Maximum Achievable Beam Brightness from Photoinjectors

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Electron injectors delivering relativistic electron beams with very high brightness are essential for a number of current and proposed electron accelerator applications. These high brightness beams are generally produced from photoemission cathodes. We formulate a limit on the electron beam brightness from such cathodes set by the transverse thermal energy of the electrons leaving the photocathode and the accelerating field at the cathode. Two specific examples—direct measurement of the transverse phase space of a space charge dominated beam from a high-voltage photoemission electron gun and a numerical optimization of the same at a higher gun voltage—illustrate the importance of this limit.

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In this Letter we formulate a limit on the maximum beam brightness from electron sources that produce short duration bunches from photocathodes. The accelerating electric field at the photocathode sets a limit on the maximum charge density extractable from the photocathode without degrading the brightness, while the transverse thermal energy of the photoemitted electrons determines the beam solid angle from the source. We present results of experimental measurements of beam brightness from a dc high-voltage (HV) photoemission gun operated both at and below the virtual cathode limit. We observe that the core brightness of the beam is about a factor of 2 lower than the expected maximum brightness when operating at the onset of the virtual cathode instability. Below the virtual cathode limit space charge forces are linear, preserving the core brightness. Finally, we present the results of 3D space charge simulations over a wide range of bunch charges. We show that better beam emittances are possible from longer electron pulses than for the case of the ultrashort pulse “blowout” regime [1] because the longer pulses allow smaller laser spots with correspondingly smaller thermal emittances, while avoiding the virtual cathode instability.

In the broadest terms, the brightness of a charged particle beam is defined as the number of particles per unit volume of six-dimensional phase space. For the case of relativistic electron beams in accelerators and beam transport systems, the motion along the beam direction is to a very large degree decoupled from the motion in the two transverse planes. This leads one to simplify the problem by considering the normalized beam brightness in 4D transverse phase space $(x, \gamma\beta_x, y, \gamma\beta_y)$, where $\gamma\beta_{x,y} = p_{x,y}/mc$ are normalized transverse momenta, with m and c the electron mass and the speed of light, respectively. Following Ref. [2] we define the normalized brightness as

$$\mathcal{B}_{n,\mathrm{av}} = I_{\mathrm{av}}^{-1}\frac{1}{(mc)^2}\int \rho_4^2 dxdydp_xdp_y, \tag{1}$$

where $I_{\mathrm{av}} = (mc)^{-2}\int \rho_4 dxdydp_xdp_y$ is the average beam current. Here $\rho_4 = d^4 I_{\mathrm{av}}/d\mathcal{V}_4$ is the local current density in 4D phase space, also known as the microscopic beam brightness [3], and $d\mathcal{V}_4 = dxdydp_xdp_y/(mc)^2$. The normalized brightness defined in Eq. (1) remains constant during acceleration provided that linear forces dominate the beam dynamics.

For bunch durations from a photoemission cathode short compared to the time to transit the cathode-anode gap of a dc or rf gun, space charge forces lengthen the bunch and degrade the beam brightness from the cathode onward. The discovery that much of the emittance growth following the cathode was strongly correlated with the longitudinal position within the bunch, and thus that appropriate focusing following a photoemission electron gun could recover much of the brightness lost from space charge degradation—a process termed emittance compensation—has led to the development of a number of electron injectors delivering high peak brightness beams [4]. The emittance compensation process can be optimized by carefully tailoring the transverse and longitudinal profiles of the optical pulse illuminating the cathode. For example, an ellipsoidal bunch has linear space charge forces, implying high beam brightness [1]. Nevertheless, the maximum brightness available from such photoinjectors remains unclear.

Here we point out a basic limit to beam brightness arising from the surface charge density on the cathode, as determined by the accelerating field present and the transverse energy of the photoemitted electrons. This simple physical picture is refined by considering the virtual cathode instability, which sets a limit on the maximum charge density that can be extracted from a photocathode by a short laser pulse without significant beam brightness degradation.

