SLAC-PUB-8284
LCLS TN 99-8
October 1999

Reduction of thermal emittance of rf guns*

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Abstract

The transverse emittance from optimized rf photoinjectors is limited by the thermal emittance. The thermal emittance can be lowered by a factor >2 by using a semiconductor photocathode.

Presented at the International Symposium on
New Visions in Laser-Beam Interactions
Tokyo, Japan
October 11-15, 1999

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* Work supported by Department of Energy contract DE-AC03-76SF00515.

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1. Introduction

Present and future accelerator applications are increasingly dependent on the availability of low emittance, high-brightness beams. RF photoinjectors are the most cost-effective way to generate such beams. Some ideas on how to lower the transverse emittance of a rf gun are discussed in this paper.

The development of rf photocathode guns over the past decade has ushered in a new era for electron sources. Since these guns operate with much higher extraction fields than traditional dc-biased guns, the space-charge forces near the cathode are dramatically reduced, making it possible to extract and accelerate very high current beams directly from the cathode. In addition, it was realized quite early that since the emittance from an rf gun is largely correlated, its growth can to a large extent be reversed by the application of a longitudinal magnetic field immediately following the cathode. A number of experiments have demonstrated the viability of these concepts.

The operation of rf guns has received extensive theoretical treatment, and several simulation codes that take into account space charge have proven extremely useful for optimizing emittance-compensating designs. A design that has been optimized can be scaled to any desired operating frequency. For S-band, the parameters associated with this optimum design are 1 nC of charge in a cylindrically uniform charge distribution of length 10 ps by radius 1 mm. Simulations indicate that using an appropriate rf design coupled with an emittance compensating solenoid, a normalized rms emittance of 10^{-6} m should be achievable simultaneously in all three planes at a fully relativistic energy (>100 MeV). Experimental confirmation of this conclusion is presently only approximate.

An important application for high-brightness sources is for x-ray FELs such as the Linac Coherent Light Source (LCLS) planned at SLAC. The LCLS injector design includes a high-gradient S-band gun followed by a separate S-band booster. Recognizing that the LCLS requires the injector to operate at the optimum design discussed above, a considerable amount of attention has been paid to the details of this design. The LCLS Design Report [1] presented a design predicting the required transverse emittance of 10^{-6}

m, but with no headroom for unaccounted factors, the principal one of which is the thermal emittance. More recent studies indicate that significantly lower emittances should be achieveable [2].

2. Thermal emittance

The term “thermal emittance” refers to the uncorrelated emittance of the electrons as they are extracted from the cathode surface. The term is derived from the performance of a thermionic gun. A thermionic cathode generally consists of a metal with a relatively low work function, Φ*,* that is heated until electrons are emitted. This emission is explained by treating the free electrons in the metal as a Fermi-Dirac gas. The probability that an energy state is occupied diminishes rapidly from unity towards zero as the energy is increased significantly above the Fermi energy, ε_F, over an energy range characterized by $kT/2$, where T is the temperature of the metal. Based on this model, the probability for electrons to tunnel through the surface barrier to vacuum is given by the Richardson-Dushman equation,

$$j = A(1-r)T^2 e^{-e\Phi/kT}, \tag{1}$$

where r is the reflection coefficient at the metal-vacuum interface, and A is an empirical constant. The normalized rms transverse emittance, $\varepsilon_{n,rms}$, from a uniformly emitting thermionic cathode of radius r_c and operating temperature T is given [3] by

$$\varepsilon_{n,rms} = \beta\gamma\left(\langle x^2\rangle\langle x'^2\rangle\right)^{1/2} = \frac{\gamma r_c}{2}\sqrt{\frac{kT}{m_o c^2}}\,. \tag{2}$$

Thus the initial thermal emittance of a beam generated by a thermionic cathode can be determined by measuring the cathode temperature using a pyrometer.

3. Photoemission from metals

Since kT~0.025 eV at room temperature, a cold emitter must have a low value of Φ. The presence at the cathode of a strong electric field, E_c, will significantly lower the work function of photoemissive materials. Field emitters depend primarily on this factor. Photoemitters for practical electron beam sources are affected by all three factors: Φ, T, and E_c, although use of elevated temperatures is rare.

