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EMITTANCE COMPENSATION IN A HIGH CHARGE TOPGUN PHOTOINJECTOR*

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Abstract

A simple acceleration of a high charge, needle-shaped electron bunch from a cathode is affected by strong correlated emittance growth due to current-dependent transverse space-charge forces. It was shown that such emittance growth could be reversed by focusing the bunch soon after it emerges from the cathode, and that one can expect to retrieve the emittance the beam was born with – the intrinsic emittance. We present a space charge emittance compensation study for a 250 pC radiofrequency photoinjector based on a 100 pC design developed by the UCLA team. We expect that a bright electron beam with an order of magnitude improvement over currently operating photoinjectors can be achieved with 250 pC electron bunches that maintain their emittance below 100 nm rad.

INTRODUCTION

Photoinjectors deliver electron beams with high peak currents I and low normalized emittance ε_n and are essential for future linear accelerator-based facilities. Achievable brightness, $B_{5D} = 2I/\varepsilon_n^2$, in these sources scales up with an accelerating gradient and the TOPGUN collaboration between UCLA, SLAC, and INF has shown evidence of 250 MV/m accelerating gradients in cryogenically cooled copper structures. They have also developed the RF design for TOPGUN photoinjector, which is a 1.6-cell S-band cavity ($f = 2.856$ GHz) [1]. Further work has led to the design of versatile, high brightness, cryogenic photoinjector, which is a 1.6-cell C-band cavity ($f = 5.712$ GHz, $\lambda = 5.25$ cm), electron source delivering 100 pC [2], which seems to be the limit for currently operating photoinjectors. Here, we propose to study this electron source for high brightness operation with 250 pC bunches but without optimizing the booster LINAC used to transition from space charge to emittance dominated beam dynamics.

The TOPGUN design is based on the combination of 0.6 and 1.0 C-band cells. Figure 1 shows the profiles of accelerating fields, which have multiple spatial modes. This helps with acceleration efficiency and provides additional focusing but increases the radiofrequency (RF) emittance by 20% over the single spatial mode cavities. The UCLA team has also designed a solenoid, with 0.047 Tm magnetic field integral, required for space charge emittance compensation [3]. Figure 2 shows the on-axis magnetic field profile

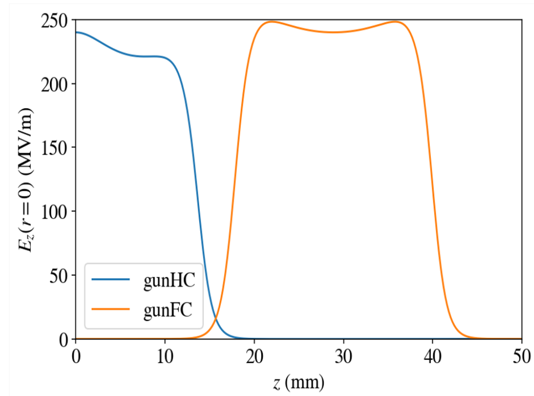

Figure 1: The on-axis field profiles for 0.6 (gunHC) and 1.0 (gunFC) C-band cells (gunFC) designed by UCLA to have 240 MV/m accelerating field on the cathode.

of the solenoid that can be fit to

$$B_z(r=0) = \frac{B_0}{2}\{\tanh\left[b\left(d+z-z_0\right)/2\right] + \tanh\left[b\left(d-z+z_0\right)/2\right]\}$$

function, which implies that the solenoid is $2d = 72.5$ mm long and its center is located $z_0 = 125$ mm from the cathode. The solenoid has the maximum magnetic field of about $B_0 = 0.6504$ T and the bore radius of $\pi/b = 23.5$ mm, which determines the region of the fringe field.

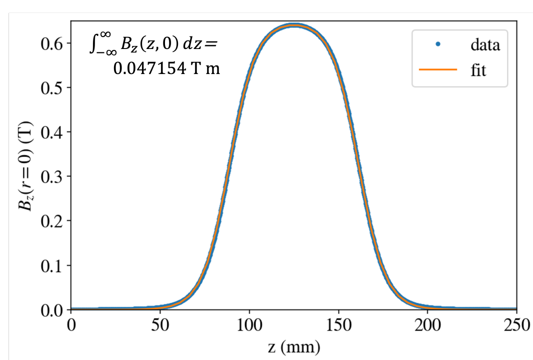

Figure 2: The on-axis magnetic field of the UCLA solenoid positioned 125 mm away from the cathode. The profile suggests that it is 72.5 mm long with a bore radius of 23.5 mm.

