SLAC-PUB-13387
September 24, 2008

LONGITUDINAL BUNCH LENGTHENING COMPENSATION IN A HIGH CHARGE RF PHOTOINJECTOR

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Abstract

In high charge RF photoinjectors for wakefield two beam acceleration studies, due to the strong longitudinal space charge, bunch lengthening between the photocathode and photoinjector exit is a critical issue. We present beam dynamics studies of bunch lengthening in an RF photoinjector for a high charge electron beam and describe methods to compensate the bunch lengthening to various degrees. In particular, the beam dynamics for bunch charge from 1nC to 30nC are studied for an S-band 2856MHz photoinjector.

Contributed to the XXIV Linear Accelerator Conference, LINAC08, Victoria, British Columbia, Canada, September 29 – October 3, 2008

*Work supported by the DOE under contract DE-AC02-76SF00515.
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LONGITUDINAL BUNCH LENGTHENING COMPENSATION IN A HIGH CHARGE RF PHOTOINJECTOR

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Abstract

In high charge RF photoinjectors for two-beam wakefield accelerators, bunch lengthening between the photocathode and photoinjector exit is a critical issue due to the strong longitudinal space charge forces. We present beam dynamics studies of bunch lengthening in an RF photoinjector for a high charge electron beam and describe methods to compensate the bunch lengthening to various degrees. In particular, the beam dynamics for bunch charge from 1 nC to 30 nC are studied for an S-band (2856 MHz) photoinjector.

INTRODUCTION

RF photoinjector technology [1] is used world-wide in low emittance sources for linac-based free electron lasers [2] and in electron sources for electron storage rings [3]. It has been demonstrated that photoinjectors can produce high brightness and low emittance electron beams [4-6]. A particular challenge for high charge electron photoinjectors for two-beam wakefield accelerators is the longitudinal bunch lengthening that occurs due to strong space charge forces [7].

The longitudinal evolution of electrons in an RF injector can be divided into four steps as discussed in Ref. [8]: 1) initial launching and expansion; 2) RF compression inside the gun cavity; 3) drift space bunch compression or expansion; 4) longitudinal emittance compensation through the booster linac. To reduce the bunch lengthening in the first step, the laser pulse length can be reduced and beam radius increased, which usually results in transverse emittance growth. In the second step, one wants to accelerate the electron beam with as high a gradient as possible [9], which is constrained by the available klystron power and the maximum sustainable surface electric fields in the gun cavity. For the third step, appropriate tuning of the emittance compensation solenoid is needed to reduce the bunch lengthening. The fourth step, which ultimately determines whether the bunch is lengthened, preserved or shortened, appropriate phasing (off-crest acceleration to create an energy chirp along the bunch) is done in part of the booster linac and the electron beam focusing is adjusted along the entire injector.

Here we present two studies of longitudinal bunch lengthening compensation. In the first, we consider only increasing the RF gun acceleration gradient while optimizing the initial phase of the electron beam with the booster linac operated on-crest. The second study focuses on phasing both the RF gun and the first half booster linac for gun acceleration gradients ranging from 120 MV/m to 200 MV/m.

PHOTOINJECTOR DESIGN

Fig. 1 shows the schematic layout of the photoinjector. Due to the strong space charge effect of a high charge beam (10 nC - 30 nC), the RF gun is immersed in the magnetic field of an integrated cathode solenoid. This magnet is composed of two symmetric solenoid coils whose symmetry plane is the cathode plane. The two coils are powered by separate supplies with opposite current flows so the magnetic field at the cathode surface can be easily adjusted to be near zero. The solenoid and the drift space just after the gun are used to compensate the linear space charge induced emittance growth in the gun region. For high charge, the combined axial magnetic field profiles of the cathode solenoid and the emittance compensation solenoid are shown in Fig. 2 (left) for a typical case. For low charge, only the emittance compensation solenoid is used, and a field profile example is shown in Fig. 2 (right, the two lines coincide with each other).

The basic parameters of the RF gun are listed in Table 1. The RF gun operates in π-mode, and Fig. 3 shows the 0-mode and π-mode electric field profiles for the geometry with a balanced π-mode at 2856 MHz.

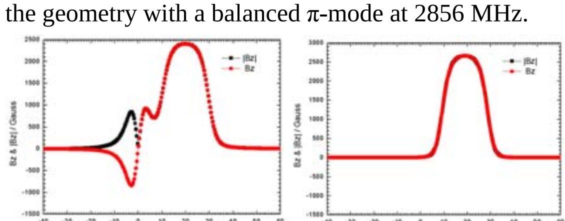

Fig. 2: Typical axial magnetic field profiles in the gun region for high charge (left) and low charge (right).