Since $I_{\mathrm{av}} = qf$ for a train of bunches of charge q delivered at repetition rate f, we write the normalized brightness of a single bunch as

$$\frac{\mathcal{B}_{n,\mathrm{av}}}{f} = q^{-1}\frac{1}{(mc)^2}\int \rho_4'^2 dxdydp_xdp_y, \tag{2}$$

where $\rho_4' = \rho_4/f$ is the local charge distribution in 4D phase space for a single bunch. For a laser pulse of duration σ_t and transverse size $\sigma_{x,y}$, one can form a dimensionless quantity $A \equiv \sigma_{x,y} m/\sigma_t^2 E_{\mathrm{cath}} e$, with e and E_{cath} being the electron charge and the electric field at the cathode at the time of photoemission, respectively. A is the aspect ratio the electron bunch assumes following emission from the photocathode. $A \gg 1$ corresponds to a "pancake" shape bunch, for which the maximum charge density supported by the cathode field is simply

$$\frac{d^2q}{dxdy} \approx \epsilon_0 E_{\mathrm{cath}}, \tag{3}$$

where ϵ_0 is the vacuum permittivity. Note that a factor of 2 has been included to account for the image charge.

For Maxwellian transverse velocity distributions of the photoelectrons leaving the photocathode, the rms transverse momentum spread is $\sigma_{p_{x,y}} = \sqrt{mkT}$, where kT is the effective transverse thermal energy of the photoelectrons. This transverse energy approaches the physical cathode temperature for negative electron affinity (NEA) photocathodes illuminated by near band gap energy photons [5,6], or is considerably larger for positive affinity cathodes illuminated at much shorter wavelengths. With the maximum charge density given by Eq. (3), one finds the maximum normalized microscopic brightness in a single bunch:

$$\left.\frac{\mathcal{B}_n}{f}\right|_{\mathrm{max}} = \frac{mc^2 \epsilon_0 E_{\mathrm{cath}}}{2\pi kT}. \tag{4}$$

The average brightness is related to the maximum (core) brightness as $(\mathcal{B}_{n,\mathrm{av}}/f) = \kappa_{\mathcal{B}}(\mathcal{B}_n/f)|_{\mathrm{max}}$, where the numerical coefficient $\kappa_{\mathcal{B}}$ depends on the spatial distribution at the cathode: $\kappa_{\mathcal{B}} = 1/2$ for a uniform circular distribution, 3/8 for an ellipsoidal distribution, and 1/4 for a Gaussian. The brightness limit depends only on the cathode accelerating field E_{cath} and the transverse thermal energy kT of the photoemitted electrons, and is independent of the bunch charge.

To approach the limit of Eq. (4), it is necessary to avoid the formation of a virtual cathode [7]. For example, for $A \gg 1$, consideration of Eq. (3) shows that the accelerating field is significantly reduced for the fraction of the bunch closest to the photocathode. As a result, the bunch can break apart longitudinally, with a corresponding degradation in beam brightness due to the loss of linearity of the space charge forces [8]. Therefore, the maximum charge density must be below the limit of Eq. (3) for maximum beam brightness, with the actual value being a function of the pulse shape and the duration, the transverse size and distribution, and the cathode electric field [7].

To check the applicability of Eq. (4), we compare it with direct phase-space measurements of the bunched beam generated from a 250 kV dc gun ($E_{\mathrm{cath}} = 2.7$ MV/m). The gun is followed by a solenoid lens and a double horizontal slit (20 μm opening) phase-space measurement system. The experimental setup, detailed elsewhere [9], was used to benchmark 3D space charge codes by direct phase-space measurements of space charge dominated beams. The measurements were performed with 80 pC bunches, just above the virtual cathode condition, and 20 pC bunches, well below that limit. The average ratio of the space charge to emittance terms in the beam envelope equation is about 56 for the 80 pC/bunch case, and 43 for the 20 pC/bunch case, indicating that the beams are strongly space charge dominated in each case [10].

The photocathode was a GaAs crystal activated to NEA with cesium and NF_3. The quantum efficiency at our 520 nm wavelength was about 6% during these measurements. The measured transverse and the reconstructed longitudinal profiles of the optical beam at the cathode are shown in Fig. 1. The transverse profile was formed by placing an aperture, which clipped the nominally Gaussian laser beam at about $\pm 1.6\sigma$, and imaging this aperture onto the photocathode. The temporal profile was obtained by optical pulse stacking using three birefringent crystals [11]. The temporal profile of electron bunches with negligible space charge was measured using a rf deflecting cavity. The measured temporal profile is smeared by the 1.5 ps rms temporal resolution arising from the finite beam spot size and jitter in the laser-to-deflecting rf cavity synchronization. The far from ideal reconstructed profile is obtained from the width of the individual laser pulses as measured by autocorrelation. The aspect ratio parameter for our measurements $A = 17$.