SPACE CHARGE EMITTANCE COMPENSATION

The emittance compensation scheme developed by the UCLA team aims to eliminate effects of the space charge

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forces in a needle-shaped bunch, $\sigma_r \ll \sigma_z$, by reversing transverse dynamics with solenoid focusing. They utilize a sigma-cut Gaussian profile, $r \leq \sigma_{\text{uv}}$, of the laser beam for photoemission in order to linearize transverse space charge forces. Ref. [3] suggests that the charge density near cathode determines transverse dynamics and that the choice of the laser spot size and length should be $\sigma_{r,z} \propto Q^{1/3}$ while maintaining the same aspect ratio. The laser parameters for 100 pC UCLA design are $\sigma_{\text{uv}} = 151\,\mu\text{m}$ pre-cut, or $\sigma_{\text{x}} = 68\,\mu\text{m}$ post-cut, and a uniform pulse length $\Delta T = 5.8$ ps [2]. We expect that a 250-pC photoinjector should operate with $\sigma_{\text{uv}} = 205\,\mu\text{m}$ and $\Delta T = 7.87$ ps in order to achieve the same level of space charge emittance compensation. The UCLA design uses the solenoid peak field of 0.58 T, which is 0.892 fraction of the maximum field.

The space charge emittance compensation also depends on the accelerating gradient. We can control acceleration profile by choosing phases of the fields in each cell. The maximum mean momentum gain (MMMG) is achieved when the phases of the cells are set to 115° and 319° with respect to the on-crest deceleration. In this case, the final energy from the TOPGUN photoinjector is equal to $\bar{E}_{\text{f}} = 6.55$ MeV with 240 MV/m peak electric field at the cathode. The UCLA TOPGUN photoinjector operates in π-mode, where the phase difference is 180° [2]. The MMMG is then achieved when the launching phase is set to 134° resulting in the final energy being equal to $\bar{E}_{\text{f}} = 6.40$ MeV.

A preliminary design of a high charge TOPGUN photoinjector has considered optimization of the two acceleration cases above. In the case of independent phasing of the cells, we have found the minimum projected normalized emittance to be $\varepsilon_n^{(r)} = 140$ nm rad for $\sigma_{\text{uv}} = 298\,\mu\text{m}$ and $\Delta T = 7.33$ ps with 0.914 solenoid field fraction. The π-mode case provides even lower emittance of $\varepsilon_n^{(r)} = 116$ nm rad for $\sigma_{\text{uv}} = 240\,\mu\text{m}$ and $\Delta T = 7.24$ ps with 0.897 solenoid field fraction and accuracy of 10 G. These optimized values are slightly different from the scaled values above that produces a slightly larger emittance of $\varepsilon_n^{(r)} = 125$ nm rad.

Figures 3 and 4 show the sensitivity of the found solution to the changes in the laser spot size and the laser pulse length. It suggests $\pm 20\,\mu\text{m}$ spot size and ± 0.5 ps pulse length variations are tolerable.

LOS ALAMOS TOPGUN DESIGN

The Los Alamos (LA) team has designed a realistic 1.6 cell C-band structure with RF waveguides and a laser port included [4]. The length of the waveguides has been optimized to provide equal field strength and a 180-degree phase difference between the cavities (see Fig. 5). The MMMG case of $\bar{E}_{\text{f}} = 6.40$ MeV energy is achieved with 131° launching phase 230 MV/m peak field on the cathode, which is lower that was required for the UCLA design. The minimum projected normalized emittance, however, is $\varepsilon_n^{(r)} = 133$ nm rad for $\sigma_{\text{uv}} = 282\,\mu\text{m}$ and $\Delta T = 7.5$ ps with 0.9 solenoid field fraction, which is higher than our goal of $\varepsilon_n^{(r)} = 100$ nm rad.

