INJECTOR OPTIMIZATION FOR A HIGH-REPETITION RATE X-RAY FEL

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Abstract

In linac driven free electron lasers, the final electron beam quality is constrained by the low energy (<100 MeV) beam dynamics at the injector. In this paper, we present studies and the optimized design for a high-repetition (> 1 MHz) injector in order to provide a high brightness electron beam. The design effort is also extended to multiple modes of operation, in particular different bunch charges. The effects of space charge and low energy compression on the electron beam brightness are also discussed for the different modes.

INTRODUCTION

The Next Generation Light Source (NGLS) is a proposed fourth generation soft xray FEL facility at Lawrence Berkeley National Lab, based on a high repetition rate, superconducting linear accelerator. In this paper, we present the beam dynamics studies and optimization results for the NGLS injector, defined as the low energy ($<$ 100 MeV) part of the accelerator. For this, a photoinjector based on a VHF frequency electron gun is used. The constraints imposed by the high repetition rate ($>$ 1 MHz) lead to a design that includes compression at low energy, in addition to the emittance compensation process used in other facilities.

A schematic of the injector, showing only the components directly affecting the beam dynamics studies, is shown in Fig. 1.

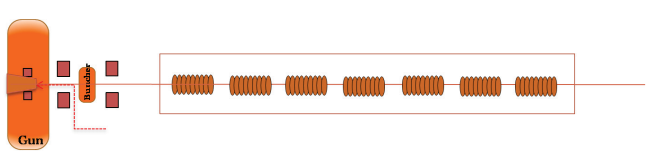

Figure 1: Conceptual design of the high rep. rate injector.

Injector Beamline

The basis of the photoinjector setup is a normal conducting electron gun, operating at a continuous wave (CW) mode at 186 MHz. A more detailed description of the injector subsystems is given in [1]. For our current purposes of beam dynamics optimization, the electron gun is defined by the on-axis z component of the electric field. In contrast to higher frequency and lower repetition rate systems, the peak value of E_z at the cathode is limited to 20 MV/m, which is sufficient to guarantee good transverse beam emittance. The cathode-to-anode gap of the gun is 4 cm, leading to a final beam energy of 750 keV at the gun exit.

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Using a load-lock system, different cathodes can be used, as described in [1]. In our simulations, we assume an initial distribution compatible with a Cs_2Te cathode, that is we assume an initial emittance given by $\epsilon_{nx}[mm - mrad] = c_e[mrad] * \sigma_x[mm]$, where σ_x is the rms beam size at the cathode and c_e a factor experimentally measured to be 0.8 [2] and conservatively estimated to be 1 in the simulations.

Downstream of the gun, 2 solenoids are present in order to perform the emittance compensation process [3]. In addition to those, a bucking coil is present behind the cathode, in order to cancel any residual magnetic field on the cathode, which would lead to an effective emittance growth. Also present, is a single cell normal conducting cavity at 1.3 GHz. This is used at 0 crossing in order to compress the beam longitudinally.

In addition to this, the simulations follow the beam across the first 7 TESLA cavities of the linac, corresponding to 1 cryomodule and about 100 MeV of energy gain. The energy gain in the TESLA cavities is limited to 16 MV/m, in order to minimize the cost of the cryoplant and the generation of dark current. The simulations show that this limit is sufficient to accelerate the beam and manipulate it longitudinally while maintaining the six dimensional brightness.

Beam Dynamics Considerations

In the case of the VHF electron gun, the relativistically correct transit time t across the gap is given by the formula $t = \sqrt{(d/c)^2 + 2d/a}$, where d is the gap length, c the speed of light and $a = eE/m$ is the acceleration of an electron of charge e, mass m under and electric field E, assumed to be constant. We can thus estimate the transit time to be $t \simeq$0.2 ns, a value much smaller than the period of the RF field given by $\tau_{RF} = 1/187MHz \simeq$5.35ns. Comparing these time scales, we can see that the dynamics in our case are conceptually closer to a DC gun than an LCLS-type cavity with RF frequency $\simeq$ 2.85 GHz.

The other dynamically important quality of the gun is the peak field at the cathode. In order to minimize dark current and power dissipation requirements this is kept at the relatively low value of $20MV/m$. This is sufficient for keeping the transverse emittance low, but requires longer bunches in order to overcome the space charge limit, as well as to minimize transverse space charge effects that may dilute the beam quality.

