THEORETICAL LIMIT OF ELECTRON BEAM BRIGHTNESS GENERATED FROM ELECTRON GUNS

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Abstract

The brightness of the electron beam is important for linear accelerator and it is fundametally limited by that from electron gun. In this article, we discuss the fundamental limit on the beam brightness defined as the ratio of the bunch charge and the 6D emittance from DC and RF guns. The brightness is limited by the thermal energy of electron, space charge effect, particle motion in the gun structure, break-down limit, etc. As the highest brighness according to my considerations, DC gun generates $10^{13\sim16}$ C/m^3. That from RF gun is slightly less than that of DC gun, $10^{13\sim15}$ C/m^3.

INTRODUCTION

In this article, I consider the fundamental limit on the beam performance from electron guns. The emittance and the bunch charge are important especially linear accelerator facility, because the beam performance from the electron gun determine the accelerator performance. The emittance and the bunch charge are in the relation of trade-off. The discussion on the fundamental process which limit the beam performance is useful to consider a new concept of accelerator facility.

In the following sections, we discuss the possible highest beam performance from DC and RF guns. DC gun technology is quite conventional and one might consider it is out of date, but it is not true by several reasons. DC bias gun has a limitation on the acceleration voltage, but it doesn't mean the performance is poor. The acceleration by a static field has a big advantage, because the acceleration voltage is a constant and there is no emittance growth mechanism associated with the acceleration. In addition, DC gun can generates highly spin polarized electron beam, which is strongly demanded by High energy physics, some of material science, and applications.

RF electron gun can generate a high brightness beam because the high surface field on the cathode. The peak current is much higher than that of DC gun, but there is non-linear effects degrading the beam brightness associated with the RF acceleration.

In the following section, we discuss the beam brightness from each gun structure. In this article, we define the beam brightness as the ratio of the bunch charge Q to the normalized 6D emittance $\varepsilon_{n,6D}$ as

$$B \equiv \frac{Q}{\varepsilon_{n,6D}}. \tag{1}$$

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DC BIASED ELECTRON GUN

DC biased gun is originally developed as a thermionic gun which use a thermionic cathode as the electron source. The DC biased thermionic gun is conventional and widely used. Some people consider that the DC biased thermionic gun is out of date, but it is not a correct understanding. SACLA (XFEL in Japan) [1] employs a DC biased thermionic gun (500 kV, pulsed) and the brightness is sufficient to generate X-ray as same as other XFEL facility. The thermionic gun generates a quite long bunch ~ 1 ns due to the limited bias voltage comparing to RF field, but this long bunch is decreased by a multi-stage bunching. If the process is linear, there is no brightness degradation. The key is controlling the non-linearity and this is the part which they concern about the most.

Technical advantage of DC gun is the capability to generate the spin polarized electron beam, which is strongly demanded from High energy physics. If the spin polarization is required for ALC, negative electron affinity (NEA) super-lattice (SL) GaAs cathode [2] is the only solution, which is able to generate 90% spin polarized electron beam with circularly polarized laser [3]. Although GaAs cathode is not compatible with RF photo-injector at this moment, but it is not fundamental limitation.

An unique feature of the DC electron gun is that a perfectly parallel electron flow from a cathode that completely satisfies the Poisson equation is made. This is called as space-charge dominated flow. The emission current density J is expressed as [4]

$$J = 2.33 \times 10^{-6} \frac{V^{3/2}}{d^2}, \tag{2}$$

where V is gun bias voltage, d is the cathode-anode gap length. The gun bias voltage is limited by vacuum breakdown. The highest voltage ever demonstrated is 500 kV by the cERL gun at KEK [5].

The vacuum break-down is determined by the highest field in the gun structure, and not the voltage. In addition, the average acceleration field is lower than the highest peak field which gives the actual limit. The peak field E_{peak} should be proportional to the average field $E = V/d$ as $E_{peak} = \kappa E$, where κ is determined by the gun geometry. With E_{peak}, J is rewritten as

$$J = 2.33 \times 10^{-6} \frac{E_{peak}^{3/2}}{\kappa^{3/2}\sqrt{d}}. \tag{3}$$

The highest current from a DC gun is obtained when E_{peak} is equal to the vacuum break down limit field, E_{BD}.

