A SPATIALLY SEPARATED TWO FREQUENCY RF GUN DESIGN FOR BEAM BRIGHTNESS IMPROVEMENT

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Abstract

Recent theoretical and experimental studies show that transverse beam brightness of photoinjector can be improved by cigar beam photoemission, and then beam peak current is increased with a RF buncher following the gun. We apply this concept to a S-band photoinjector by adding a harmonic RF buncher closely to a S-band RF gun, forming a spatially separated two frequency RF gun, targeting a 200 pC beam with emittance < 0.2 mm·mrad and 30 A peak current. Both S/X-band and S/C-band combinations are considered, and an optimized solution with 30 A peak current and 0.1 mm·mrad slice emittance are presented.

INTRODUCTION

Transverse beam brightness of state of the art photoinjectors is approaching maximum beam brightness at photocathode [1]. Cathode beam brightness can be further improved by increasing the electric field at the cathode, reducing residual thermal electron energy at photoemission, or changing the aspect ratio of laser dimensions from pancake to cigar photoemission regime, i.e. reducing transverse laser spot size and increasing longitudinal laser duration proportionally [2]. The last method trades photoemission peak current for transverse beam brightness, thus a buncher cavity is needed after the gun to increase beam peak current at photoinjector exit. However, the RF emittance growth in the gun is increased due to the longer initial bunch length, and the longitudinal beam distribution could be highly asymmetric after compression, which leads to a less effective beam for applications such as XFELs.

In order to reduce the RF emittance growth and longitudinal beam distribution asymmetry, the spatially superimposed two frequency RF gun was proposed [3–5]. Though the idea being verified by beam dynamics simulations, the realization is hard due to engineering and tuning difficulties on achieving the fundamental mode and High Order Mode (HOM) overlapped in the same RF structure simultaneously. In this paper, we propose a different routine for two frequency RF gun, separating the two RF modes into the fundamental mode cavity and the HOM cavity. By integrating a BNL-type 1.6 cell S-band RF gun and a harmonic RF buncher, the beam can be compressed downstream the gun, so that beam peak current at injector exit can be achieved with a lower beam peak current at cathode, therefore the laser duration can be longer and laser radius can be smaller, consequently the emittance contributed by the cathode is then reduced. The buncher can also work as a phase-space linearizer for compensating the 2^{nd} order RF effect to shape a more symmetric beam. In the following we'll go through the gun cavity design and the preliminary beam dynamic studies by employing a genetic optimizer.

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GUN CAVITY DESIGN

A typical S/X-band gun profile is shown in Fig. 1. The fundamental mode cavity is inherited from the BNL-type 1.6 cell S-band RF gun, and the HOM cavity is a single pillbox-like X-band cavity. The beam tube between the two cavities could be long enough to make room for a solenoid, which is called split configuration, otherwise could be very short for compactness, which is the combined configuration. For the S/X-band gun we take the latter configuration.

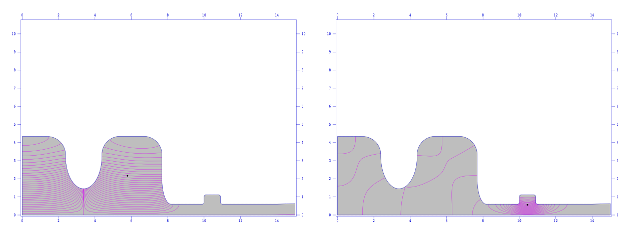

Figure 1: Electric field distribution in the gun cavities. Left: field distribution of the fundamental mode; Right: field distribution of the HOM.

Table 1: Properties of the S-band Cavity

Parameter	Value	Description
freq	2856.00 MHz	RF frequency
flatness	0.9996	field flatness
l_h	3.38 cm	half cell length
r_h	4.3341 cm	half cell radius
c_h	1 cm	half cell chamfer
j_h	1 cm, 1.8 cm	half cell joint a, b
l_f	4.8 cm	full cell length
r_f	4.3431 cm	full cell radius
c_f	1 cm	full cell chamfer
$j_{f,l}$	1 cm, 1.8 cm	full cell left joint a, b
$j_{f,r}$	0.5 cm, 1.4 cm	full cell right joint a, b
$r_{f,t}$	1.45 cm	beam tube radius

While designing the profile of the fundamental mode cavity, the two main figure of merits are the frequency (which is set to be 2856 MHz) and the field flatness (the ratio of the half cell peak field to the full cell peak field, the desired flatness is 1). The optimized figure of merits and the geometry parameters of the fundamental mode cavity are shown in Table 1. The S-band field distribution is shown in the left subplot of Fig. 1.

