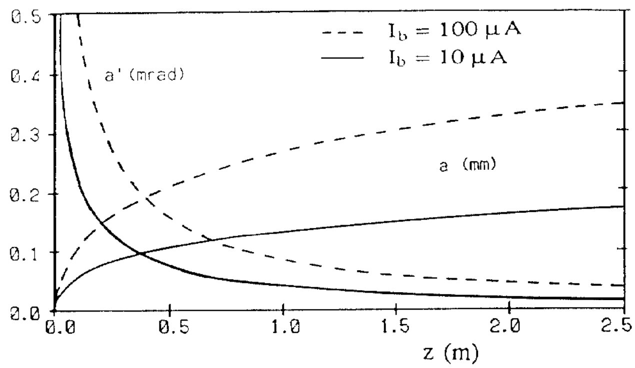

Fig. 4. Beam radius and divergence vs axial position in the accelerator. The beam energy is 10 MeV at z = 2.5 m.

charge is insignificant, the beam is very paraxial, and there exists no lens to cause aberration. The beam is finally focused to a spot whose size is limited by the emittance [6, 8].

APPLICATION OF MICROBEAMS TO FEL

The beam parameters crucial to the FEL operation are peak current and energy spread. Electron beams from microemitters have low current and will be used for FELs in the Compton regime, where the space-charge force is negligible. A single-pass and short-wavelength FEL should be the most suitable target in view of the small beam emittance. In the high-gain Compton regime, the velocity spread $\Delta\gamma_z$ directly affects the interaction between the beam and the co-moving radiation through the trapping of electrons into the pondermotive potential well; the acceptable velocity spread is expressed as $\Delta\gamma_z/\gamma_z << 1/2N$, where N is the number of wiggler periods.

Finite transverse emittance of the beam causes an axial electron velocity spread $\Delta\gamma_z/\gamma_z \approx (\varepsilon_n/r_b)^2 / 2(1+K^2)$, where ε_n is the normalized emittance, r_b the radius of the electron beam and K is the normalized rms undulator vector potential amplitude. Axial velocity spread is also introduced by many other factors including the space-charge, wiggler field error, wiggler focusing field and the axial magnetic field in the beam source and/or the wiggler [11, 12]. (The presence of axial magnetic field at the source induces effective emittance due to the canonical angular momentum. In that case it is desirable to extend the axial field over the whole system to the wiggler section.) However, the contribution of emittance to the total effective axial energy spread is the most important limiting factor in the application of the beam to the generation of short-wavelength radiation.

Another effect of the beam emittance ε on FEL is related to geometrical overlap of the beam and the radiation. Though the laser efficiency peaks at a nonzero value of ε [13], the beam emittance must be smaller than, or at least nearly equal to, λ/π for good overlap to be achieved. This requirement sets an upper bound to the radiation wavelength λ and suggests that the beam from microemitters would take advantage of its small emittance to lase at λ's smaller than a few μm.

Thin beams from microemitters fit into different kinds of microwigglers. Tunable millimeter and submillimeter waves have been generated by ledatron [14] using a Fabry-Perot resonator as wiggler; an electron beam propagating through a closely arranged pair of a metallic diffraction grating and a reflector gives rise to stimulated emission. Generation of visible light has also been studied with this device. Another FEL has been proposed based on the Cherenckov emission of light by a beam passing through a waveguide loaded with a dielectric pipe, whose inner radius is of the order of 1 μm [15].

Generation of coherent X-rays due to crystal channeling of electrons is also an attractive subject. It has been shown theoretically that the necessary current density is ~ 10^5 A/cm^2, when multiple Bragg reflections are effectively utilized for radiation guiding [16]. A 10 MeV, 10 μA pulsed beam with normalized brightness ~ 10^{13} A/m^2 rad^2 is supposed to yield X-ray emission which is intense enough for practical use.

In this paper we have shown that diversion of a microbeam is greatly reduced by applying a strong accelerating field in the region directly connected to the source. The beam quality may be significantly improved by increasing the (peak) electric field to ~ 100 MV/m as in RF linacs, and the microbeam will find wide application to FEL owing to their unique characteristics.

REFERENCES

[1] C.W. Roberson and B. Fafizi, IEEE J. Quantum Electron. **27**, 2508 (1991).

[2] C.M. Tang, B. Fafizi, E. Esarey, A. Ting, W. Marable and P. Sprangle, " Key Physics Issues Affecting the Performance of Free-Electron Lasers," AIP Conference Proceedings No. 249, Physics of Particle Accelerators, ed. M. Month and M. Dienes (1992).

[3] J. Fraser and R. L. Sheffield, IEEE J. Quantum Electron. **23**, 1489 (1987).

[4] C.A. Spindt, C.E. Holland, A. Rosengreen and I. Brodie, IEEE Trans. Electron Devices **38**, 2355 (1991).

[5] C.M. Tang, A.C. Ting and T. Swyden, Nucl. Instr. and Meth. **A318**, 353 (1992).

[6] H. Ishizuka, Y. Nakahara, S. Kawasaki, N. Ogiwara, K. Sakamoto, A. Watanabe and M. Shiho, 14th Intern. Conf. FEL, 1992, to be published in Nucl. Instr. Meth.

[7] W.B. Herrmannsfeldt, R. Becker, I. Brodie, A. Rosengreen and C.A. Spindt, "High-Resolution Simulation of Field Emission," SLAC-PUB-5217 (1990).

[8] J.D. Lawson, " The Physics of Charged-Particle Beams," Second Edition (Clarendon Press, Oxford, 1988).

[9] R. M. Mobley and J. E. Boers, IEEE Trans. Electron Devices **38**, 2383 (1991).

[10] J.R.A. Cleaver, Optik **52**, 293 (1978/79).

[11] L.H. Yu, S. Krinsky and R.L. Gluckstern, Phys. Rev. Lett. **64**, 3011 (1990).

[12] H.P. Freund and R.H. Jackson, Phys. Rev. **A45** (10) 7488 (1992).

[13] B. Fafizi and C.W. Roberson, Phys. Rev. Lett. **68**, 3539 (1992).

[14] K. Mizuno and J. Bae, JAERI-M **91-141**, p. 94 (1991).

[15] T. Taguchi and K. Mima, 14th Intern. Conf. FEL., 1992, to be published in Nucl. Instr. Meth.

[16] M. Strauss and N. Rostoker, Phys. **A40**, 7097 (1989).