E_{BD} is determined by material, surface treatment including a local enhancement. Well trained class 1 copper electrode gives 200 MV/m E_{BD} [6]. There isn't many investigation E_{BD} for semiconductor. SACLA electron gun employ

CeB_6 and the bias voltage is 500 kV with 50 mm gap, i.e. the field is 10 MV/m. This gun is operated in pulse with 1 s duration [7]. cERL gun operates GaAs cathode at 500 kV with 100 mm gap in CW. E_{BD} depends on the pulse length and it is proportional to $\tau^{-1/6}$ keeping a same break down rate for RF case [8]. If the relation is applied to SACLA electron gun (10 MV/m field at 1 s pulse), we get 32 MV/m with 1 ns pulse. We use this number as E_{BD} for GaAs cathode. Usually, the peak field in a gun structure is observed in a corner of electrode and not on the cathode. Therefore, we assume $\kappa = 1$ for GaAs case. Other metal which has higher E_{BD} than that of GaAs doesn't cause breakdown even the field is higher than that on the cathode.

An empirical relation between the breakdown voltage V_{BD} and the electrode gap d is known as [9],

$$\begin{cases} V_{BD} \propto d & d \leq 1.0 \times 10^{-3} \\ V_{BD} \propto d^{0.6} & d > 1.0 \times 10^{-3}. \end{cases} \tag{4}$$

If d is less than 1 mm, V_{BD} is proportional to d, i.e. the breakdown field is a constant, 200 MV/m for the class 1 copper and 32 MV/m for GaAs. On the other hand, for $d >$ 1mm, the breakdown voltage is proportional to $d^{0.6}$ and E_{BD} is less.According to Eq. (3), smaller d gives higher current.

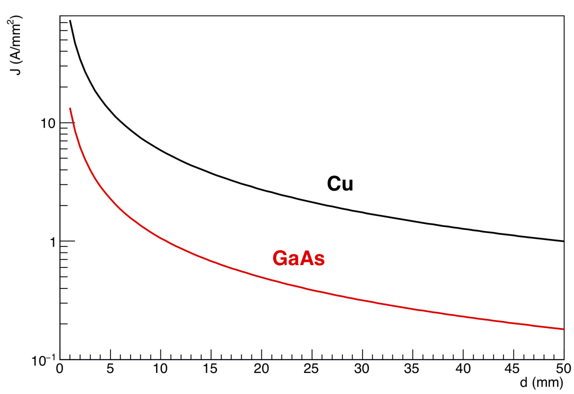

Figure 1: Current density J from DC electron gun $(\mathrm{A/mm^2})$ as a function of d. The gun is operated at E_{BR}.

The current density from a DC gun is

$$J = 2.33 \times 10^{-6} \frac{E_{BD}^{3/2}}{\kappa^{3/2}\sqrt{d}} = 3.68 \times 10^{-8} \frac{E_{BDO}^{3/2}}{\kappa^{3/2} d^{1.1}}. \tag{5}$$

J is proportional to $E_{BDO}^{3/2}$ and $d^{-1.1}$. Figure 1 shows the current density J from DC gun as a function of d for Cu (black line) and GaAs (red line). The current density is calculated as the gun is operated at E_{BD}. κ is assumed to be 2 for Cu and 1 for GaAs in these calculations. The current density is rapidly decreased for large d.

To extract bunch charge Q from a cathode with area S, the bunch length σ_z in RMS is

$$\sigma_z = \frac{Q}{JS\sqrt{12}} = 2.72 \times 10^7 \frac{Q\kappa^{3/2} d^{1.1} c}{E_{BDO}^{3/2} S}, \tag{6}$$

where c is speed of light. The bunch length σ_z is defined as moving with c.

Because the acceleration is done by the static field, we account only the thermal contribution as the energy spread. Space charge makes acceleration and deceleration field, but it doesn't contribute to the emittance as long as the field is linear. Because the energy spread is flat over the bunch, the product of σ_z and the energy spread by the thermal energy gives the longitudinal emittance, $\varepsilon_{n,z}$. It is given as

$$\varepsilon_{n,z} = 2.72 \times 10^7 \frac{Q\kappa^{3/2} d^{1.1}}{E_{BDO}^{3/2} S} \frac{kT}{2mc^2}, \tag{7}$$

where k is Boltzmann constant, T is temperature of cathode.