Equation (3) implies that the charge extracted from the photocathode will be a linear function of the laser power until the limit of Eq. (3) is reached. Beyond this point, the slope of the extracted charge versus laser power will decrease. Figure 2(a) shows a simulation of the extracted bunch charge versus its expected value in the absence of space charge for the measured 3D laser distribution. The temporal electron bunch profile 1 mm from the photocathode is shown in Fig. 2(b) for the two bunch charges. The formation of a temporal tail due to the virtual cathode in the 80 pC/bunch case can also be seen.

Figures 3(a) and 3(c) show the measured transverse phase space for the two charges for the solenoid lens

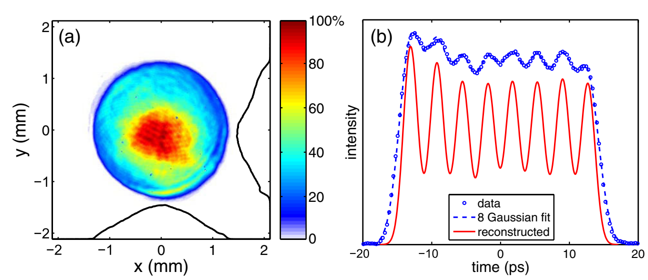

FIG. 1 (color online). Laser transverse (a) and temporal (b) profiles used in the experiment for creation of bunched beam.

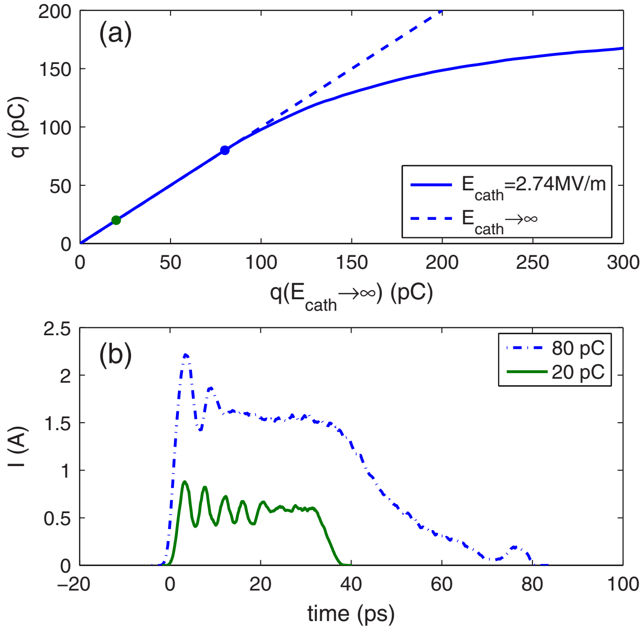

FIG. 2 (color online). (a) Charge extracted from the photocathode (solid line) versus the charge that would be extracted in the absence of space charge (dashed line). The dots indicate the conditions of the experiment. (b) Simulated temporal bunch profiles for the two bunch charges 1 mm from the photocathode.

strengths that gave maximum emittance compensation. The ratio of the measured emittance to the maximum emittance preceding it is $1/1.9$ and $1/1.5$ for 80 and 20 pC, respectively. To evaluate the beam brightness, we first compute $\epsilon_{ny} = (\langle y^2\rangle\langle p_y^2\rangle - \langle y p_y\rangle^2)^{1/2}/mc$, the rms normalized beam emittance containing a fraction ξ_2 of the bunch charge, with $\langle\cdots\rangle$ representing the ensemble average over the available distribution [3]. Figures 3(b) and 3(d) show the rms normalized emittance $\epsilon_{ny}(\xi_2)$ as a function of the beam fraction $0 \le \xi_2 \le 1$ for 80 and 20 pC bunch charge, respectively. It includes a comparison with the 3D space charge code GPT [12] demonstrating an excellent agreement with the measured data below the virtual cathode limit (20 pC case). The core emittance, $\epsilon_{ny,\mathrm{core}}$, and core fraction, $\xi_{2,\mathrm{core}}$ are indicated in each figure. The core emittance is defined as the abscissa where the tangent line $d\epsilon_{ny}(\xi_2 = 0)/d\xi_2$ crosses the line $\xi_2 = 1$, and the core fraction is defined such that $\epsilon_{ny}(\xi_{2,\mathrm{core}}) = \epsilon_{ny,\mathrm{core}}$. The details of the emittance measurements and beam fraction computation are given in Ref. [9].