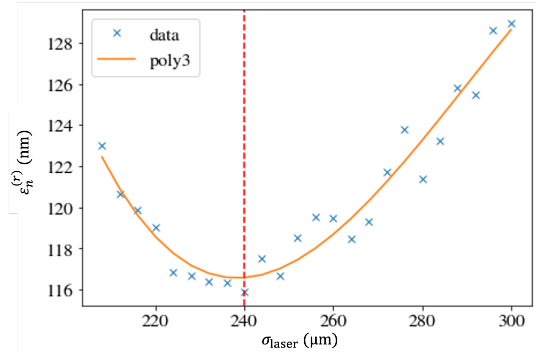

Figure 3: The dependence of the minimum projected normalized emittance on the laser spot size. The spot size change of about $\pm 20\,\mu\text{m}$ does not significantly affect the emittance value.

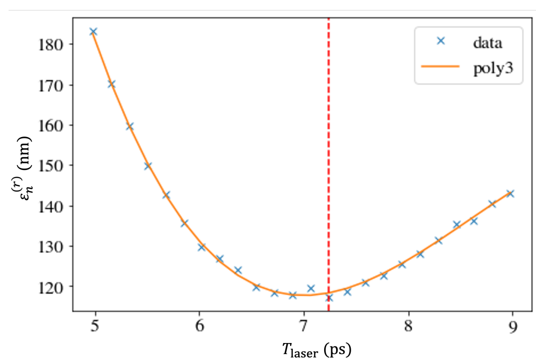

Figure 4: The dependence of the minimum projected normalized emittance on the laser pulse length. The pulse length change of about ± 0.5 ps does not significantly affect the emittance value.

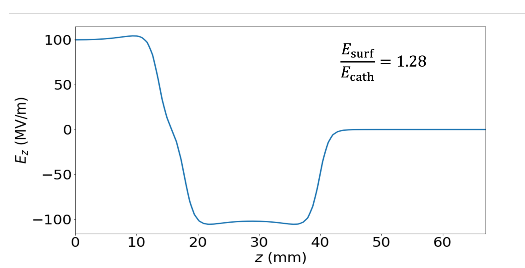

Figure 5: The electric field values on axis of the LA TOPGUN injector.

INTRINSIC AND RF EMITTANCES

What limits us from achieving our emittance goal? This is due to the intrinsic emittance of the cathode and the emittance due to RF field. In the above results, we have followed GPT [5] prescription to describe a metallic cathode with a sigma-cut Gaussian distribution. This prescription results in the intrinsic emittance due to the excess energy of emitted electrons $E_o = 0.01$ eV and the laser spot size $\sigma_{\text{uv}} = 300\,\mu\text{m}$: $\varepsilon_n^{(x)} = \sigma_x \sqrt{\langle p_x^2 \rangle}/m_e c$ or $\varepsilon_n^{(x)} = \sigma_x \sqrt{2eE_o/3m_e c^2} = 15$ nm rad, which is small.

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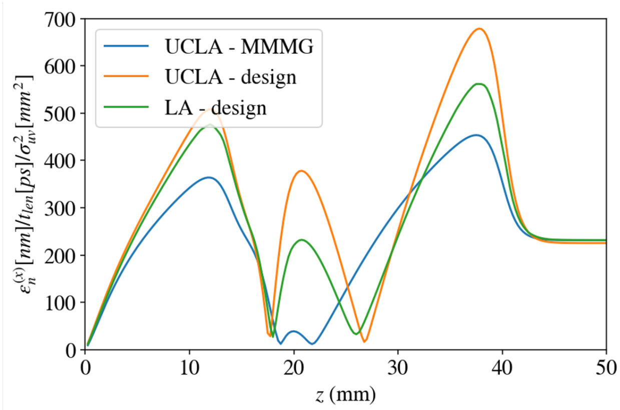

Figure 6: Evolution of the RF emittance in the TOPGUN photoinjector. It is scaled to an initial volume occupied by the beam. The different evolution converges to roughly the same value at the exit of the photoinjector.