While designing the profile of the HOM cavity, the two main figure of merits are the frequency (which is set to be 11 424 MHz) and the field penetration (the ratio of the peak field penetrates into the fundamental mode cavity to the peak field in the HOM cavity, desired value 0). The optimized figure of merits and the geometry parameters of the fundamental mode cavity are shown in Table 2. The X-band field distribution is shown in the right subplot of Fig. 1.

Table 2: Properties of the X-band Cavity

Parameter	Value	Description
freq	11 424.25 MHz	RF frequency
penetration	3.02×10^{-4}	field penetration
p	9.9 cm	cell start position
l	1.1 cm	cell length
r	1.1088 cm	cell radius
c	0.1 cm	cell chamfer
j	0.1 cm	cell joint
r_t	0.6 cm	beam tube radius

BEAM DYNAMICS STUDIES

To evaluate the brightness improvement that induced by the two frequency RF gun, we put the gun into a LCLS-like photoinjector (see Fig. 2 and Fig. 6, which visualize the split and combined configuration of the two frequency RF gun respectively) and compare the beam emittance and peak current of the case with and without the HOM cavity. To be reasonable, one has to optimize the whole photoinjector in order to get the best possible beam quality for comparison. Be aware of the large amount of work of the multivariate optimization, Genetic Algorithm (GA) optimizer [6] is employed. We picked up the efficient and widely used genetic algorithm NSGA-II [7] to drive our optimizer. To guarantee a practical optimization time, the parallel computation platforms of LBL and Tsinghua University are extensively used.

S/C-band RF Gun

In this section, a two frequency gun of split configuration, in which the solenoid is located in between the S-band RF gun and the C-band buncher, is investigated by the genetic optimizer for the 200 pC case.

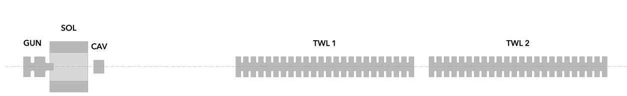

Figure 2: Layout of the injector with the split S/C-band gun.

The photoinjector layout shown in Fig. 2 is modified based on the conventional S-band photoinjector, including a BNL type S-band RF gun (120 MV/m), an emittance compensation solenoid, a C-band buncher and two S-band travelling wave linacs (< 78 MV per linac). The photocathode laser distribution is longitudinally flattop with rising and falling time equal to 10% of the pulse length, transversely Gaussian with radius truncated at one sigma. The laser dimensions, gun phase, solenoid strength, C-band buncher location, gradient, phase, booster linac gradient and position are optimization parameters for the optimizer. As shown in Fig. 3, the 100% emittance and RMS bunch length at injector exit are minimized with beam energy constrained above 100 MeV at injector exit. The 0.65 mm RMS bunch length corresponds to 30 A peak current for 200 pC. Figure 3 shows, with a C-band buncher added, emittance at injector exit can be reduced by ~25% at 30 A peak current. Besides, Fig. 3 (b) also shows the cathode emittance are almost the same as the 95% emittance, which means the transverse beam brightness at cathode is preserved to the injector exit.

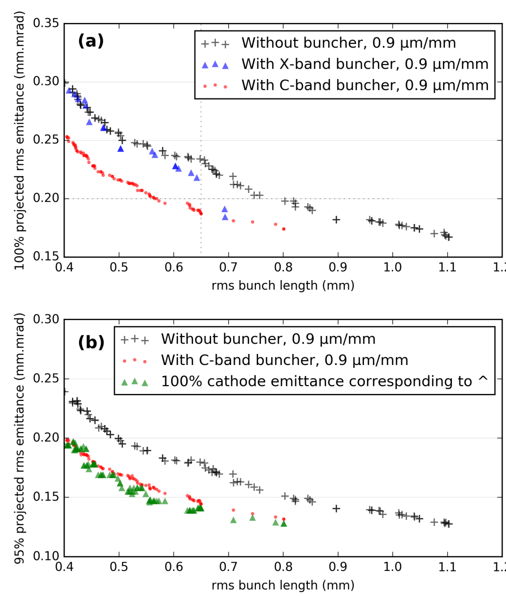

Figure 3: Pareto front of emittance vs rms bunch length for 200 pC bunch charge (ASTRA simulations with 10k macro particles), the Pareto front of a S-band photoinjector with and without a C-band buncher is compared.