The brightness as a function of beam fraction is evaluated using

$$\frac{\mathcal{B}_{n,\mathrm{av}}}{f} = q\left(\frac{\xi_2}{4\pi\epsilon_{ny}(\xi_2)}\right)^2, \tag{5}$$

with q being the bunch charge. Here we have assumed that the beam distribution in each transverse plane is identical, as we measure only the vertical plane phase space. Evaluating Eq. (5) for a Gaussian transverse distribution with the same 100% transverse rms emittances $\epsilon_{nx,y}$ leads to $\mathcal{B}_{n,\mathrm{av}}(\xi_2 = 0)/f = 4q/(4\pi\epsilon_{nx,y})^2$, and $\mathcal{B}_{n,\mathrm{av}}(\xi_2 = 1)/f = q/(4\pi\epsilon_{nx,y})^2$. The corresponding plots are shown in Fig. 4 for $q\xi_2$ in the case of the two bunch charges along with expected beam brightness assuming a Gaussian distribution. The measured value $kT = 120 \pm 8$ meV was used for the transverse thermal energy [5]. It is seen that the brightness calculated from the measured transverse phase space approaches the limit set by the accelerating gradient and the transverse thermal energy of the photoelectrons within a factor of 2 for a small charge fraction ($\xi_2 \lesssim 0.05$) at 80 pC/bunch. In contrast, the

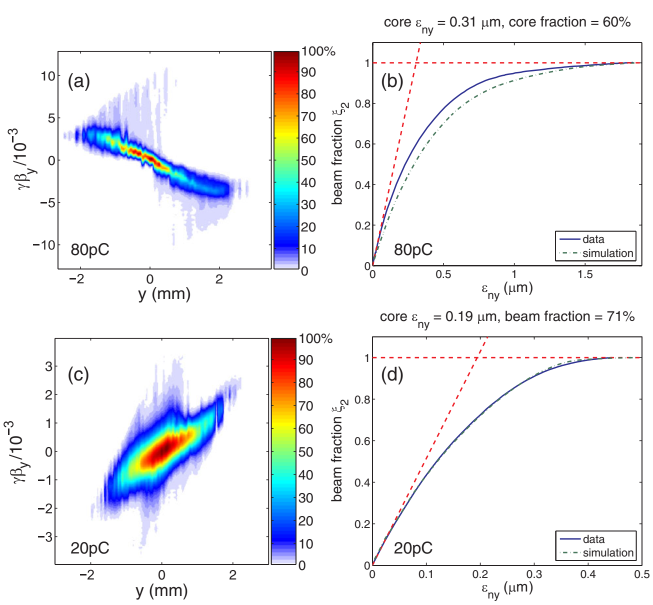

FIG. 3 (color online). Measured (a),(c) transverse phase space and the corresponding emittance versus beam fraction curve (b), (d).

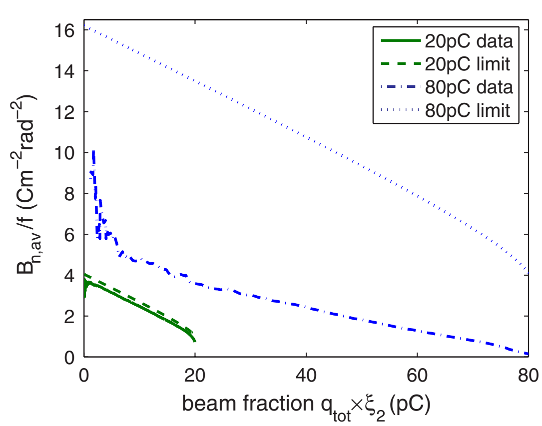

FIG. 4 (color online). Beam brightness versus the beam fraction as obtained from the measured phase space with the estimated brightness limit assuming a Gaussian transverse distribution at the photocathode for two different bunch charges.