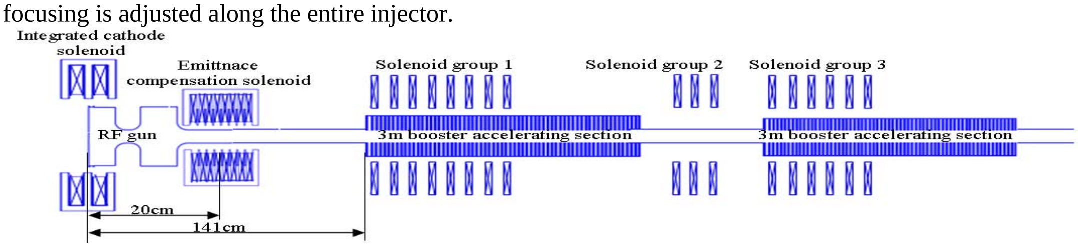

Fig. 1: Schematic layout of the photoinjector.

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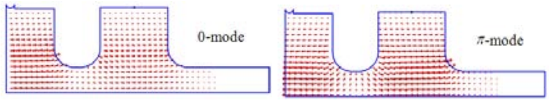

Fig. 3: 0-mode and π-mode electric field profiles for the balanced π-mode at 2856 MHz.

Table 1: Basic parameters of the RF gun

parameter	SUPERFISH
Field balance ratio for π-mode (E2/E1)	0.99960
π-mode frequency / MHz	2856.0
π-mode quality factor	15392
π-mode shunt impedance / MΩ/m	55.191
Field balance ratio for 0-mde (E2/E1)	0.57499
0-mode frequency / MHz	2852.6
0-mode quality factor	15764
0-mode shunt impedance / MΩ/m	61.803
Mode separation / MHz	3.4127
RF gun cavity length / cm	12.611

BEAM DYNAMICS SIMULATION

The beam dynamics were studied with SUPERFISH and PARMELA [10]. The beams at the photocathode have a uniform transverse distribution and their radii are 1.2 mm (1nC) and 5.4 mm (10 nC - 30 nC) [11][12]. The initial bunch in all simulations was assumed to have zero transverse emittance and a flat longitudinal distribution that is 10 ps long (~ 3 ps RMS). The beam injection phase, solenoid field position and amplitude, beam acceleration phase etc., were varied in each PARMELA simulation to optimize the final bunch length and the transverse emittance at the photoinjector exit. The beam dynamics of 1 nC beam was investigated first, through which the photoinjector layout shown in Fig. 1 was determined, and then high charge beams were studied.

Increasing the gun gradient

For this case, the first 3-m long booster section was run on-crest (90^o), which yields a beam energy of about 50 MeV, and the second booster section was not included in the simulation as it has little effect on the bunch length.

Fig's. 4-6 show the effect of the photocathode peak electric field on bunch length, emittance and energy spread for beams with different bunch charge. The solenoid current was adjusted to compensate the different space charge forces as the bunch charge was varied. The gun phase was about 12^o, which is far off-crest to create a relatively big energy chirp. To preserve the initial 3 ps RMS bunch length, the RF gun should be run at ~ 140 MV/m for a 10 nC beam, and for each additional 5 nC of bunch charge, an 20 MV/m increase in gun accelerating gradient is needed. Running the gun at high gradient can also decrease the emittance and energy spread. Fig. 7 shows the emittance, energy, energy spread and bunch length as a function of distance from the photocathode for a 20 nC beam when the gun gradient was 160 MV/m.

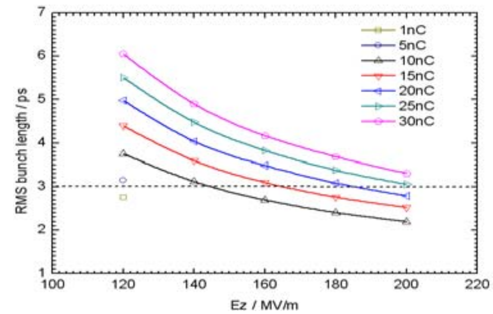

Fig. 4: RMS electron bunch length dependence on the photocathode peak electric field and bunch charge.

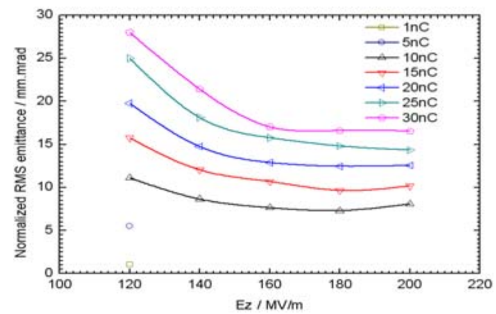

Fig. 5: Normalized RMS emittance dependence on the photocathode peak electric field and bunch charge.

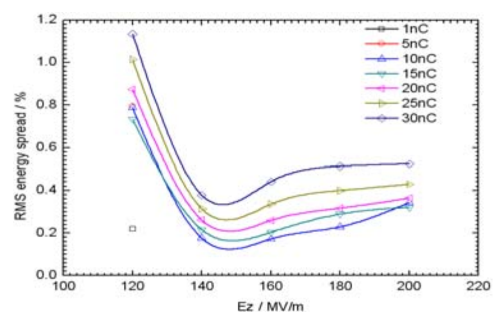

Fig. 6: RMS energy spread dependence on the photocathode peak electric field and bunch charge.

