OFF-AXIS BEAM DYNAMICS STUDY IN RF PHOTOCATHODE ELECTRON SOURCES *

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Abstract

We report on simulations and analysis of off-axis electron emission in a high-field VHF electron gun and beam dynamics in the photoinjector downstream. The electron gun is the core of the Advanced Photoinjector Experiment at Lawrence Berkeley National Laboratory, aimed toward the development of a novel source for a high repetition rate Free Electron Laser. People may operate the drive laser away from the cathode center in some special cases. However, off-axis emitted beam will result in a growth of the projected transverse emittance due to correlations between the transverse and longitudinal degrees of freedom. In this paper, we will evaluate the off-axis beam characteristic and describe simulation results which indicate that a realistic implementation of correction procedure would compensate this source of emittance growth. A multi-objective genetic optimizer tool is induced for beam property improvement.

INTRODUCTION

RF photocathode electron guns are built to generate high brightness beams with low emittance and large charge. Typically on RF cathode, a laser excites photo-emission in the center area to get the best performance in terms of emittance. However, in some cases, it is necessary to operate off-axis electron emission, such as the quantum efficiency (QE) depletion in the cathode center after hours of center emission. The challenge in using off-axis emission at the cathode is controlling emittance growth that can be induced in RF guns. This is because the time-dependent focusing effects lead to distribution asymmetries and longitudinal-transverse correlations, which will finally increase the beam emittance.

In this paper, we evaluate this effect as an example on the the VHF gun of Advanced Photoinjector Experiment (APEX) at Lawrence Berkeley National Laboratory (LBNL), and define a correction procedure that can largely compensate for the emittance growth. A useful computational tool to optimize multi-objective is applied in order to enable global optimization of high brightness injector parameter and correct off-axis emission. The introduction to the APEX and the recent status can be found in [1, 2]. Figure 1 shows the schematic layout based on VHF gun that will be used in simulations. A 100 pC charge bunch is emitted in a 186 MHz normal-conducting VHF gun, accelerated to 800 keV at the gun exit, and further boosted to 95 MeV by eight 9-cell 1.3 GHz TESLA-type cavities. The beam out of the cathode has a bunch length of 33 ps with plateau distribution and rms beam size of 192 μm with uniform distribution. The two solenoids between the gun and TESLA cavities are tuned to optimized emittance compensation setting, and a 1.3 GHz Buncher cavity is applied for proper bunch compression. The off-axis emitted beam will result in great emittance increase and misalignment propagation through the beamline. Correcting the beam to on-axis downstream the gun exit does not solve the problem because the emittance growth is produced by time-dependent defocusing force in the gun cavity. We will introduce an effective correction procedure to mostly compensate the emittance growth. Space charge effect is not considered in this paper for simplify, further calculation and analysis will be discussed in [3].

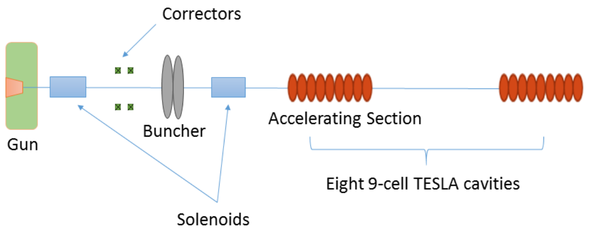

Figure 1: Schematic of the beamline based on the VHF gun. The injector exit is located at 15 m downstream from the cathode.

MULTI-OBJECTIVE GENETIC OPTIMIZATION

In this section, we will introduce a multi-objective genetic optimizer as a useful tool to optimize high-brightness injector parameters.

The method of multi-objective genetic optimization is an effective approach to solve the problem with multiple competing goals. The optimizer was written by integrating the multi-objective genetic algorithm NSGA-II [4] together with the beam dynamics tool ASTRA [5], in order to enable global optimization of high-brightness injector parameters. It has been actively used in injector design for APEX with two objectives of minimizing the emittance and the bunch length. The optimizer is written primarily in C language and typically run in parallel on about 100 processors. Once the optimizer is converged after adequate generations, a

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population of good solutions can be obtained in a Pareto front, showing trade-offs between the emittance and bunch length. Detail optimization procedure to obtain the settings for the gun, the solenoid, and RF cavities is reported in [6], which determines the nominal settings used in this paper.

CORRECTION OF EMITTANCE GROWTH

Previously, we have introduced the method of multi-objective genetic optimization to obtain optimal settings in the injector. Based on the nominal settings, a possible correction procedure for off-axis beam is investigated to finally reduce the off-axis beam emittance growth.