The thermal energy can be measured as MTE (Mean Transverse Energy) in the transverse emittance. The normalized transverse emittance $\varepsilon_{n,x}$ is given as

$$\varepsilon_{n,x} = \sigma_x \sqrt{\frac{MTE}{mc^2}}, \tag{8}$$

where σ_x is RMS of the transverse beam size. In the ideal case, MTE depends only on temperature, but it is distorted by surface roughness, laser wave length (residual energy), etc. If the thermal energy is isotropic, MTE measured in the transverse direction is equivalent to that in the longitudinal direction with a factor of 1/2.

By comparing MTE between bulk GaAs and super-lattice (SL) GaAs, SL GaAs has an advantage, because SL GaAs crystal forms a mini-band with its width is 35 meV [10]. By assuming a fixed laser wave-length, electron excited by the laser has an energy and momentum values, but they are blurred by thermalisation. That is same for bulk and SL GaAs, but the spread is smaller for SL than that of bulk GaAs, because the band width of the SL mini-band is smaller. N. Yamamoto obtained $\varepsilon_t = 0.15 \pm 0.02\pi mm.mrad$ for SL GaAs/GaAsP cathode with 1 mm radius and > 760 nm laser wavelength, which corresponds to 51 meV MTE. This MTE is in a same order of the thermal energy at 300 K, $kT \sim 26\, meV$. For copper, the lowest MTE ever observed is 6 meV [11]. In this measurement, the copper is cryogenically cooled at 30 K. We use MTE 51 meV for GaAs and 6 meV for copper.

The normalized 6D emittance $\varepsilon_{n,6D}$ is obtained as a product of these emittances without any correlations as,

$$\varepsilon_{n,6D} \equiv \varepsilon_{n,t}^2 \varepsilon_{n,z} = 2.72 \times 10^7 \frac{(kT)^2 c}{2(mc^2)^2\sqrt{12}} \frac{Q\kappa^{3/2} d^{1.1}}{E_{BDO}^{3/2}\pi}. \tag{9}$$

which is independent from the emission area, S and depends on Q and d. Figure 2 shows $\varepsilon_{n,6D}$ as a function of d with the dotted, dashed, and solid lines for 1000 pC, 100 pC, and 10 pC bunch charge, respectively. The black and red lines show those for copper and GaAs, respectively. It is proportional to Q and simply increased with a larger d.

The beam brightness from DC gun B_{DC} is expressed as the ratio of Q and $\varepsilon_{n,6D}$ as

$$B_{DC} \equiv \frac{Q}{\varepsilon_{n,6D}} = 3.68 \times 10^{-8} \frac{2(mc^2)^2\sqrt{12}}{(kT)^2 c} \frac{E_{BDO}^{3/2}\pi}{\kappa^{3/2} d^{1.1}}. \tag{10}$$

It is independent from the bunch charge Q and the cathode area S. It depends on the thermal energy kT, the breakdown limit E_{BDO}, and the electrode distance d. Figure 3 shows

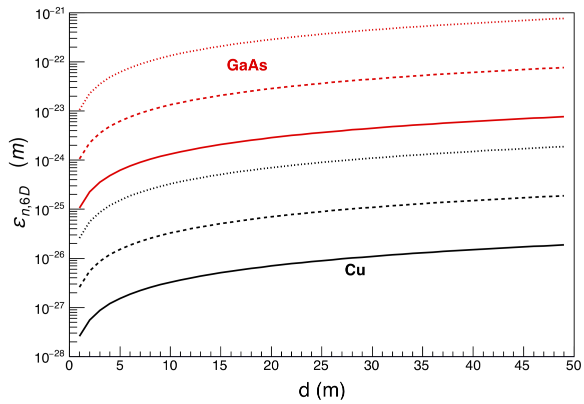

Figure 2: $\varepsilon_{n,6D}$ is plotted as a function of d for 1000, 100, and 10 pC bunch charge with dotted, dashed, and solid lines, respectively. The black and red lines are copper and GaAs cathode, respectively. The cathode radius is 1 mm radius.

the brightness as a function of d for Cu (red line) and GaAs (black line). They are peaked at d=1 mm, $3.8 \times 10^{16}\mathrm{C/m^3}$ for Cu, and $9.5 \times 10^{13}\mathrm{C/m^3}$ for GaAs. The difference between copper and GaAs come from the thermal energy kT and the breakdown limit, E_{BDO}.

