PHOTOINJECTOR BEAM DYNAMICS FOR A NEXT GENERATION X-RAY FEL*

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Abstract

In this paper, we will present the status of the beam dynamics simulations for a Next Generation Light Source (NGLS) injector, based on a high repetition rate (1 MHz), high brightness design. A multi-stage beam compression scheme is proposed, based on the concepts of velocity bunching and emittance compensation. For the optimization of the design parameters we use a genetic algorithm approach, and we focus on a mode providing charges of 300 pC, with normalized transverse emittance less than 0.6 microns, suitable to operate a next generation light source based on an X-ray FEL. In addition, we discuss the effects of bunch compression and linearity of the transverse and longitudinal phase space of the beam.

INTRODUCTION

The development of free electron lasers used as sources for X-rays requires high beam quality, quantified by the beam brightness $B = \frac{N}{\epsilon_{nx}\epsilon_{ny}\epsilon_{nz}}$, at energies greater than 1 GeV. The number of electrons per bunch is N and $\epsilon_{nx,ny,nz}$ the normalized RMS emittances. Additionally, relatively high peak currents, on the order of kA, are typically required at the FEL undulators for lasing to occur. Thus, the challenge posed by the demand for X-ray FEL sources is to accelerate and compress the beam, while keeping B high. On top of that, for the NGLS design, a high repetition rate is required. As discussed in [1], the requirements for the NGLS FEL concept, currently being designed at LBNL are given in Table 1. The relatively low emittance and energy spread are determined by the high beam brightness required by the FEL process, whereas the bunch charge was determined based on the desired bunch length, peak current as well as the expected shot-to-shot jitter of the beam with respect to the laser pulse in the case of seeded FEL operation [2].

Table 1: Target Beam Quantities

Parameter	Value at injector	Value at FEL
Energy	70 MeV	1.8 GeV
Peak Current	50 A	500 A
Slice transverse emittance	$< 0.6\ \mu$m	0.6 μm
Slice energy spread	< 5 keV	50 keV

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In the injector stage of the accelerator, significant phase space degradation can result from the intense transverse and longitudinal space charge forces [3] present at low energies. Hence, a code that includes both components of the space charge forces is required. The code chosen is ASTRA [4], a widely used and thoroughly benchmarked particle-in-cell (PIC) code that includes a cylindrical (r-z) model for the space charge forces.

INJECTOR LAYOUT

The injector setup is shown in Fig. 1. The first component is the normal conducting RF gun with a frequency of about 187 MHz in the VHF frequency range, operating in CW mode [5], which can accelerate the beam up to 750 keV. This VHF gun has been optimized for operation in a high rep. rate RF environment, and its design is based on mature technologies. The characteristics of the cathode used in the simulations are taken from measurements of Cs_2Te cathodes [6], but the gun can also operate with K_2CsSb cathodes, as well as other high quantum efficiency cathodes.

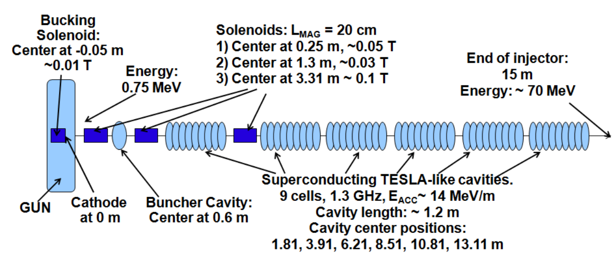

Figure 1: Schematic of the injector

A bucking coil is integrated in the gun right behind the cathode in order to cancel out magnetic fields at the region where the electron beam is generated, and thus avoid correlated emittance growth. Three more solenoids are placed downstream in order to provide transverse focusing, as well as perform the emittance compensation.

The buncher and superconducting RF cavities have an operating frequency of 1.3 GHz, and the latter are TESLA-like 9-cell cavities, as in the downstream main linac of NGLS. In the current setup, the buncher is assumed to be normal conducting and hence field penetration from the neighboring solenoids is not an issue. The available knobs for both types of cavities are the phase and the on-axis longitudinal component of the electric field, corresponding to the accelerating gradient.

The initial distribution assumed for the simulations is matched to the type of distribution expected from a properly shaped laser beam. That is, we assume a gaussian distribution in v_x,v_y and v_z and uniform in the transverse directions (x and y). In the z (or t) direction, the profile consists of a plateau, as well as rise and fall times set to 10% of the plateau length respectively. One final note is that we follow the convention of the head of the beam being at larger t values than the tail.