Assume that a beam with 2.0 mm misalignment in horizontal, ten times of rms laser spot, is emitted on the cathode of the VHF gun. The beam will maintain offset downstream, go as far as 7.3 mm offset in the first solenoid and 4.1 mm at injector exit. The misalignment is transferred from horizontal to vertical due to the two solenoids that rotate the beam by roughly 90 degrees. Compared with on-axis beam, the final emittance of the 2.0 mm offset beam is increased by 2.6% and 147.9% in the horizontal and vertical, respectively. If we further investigate particle distribution at the injector exit, we can see an evident correlation between the vertical plane and longitudinal position, and the beam's cylindrical symmetry is destroyed by transverse RF kicks in RF cavities.

Before introducing the correction optimization, we will adjust the first solenoid to enforce the beam passing through the symmetry axis, for the purpose of future emittance compensation. Since the solenoid is equipped with remotely controlled motors, it can be adjusted for both its position and orientation angle. For 2 mm off-axis beam, the first solenoid is shifted to 8 mm off-center and rotated in the $x-z$ plane by 22 mrad, which can be found by ASTRA simulation.

Simulation indicates that steering the beam back into axis alignment results in a beam with a larger projected emittance. In order to obtain a minimum emittance solution at the injector exit, the bending radii of the two pairs of correctors before the buncher cavity are adjusted to vary the beam alignment. Based on the full injector optimized setting, the four bending radii are set as knobs, the normalized horizontal rms emittance and the vertical rms emittance are chosen as two objectives to be minimized. As described previously, the result is not a single solution, but instead a set of solutions that are optimal in a Pareto sense Fig. 2. It is a trade-off between horizontal and vertical emittance. The final decision on the correction procedure is the one that gives the minimum value of the emittance geometric mean ε_G:

$$\varepsilon_G = \sqrt{\varepsilon_x \varepsilon_y} \tag{1}$$

where ε_x and ε_y are the horizontal and vertical normalized emittances. The minimum ε_G attained along the Pareto front is 0.207 mm-mrad, while the corresponding values are 0.312 mm-mrad for the off-axis uncorrected beam and 0.196 mm-mrad for the on-axis emitted beam, respectively. This indicates that the optimization scheme can almost remove the emittance growth due to off-axis emission.

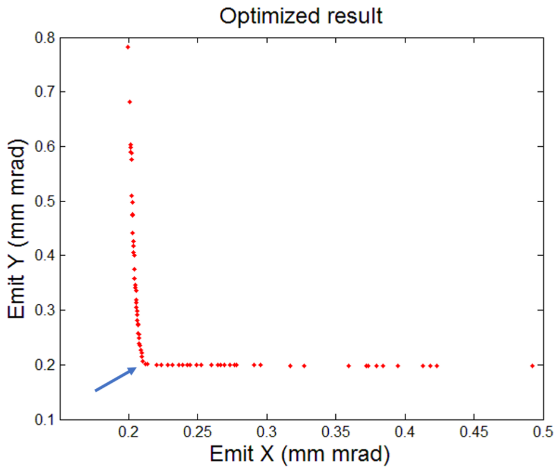

Figure 2: Pareto front of correction for off-axis emitted beam. The solution with minimum ε_G is marked as an arrow.

The bending radii of the correctors corresponding to this optimized solution are listed in Table 1. A negative bending radius represents a bending direction opposite the bends with positive radii. In Fig. 3, it has compared along the injector the evolution of the transverse beam centroid and the rms beam emittance between the optimized beam and the uncorrected beam. It is notable that the optimized beam is not steered into axis alignment by the correctors, shown in black of the upper graph. Instead, the beam propagates off-axis through the buncher and accelerating cavities, and it remains off-axis at the exit of the injector (15 m). Compared with uncorrected beam, the optimized corrected beam has a noteworthy decrease in emittance.

Table 1: Correctors Bending Radii for 2 mm Off-axis Beam Emittance Optimization

Parameter	Value
1^{st} corrector in horizontal	0.659 m
1^{st} corrector in vertical	6.447 m
2^{nd} corrector in horizontal	14.672 m
2^{nd} corrector in vertical	-32.992 m

Although the off-axis emitted beam remains off-center at the exit of the present stage of the injector, one may still align the beam on-center before downstream acceleration to higher energy. More correctors should be applied downstream to steer the beam to on-axis, proceeding with further accelerating sections. One may notice that the beam at the second series of correctors has larger rigidity than at the first one, because of the higher energy. The bending radii for the second series of correctors, which can also be evaluated by similar ways as in previous section, are still practical. At the end of the second accelerating section, the final beam emittance and other parameters are nearly identical to those of a beam emitted on-axis at the cathode.