This constraint leads to low beam current at the injector, unless some compression is done at low energy. For this reason, we employ the single cell buncher at 0 crossing, in

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order to perform ballistic compression [4] and also dephase the TESLA cavities from the maximum acceleration phase, in order to perform velocity bunching [5].

A full discussion of the emittance compensation process and the low energy compression methods mentioned above is beyond the scope of this paper, but for our current purposes we note that for standing wave linacs, the laminarity condition assumed in the theory extends up to the energy $\gamma = \sqrt{2/3}\, I_{peak}/(I_0 \epsilon_{n,th} \gamma')$, where I_{peak} is the peak current, $I_0 = 17kA$ the characteristic current, $\gamma' = eE/(mc^2)$ and $\epsilon_{n,th}$ is the component of the emittance due to factors other than space charge. For our case, this number is below 90 MeV for all the currents under study, and hence we expect the emittance to be "frozen-in" at the injector exit, as indeed is shown in simulations. In addition, the longitudinal compression is also "frozen-in" as the relativistic β factor of the beam approaches 1.

SIMULATIONS AND OPTIMIZATION PROCEDURE

The simulation code used to model the low energy effects, including space charge and $\beta < 1$ effects, is ASTRA [6], which has been widely used and extensively benchmarked against experiments as well as other simulation codes. The initial transverse distribution of the bunch is radially symmetric in transverse positions $(x - y)$, and gaussian in the transverse momenta $(p_x - p_y)$, as is expected in the case of photoemission from a cathode illuminated by a transversely uniform laser. For the longitudinal component of distribution, a distribution with variable time duration, a plateau in the range of 10s of ps and a rise/fall time of 2 ps, is assumed for the emission time, whereas a gaussian distribution is assumed for the longitudinal component of the momentum. Again, this is compatible with the laser system employed.

The process of optimizing the injector operating point depends on a multitude of parameters that influence the final results in a nonlinear way, especially since ballistic compression, velocity bunching and emittance compensation are performed simultaneously. The approach taken during the injector design is based on [7] and [8], which use mutliobjective genetic algorithms for the optimization process. For this class of optimizers, the results comprise of a population of solutions, ordered according to their relative merits as defined by the user. This population of solutions is called the Pareto optimal front and allows the comparison of the offsets and advantages of different injector solutions a posteriori, without biasing the initial optimizer choices.

Optimization Objectives

Since NGLS is designed to be a user facility, the ultimate goal will be to optimize the properties of the xray beam at the user end. In order though to isolate and understand the effects of the injector dynamics, we take an intermediate approach and optimize the electron beam at the exit of the injector.

The first such objective we choose is the transverse, normalized emittance, which affects the performance of the FEL process [9]. The radial symmetry of the components relevant to beam dynamics is kept at all stages in the injector, and thus we can assume for design purposes a radial symmetry in the beam as well. Hence the x component of the emittance can be chosen as an objective, without loss of generality.

In addition to the transverse emittance, another important quantity affecting the FEL process is the longitudinal beam quality, quantified by the longitudinal beam emittance. In the case of relatively high charges, such as the nominal 300 pC case, both experiments and simulations show that a laser heater that increases the uncorrelated energy spread is required in the downstream linac in order to suppress microbunching [10]. Hence, since the longitudinal emittance is spoiled downstream on purpose, it is not a suitable optimization objective.

On the other hand, the microbunching instability is driven by magnetic compression in the downstream linac, and hence can be minimized if the linac compression ratio is reduced. Since the requirements at the undulator magnets on the user end call for specific pulse length and peak current, we choose the longitudinal rms bunch length as an optimization parameter.

Another set of constraints imposed by the downstream linac dynamics is defined by the correlated energy spread. Due to the ballistic and velocity bunching used in the injector, as well as the compression using magnetic chicanes in the downstream linac, an almost linear correlation between position z and energy E is imprinted on the beam by dephasing the RF fields in the buncher and TESLA cavities. Ideally this correlation should be linear, but the sinusoidal nature of the RF fields, imprints second order correlations as well. That is, the dominant correlations in longitudinal phase space can be described by $E(z) = E_0 + az + bz^2$.