Photoemission from a metal involves first the absorption of a photon with $\hbar\omega > \Phi_e$, where $\Phi_e = \Phi - \Delta$. Here Δ is the lowering of the work function by E_c and is given [4] by $\Delta = e\sqrt{eE_c/4\pi\varepsilon_o}$. With normal-incidence illumination by a cylindrical laser pulse of uniform transverse and temporal distributions, the upper limit for the thermal emittance of the extracted electron bunch is given [5] by

$$\varepsilon_{n,rms}^{therm} = \frac{r_c}{2}\sqrt{\frac{2E_{kin}}{m_o c^2}}\frac{1}{\sqrt{3}}\sqrt{\frac{2+\cos^3\varphi_{\max} - 3\cos\varphi_{\max}}{2(1-\cos\varphi_{\max})}}, \tag{3}$$

where $\varepsilon_{kin} = \varepsilon_F + \hbar\omega$ and the maximum emission angle, ϕ_{max}, is given by

$$\varphi_{\max} = \arccos\left(\frac{\varepsilon_F + \Phi_e}{\varepsilon_F + \hbar\omega}\right)^{1/2}. \tag{4}$$

Using 4.6 and 7.0 eV for Φ and ε_F respectively for the case of a Cu cathode, and letting $\hbar\omega = 4.6$ eV and E_c=84 MV/m, we find $\varphi_{\max}$~10°. For a cathode of 1-mm radius, $\varepsilon_{n,rms}^{therm}$ is thus ~0.3×10^{-6} m. The thermal emittance adds quadratically to the residual correlated emittance at high energies, thus the total emittance predicted for an optimized S-band system using a metal cathode appears to be seriously limited by the thermal emittance.

Surface roughness will increase the local value of $\varphi_{\max}$ relative to the normal to the macrosurface. On the other hand, the effects of electron-electron scattering in the bulk as well as promotion from below the Fermi level, both of which would lower the thermal emittance, have been ignored. Any field enhancement due to the presence of surface contaminants or other factors has also been neglected. Such field enhancements for poorly prepared surfaces can be quite large, but it is noted that the field emission from which these enhancements are calculated (using a Fowler-Nordheim analysis) includes the gross area of not only the whole vacuum system subject to the high electric fields (the gun rf cavities in the case of an rf photoinjector system) while the electron beam is extracted from a much smaller area on the order of 1 mm radius for an S-band gun. In addition field emission is generally associated with specific emission points that can in principle be eliminated or avoided in real systems [6].

Direct measurements of the thermal emittance of metals have not been made. However, since the QE is proportional to $e^{-\Phi_e/kT_e}$, where T_e is the effective temperature of the excited electrons at emission, the change in the QE observed for a small change in Φ_e can be used to derive an experimental value of T_e. In this manner a value of T_e=0.14 eV for a Cu cathode excited at 263 nm has been determined by changing the extraction phase to vary the Schottky effect [7]. From Eq. (2), a corresponding thermal emittance of 0.26×10^{-6} m per mm-radius is predicted for a transverse uniform pulse, which is consistent with the maximum value derived earlier.

4. Photoemission from semiconductors

The principal energy-loss mechanism for electrons in a metal is electron-electron scattering. Near threshold, the primary electron can lose a significant fraction of its energy in a single scattering event, while the secondary electron may not gain enough energy to allow it to escape to vacuum. Thus the escape depth for metals is very short. By contrast, semiconductors lose energy primarily by electron-phonon scattering since electron-electron scattering is forbidden for excitation energies less than twice the band gap, E_{BG}. The photoemission process for semiconductors is illustrated in Fig. 1. First a photon with $\hbar\omega > E_{BG}$ is absorbed promoting an electron from near the top of the valence band into the conduction band. Second the excited electron loses energy by electron-phonon scattering as it diffuses to the surface. Since the photon absorption length near threshold is on the order of 1 μm, most of the excited electrons arriving at the surface have been thermalized. The third and final stage is discussed next.

The electron affinity, E_A, of many materials, including most semiconductors, can be significantly reduced by coating the surface with a monolayer or so of an alkali metal such as Cs. Adding a small amount of an oxide facilitates this process. For III-V semiconductors, this will lower the vacuum level to about the conduction band minimum (CBM) in bulk. In addition, if the semiconductor is p-doped, negative band bending is exhibited at the surface, so that the vacuum level at the surface is actually below the CBM in bulk, resulting in a negative electron affinity (NEA) emitter. The band bending results from the positive charge associated with the surface dipole layer. Since for high doping density (~10^{19} cm^{-3}) the width of the band bending region (BBR) is only about 10 nm, extremely high electric fields are present that can greatly increase the kinetic energy of a transiting electron. Although the MFP for electrons is greater than the BBR width, most of the excited electrons approaching the surface are reflected by a thin interfacial barrier, as indicated in the figure, or trapped in surface states. However, energy-wise the reflected electrons are confined to the BBR where they tend to heat up before some of them manage to tunnel through the surface barrier to vacuum while the remainder eventually recombine with holes.

A measurement of the mean energy parallel to the surface, $\varepsilon_{//} = \hbar k^2 / 2m_e^*$, as a function of the mean perpendicular energy, $\varepsilon_\perp$, for an NEA GaAs photocathode is shown in Fig. 2. The measurement was performed by the Heidelberg group [8] using a novel technique that eliminates the effect of the space charge on the measured parallel energy. It is seen that of the electrons escaping to vacuum, only the “hot” electrons (electrons promoted near the surface) and the thermalized electrons from the bulk that have not experienced significant energy loss in the BBR retain their low temperature.