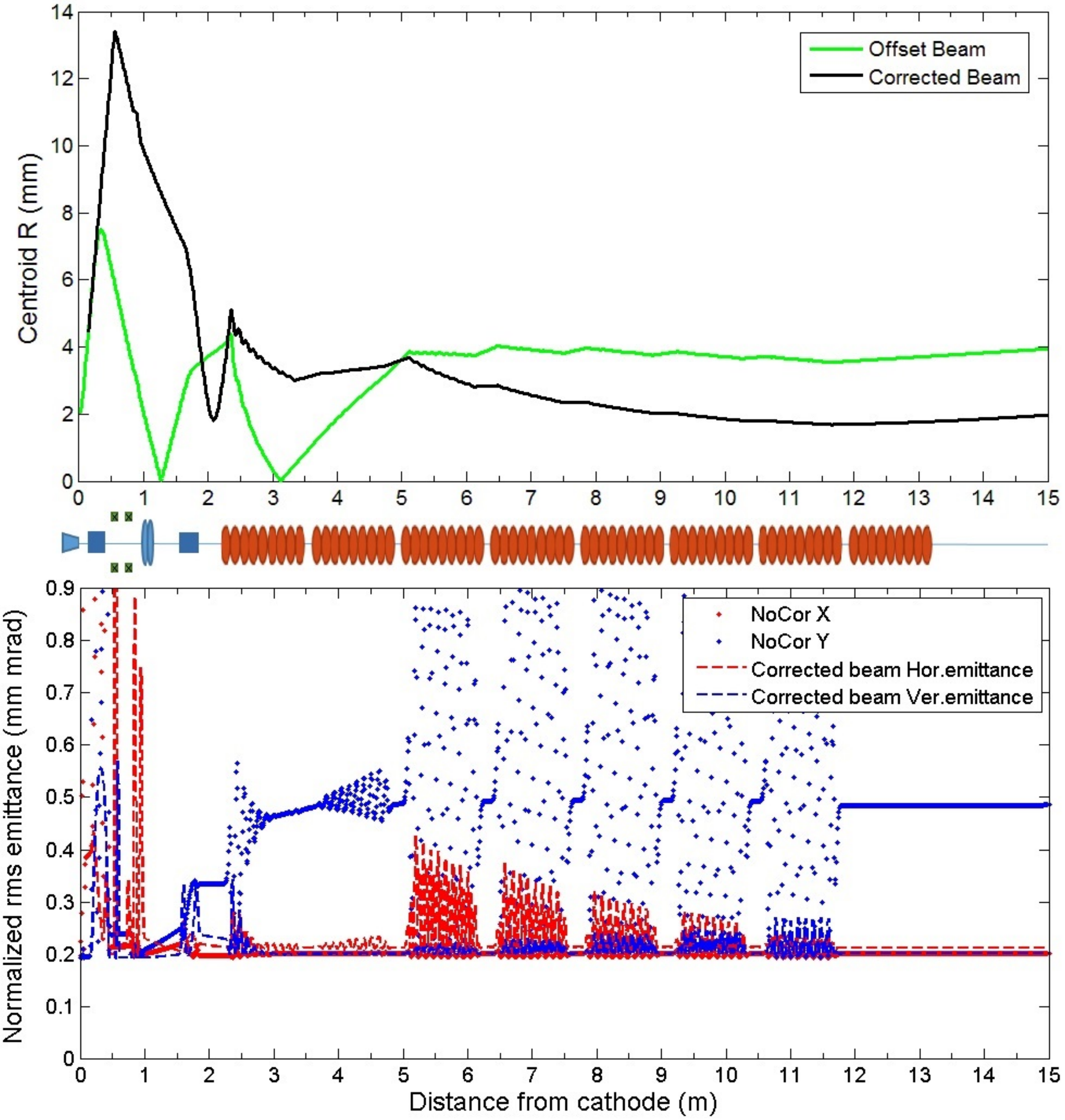

Figure 3: Centroid and emittance evolution of optimized corrected beam. Optimized and uncorrected beam centroid are plotted with black and green lines respectively in upper graph. Transverse emittance for optimized beam and uncorrected one are plotted with dash lines and dots. Red color stands for horizontal plane and blue one represents vertical plane.

CONCLUSION

By using a proper setting for the corrector dipoles, the emittance growth of a beam emitted off-axis in an RF photoinjector can be compensated to achieve an emittance similar to that of a beam emitted on-axis. By further alignment, the beam can be made to return on-axis with acceptable emittance growth at high energy. The emittance growth of off-axis emitted beam is due to time-dependent RF effect, which is independent of space charge effect. Although the space charge effect was not taken into consideration above, the correction procedure is still practicable. Further space charge calculation will be included in the future [3].

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