INJECTOR BEAM DYNAMICS FOR A HIGH-REPETITION RATE 4th-GENERATION LIGHT SOURCE [*]

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Abstract

We report on the beam dynamics studies and optimization methods for a high repetition rate (1 MHz) photoinjector based on a VHF normal conducting electron source. The simultaneous goals of beam compression and preservation of 6-dimensional beam brightness have to be achieved in the injector, in order to accommodate a linac driven FEL light source. For this, a parallel, multiobjective optimization algorithm is used. We discuss the relative merits of different injector design points, as well as the constraints imposed on the beam dynamics by technical considerations such as the high repetition rate.

INJECTOR BEAM DYNAMICS

Definition and Requirements of the Injector

The Next Generation Light Source (NGLS) is a proposed xray Free Electron Laser user facility at LBNL [1], based on a superconducting linac design that accommodates a high repetition rate of 1 MHz. In this paper we will describe the beam dynamics issues and the design study for the NGLS injector.

In terms of beam dynamics, the injector is defined as the low energy part of the accelerator, where space charge forces and low $\beta = v/c$ kinematic effects are dominant and cannot be treated as a perturbation. In particular, the processes of emittance compensation, which depends on space charge forces, and ballistic and velocity bunching, both of which depend on β not being almost 1, are important. In the beamline dynamics section, we will see that, for the relevant electron beam parameters, these low energy phenomena become small for energies in the tens of MeV range, and can be ignored to a first approximation above 90 MeV. Hence, the injector is hereafter defined as the section of the accelerator that includes the electron gun, the two solenoids used for emittance compensation, one single cell buncher cavity and the first 7 TESLA cavities in the 1st cryomodule as shown in Fig. 1. The main goal of the design effort for the injector is the acceleration of the electron beam across the beamline while keeping the 6D phase space quality of the beam at an acceptable level. In addition to this, due to the special circumstances of the high repetition rate electron gun discussed below, longitudinal compression is required at low energy, in order to accommodate the required beam current at the injector exit.

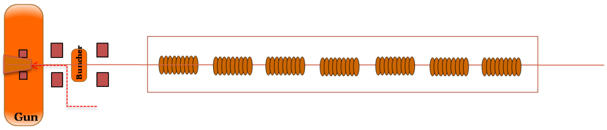

Figure 1: Schematic depiction the NGLS injector that includes the electron gun, two emittance compensation solenoids, one 1.3 GHz normal conducting buncher cavity and seven 1.3 GHz superconducting TESLA cavities.

Dynamics at the Gun/Cathode

The electron gun used [2] is a 187 MHz cavity with a cathode-to-anode gap of 4 cm, which can accelerate electrons up to 750 keV, with a 20 MV/m field gradient at the cathode. This leads to a relativistically corrected transit time t across the gap, $t = \sqrt{(d/c)^2 + 2d/a}$, where d is the gap length, c the speed of light and $a = eE/m$ is the constant acceleration of an electron of charge e, mass m under and electric field E. This gives an estimated $t \simeq 0.2$ ns, much smaller than the period of the gun RF field which is $\tau_{RF} = 1/187MHz \simeq 5.35$ns. Hence, for the relevant time scales, the dynamics in this gun are conceptually closer to a DC gun, than an LCLS-type cavity with RF frequency $\simeq$ 2.85 GHz.

Based on FEL and downstream linac simulations and requirements [1], as well as the injector constraints discussed in the following, a design value of 300 pC was chosen for the bunch charge.

The cathode material used plays an important role in the operation of the gun and the initial properties of the beam, and is discussed elsewhere [2]. For our current purposes the most important cathode dependent parameter is the initial normalized emittance. In the case of a Cs_2Te cathode, this has been experimentally measured [3] to be $\epsilon_{nx}[mm-mrad] = c_e[mrad] * \sigma_x[mm]$, where σ_x is the rms beam size and c_e a factor around 0.8, conservatively estimated to be 1 in the simulations.

Since the dynamics of the gun are similar to the DC case, we can use the formula [4]: $\tau_{l,min} = (\epsilon_0 V/d)/J_{sc.l.}$ to estimate the minimum allowable laser pulse length for a given gradient V/d and space charge limited current density $J_{sc.l.}$. Hence, for a given bunch charge and transverse size, we cannot have a laser pulse shorter than $\tau_{(l,min)}$. In addition to this, the relatively low energy of the beam at the gun exit leads to stronger space charge effects, such as emittance growth due to space charge nonlinearities and transverse beam size increase, both of which scale with beam current and energy as I/γ^3 [4].