The experimental data discussed above suggests that to minimize the thermal emittance using a semiconductor photocathode, it should be operated with E_A~0. The effective temperature of the emitted electrons would then be ~0.025 eV compared to ~0.14 eV for the Cu example discussed earlier, resulting in more than a factor of 2 reduction in the thermal emittance per mm-radius. Cooling the cathode to ~100 K would reduce the thermal emittance another factor of $\sqrt{3}$. Operating at E_A~0 will reduce the QE by about an order of magnitude, or to a level of ~1% for GaAs, which is still high considering that the excitation light, at threshold, is in the visible regime.

5. Conclusions

To take full advantage of recent progress in rf photoinjector designs for producing low emittance beams, the thermal emittance must be reduced. Semiconductors have been shown to offer the possibility of such a reduction, by a factor of 2-3 compared to Cu.

References

[1] The Linac Coherent Light Source Design Study Report, SLAC-R-0521 (Rev. Dec. 1998).

[2] In fact an emittance of ~0.5×10^{-6} m is now predicted by simulation codes for a 1.6-cell S-band gun properly matched to a high-gradient booster section with continuous focusing. These simulations assume a near-perfect uniform temporal electron distribution in the bunch, and also they ignore thermal emittance. See Proc. of the Mini-Workshop on the LCLS Photoinjector Design, ed. J. Clendenin, SLAC-WP-014 (Sept. 1999).

[3] J.D. Lawson, The Physics of Charge-Particle Beams (Clarendon Press, Oxford, 1988) p. 210.

[4] The lowering of the work function by an electric field is also known as the "Schottky effect." To a large extent the Schottky effect accounts for the additional momentum normal to the surface acquired by an electron prior to emission due to field penetration.

[5] J.E. Clendenin and G.A. Mulhollan, in: Quantum Aspects of Beam Physics, ed. P. Chen (World Scientific, Singapore, 1999) p. 254.

[6] M. Yoshioka et al., Proc. of the 1994 Int. Linac Conf., Tsukuba, Japan, 1994, p. 302

[7] J.F. Schmerge et al., SPIE 3614 (1999) 22.

[8] S. Pastuszka et al., Appl. Phys. Lett. 71 (1997) 2967. The data suggest that at the surface, the effective mass of the electron, m_e^*, is approximately equal to m_e.

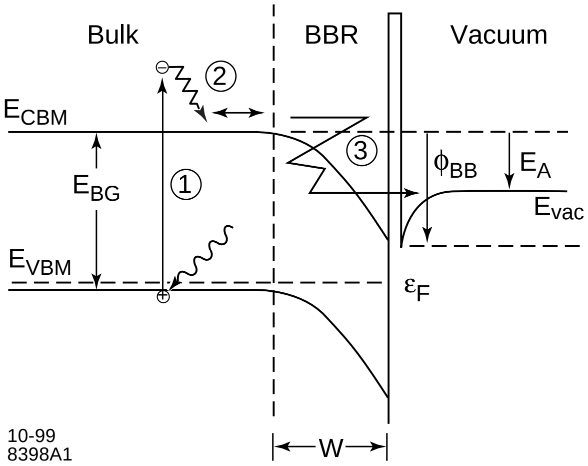

Fig. 1. Schematic energy diagram near the surface for GaAs illustrating the three-step emission process. E_{VBM}, E_{CBM} and E_{vac} are valence band maximum, conduction band minimum, and vacuum level energies respectively. E_{BG} is the band gap, ε_F the Fermi energy, E_A the electron affinity, and W and ϕ_{BB} the width and depth of the BBR respectively.

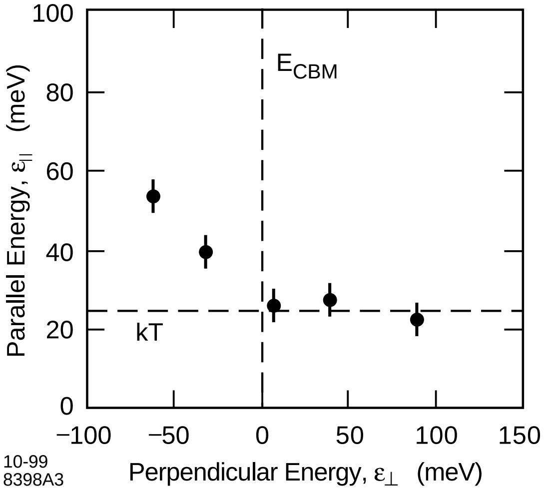

Fig. 2. Mean energy parallel to the surface as a function of the mean emission energy perpendicular to the surface with respect to the conduction band minimum, E_{CBM}.