Figure 4 shows why the transverse emittance is reduced after a C-band buncher is added into the S-band photoinjector. With a buncher compressing bunch length downstream of the gun, the beam peak current at cathode can be lower, so laser duration can be longer and laser radius can be smaller, and emittance contributed by the cathode are then reduced. Corresponding to 30 A peak current, the laser pulse duration increased from 5 ps to 10 ps, and laser radius reduced from 0.4 mm to 0.32 mm. According to the charge saturation in the "cigar" regime [2], the laser duration is inversely proportional to $R^{3/2}$, so a laser radius reduction of 37% is expected, instead, a 20% reduction is chosen by optimizer, which means the laser dimensions chosen by optimizer are a bit off the max cathode transverse brightness after a buncher

ISBN 978-3-95450-147-2

is added, unlike the case without a buncher [8]. Besides, the max laser pulse lengths chosen by the optimizer for both with and without buncher cases are below 15 ps, which is suspicious and may be caused by chromatic effects or other reasons, such issues will be investigated in future in order to further reduce beam emittance.

The slice emittance of the 30 A solutions in Fig. 3 are shown in Fig. 5, which shows a core slice emittance of 0.15 μm after a buncher is added, a 25% reduction compared to the no buncher case. After the thermal emittance is reduced from 0.9 to 0.5 μm/mm, the core slice emittance is further reduced to 0.1 μm.

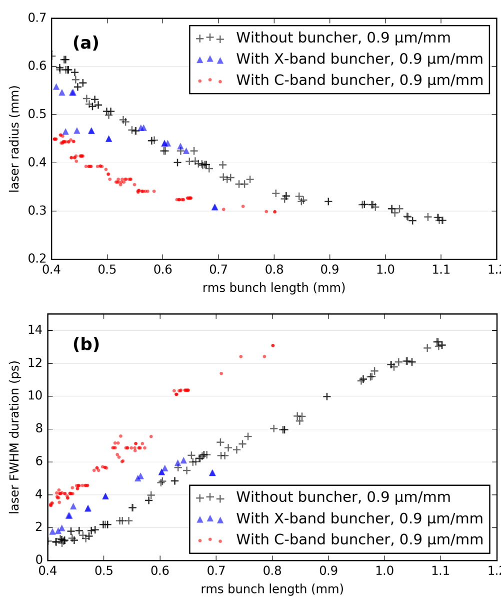

Figure 4: Laser radius and FWHM duration corresponding to solutions in the Pareto front of Fig. 3.

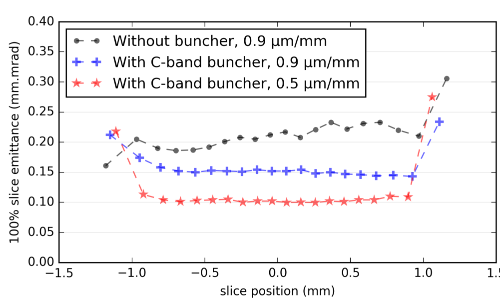

Figure 5: Slice emittance of 200 pC beam with 30 A peak current (`ASTRA` simulations with 200k macro particles).

S/X-band RF Gun

In this section, a two frequency RF gun of combined configuration is investigated by the GA optimizer for the 200 pC case. The injector layout is shown in Fig. 6. The multivariate optimization settings are almost identical to the previous presented S/C-band gun case, except for the longitudinal distribution which is uniform in the S/X-band gun case.

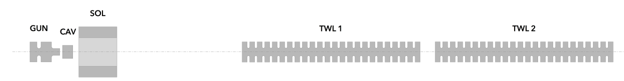

Figure 6: Layout of the injector with the combined S/X-band gun.

Figure 3 (a) shows the optimized Pareto front of the S/X-band gun injector compared with the S/C-band gun injector one. The Pareto front with the X-band buncher is better than the one without buncher and approach to the one with C-band split buncher when rms bunch length > 0.65 mm (corresponding to peak current < 30 A). The reason why the split gun dominates the combined gun in regard of emittance reduction with peak current ≥ 30 A remains to be investigated.

CONCLUSION

By adding a harmonic buncher either before or after the emittance compensation solenoid, a two frequency photoinjector is proposed to further improve beam brightness by using cigar beam photoemission. Both the initial RF design and beam dynamics investigations with a GA optimizer are presented. The preliminary simulation results show that with a HOM cavity added, the emittance at injector exit can be reduced by ~25% at 30 A peak current for 200 pC, and slice emittance can be reduced to ~0.10 mm·mrad with a 0.5 μm/mm thermal emittance. Nevertheless there're several issues yet to be solved. To name a few, the GA optimizer chooses not to take full advantage of the buncher by lengthening the laser pulse beyond 10 ps; putting the buncher downstream the solenoid could achieve smaller emittance compared with buncher before the solenoid. We would continue to investigate the mechanisms behind all these issues in order to further improve the beam emittance.

ACKNOWLEDGMENT

The authors would like to thank Christos F. Papadopoulos for his generous help on genetic algorithm and parallel computation, thank Zan Nie for assistance on the usage of the THU cluster. The authors also very much appreciate the helpful suggestions and comments from Xinlu Xu, Renkai Li and Dan Wang.

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