Since a laser heater of finite energy acceptance is used in the downstream linac, the linear part of the correlation needs to be kept minimal for efficient operation of the heater. Additionally, second order terms can degrade the final beam quality after magnetic compression, and hence also need to be minimized. Third harmonic cavities have been successfully used to remove such second order correlations [10], and by dephasing the accelerating cavities we can also remove the linear component of the correlation. Hence, these issues can be addressed by manipulating the dynamics of the downstream linac. On the other hand, no method has been proposed so far to remove correlations of order higher than second, and the longitudinal beam quality is effectively degraded when such correlations are present, for example due to longitudinal space charge.

In order to isolate these higher order correlations, a new figure of merit is used, namely the reduced RMS energy spread of the beam after removing the first and second order correlations. Quantitatively, this is done by calculating $\sqrt{< E^2_{H.O.} >}$, where $E_{H.O.}(z) = E_{old}(z) - E_0 - az - bz^2$. In this equation, $E_{old}(z)$ is the initial energy of the particles

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as a function of longitudinal position z, and $E_0 + az + bz^2$ is the least-squares fit to $E_{old}(z)$.

The knobs available for optimizing the injector are the gradients and phases of the buncher and the first two TESLA cavities, required for compression and the emittance compensation process. In the case of the gun cavity, only the phase is varied and the gradient is kept at its maximum allowable value. In order to remove the linear chirp, we also allow the phases of the last 2 TESLA cavities to vary. In addition to the RF knobs, the strength of the solenoids is also changed, as required for emittance compensation. Finally, the initial transverse size and longitudinal bunch length are also varied by the optimizer. This is allowed through the shaping of the laser system [1].

OPTIMIZATION RESULTS

Nominal Charge Beam

From simulations of the downstream linac and the FEL process [11], as well as the dynamics considerations of the injector as described in the previous section, the nominal beam charge for NGLS is set at 300 pC. The result of the optimization process is, as mentioned, the Pareto optimal front, a 1 dimensional curve in the 2 dimensional objective space of transverse emittance and longitudinal bunch length. For the nominal bunch charge, this is shown in Fig. 2

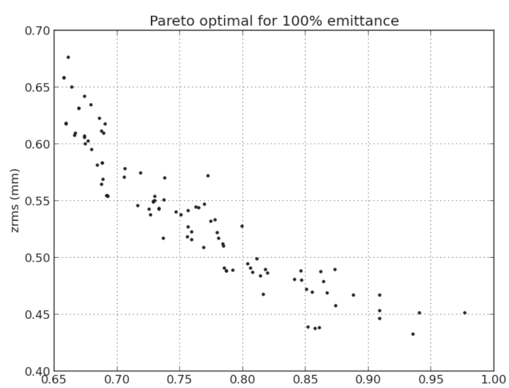

Figure 2: Pareto front for the 300 pC nominal charge. Quantities plotted at the exit of the injector (15 m from the cathode, energy > 90 MeV)

One of the solutions represented in Fig. 2 is shown in Fig. 3, where we plot the current profile, slice emittance and the longitudinal phase space of the beam at the exit of the injector. In addition to this, the longitudinal phase space is plotted after removing the first and second order correlations, as described in the previous section.

Another solution for the nominal 300 pC bunch charge is plotted in Fig. 4. In this case, in order to minimize the deleterious high order correlations, less compression is performed and the beam current is reduced by a factor of more than 2, while keeping the emittance at similar levels. This

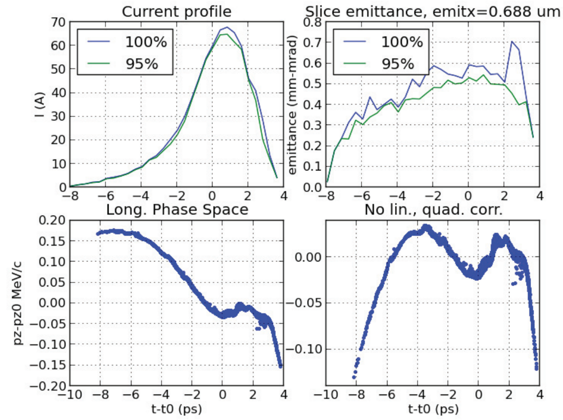

Figure 3: High compression solution for 300 pC bunch charge

is achieved by shifting the compression to the single cell buncher and operating the TESLA cavities on crest.

