INJECTOR DESIGN STUDIES FOR NGLS*

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Abstract

The APEX project at LBNL is developing an electron injector to operate a high repetition rate x-ray FEL. The injector is based on the VHF gun, a high-brightness, high-repetition-rate photocathode electron gun presently under test at LBNL. The design of the injector is particularly critical because it has to take the relatively low energy beam from the VHF gun, accelerate it at more relativistic energies while simultaneously preserving high-brightness and performing longitudinal compression. The present status of the APEX injector design studies is presented.

INTRODUCTION

The Next Generation Light Source (NGLS) [1] concept is an array of multiple FEL beamlines, each capable of operating at high repetition rates (> 100 kHz) simultaneously with the other beamlines. In order to achieve this, the repetition rate requirements on the linac and injector are of the order of 1 MHz, requiring continuous wave (CW) operation of the machine. As part of the R&D effort for NGLS, the Advanced Photoinjector Experiment (APEX) is currently under commissioning at LBNL, in order to demonstrate the feasibility of a high repetition rate photoinjector, satisfying all the machine requirements of NGLS.

Both the NGLS and APEX injectors are based on a normal conducting electron source cavity, operating at the VHF band (186 MHz) and in CW mode. The beam dynamics implications of this novel (for FEL injectors) mode of operation have been described elsewhere [2], and in this paper we will describe the current status of simulations for APEX, based on initial energy measurements of the electron beam. Start-to-end simulations of the full NGLS machine are reported elsewhere in these proceedings [3].

THE APEX BEAMLINE

A schematic of the APEX beamline is shown in Fig. 1. The beamline consists of 1 normal conducting electron gun cavity at 186 MHz, 3 focusing solenoid magnets and 1 bucking coil, 1 single cell buncher cavity at 1.3 GHz and 3 7-cell accelerating cavities. The nominal final energy at the exit of the APEX injector can be as high as 30 MeV, but due to RF focusing of the beam, in the optimized case the energy is typically lower than 15-20 MeV.

The low energy (< 750 keV) part of the beamline is identical to the current design for NGLS, with 1 MHz rep. rate, while the higher energy part is similar, with standing wave accelerating cavities at 1.3 GHz. The main difference is that due to space and shielding limitations in the current

location of APEX, there are only 3 normal conducting cavities instead of the superconducting TESLA-like cavities that would support CW operation at energy higher than 750 keV, as required by the NGLS design. The buncher and accelerating cavities will operate in pulsed mode instead, although the current design of the buncher includes the cooling required for CW operation. Additionally, studies are under way to optimize the coupler design for the buncher and accelerating section, to be reported on a later publication. Although some RF design considerations change for superconducting cavities, the single bunch beam dynamics are expected to be similar in the 2 cases.

The VHF gun has a load-lock system installed that can accommodate different cathodes, and the one assumed in the simulations is based on Cs_2Te, with an intrinsic emittance coefficient conservatively estimated to be 1 mm-mrad/mm [4]. The combination of laser power available at 1 MHz rep. rate [5] and high quantum efficiency of the photocathode allow for bunch charges > 500 pC, but beam dynamics considerations in the start-to-end simulations set the design bunch charge to 300 pC.

The energy out of the electron gun has the design value of 750 keV, corresponding to a peak RF gradient at the cathode of 19.5 MV/m, but during initial commissioning and operations this specification was exceeded and the energy was measured to be 800 keV, corresponding to peak gradient of 21.3 MV/m. This higher gradient is expected to improve the beam quality [6], as discussed later.

INJECTOR OPTIMIZATION

In the case of the injector, there are 2 main processes related to beam dynamics. First is the longitudinal compression of the beam, either by setting the phase of the buncher cavity at zero crossing (-90 deg. from peak acceleration) or by dephasing the accelerating cavities. This is required in the case of high repetition rate injectors, as the initial bunch length at the cathode is higher than pulsed guns with higher peak gradients [2]. The other important process is the well known emittance compensation [7] that minimizes the projected emittance of the beam, removing the correlated emittance growth due to linear space charge.