The emittance growth is hard to estimate analytically, but

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its inverse cubic dependence on γ means that we need to further limit the initial peak current in order to control such effects. On the other hand, since the requirements at the exit of the injector call for a specific, intermediate peak current, and high compression in the injector can be deleterious for beam quality, an optimum needs to be found. The shape of the laser pulse is approximated by a plateau distribution of length $\simeq$60 ps, with a rise/fall time of 2 ps.

Dynamics in the Beamline

The term emittance compensation refers to the well documented [5] and experimentally verified [6] method used to remove the correlated emittance growth due to the linear component of space charge. In the case of standing wave linacs, the laminar regime required for emittance compensation 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 Alfvén current, $\gamma' = eE/(mc^2)$ and $\epsilon_{n,th}$ is the component of the emittance not due to space charge. For the NGLS injector, this leads to beam energy in the 90-100 MeV range for the freezing-in of the space charge. Ballistic bunching [7] is a method used to compress low energy beams, based on the energy dependence of velocity at relatively low energies. In particular, by using a cavity at 0-crossing (roughly -90 deg. from the maximum accelerating phase), we can imprint a time-energy correlation in the electron bunch. If the tail of the bunch has a higher energy than the head, the resulting velocity differential will cause the bunch to be compressed. In the case of velocity bunching [8], the beam is injected in an accelerating RF cavity with a phase offset between 0 and -90 deg. from the maximum accelerating phase. This leads to simultaneous compression and acceleration. The efficiency of both methods depends on the relation $\Delta L = \Delta\beta ct$, where ΔL is the path length differential for particles travelling with a speed differential $\Delta\beta$ for time t. Since $\Delta\beta = \Delta\gamma/\gamma^3$, both these effects become weaker with increasing energy.

OPTIMIZATION APPROACH

ASTRA Simulations

As we have seen already, a detailed description of the space charge forces, as well as the kinematic effects of $\beta < 1$ is needed to accurately calculate the beam properties across the injector. The code used to model these effects is ASTRA [9], which has been widely used in the field, and has been extensively benchmarked against experiment as well as other codes. The initial transverse distribution of the bunch is radially symmetric in x-y space, and gaussian in x-y, as is expected according to the emission model. For the longitudinal distribution, a plateau distribution with variable time duration and a rise/fall time of 2 ps, compatible with the laser system, is assumed for t, whereas a gaussian distribution is assumed for p_z. The photo-emission process requires that all particles be initially at z=0. Great care is taken to establish numerical convergence.

It is clear from the previous discussion that the problem of optimizing the injector setup depends on a multitude of parameters that influence the final results in a nonlinear way. The approach taken during the injector design is based on [10], which uses mutliobjective genetic algorithms for the optimization process. In this case, the result is not a single solution, but a population of solutions, ordered according to their relative merits. Hence, the offsets and advantages of each optimized solution for the injector can be judged with respect to other optimal solutions.

Objectives and Constraints

The ultimate objective of the optimization process is of course the final quality of the electron beam at the FEL undulators. But, in order to evaluate and better understand the effect of the injector, an intermediate approach of optimizing the beam at the injector exit is taken.

The first objective of the optimization process is the transverse, normalized emittance. Since the radial symmetry of the components is not broken at any stage in the injector, for design purposes we can assume a radial symmetry of the beam as well, and hence the x component of the emittance can be chosen as a figure of merit that needs to be minimized.

In addition, the bunch needs to be compact in the longitudinal phase space as well. This can in principle be quantified by the longitudinal emittance of the beam. In the particular case of the 300 pC charge though, both experimental experience and simulations show that a laser heater that increases the uncorrelated energy spread is required in the downstream linac in order to suppress microbunching [11]. This implies that the acceptable longitudinal emittance may be higher than what the injector can provide, and hence is not a suitable optimization objective.

On the other hand, microbunching is driven by magnetic compression in the downstream linac, and hence can be minimized if the linac compression ratio is minimized. Since the final requirements at the undulators call for a specific pulse length, we choose the longitudinal rms bunch length as an optimization parameter.

