ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-THB04

LONGITUDINAL PHASE SPACE STUDY ON INJECTOR BEAM OF HIGH REPETITION RATE X-RAY FEL*

Qiang Gu†, Zhen Wang, Shanghai Advanced Research Institute, Shanghai, China

Abstract

The longitudinal phase space of electron beam from the high repetition rate injector usually twisted and deteriorated by the space charge force. It causes the high order correlated energy spread and the local chirp within the beam, which could not be compensated by the harmonic correction before the compression in the linac. As a consequence of this problem, one could not get ideal beam with a peak current more than kiloamperes. In this paper several approaches have been studied to relieve this effect and get the well compressed beam for the lasing.

INTRODUCTION

Two high repetition rate X-ray free electron laser facilities based on the continuous wave linac are under construction [1-2]. In the early stage of the LCLS-II injector design, people have compared the beam dynamics optimization, as well as the beam performance between the VHF gun and DC gun based injectors. Both of the injectors shown the good transverse emittance, but the longitudinal phase space of the electron beam at the exit of the DC gun based injector had larger high order correlated energy spread which could not be compensated before compression system in main linac. Finally, the VHF gun has been adopted by LCLS-II.

Table 1: Main Parameters of the Electron Beam

Parameter	Value	Unit
Beam energy	8	GeV
Slice emittance, nor.	0.2-0.7	μmrad
Bunch charge	10-300	pC
Repetition rate, max.	1	MHz
Peak current	0.5-1.5	kA

SHINE is a hard X-ray free electron laser facility with a shortest FEL wavelength of 15keV. The main parameters of the electron beam are listed in Table 1. To obtain the FEL with higher energy, LCLS-II HE chose the lower emittance [3], while SHINE chose higher peak current and even higher peak current is preferred for the higher photon energy up to 25keV. LCLS-II and SHINE now has adopted a photo-injector consisting of a VHF gun followed by a velocity bunching and accelerating system to generate the qualified beam. It has shown that even with the VHF gun, the high order correlated energy spread is too large to get a beam current larger than kA. The solution for SHINE is to linearize the global or local high order correlated energy spread before compression and it is better to complete the correction locally in the injector.

The high repetition rate photo injector usually consists of a photo cathode gun which generates the electron beam, followed by a velocity bunching system to reduce the bunch length which could be accepted by the further acceleration and compression in the linac, and an emittance compensation system with solenoids, drifts and acceleration. Here we show the layout of SHINE injector in Figure 1 for example.

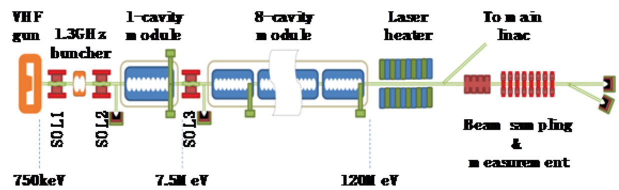


Figure 1: Layout of SHINE injector.

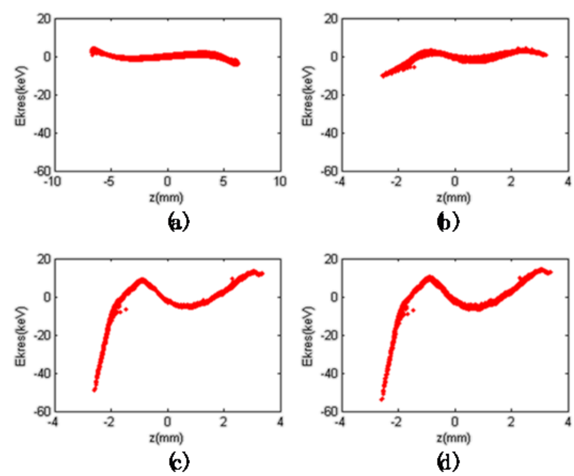


Figure 2: High order energy spread along the injector,
(a) at the middle of the buncher;
(b) at the entrance of the 1-cavity module;
(c) at the entrance of the 8-cavity module;
(d) at the end of the injector.