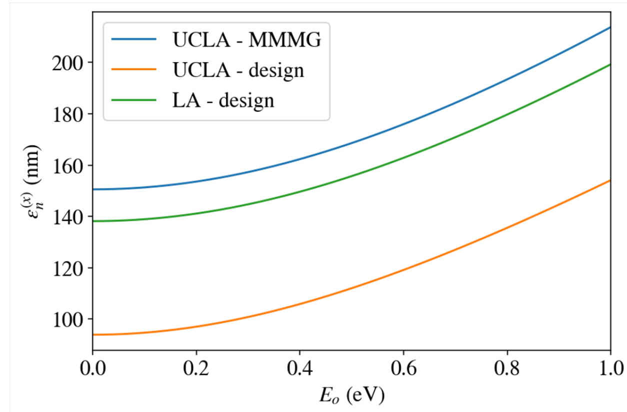

Figure 7: Combining the intrinsic and RF emittance for different values of the excess energy. The intrinsic emittance in the high charge TOPGUN photoinjector becomes important for $E_o > 0.3$ eV.

The RF emittance contribution has been studied in a series of simulations without intrinsic emittance and space charge. We have found that the scaling of RF emittance in TOPGUN is $\propto \Delta T \sigma_{\mathrm{uv}}^2$. Figure 6 shows how the proportionality coefficient changes inside the RF gun. We can see that the phase choice affects the RF emittance in UCLA cavities and that LA design has RF emittance different from the both cases of UCLA design. The different evolution have the same scaling coefficients at the end of the gun, (231.3, 225.2, 231.7) $\mathrm{nm\,rad\,ps^{-1}mm^{-2}}$. We thus believe that the RF emittance comes from the RF kick in the final iris.

The analysis to this point has been done for $E_o = 0.01$ eV, which is somewhat arbitrary. The CARIE collaboration [6] will use high quantum efficiency photocathodes with excess energy higher than 0.01 eV. The presented analysis shows that the intrinsic and RF emittances scale differently and dominate at different E_o values. Figure 7 combines the intrinsic and RF emittance contributions in quadrature as a function of excess energy. It implies that for $E_o < 0.3$ eV, or for the mean transverse energy (MTE) less than 0.1 eV, the TOPGUN photoinjector is limited by the RF emittance.

We have finally performed optimization of LA TOPGUN design for each value of the excess energy as shwon in Fig. 8. The conclusion is that 240 MV/m peak field and 125.4° launching phase in combination with $\Delta T = 7.34$ ps are the best. We have however observed that σ_{uv} should be reduced from 250 µm to 220 µm in order to counteract the growth of intrinsic emittance with increase of the excess energy.

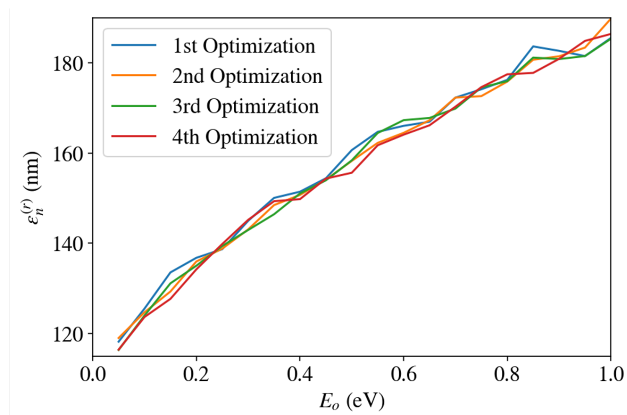

Figure 8: Four different optimizations strategies for LA TOPGUN design as a function of the excess energies. The goal of these optimizations was to produce minimum projected normalized emittance while constraining parameters of the design. In one optimization, the launching phase and the pulse length were kept at 125.4° and $\Delta T = 7.34$ ps values. It seems that each optimization converges to the same minimum value with different underlying settings.

CONCLUSION

We have presented the space charge emittance compensation study in a high charge TOPGUN photoinjector and compared it to the UCLA design with a 2.5x times lower charge. The space charge compensation does not depend on the total charge as long as the charge density at the cathode remained the same. Our study has also demonstrated that the emittance is limited by the RF contribution of the gun that scales linearly with charge if MTE is below 0.1 eV. The relative phase of the cells in the RF gun and the field profile can however change this contribution and requires further examination. The minimal emittance in case of the larger excess energy is limited by the intrinsic emittance that could be controlled by the laser spot size on the cathode. This control however must be balanced with the ability to compensate the space charge induced emittance.

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