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HIGH GRADIENT C-BAND PHOTOINJECTOR PERFORMANCE UTILIZING SACRIFICIAL CHARGE TO ENHANCE BRIGHTNESS

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Abstract

We report simulation results showing the use of sacrificial bunch charge to achieve high brightness in photoinjector beamlines designed for Ultrafast Electron Diffraction (UED) and Inverse Compton Scattering (ICS). The beam undergoes nonlaminar focusing during which the tails dynamically linearize the core's transverse phase space. An aperture then removes the resulting diffuse tails, leaving a beam with high brightness. We employ this scheme in C-band photoinjector guns, whose high gradients are attractive for both low (UED) and high charge (ICS) applications. In our simulations we use a 1.6 cell distributed coupling gun with a peak field at the cathode of 240 MV/m. We start with a momentum spread typical for beams emitted from Cu photocathodes and use a multi-objective genetic algorithm to obtain a Pareto front minimizing bunch length and emittance. For ICS applications, we obtain an extremely small minimum emittance of 137 nm at a final charge of 250 pC per bunch and 1.73 ps rms bunch length. For a final bunch charge of 10^5 electrons, typical for UED experiments, we obtain an emittance of 4.2 nm at an rms bunch length of 54 fs. Both results far exceed the experimental brightness state of the art for these applications.

INTRODUCTION

Cold copper C-band photoinjectors promise to enhance accelerator performance in a wide variety of applications due to the high gradients they can achieve which enable high initial beam brightness [1–3]. These applications range from low bunch-charge applications such as Ultrafast Electron Diffraction (UED) [4] to high bunch charge applications such as Inverse Compton Scattering (ICS) [5] and Free Electron Lasers [6, 7]. In UED, the increase in brightness leads to shorter bunch lengths and lower transverse emittances which improve time resolution and unlock the ability to do UED experiments on samples with long coherence lengths and spatial dimensions on the few micron scale. In ICS, the increased brightness improves the efficiency of the high energy photon production as well as the brightness of the produced beam.

Maximizing the benefits of this increase in initial beam brightness requires mitigating brightness degradation. Nonlinear space charge forces distort the phase space of the beam increasing the effective volume of the beam in phase space and decreasing beam brightness, which can be thought of as the effective phase space density of the beam. Recent simulation work has shown that using sacrificial charge can be used to linearize the phase space of the final beam [8]. In this work, we report the results of optimizations in simulation using a cold copper C-band photoinjector and sacrificial charge in low bunch charge and high bunch charge regimes. In both regimes the brightness values obtained exceed the state of art.

OPTIMIZATIONS AND RESULTS

The simulations were carried out using the General Particle Tracer (GPT) [9] code and we employ the Xopt framework to perform multi-objective optimizations using its implementation of the Non-dominated Sorting Genetic Algorithm II (NSGAII) [10]. Each simulation takes an input set of parameters defining the initial beam distribution and a set of beamline parameters which are varied by the genetic optimizer. At the final output location, the particles within some radius are selected. The radius is chosen such that the total charge of those particles is the desired final charge. We denote these particles as the "survivors" and the particles outside that radius as the "clipped" particles. Thus the initial bunch charge is an optimization parameter. The transverse emittance (from here on referred to simply as the emittance) of the survivors is computed as the square root of the four dimensional transverse emittance of the survivors. The optimization objectives are the bunch length and emittance of the survivors which determine the five dimensional brightness according to $B_{5D} = \frac{Q}{\sigma_t \epsilon_n^2}$. Generally these are competing objectives, therefore the result of the optimizations is a Pareto front showing the trade off between emittance and bunch length.

The beamline used in these simulations consists of a 1.6 cell 5.712 GHz (C-band) distributed coupling gun producing a 240 MV/m peak field at the cathode. The gun accelerates the beam to approximately 6.7 MeV, and is followed by a solenoid lens at a distance of 0.125 m from the cathode, which may be difficult in practice due to geometric constraints, especially for cryogenically cooled guns. An aperture at the end is simulated by selecting a subset of the particles within a given radius as described previously. For UED applications, the sample plane would be located shortly after the aperture. In the beamline design for ICS, the aperture is placed after a linac section which accelerates the beam to approximately 100 MeV.

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Initial Beam Distribution

In these simulations, the initial distribution is assumed to be generated via photoemission from a flat photocathode. The longitudinal and transverse beam profiles are then given by the respective incident laser profiles, which can be shaped. The longitudinal distribution is given by a supergaussian of power p. In the limit $p \to \infty$, the supergaussian approaches uniform distribution. The transverse profile is given by a Gaussian distribution truncated at a radius $n_c\sigma$, where σ is the rms width of the full Gaussian.

The momentum distribution is a $3D$ gaussian with $\sigma_{p_x} = \sigma_{p_y} = \sigma_{p_z} = \sigma_p$ and $p_z > 0$. The momentum spread is given by $\sigma_p = \sqrt{m_e MTE}$, where m_e is the electron mass and the mean transverse energy (MTE) is the effective termperature of the initial beam. The MTE is determined by the photoemission wavelength and photocathode workfunction. For copper photocathodes at room temperature, the MTE is on the order of 500 meV. This value was used to set the initial momentum spread in the optimizations discussed in this proceding. Lower MTE values would yield higher brightness.