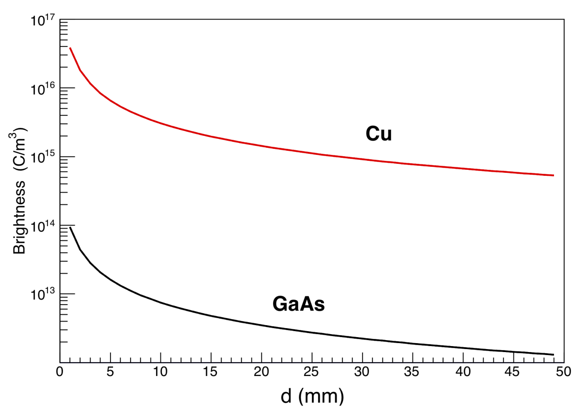

Figure 3: Brightness ($\mathrm{C/m^3}$) for Cu and GaAs are plotted as a function of the electrode distance d with red and black lines, respectively. They are peaked at the lowest d.

As a summary of electron emission from a DC biased gun, the beam emittance can be very small, because the space charge limited flow is made by a simple structure. Although the bias voltage is limited, but the surface field can be large if a narrow electrode gap is employed. The narrow gap has an advantage to increase the current density at the space charge limitation and increase the breakdown limit field, E_{BD}. Of course, there are practical limitations to limit the narrow gap, but a narrow gap is a possible solution to improve the beam performance.

If the surface field is limited very low, the bunch length from gun is huge. In this case, we have to start a low frequency buncher and employ a multi stage bunching sections to reach a short bunch length such as 10 fs. Although it doesn't necessarily make it worse, but we have to care about the non-linearity in these processes to suppress the emittance growth. An example is SACLA [1] starting from a DC biased gun with 1 ns beam, and ending to 10 fs bunch with the multi-stage bunching. The compensation of the non-linearity is essential.

Emittance growth by non-linear space charge is also an issue. In principle, if the space charge is linear in all axes, the emittance growth doesn't occur. 3D ellipsoidal bunch is proposed for the full linearization [12]. An essential problem is that the solutions in free space (3D ellipsoidal) and in gun structure (Space charge limited flow) are different. We have to consider the matching between the different boundary conditions to obtain the highest brightness from the DC gun.

RF ELECTRON GUN

A photo-cathode RF gun is a device to generate electron beam by the photo-electron emission in an RF cavity. The voltage to extract the beam is higher than that of DC gun, which is capable to generate a high intensity bunch with a short bunch length. The emittance growth by the non-linear space charge effect can be suppressed by the linearization and the quick acceleration.

In the RF electron gun, the bunch length is controlled by the time width of the laser pulse. However, the space charge force, especially in near of the cathode, where Lorentz γ is still low, limits the electron emission. Therefore, when considering the ultimate short bunch generation from an RF electron gun, the space charge, not the laser pulse duration, is the main factor that determines it. We consider a delta-function like laser pulse for the electron emission. The charge density is computationally infinite, but the amount of charge is finite, so the electric fields at the head and tail of each bunch can be calculated. In other words, the head and tail of the bunch sees different accelerating fields, resulting a finite bunch length by velocity modulation. This bunch length is then used as the shortest bunch length that can be generated from the RF gun.