In the injector, the high order correlated energy spread is driven by the space charge force and velocity bunching process. The initial energy modulation is generated from the cathode to the buncher, which contributes the nonlinear chirp during the bunching process. Together with the nonlinear velocity modulation from the buncher, the nonuniform longitudinal density distribution of the bunched beam is produced. After bunching, this distribution enhances the energy modulation when the electron beam goes through the accelerating and drifting. Growth of the energy modulation almost stops at the end of the injector,

* Work supported by SHINE project
† guqiang@sinap.ac.cn

ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-THB04

but this is too large to get the higher current at the linac. The high order energy spread along the injector is shown in Figure 2.

METHOD ON HIGH ORDER ENERGY MODULATION COMPENSATION

To cure this problem, one should linearize the energy modulation driven by the space charge force during accelerating and drifting, as well as the velocity modulation from the buncher. As noted, the all the steps of the high order term in longitudinal density and energy distribution mix up in the injector, so divide-and-rule for each cause and result is not practical. We hope to introduce simple corrector to resolve most of the problem.

The 3D-ellipsoid distribution of the electron beam is used to minimize the longitudinal mismatch of the transverse sliced emittance and reduce the projected emittance [4]. There are several methods to get the 3D-ellipsoid distribution electron beam based on laser pulse shaping or self-evolving by space charge [5-8]. Here, it is used to linearize the space charge force directly, while the nonlinear velocity modulation is left uncompensated.

Harmonic cavity is widely used to correct the nonlinear energy modulation before compression in free electron laser facilities [9]. In velocity bunching system, the nonlinear velocity modulation also could be compensated by a harmonic cavity [10]. In high repetition rate injector, the harmonic cavity could play the same role to correct the nonlinear velocity modulation introduced by the fundamental bunching cavity. In the layout of SHINE injector, there are no extra place to put an individual harmonic cavity near the buncher, so a dual mode cavity is designed for the beam dynamics study. The field distribution of the two modes is shown in Figure 3.

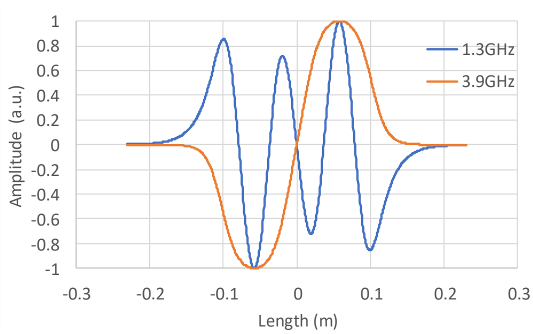


Figure 3: Fundamental and Harmonic electric field along the axis of the buncher.

Another idea has come out when we look at the electron bunch length at the buncher. It is long enough to feel the nonlinear field of the harmonic cavity, which means one can use the harmonic cavity to correct the high order energy modulation along the beam. The principle of this scheme is shown in Figure 4, in which only the correction is shown and the bunching voltage is not applied.

All the methods noted has been studied through injector to the linac with Astra [11] and LiTrack [12]. In the 2D tracking in linac, the longitudinal distribution will be affected by lots of parameter and nonlinear terms [13]. We hope to use the genetic algorithm [14] to optimize the whole accelerator, but it turns out that this scheme was time-consuming and error-prone. Finally, we optimize the injector beam and linac beam separately. In linac optimization, we stop the tracking after the last compressor, because the longitudinal density distribution does not charge through the last acceleration section.

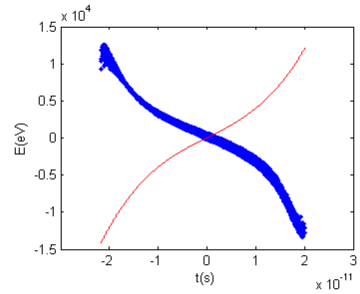


Figure 4: Correction of the high order energy modulation by harmonic cavity. Blue dots represent the longitudinal distribution at the entrance of the buncher. Red line is the combined electric field of two modes.

RESULTS AND DISCUSSION

We used the same bunch length as the beer-can distribution for the 3D-ellipsoid distribution. There are a lot of solutions on the pareto front with GA optimizer, but only the solution of the highest current is shown in Figure 5.