One other set of constraints is defined by the energy-position longitudinal correlations, and in particular the resulting correlated energy spread. Ideally, a high quality beam for FEL applications should have very low correlated and uncorrelated energy spread, as long as the spread is above the microbunching limit. But due to the ballistic and velocity bunching used in the injector, as well as the magnetic compression in the downstream linac, a linear correlation between z and E has to be imprinted on the beam. Additionally, due to the sinusoidal nature of the accelerating RF fields, second order correlations are also present. That is, the most important correlations can be described by $E(z) = E_0 + az + bz^2$.

Since a laser heater of finite energy acceptance is placed close after the exit of the injector, the linear part of the correlation needs to be minimized for the proper operation of the heater. Additionally, second order nonlinearities can degrade the beam quality in the case of downstream magnetic compression, and hence also need to be kept minimal. In the case of linac based FELs, third harmonic cavities have been successfully used to remove the second order correlations [11], and dephasing of the accelerating cavities from the maximum accelerating phase can be used to remove linear correlations. Hence, although care needs to be taken, these issues can be partly or wholly addressed by the downstream linac. On the other hand, as of yet no method has been proposed to remove correlations of higher order, and thus the longitudinal beam quality is effectively degraded when such correlations are introduced, for example due to space charge.

In order to estimate only the high-order correlations, the figure of merit used is a reduced RMS energy spread of the beam after removing the first and second order correlations. Specifically, we calculate $\sqrt{< E_{new}^2 >}$, where $E_{new}(z) = E_{old}(z) - E_0 - az - bz^2$. In the latter equation, $E_{old}(z)$ is the original energy of the particles as a function of longitudinal position z, and $E_0 + az + bz^2$ is the least-squares fit to $E_{old}(z)$.

OPTIMIZED SOLUTION

As described previously, the result of the optimization algorithm is not a single solution, but a population of solutions that can be evaluated individually, based on their relative merits. The longitudinal phase space for one of those solutions, chosen as a design point for NGLS with nominal charge 300 pC, is presented in Fig.2, along with the slice current and slice emittance of the beam. As seen in Fig. 2, the peak current is $\simeq$ 60 A, while the slice emittance is $<$ 0.6 mm-mrad for most of the beam, and $<$ 0.5 mm-mrad for the 95% of the particles that form the beam core. The evolution of the emittance and the longitudinal rms bunch length across the injector are shown in Fig. 3, as well as the energy. As we see, the rms bunch length is “frozen-in”, in the sense that it remains constant, even though there is still a correlation between energy and longitudinal position. On the other hand, the emittance is also very close to being “frozen-i”. The final properties of the optimized beam are given in Table 1.

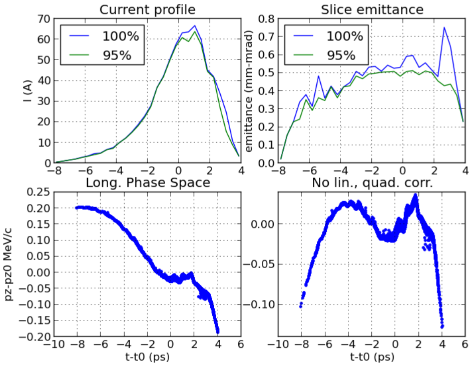

Figure 2: Properties of the optimized beam at the injector exit. The linear and quadratic correlations in $z - p_z$ are removed as described in the text.

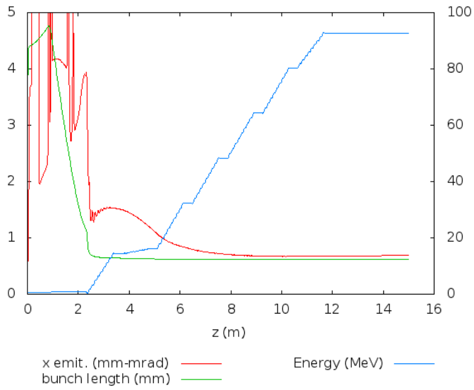

Figure 3: Evolution of trans. norm. emittance and bunch length (left y axis) and beam energy (right y axis) across the injector

Table 1: Final properties of the optimized beam

100% projected emittance	0.691 (mm-mrad)
95% projected emittance	0.517 (mm-mrad)
Peak current	60 (A)
Beam energy	92.54 (MeV)
Trans. Beam size	0.241 mm

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