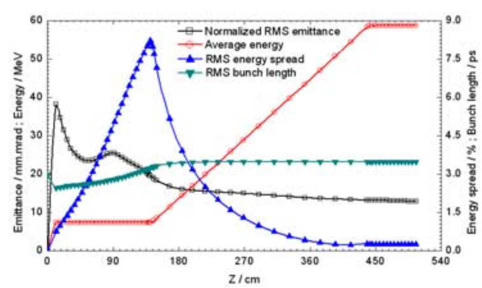

Fig. 7: Emittance, energy, energy spread and bunch length variation along the injector (20 nC, 160 MV/m).

Also changing the booster linac phase

Fig's. 8-10 show the dependence of RMS bunch length, emittance and energy spread on the photocathode peak electric field when the first booster acceleration section was run off-crest to create an energy chirp along the bunch. The phases of the gun and first booster section were 25^o and near 0^o, respectively, so the beam energy at the end of the first booster section was only several MeV. Adjusting the additional solenoids (i.e., solenoid group 2 and 3) was necessary to control the transverse emittance growth. In this case, the whole photoinjector including both booster sections was simulated and the final beam energy was larger than 50 MeV. Running the first booster section off-crest resulted in a shorter bunch length than just increasing the gun gradient with the drawback that the final energy spread was relatively large.

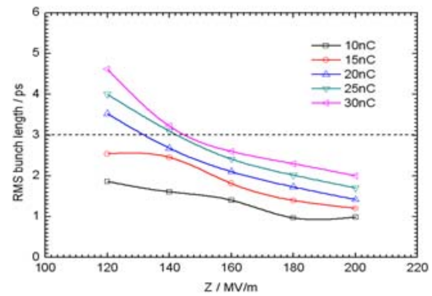

Fig. 8: RMS electron bunch length dependence on the photocathode peak electric field and bunch charge.

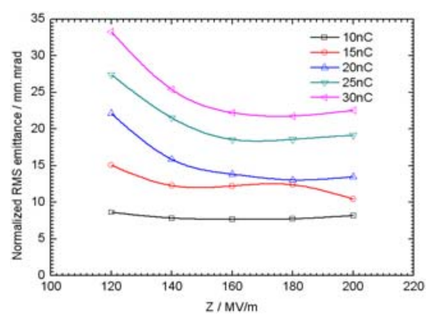

Fig. 9: Normalized RMS emittance dependence on the photocathode peak electric field and bunch charge.

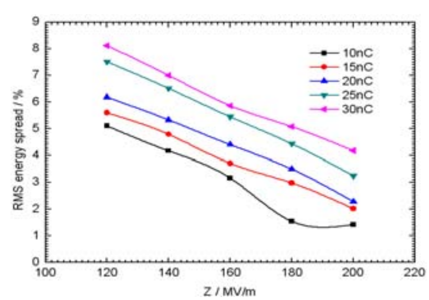

Fig. 10: RMS energy spread dependence on the photocathode peak electric field and bunch charge.

Fig. 11 shows the emittance, energy, energy spread and bunch length variation along the photoinjector for a 20 nC beam when the gun gradient was 160 MV/m. Fig. 11 is more complicated than Fig. 7 in that there are two more oscillations for emittance and one more for energy spread and bunch length; these are caused by the off-crest operation of the first booster section and the emittance re-compensation process in the middle of the booster linac. However, by the end of the photoinjector, the beam parameters were very stable with a smaller emittance and a shorter bunch length but a larger beam energy spread.

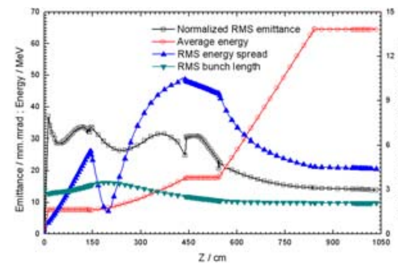

Fig. 11: Emittance, energy, energy spread and bunch length variation along the injector (20 nC, 160 MV/m).

DISCUSSION AND SUMMARY

It has been shown that increasing the acceleration gradient in the RF gun and operating the gun and/or part of the booster linac off-crest to create an energy chirp along the beam can be used to compensate longitudinal space-charge induced bunch lengthening. In this way, a high current (a few tens of nano-Coulombs), short bunch length (few picoseconds), moderate transverse emittance (a few tens of mm-mrad) electron beam can be produced. The disadvantage of the off-crest operation to create an energy chirp is a larger final bunch energy spread. However, by appropriate design, the electron beam can meet both the low emittance requirements for free electron lasers and high charge requirements for two-beam wakefield accelerators.

ACKNOWLEDGEMENT

Thanks to K. L. Bane and F. Zhou for reading the manuscript and helpful comments.

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