Lorentz γ in a RF gun cavity as a function of the distance from cathode z is [13]

$$\gamma(z) = 1 + \alpha kz + \frac{1}{2}\left\{\cos\phi - \cos\left(\frac{\pi}{2} + kz\right)\right\}, \qquad (11)$$

where k is wave number of RF, α is defined as

$$\alpha \equiv \frac{eE_0}{2kmc^2}, \qquad (12)$$

where e is elementary charge, E_0 is peak field (envelope), mc^2 is the rest mass energy of electron, ϕ is RF phase. As an efficient acceleration, $\phi = \pi/2$ is assumed. The second cosine term of Eq. (11) shows the variation of γ in the cell boundary, but we neglect this term since this is not essential for our purpose. Then, Eq. (11) is rewritten as

$$\gamma(z) \sim 1 + \alpha kz. \qquad (13)$$

Time to travel from the cathode to the gun end is

$$\tau = \int_0^L \frac{dz}{\beta c} = \int_0^L \frac{\gamma}{c\sqrt{\gamma^2 - 1}}dz, \qquad (14)$$

where L is the RF gun cavity length, β is Lorentz beta, c is speed of light. It can be integrated by replacing $t = \gamma^2 = (1 + \alpha kz)^2$

$$\tau = \int_{t_1}^{t_2} \frac{1}{2\alpha kc} \frac{dt}{\sqrt{t-1}} = \frac{\sqrt{(1+\alpha kL)^2 - 1}}{\alpha kc}. \quad (15)$$

With a typical parameters such as $eE_0 = 100MV/m$ and $L = 0.15m$ (1.5 cells in S-band), $(1+\alpha kL)^2 - 1$ can be approximated as $\sim (1+\alpha kL)^2$, then Eq. (15) becomes

$$\tau \sim \frac{1+\alpha kL}{\alpha kc} \quad (16)$$

Due to the space charge effect, the acceleration field at the bunch tail is decreased. We consider a cylindrical bunch with charge Q and cross section S in electric field.We assume the electric field is parallel to the cylinder axis. The field at the bunch head E_0, and at the bunch tail E_1 is in a relation $E_1 = E_0 - Q/(\varepsilon_0 S)$ according to Gauss's law, where ε_0 is permittivity of vacuum. The reduction of the accelerating field by the bunch charge is $Q/\varepsilon_0 S$. Due to this reduction of the accelerating field, the bunch tail is delayed as

$$d\tau = -\frac{1}{\alpha kc} \frac{Q}{\varepsilon_0 S E_0}. \quad (17)$$

$d\tau$ is the delay of the bunch tail from the bunch head. The bunch length in RMS σ_z caused by the space charge effect is obtained as

$$\sigma_z = \frac{1}{\sqrt{12}} \frac{1}{\alpha k} \frac{Q}{\varepsilon_0 S E_0}, \quad (18)$$

where we assume electron is moving with c. Figure 4 shows

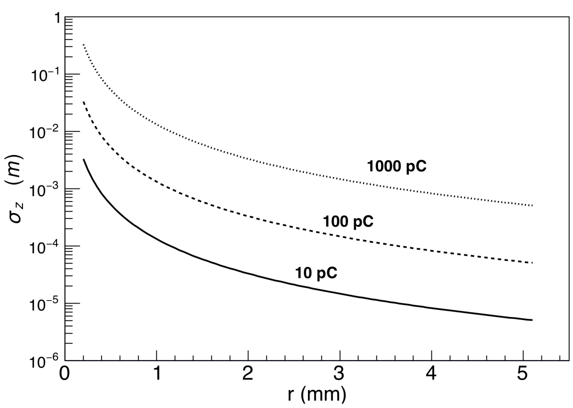

Figure 4: σ_z is plotted as a function of spot size in radius r for 1000, 100, and 10 pC bunch charge with dotted, dashed, and solid lines, respectively.

σ_z as a function of spot size in radius r for 1000, 100, and 10 pC bunch charge with dotted, dashed, and solid lines, respectively. σ_z is proportional to Q and inversely proportional to the cathode area, πr^2. Because the calculation is based on the linear approximation for cosine curve, the bunch length more than $\lambda/4$, 25 mm for S-band is not correct. The bunch splits into two in this case.