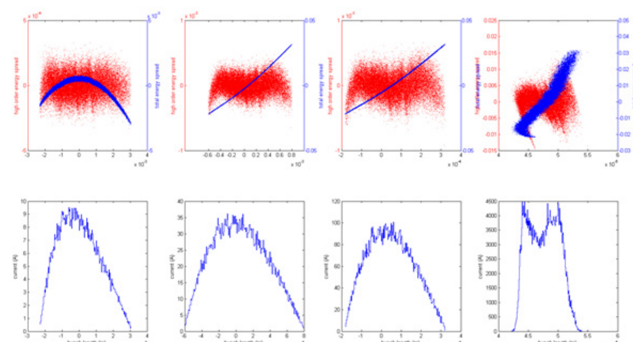
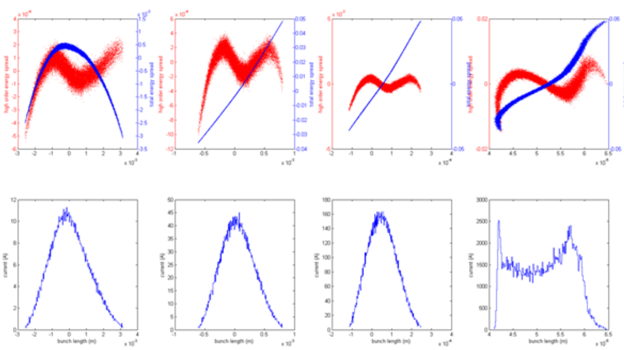


Figure 5: Longitudinal phase space along the linac (method 1). The figures from the left to right in columns are the longitudinal phase space at the end of injector, at the end of the 1st compressor, at the end of the 2nd compressor and at the end of the 3rd compressor. In the up row of the figures, the red dots represent the high order energy spread, while the blue dots represent the total energy spread.

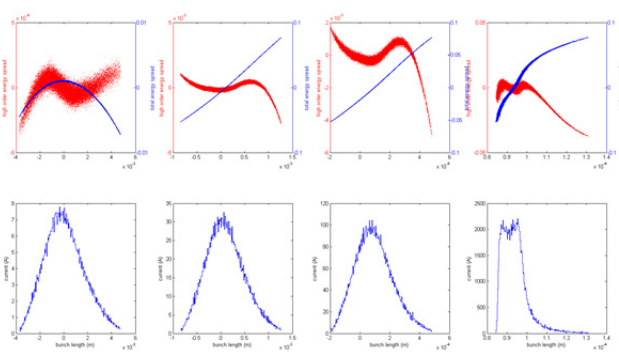
From the figures, the bunch has an almost linear energy spread at the end of the injector, while the centre of current profile is shift to the head of the bunch. The nonlinear chirp of the energy spread is observed with the compression, which introduces the double-horn current profile at the final compression. As a whole, this method could let the beam compressed to much higher current than the original request [1].

ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-THB04

To correct the nonlinear velocity modulation of the fundamental mode, a harmonic mode is applied with amplitude around 10% to the fundamentals. The linac optimization result is shown in Figure 6. It shows that the peak of the current profile shifts to the centre of the bunch with the correction. At the same time, the high order energy modulation is compensated slightly, and the double-horn current profile at the end of the linac improved. If the bunch length at the linac exit increases, the core of the current could be improved much.



(a)



(b)

Figure 6: Longitudinal phase space along the linac (method 2). (a) bunch length is 1.1 mm (original design) at the injector exit; (b) bunch length is 1.6 mm at the injector exit.

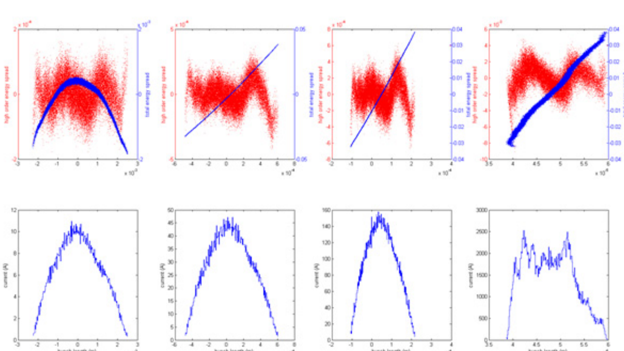


Figure 7: Longitudinal phase space along the linac (method 3).