Optimization Results for 250 pC Final Bunch Charge

The final desired bunch charge for the optimizations for a beamline designed for ICS was 250 pC. A summary of the optimization parameters and the ranges over which they could be varied is given in Table 1. The number of macroparticles used in these simulations was such that the survivor beam contained 10000 macroparticles. The initial number of macroparticles is determined by scaling this by the ratio of initial to final bunch charge.

Table 1: Optimization parameters and ranges for optimizations with 250 pC final bunch charge. When applicable the units are shown in parentheses. The solenoid field is given as a fraction of the maximum design solenoid field. The gun phase is relative to the phase that maximizes the gradient at the cathode, and the linac phase is relative to the phase that maximizes the final mean kinetic beam energy. The rightmost column lists the parameters corresponding to the minimum emittance case.

Parameter	**Range**	**Min. ϵ_n**
Bunch charge Q (pC)	250 - 800	782
Initial $\sigma_{x,y}$ (mm)	0.01 - 1	0.24
Initial cutoff radius (σ)	0.1 - 2	0.26
Initial σ_t (ps)	0.1 - 2	1.7
Supergaussian power p	1 - 100	52
Fractional solenoid strength	0 - 1.2	0.98
Gun phase (deg)	-15.0 - 15.0	-2.6
Linac phase (deg)	-15.0 - 15.0	12

The Pareto front obtained from these optimizations is shown in Fig.1. We obtain a minimum emittance of 137 nm, with a corresponding rms bunchlength of 1.73 ps. The parameters corresponding to this particular point on the Pareto front are listed on the rightmost column of Table 1. The transverse beam profile for this case is shown in Fig. 2. The rms transverse final beam size for this case is 49 µm. The initial bunch charge was in all cases between 500 pC and 780 pC so that less than 50% and in some cases less than 30% of the total charge is retained. All points on the Pareto fronts used an initial longitudinal profile with $p \geq 15$, which correspond to distributions well approximated by uniform distributions.

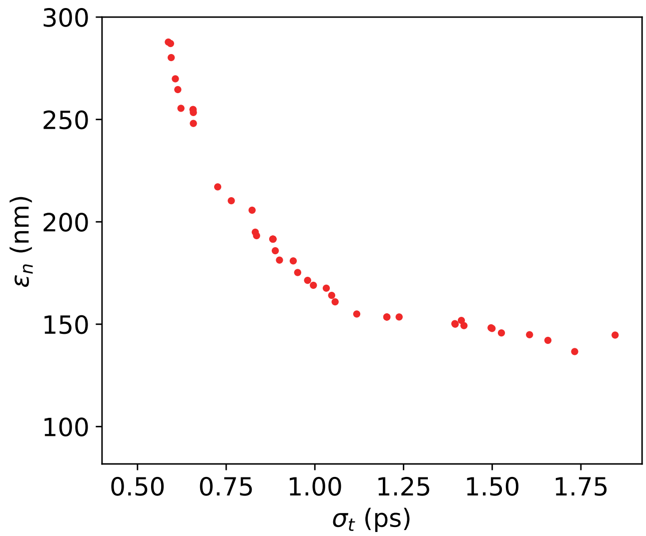

Figure 1: Pareto front from optimizations for beamline designed for ICS using a final bunch charge of 250 pC.

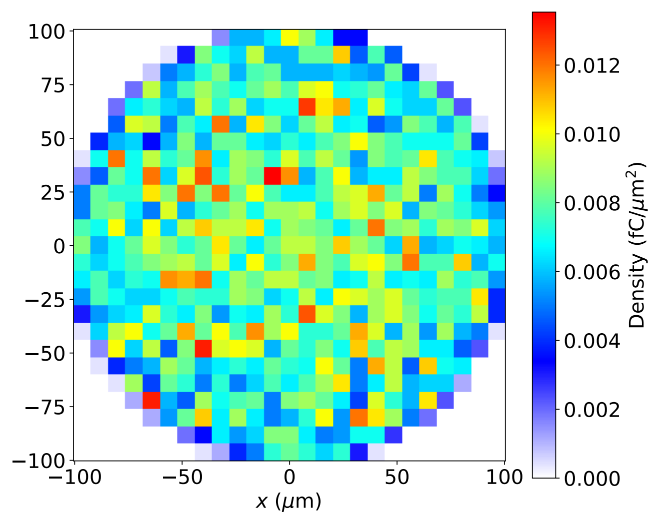

Figure 2: Transverse distribution of the survivors at the location of minimum survivor emittance for the example with ϵ_n = 137 nm and σ_t = 1.73 ps.