The total energy spread of the bunch is determined by the thermal energy of cathode, space charge effect, and energy variation by RF field. However, the energy spread by the space charge is linear regarding to the longitudinal position and it doesn't contribute to the longitudinal emittance. Then, we calculate the energy spread as

$$\Delta E^2 = \Delta E_{th}^2 + \Delta E_{rf}^2 \quad (19)$$

where ΔE_{th} and ΔE_{rf} are contributions by the thermal energy and RF, respectively. ΔE_{th} is determined by temperature T as $\Delta E_{th} = kT/2$.

The energy spread by RF is obtained as follows. Lorentz γ at the end of the gun cavity is [13]

$$\gamma = 1 + \alpha \left\{ \left(n + \frac{1}{2} \right) \pi \sin\phi + cos\phi \right\} \quad (20)$$

where n is number of cells and we set 1 for 1.5 cell RF gun. ϕ is RF phase and $\pi/2$ is assumed for the effective acceleration. Then, we consider the energy variation by phase spread $\Delta\phi$

$$\Delta\gamma = \frac{\partial\gamma}{\partial\phi}\Delta\phi \sim -\alpha \left(1 + \frac{1}{2}\right) \pi \frac{\Delta\phi^2}{2}, \quad (21)$$

where we took up to the second order. In our case, the bunch length and the phase variation in a bunch is starting from zero, and increased up to the final value, σ_z and $\Delta\phi$. We assume the phase variation as a function of z is linear,

$$\Delta\phi(z) = k\sigma_z \frac{z}{L} \quad (22)$$

where L is the cavity length. $\Delta\phi^2$ in Eq. (21) is replaced with the integral of

$$\frac{1}{L}\int_0^L \left(k\sigma_z \frac{z}{L}\right)^2 dz = \frac{k^2\sigma_z^2}{3}. \quad (23)$$

Equation (21) is rewritten as

$$\Delta\gamma = \alpha \left(1 + \frac{1}{2}\right) \pi \frac{k^2\sigma_z^2}{6}. \quad (24)$$

This variation contributes to the longitudinal emittance. RMS of the energy variation is obtained as $sigma_\gamma^2 = \bar{\gamma^2} - \bar{\gamma}^2$. The result is

$$\sigma_\gamma = \alpha \left(1 + \frac{1}{2}\right) \pi \frac{k^2\sigma_z^2}{9\sqrt{5}}. \quad (25)$$

The total energy spread is obtained as quadratic sum of these components as Eq. (19).

$$\sigma_E^2 = \left(\frac{kT}{2}\right)^2 + \left\{ mc^2\alpha \left(1 + \frac{1}{2}\right) \pi \frac{k^2\sigma_z^2}{9\sqrt{5}} \right\}^2, \quad (26)$$

The product of σ_z and σ_E gives the longitudinal emittance $\varepsilon_{n,l}$

$$\varepsilon_{n,z} = \sigma_z \frac{\sigma_E}{mc^2} \quad (27)$$

where σ_E is normalized with mc^2. The thermal energy (or MTE) depends on the material and laser wavelength. The lowest MTE observed for NEA GaAs and copper are 51 meV [10] and 6 meV [11], respectively. 6 meV MTE was observed with copper cathode at 30 K.

Transverse emittance of beam from a RF gun has two components as same as in the longitudinal case; thermal contribution and RF contribution. Time-variant focusing by RF induces the additional emittance. The first component is identical to Eq. (8). The second component by RF field $\varepsilon_{n,x}^{rf}$ is [13]

$$\varepsilon_{n,x}^{rf} = \frac{\alpha k \sigma_x \sigma_\phi^2}{\sqrt{2}}, \quad (28)$$

where σ_ϕ is the bunch size in RF phase. In this estimation by Kim, the longitudinal bunch size is assumed to be a constant in RF gun and the shape is Gaussian. If the bunch starts with zero length and grows up to a bunch length determined by the space charge effect as same as assumed in Eq. (22), $\varepsilon^{rf}_{n,x}$ becomes as

$$\varepsilon^{rf}_{n,x} = \frac{\alpha k \sigma_x^2 \sigma_\phi^2}{9\sqrt{5}}. \quad (29)$$

The transverse emittance is obtained as a sum of these two components. The sum of the energy term of the emittances is taken quadratically as

$$\varepsilon^2_{n,x} = \left(\varepsilon^{th}_{n,x}\right)^2 + \left(\varepsilon^{rf}_{n,x}\right)^2 \quad (30)$$

$\varepsilon^{th}_{n,x}$. $\varepsilon_{n,x}$ is dominated by $\varepsilon^{th}_{n,x}$, except for 1000 pC in $r < 0.5mm$.