The fundamental and harmonic field is set to another working point to compensate the high order energy modulation by space charge force. The result is shown in Figure 7. Most of the high order energy modulation is reduced to about 1/2 of the original amplitude and the double-horn like current profile is remove at the linac exit.

CONCLUSION AND EXPECTATION

To manipulation the longitudinal phase space with harmonic field is effective, but with drawbacks. The velocity linearizing with longer beam at injector exit could improve the core current of beam at linac exit, while the beam tails is lengthened. The long beam tail may cause the beam loss in the successive components. The high order energy spread could be compensated almost as good as using the 3D ellipsoid distribution, but the cavity voltage is about 1MV for fundamental field and 0.4MV for the harmonic field which could not be supported by the normal conducting structure. With the higher energy gun, optimized injector optics, and SRF technology, this method could be realizable and flexible.

Including the pulse stacking method, most of 3D ellipsoid distribution generation methods have been demonstrated with beam. So far, there are some limitations to apply to the high repetition rate photo injector, but the 3D-ellipsoid distribution electron beam is considered as an upgrade path in the future.

REFERENCES

[1] SHINE CDR, 2018.

[2] Linac Coherent Light Source at SLAC, https://lcls.slac.stanford.edu/lcls-ii

[3] Report of the Basic Energy Sciences Workshop on the Future of Electron Sources, 8-9 September 2016, SLAC National Accelerator Laboratory, Menlo Park, CA, USA.

[4] C. Limborg-Deprey, P. R. Bolton, "Optimum electron distributions for space charge dominated beams in photoinjectors", *Nuclear Instruments and Methods in Physics Research A*, vol. 557 (2006) 106–116, doi:10.1016/j.nima.2005.10.061

[5] P. Musumeci *et al*., "Experimental Generation and Characterization of Uniformly Filled Ellipsoidal Electron-Beam Distributions", Phys Rev Lett., 100, 244801 (2008), doi:10.1103/PhysRevLett.100.244801

[6] Y. Li and J. W. Lewellen, "Generating a Quasi ellipsoidal Electron Beam by 3D Laser-Pulse Shaping", *Phys. Rev. Lett.*, 100, 078401 (2008), doi:10.1103/PHYSREVLETT.100.074801

[7] S. Yu. Mironov *et al*., "Generation of 3D ellipsoidal laser beams by means of a profiled volume chirped Bragg grating", *Laser Physics Letters*, vol. 13, number 5 (2016), doi:10.1088/1612-2011/13/5/055003

[8] S. Yu. Mironov *et al*., "Shaping of cylindrical and 3D ellipsoidal beams for electron photoinjector laser drivers," *Applied Optics*., vol. 55, 1630-1635 (2016), doi:10.1364/AO.55.001630

[9] P. Emma, "X-Band RF Harmonic Compensation for Linear Bunch Compression in the LCLS", LCLS-TN-01-1, 2001.

[10] L. Serafini and M. Ferrario, "Velocity bunching in photo-injectors", *AIP Conference Proceedings*, vol. 581, 87 (2001), doi:10.1063/1.1401564

ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-THB04

[11] ASTRA, http://www.desy.de/~mpyflo/.

[12] P. Emma and K. L. F. Bane, "LiTrack: A Fast Longitudinal Phase Space Tracking Code with Graphical User Interface", in *Proc. 21st Particle Accelerator Conf. (PAC'05)*, Knoxville, TN, USA, May 2005, paper FPAT091.

[13] I. Zagorodnov and M. Dohlus, "Semi-analytical modeling of multistage bunch compression with collective effects", *Phys. Rev. ST Accel. Beams*, 14.014403 (2011), doi:10.1103/PhysRevSTAB.14.014403

[14] MathWorks, NGPM -- A NSGA-II Program in Matlab v1.4, https://www.mathworks.com/matlabcentral/fileexchange/31166-ngpm-a-nsga-ii-program-in-matlab-v1-4