Optimization Results for 16 fC Final Bunch Charge

For the low bunch charge simulations performed for UED applications, the final desired bunch charge was 16 fC. In

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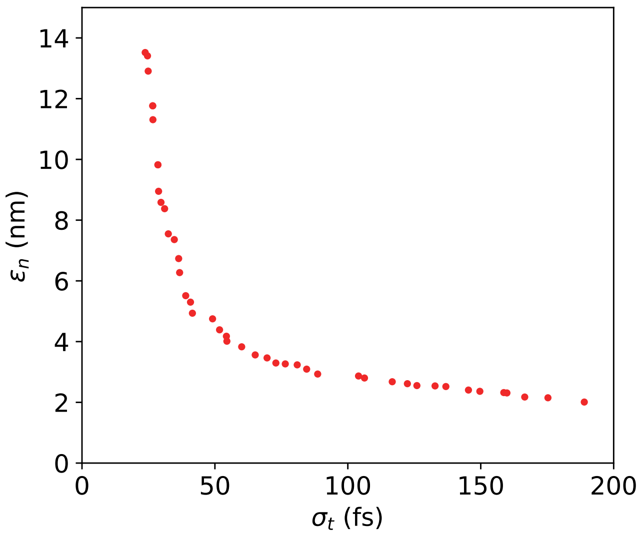

Figure 3: Pareto front from optimizations for beamline designed for UED with a 16 fC.

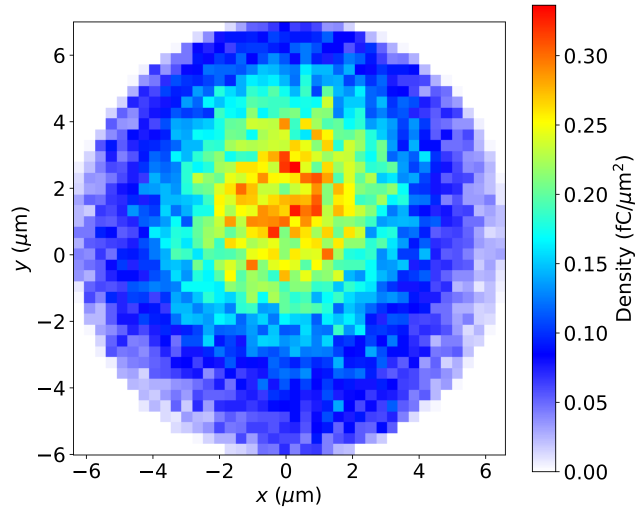

Figure 4: Transverse distribution of the survivors at the location of minimum survivor emittance for the example with ϵ_n = 4 nm and σ_t = 55 fs.

these optimizations, the location of the aperture was variable. In this case, the simulation outputs the beam distribution at a set of locations along the beamline. At each of these locations, a set of survivor particles with the desired final charge is selected. The emittance of these particles is computed to determine the location at which the minimum survivor emittance is achieved. The optimization objectives are then this minimum emittance and the survivor bunch length at this location.

Table 2 summarizes the optimization parameters and their ranges used in these simulations. In these simulations, the final number of macroparticles was set to be 2000. The initial distribution for these simulations used p = 1 and n_c = 3, such that the initial distribution is a Gaussian distribution both transversely and longitudinally.

Table 2: Optimization parameters and ranges for optimizations with 16 fC final bunch charge. As in the 250 pC optimizations, the solenoid field is given as a fraction of the maximum design solenoid field and the gun phase is relative to the phase that maximizes the gradient at the cathode. The rightmost column lists the parameters corresponding to the case with a final 55 fs bunchlength.

Parameter	**Range**	σ_t**=55 fs**
Bunch charge Q (fC)	16 - 80	20
Initial $\sigma_{x,y}$ (μm)	0.1 - 100	3.9
Initial σ_t (ps)	0.025 - 5	0.032
Fractional solenoid strength	0 - 2	0.98
Gun phase (deg)	-40 - 90	7.4

Figure 3 shows the Pareto fronts obtained from these optimizations. At an rms bunch length of 55 fs We obtain an emittance of 4 nm. The simulation parameters for this point on the Pareto front are listed in Table 2. Figure 4 shows the transverse profile of the survivors at the location of the aperture for this case. The corresponding final transverse beam size is approximately 3 μm. In these optimizations, the initial bunch charge was ≤ 30 fC, and in many cases ≤ 20 fC.

Conclusion

We performed multi-objective optimizations for beamlines designed for Inverse Compton Scattering and Ultrafast Electron Diffraction. These simulations were carried out using a Mean Transverse Energy (MTE) of 500 meV, which is typical for room temperature copper photocathodes commonly used in photoinjectors. In these optimizations, the initial bunch charge was an optimization parameter chosen to optimize the emittance and bunch length of a core with the final desired bunch charge. For a final bunch charge of 250 pC, a minimum emittance of 137 nm was obtained with an bunch length of 1.73 ps and an rms transverse size of 49 μm. The final 250 pC bunch charge was 30%-50% of the initial bunch charge. For a final bunch charge of 16 fC, suitable for UED, we find at a 54 fs rms bunch length an emittance of 4.2 nm with an rms transverse size of 3 μm. In some cases the final 16 fC was more than 80% of the initial bunch charge.

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