The parameters available for the combined optimization of these 2 processes are the gun phase, solenoid strengths[1] and phase and gradient of the 1.3 GHz cavities. The gradient of the gun is put to the maximum value possible, as increasing it is expected to always improve the beam brightness[2]. In addition, 2 knobs related to laser shaping are

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[1]the strength of the bucking coil behind the cathode is set to cancel the magnetic field of the first focusing solenoid on the cathode and hence it is not an independent variable

[2]Higher gradient is also associated with increased dark current, but in the current work we are focusing on beam dynamics
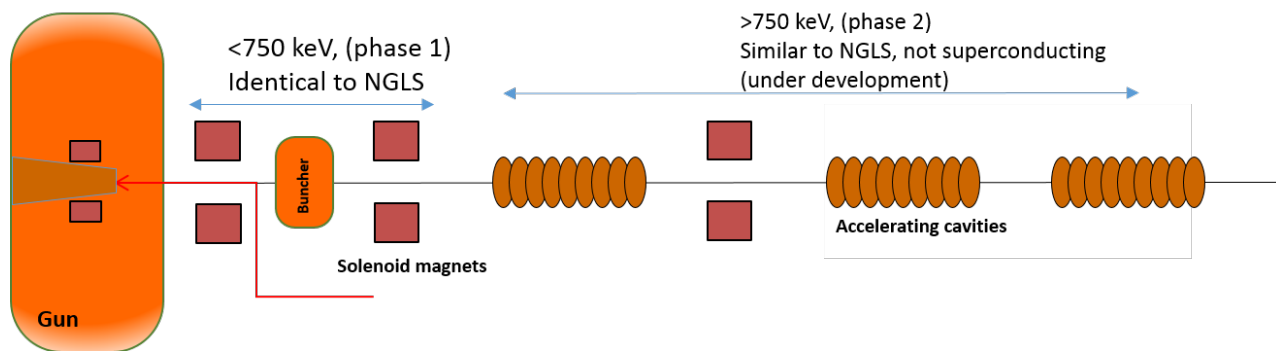
Figure 1: Schematic of the APEX injector beamline. Phase 1 is currently under operation, Phase 2 under development.

included, the transverse and longitudinal size of the laser beam, bringing the total to 14 knobs. The relative positions of the elements were optimized in previous design efforts and are kept constant in this case to accommodate the mechanical design.

The simulations for the injector are performed using the ASTRA particle-in-cell code [8], a standard tool for the modeling of photoinjectors. The optimization approach employed is a multi-objective genetic optimizer (NSGA-II) that is a proven method for the design of photoinjectors [9, 10]. In the case of multi-objective optimization, multiple (in our case 2) objectives are minimized simultaneously. The result in not a single solution, but a population of solutions which form a Pareto optimal front. In this case, the solutions on the optimal front are said to be non-dominated, in the sense that if objective f_1 is smaller for solution A than for solution B, then objective f_2 for solution B has to be smaller than for A. This way, the trade-offs inherent in choosing one solution over another become explicit.

The Pareto front resulting from the optimization process is shown in Fig. 2, for the design energy of the electron gun and the measured energy. The objectives chosen for this case are the transverse emittance in x (ϵ_{nx}) and the rms bunch length (σ_z). Since the cylindrical symmetry is not broken (to first order) in the NGLS design for low energies, only the emittance in the x projection is taken into account.

As shown in Fig. 2, there is a non-trivial improvement in the emittance of the beam when the energy out of the gun is increased to 800 keV, in the sense that keeping the bunch length constant, a lower emittance is possible in the 800 keV case. Conversely, if the emittance is kept the same, more compression can be done to decrease the rms bunch length. Intuitively this can be explained by the reduction of the space charge force (transversely and longitudinally) due to an increase in the relativistic γ factor of the beam, as well as the well know effect of peak gradient at the cathode on beam brightness [6].