For all of the aforementioned components, the requirements on peak and average power are within the limits of current technology, and an active research and development program is under way to experimentally demonstrate the feasibility of this design [7].

BEAM DYNAMICS CONSIDERATIONS

Bunch Compression and Emittance Compensation

As discussed before, the main goal of the injector is to compress the beam, while maintaining the beam brightness. In order to achieve this, two established methods are used, namely emittance compensation and velocity, or ballistic, bunching.

The emittance compensation process was originated in [8] and can be thought of as a realignment of the ellipses in transverse phase space of the different z-slices of the beam, to remove the differential rotation induced by the transverse space charge forces. In this way, the total emittance of the beam, which is related to the phase space area of the sum of all the projections of the said slice-ellipses, is minimized.

Velocity bunching [9] is a method to compress the beam at injector energies. This is achieved by dephasing the first accelerating cavities in the injector creating an energy chirp along the bunch (with particles in the head with lower energy with respect to those in the tail) that generates compression during the propagation along the injector.

In order to imprint the time-energy (t-E) correlation required for velocity bunching, we can use either the single cell buncher cavity or the 9 cell accelerating cavities. In the first case, the bunch center in t is injected with a -90 deg. phase difference with respect to the maximum acceleration phase, which leads to no net acceleration of the beam, but t-E correlation that is close to linear. In the second case, the bunch center in t is injected at a phase difference of around 60 deg., which results in net acceleration and linear chirp, but also quadratic and higher order components in the t-E correlation. Hence, the first method leads to more symmetric long. profiles, while the second accelerated the beam faster, and thus minimizes the transverse space charge effects that lead to emittance degradation. In practise, a combination of both methods is used.

The two tasks of achieving emittance compensation and bunch compression are coupled, since the slice current, which increases during compression, affects the transverse space charge forces that govern the realignment of the beam-slice ellipses along the bunch. Additionally, increasing the slice current also increases the nonlinear component of space charge forces, which may cause irreversible emittance growth.

Genetic Optimization

Based on the previous discussion, the two objectives of low emittance and high peak current are conflicting. As a result of that, a multivariate genetic optimizer is ideally suited, following [10]. The decision to use transverse emittance instead of 6D beam brightness as an optimization objective is driven by the fact that, in order to suppress collective instabilities, virtually all 4^{th}-generation light-source designs allow for controlled increase of the longitudinal emittance downstream in the main linac ('laser heater'). This is justified since typically the normalized longitudinal emittance at the injector is lower than the one required downstream at the FEL. Minimizing the bunch length is conceptually equivalent to maximizing the current for a given bunch charge, and indeed the former method avoids very narrow spikes in the current profile which are in general undesirable.

The number of available knobs includes the initial beam sizes, the fields of the solenoids, the gradients and phases of the accelerating structures, as well as some of the relative positions of the components involved. Overall, 10-15 different parameters are used, depending on the particular setup.

In the case of multiobjective algorithms such as the one used in our case (NSGAII [11]), the result is not a single solution, but a set of solutions, populating an optimal curve in the ϵ_n-z_{rms} plane. This curve is also called a Pareto optimum front, and a numerical approximation of it is shown in Fig. 2 for the NGLS 300 pC case at the exit of the injector. Starting from the Pareto front, and taking into account

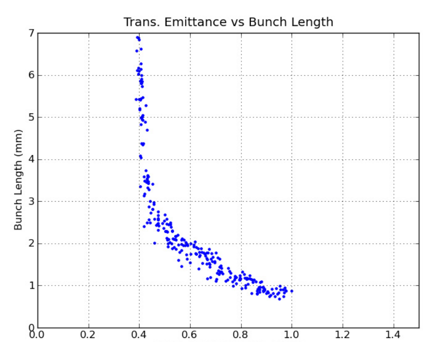

Figure 2: Approximation of the Pareto optimum front (normalized trans. emittance vs bunch length) at the exit of the injector (15 m from the cathode, beam energy of about 70 MeV)

the beam dynamics considerations of the linac design described in [2], we identified one solution meeting the desired properties, in particular peak current, slice emittance and also minimal transverse and longitudinal tails (or halo).