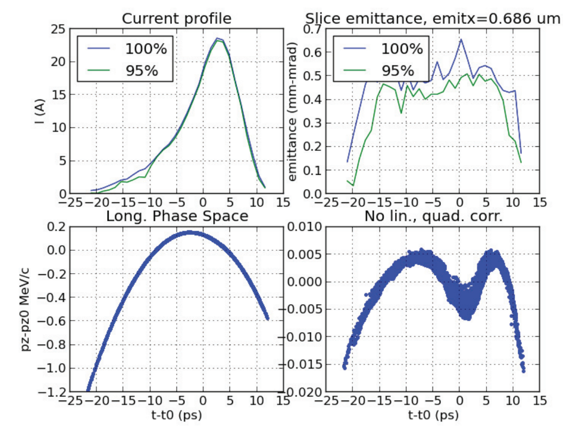

Figure 4: Low compression solution for 300 pC bunch charge. Compare with Fig. 3

Low Charge Mode

In addition to the nominal charge of 300 pC, a smaller charge of 30 pC may be of interest for users NGLS. The choice of the lower bunch charge is based on the successful operation of a similar mode for the LCLS [10]. In this case, the emittance and the bunch length decrease significantly, as expected. From operational experience at the LCLS, the laser heater in the downstream linac is not required in this case, leading to a simplified operation of the machine.

As before, a genetic optimizer is employed for the low charge optimization, with the resulting pareto front shown in Fig.5 Although the optimization for this mode is still in progress, one initial solution is shown in Fig. 6.

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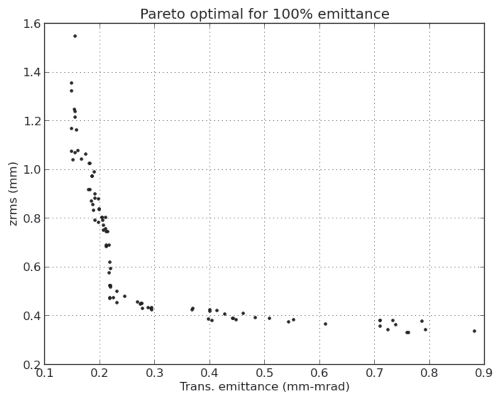

Figure 5: Pareto front for the low charge (30 pC) operating mode

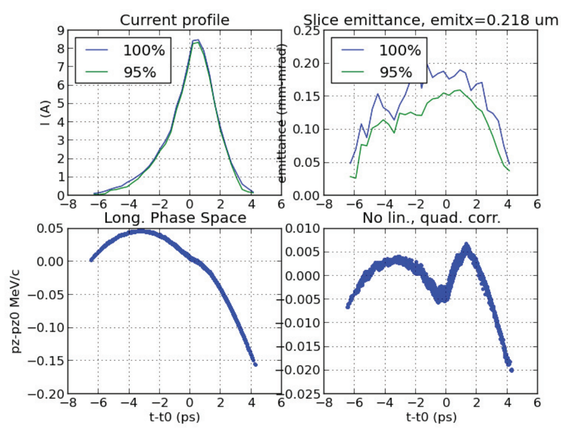

Figure 6: Solution for 30 pC at the exit of the injector

CONCLUSIONS

We present the results of the beam dynamics optimization for a high repetition rate photoinjector. Two solutions for the nominal charge of 300 pC are presented, with a relatively high and low peak beam current at the exit of the injector. This is done in order to minimize high order longitudinal correlations that may be deleterious downstream. In addition to this, initial results for a lower bunch charge of 30 pC are shown, with the expected reduction in emittance. Downstream linac simulations are presented elsewhere [12] for cases similar high compression 300 pC case presented here. In the case of the low compression 300 pC charge and the 30 pC charge, additional linac and FEL studies are required.

In Table 1, we show the final normalized emittance (100% and 95%), the peak current, the final energy and the rms energy spread $E_{H.O.}$ due to high order correlations, calculated as discussed previously.

Table 1: Final Properties of the Optimized Beams

	300 pC (high compr.)	300 pC (low compr.)	30 pC
ϵ_{nx} (mm-mrad)	0.688	0.68	0.218
ϵ_{nx95} (mm-mrad)	0.517	0.48	0.156
I_{peak} (A)	62	24	8
E_f (MeV)	92.53	106.4	111.8
$E_{H.O.}$ (keV)	17.4	3.5	3.7

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