As shown in Fig. 2, a range of values for the emittance and the bunch length is obtained, respectively from 0.63 mm-mrad to $<$ 1 mm-mrad and from $<$ 0.5 mm to 4 mm. The latter range corresponds to peak currents from
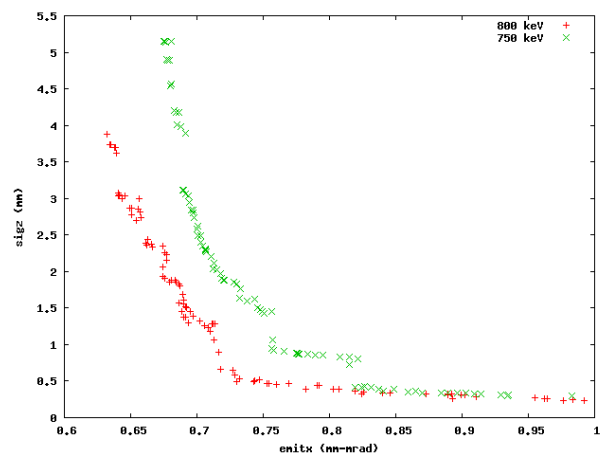

Figure 2: Comparison of Pareto optimal fronts for the design (750 keV) and measured (800 keV) beam energy out of the electron gun

10 A to higher than 70 A. In the case of the start-to-end NGLS simulations, the solution is picked according to requirements at the FEL beamlines, while for the APEX injector, one sample solution in the middle of the emittance and bunch length ranges is shown in Fig. 3 at the end of the injector beamline. The beam characteristics for this solution are shown in Table 1.

Table 1: Beam Quantities for the APEX Injector (300 pC)

	Cathode (0 m)	Injector exit (9 m)
Energy (MeV)	0	11.45
σ_x (mm)	0.28	0.59
ϵ_{nx} (µm)	0.28	0.69
95% ϵ_{nx} (µm)	0.266	0.52
Δt (ps)	59[a]	4.33[b]
I_{peak} (A)	5	30
$\sigma_E{}^c$ (keV)	0	720

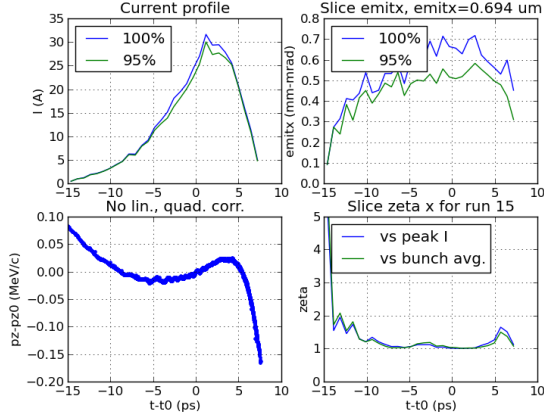[a]plateau distribution
[b]asymmetric gaussian-like distribution
[c]correlated energy spread

Figure 3: Phase space plots of the chosen solution at the exit of APEX. Head of the beam is to the right.

Table 2: Sensitivity Table for Select Error Inputs and Resulting Fractional Change in Beam Quantities ($\Delta q/q$, dimensionless)

	Energy	σ_z	σ_E	ϵ_{nx}
Φ_{gun}	-0.03%	0.17%	0.24%	-0.04%
Φ_{buncher}	0.03%	1.08%	1.05%	-0.07%
$\Phi_{\text{cav.1}}$	0.18%	2.86%	1.60%	0.43%
Gun x_{off}	0.00%	0.00%	0.00%	0.61%
Cav. 1 x_{off}	0.00%	0.00%	0.00%	0.61%
Solenoid 3 x_{off}	0.00%	0.00%	0.00%	0.63%
$E_{\text{gun}} \times 0.99$	-0.13%	0.44%	0.44%	1.70%
$E_{\text{gun}} \times 1.01$	0.05%	-0.46%	-0.34%	10.13%

In the case of the longitudinal phase space shown in Fig. 3, the linear and quadratic correlations present have been removed in post-processing, in order to mimic the effect of the downstream linac and 3rd harmonic cavity and evaluate the effect of higher order terms more clearly.