Beam Characteristics at the Injector Exit

The phase space characteristics of the chosen solution, based on the target values of Table 1 is shown in Fig. 3. From these plots, we can see that the slice quantities of the

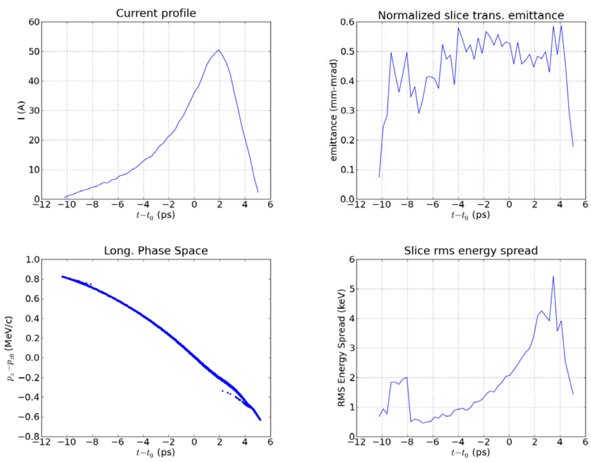

Figure 3: Beam characteristics at the exit of the injector for the design solution. Note that the beam head is located to the right of the beam tail.

beam satisfy our requirements at all points. In the case of the t-p_z correlation, we see a very strong linear component, as expected from the velocity bunching method. Additionally, a second order correlation exists, as discussed before, due to the dephasing of the accelerating cavities. The first order component can be removed downstream by dephasing the remaining accelerating structures so as to equalize the momentum of the head and the tail. In order to remove the second order component a dedicated, third harmonic cavity is required as described in [2]. For the present design, the higher order components, due to longitudinal space charge (third order), rf nonlinearities etc appear to be acceptable.

The evolution across the injector of the RMS beam size, the RMS transverse emittance, and the average beam energy is shown in Fig. 4 for the design solution. We note that in Fig. 4, neither the emittance nor the bunch length change substantially after about 9 m or 40 MeV. Thus, we expect transverse space charge forces to be small and the beam to be ”frozen-in” or rigid after this point. This implies that further longitudinal compression requires the use of a magnetic chicane.

CONCLUSIONS

We describe the beam dynamics for a high repetition rate photoinjector. The inclusion of space charge forces at low energies results in an inherently nonlinear problem. High beam brightness and moderate longitudinal compression are achieved by applying the velocity bunching and emittance compensation methods. In order to optimize the injector design, a genetic optimization algorithm is used,

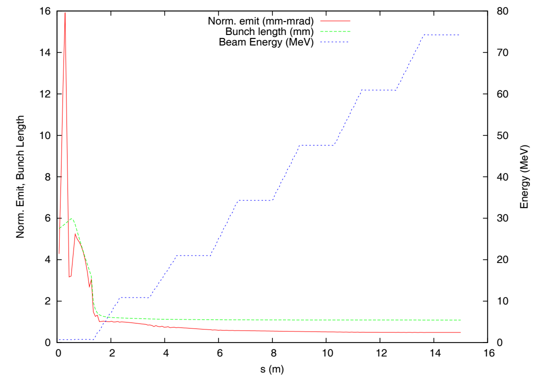

Figure 4: Evolution of full, normalized, RMS x emittance (mm-mrad, red), RMS bunch length (mm, green) and average beam energy (MeV, blue).

that achieves the goals within the constraints posed by current technology.

REFERENCES

[1] J. Corlett et al. A next generation light source facility at lbnl. In *Proc. of PAC 11*.

[2] M. Venturini et al. Studies of a linac driver for a high repetition rates x-rays fel. In *Proc. of PAC 11*.

[3] K. Kim. Rf and space-charge effects in laser-driven rf electron guns. *NIMA*, 275(2):201–218, February 1989.

[4] K. Flöttmann. ASTRA: A space charge tracking algorithm. *user's manual available at* `http://www.desy.de/~mpyflo/Astra_dokumentation`.

[5] K. Baptiste et al. A CW normal-conductive RF gun for free electron laser and energy recovery linac applications. *NIMA*, 599(1):9–14, February 2009.

[6] V. Miltchev et al. Measurements of thermal emittance for cesium telluride photocathodes at PITZ. In *Proceedings of the Free Electron Laser Conference*, 2005.

[7] D. Filippetto et al. Low energy beam diagnostic for apex, the lbnl vhf photo-injector. In *Proc. of PAC 11*.

[8] B Carlsten and D Palmer. Enhanced emittance compensation in a high-frequency RF photoinjector using RF radial focusing. *NIMA*, 425(1-2):37–50, April 1999.

[9] M. Ferrario et al. Experimental demonstration of emittance compensation with velocity bunching. *Phys. Rev. Lett.*, 104(5):054801, Feb 2010.

[10] Ivan V. Bazarov and Charles K. Sinclair. Multivariate optimization of a high brightness dc gun photoinjector. *PRSTAB*, 8(3):034202+, Mar 2005.

[11] K. Deb. *Multi-objective optimization using evolutionary algorithms*. Wiley, 2001.