Figure 5 shows 6D emittance $\varepsilon_{n,6d}$ with the same definition as that of DC gun, Eq. (9). $\varepsilon_{n,6d}$ is small for the large beam spot size. In the large r region where the thermal contribution is dominant for $\varepsilon_{n,z}$, $\varepsilon_{n,6D}$ is a constant. The reason is understood as that the dependence of r to $\varepsilon_{n,z}$ and $\varepsilon_{n,x}$ are canceled to each other.

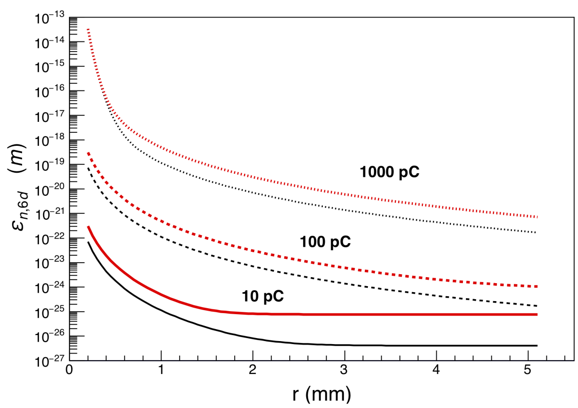

Figure 5: $\varepsilon_{n,6d}$ is plotted as a function of beam radius r for 1000, 100, and 10 pC bunch charge with dotted, dashed, and solid lines, respectively. The black and red lines those for copper and GaAs cathode.

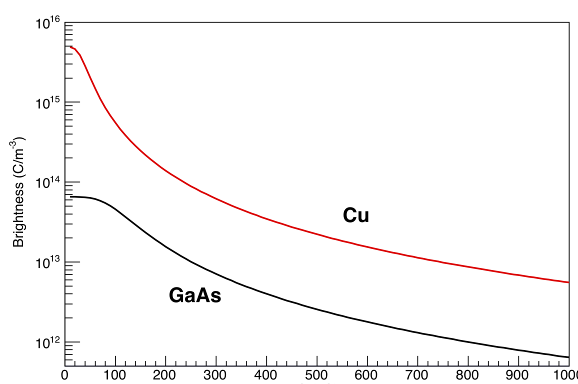

Figure 6: The brightness B is plotted as a function of Q. The red and black lines show those for Cu and GaAs, respectively. The cathode diameter is fixed at 5 mm.

Figure 6 shows the beam brightness B as a function of the bunch charge Q. The cathode radius is fixed at 5 mm. $\varepsilon_{n,z}$ and $\varepsilon^{rf}_{n,x}$ is proportional to square of Q, smaller Q gives higher brightness. The thermal contribution to $\sigma_{n,z}$ and $\varepsilon_{n,x}$ are constant, a saturation at low Q is observed. The brightness with 10 pC bunch charge is 4.9×10^{15}C/m^3 and 6.5×10^{13}C/m^3 for copper and GaAs, respectively.

SUMMARY

We discussed the highest beam brightness from DC and RF electron guns, by assuming ideal conditions such as the non-linear space charge is suppressed completely. Beam brightness is measured as the ratio of the bunch charge and the normalized 6D emittance. Table 1 summarizes the highest beam brightness from these guns in unit of C/m^3. DC gun generates the highest brightness 3.8×10^{16} C/m^3 with the cryogenically cooled copper cathode, and 9.5×10^{13} C/m^3 with GaAs cathode in room temperature. RF gun generates slightly less brightness as 4.9×10^{15} C/m^3 for the copper cathode, and 6.5×10^{13} C/m^3 for GaAs cathode.

Table 1: Summary of the Peak Beam Brightness for DC and RF guns

Gun structure	Cu cathode	GaAs cathode
DC	3.8×10^{16}	9.5×10^{13}
RF	4.9×10^{15}	6.5×10^{13}

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