In order to evaluate the efficiency of the emittance compensation process, the mismatch parameter ζ is used, as defined [11] from Eq. 1.

$$\zeta = \frac{1}{2} \left(\beta_i \gamma_j - 2\alpha_i \alpha_j + \gamma_i \beta_j \right) \qquad (1)$$

In Eq. 1, α, β, γ refer to the usual beta functions, while the indices i, j refer to different slices of the beam, and ζ has a minimum value of 1. Hence, the slice parameter ζ provides a measure of how well the different beam slices are matched to each other. In the case of Fig. 3, each individual slice is compared to the slice corresponding to the peak current and the average beta functions of the bunch. The fact that ζ increases significantly at the tail of the beam should not affect the final lasing process at the undulators, since the current in those slices is very small and no lasing is expected.

SENSITIVITY ANALYSIS

In order to control the transverse and longitudinal quality of the beam, as well as to maintain good synchronization with external signals, tight requirements are placed on the timing and sensitivity to errors of the injector setup. An initial sensitivity analysis is presented here, where we calculate the effect on the most important characteristic beam quantities (beam energy E in eV, rms bunch length σ_z, correlated energy spread ΔE in eV and beam emittance ϵ_{nx} in mm-mrad). The input errors are in the gradient of the cavities (set to $\pm 1\%$ of the nominal value), RF phases (± 1 deg. of 1.3 GHz RF or 1/7 deg. of 186 MHz RF) and transverse offsets of solenoids and cavities ($\pm 100 \, \mu$m).

In the case of the solution presented in Fig. **??**, the sensitivity to various beamline parameters is shown in the following table:

Discussion of Sensitivities to Errors

From the results of Table 2, we can comment of the effect of different beamline parameters on the characteristic quantities of the beam.

In the case of RF phases, we see that the effect of the phase of the gun cavity is small, in accordance to the expectation that for our parameter regime the gun is similar to a DC gun from a beam dynamics perspective, since the initial bunch length of 59 ps is much shorter than the RF period of 5.35 ns. On the other hand, the phase of the buncher (which operates close to 0 crossing of the RF) and the phase of the 1st accelerating cavity have a significant effect on the energy spread and the rms bunch length of the beam, as both are used to compress the beam by chirping it.

In the case of offsets of the RF cavities, we see again an effect on the quality of the beam, as expected from analyses in the literature [12]. The effect of these offsets on the energy of the beam is very small (1-2 orders of magnitude smaller than the accuracy shown). For the solenoid, the effect is wholly on the emittance of the beam, since it's effect is restricted in the transverse phase space. It should be noted that the 100 μm offset is reasonable for mechanical alignment, but even tighter control may be achievable with beam based methods.

Finally, as discussed before, the gradient of the gun has a significant effect on the emittance of the beam. This is partly due to the effect on the brightness of the beam, but mostly due to the fact that the emittance compensation solenoids are set to a specific beam energy and hence emittance compensation is not appropriately done if the energy is offset. In this case, a variation of 1% is assumed, but for CW RF better control is expected. It is interesting to note that in this case a large asymmetry is present between increasing and decreasing the peak gradient by the same amount.

Overall, this initial analysis of the sensitivities of the injector does not point to any show stoppers, although more efforts are underway to evaluate the energy and timing stability of the entire NGLS linac [13].

CONCLUSIONS

We describe the status of injector simulations and design for the NGLS injector and the related APEX R&D project. The effect of slightly higher than design energy is evaluated, showing an improved expected performance compared to the original design case. The sensitivity of the main beam quantities to errors in beamline parameters is also studied.

ACKNOWLEDGMENTS

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