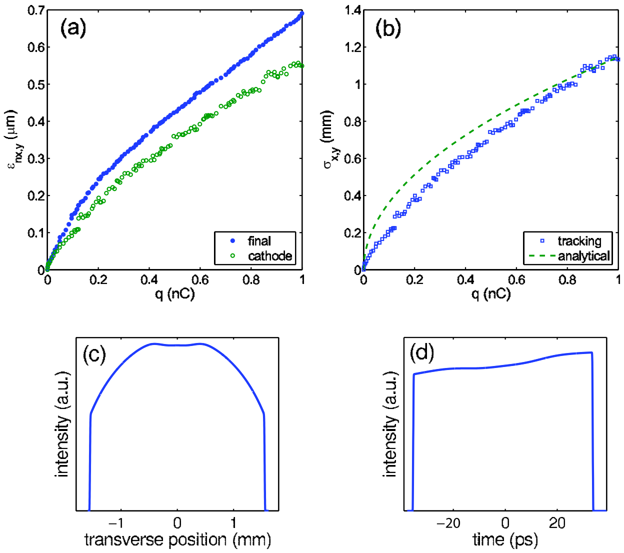

FIG. 5 (color online). Simulated rms normalized emittance (a) and the corresponding laser spot sizes (b) as a function of bunch charge. $E_{\mathrm{cath}} = 8.2$ MV/m and $kT = 120$ meV in these simulations. Typical transverse (c) and temporal (d) laser profiles ($q = 0.5$ nC) are shown as well.

20 pC/bunch case shows very good agreement with the predicted brightness limit. Given the fact that the two cases are comparably space charge dominated (due to a shorter bunch duration and a smaller emittance in the 20 pC case), we attribute the reduction in beam brightness from the predicted value at 80 pC/bunch to the virtual cathode formation present in that case.

We made 3D space charge simulations using the experimentally benchmarked codes [9] for our dc gun operated at 750 kV ($E_{\mathrm{cath}} = 8.2$ MV/m) with all conditions the same as in the present experiment except that the solenoid lens was moved 0.1 m closer to the photocathode. The emittance at the end of the beam line was minimized using a multiobjective genetic algorithm, in which we varied the laser spot size, the solenoid strength, and seven parameters that describe the transverse and temporal laser profiles [13]. Each simulation used 0.5×10^6 macroparticles with an $80 \times 80 \times 80$ nonequidistant spatial grid to calculate the space charge forces acting on the bunch. The laser pulse duration was fixed at 20 ps rms in all cases. Figure 5 shows the results of these simulations. The optimized transverse and temporal laser profiles obtained from the simulations are shown for a particular bunch charge (0.5 nC). It can be seen that the transverse profile approaches an elliptical distribution. Assuming the charge density limit of Eq. (3), the laser rms spot size would be given by $\sigma_{x,y} = (3q/10\pi\epsilon_0 E_{\mathrm{cath}})^{1/2}$ [shown as dashed line in Fig. 5(b)], with the corresponding photocathode (thermal) emittance $\epsilon_{n,\mathrm{th}} = \sigma_{x,y}(kT/mc^2)^{1/2}$. Figure 5 shows that the simulations give a final emittance dominated by the photocathode emittance provided the appropriate laser 3D shaping can be realized. For practical use with a rf accelerator, the need to produce appropriate bunch length must be incorporated into the problem.

In conclusion, we have presented a maximum limit on the transverse brightness of electron beams produced as short duration pulses from photoemission cathodes. This limit depends only on the electric field at the photocathode at the time of emission and the transverse thermal energy of the electrons. Although the limit does not depend explicitly on the charge in the electron bunch, when the charge density at the cathode becomes large enough to form a virtual cathode, the transverse beam brightness decreases. We have demonstrated the relevance of this limit by measurements of the minimum emittance of strongly space charge dominated beams from a HV dc electron gun. Although our measurements were done with a NEA photocathode in a dc gun, the limit applies to any photocathode delivering short duration pulses in either dc or rf accelerating structures. Finally, we have shown with simulations using benchmarked codes that it should be possible to generate short duration electron bunches with an emittance dominated by the thermal emittance of the photocathode over a wide range of bunch charges.

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