Numerical Investigation of a Laser Gun Injector at CEBAF*

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Abstract A laser gun injector is being developed based on the superconducting rf technologies established at CEBAF. This injector will serve as a high charge cw source for a high power free electron laser. It consists of a dc laser gun, a buncher, a cryounit and a chicane. Its space-charge-dominated performance has been thoroughly investigated using the time-consuming but more appropriate point-by-point space charge calculation method in PARMELA. The notion of "conditioning for final bunching" is introduced. This concept has been built into the code and has greatly facilitated the optimization of the whole system to achieve the highest possible peak current while maintaining low emittance and low energy spread. Extensive parameter variation studies have shown that the design will perform better than the specifications.

I. INTRODUCTION

CEBAF has been studying and developing an IR FEL and a UV FEL utilizing the superconducting accelerator technologies established at CEBAF, aimed at industrial applications and fundamental scientific research [1-4]. An FEL injector based on a DC laser gun will be used as a high-brightness cw source [5-7]. The schematic of the injector is shown in Fig. 1. The gun produces a cw train of electron bunches at 400 ~ 500 keV with bunch lengths of 60 ~ 100 ps. Then electrons are bunched using a room-temperature buncher to provide suitable injection into a cryounit containing two standard CEBAF SRF cavities. The cryounit accelerates the electrons up to ~ 10 MeV while providing suitable distribution tilt in longitudinal phase space. Then the electrons are finally bunched using a chicane with a $R_{56} = -0.085$ cm/%.

Fig. 1 Schematic of the FEL injector

The space-charge-dominated performance of the injector has been thoroughly investigated using PARMELA. The notion of "conditioning for final bunching" is introduced. This concept has been built into the code and has greatly facilitated the optimization of the whole system to achieve the highest possible peak current while maintaining low emittance and low energy spread. Extensive parameter variation studies have shown that the design will perform better than the specifications. The details will be presented in the following sections.

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II. CHICANE BUNCHING

Chicane bunching is not a new method for compressing electrons, and it has been clearly described, e.g., in Ref. 8. However, as will be shown later in this paper, it fits our injector design quite well when it is used together with two standard CEBAF SRF cavities. Therefore we introduce this bunching mechanism first instead of going to the numerical results immediately.

The bunching process using a chicane with two SRF cavities in our injector design is shown in Fig. 2. Using the

Fig. 2 Bunching using a chicane with two SRF cavities. standard σ matrix representation, we have

$$\sigma_{55}(1) = \sigma_{55}(0)(1 - R_{56}/f_{56})^2 + R_{56}^2 \sigma_{66}(-1),$$

where $\sqrt{\sigma_{55}(1)}$ is the bunch length at the exit of the chicane, $\sqrt{\sigma_{55}(0)}$ the bunch length at the entrance to the chicane, $\sqrt{\sigma_{66}(-1)}$ the momentum spread at the entrance to the second SRF cavity, $R_{56} = \delta l / (\delta p/p)$ the measure of the bunching property of the chicane, δl the path length difference between electrons having a momentum spread of $\delta p/p$, and $f_{56} = -\sigma_{55}(0)/\sigma_{56}(0)$ the measure of the tilt of the longitudinal phase space distribution of the bunch at the exit of the second SRF cavity. It is seen that when $f_{56} \simeq R_{56}$, the final bunch length depends only on the product of the momentum spread and R_{56} of the chicane. We call the above condition the *conditioning for final bunching*, which is a term borrowed from Ref. 9. We have built this concept into PARMELA so that f_{56} can be calculated statistically from all the particles, and by comparison with R_{56} of the chicane, the longitudinal matching from the second SRF cavity to the chicane can be predicted accordingly. This has turned out to be a quite accurate and indispensable means for optimizing the design efficiently.

III. NUMERICAL MODELING

The design has been optimized and thoroughly investigated using integrated numerical modeling with full space

charge taken into account. The beam dynamics is calculated using a version of PARMELA with the point-by-point method for space charge treatment [10,11]. POISSON and SUPERFISH were used to generate the DC electric fields in the gun and the 2-D RF fields in the buncher and SRF cavities in the cryounit. In each integrated simulation, the same electrons are followed from emission at the photocathode through the gun, the buncher, the cryounit and the chicane.

a) Baseline Design

The injector performance was optimized at first for the baseline design which corresponds to 500 kV gun voltage, 100 ps (4σ) laser pulse length and 3 mm (4σ) laser spot size defining the emission diameter. The distance from the gun to the buncher is reduced to account for the divergence (~ 20 mrad) of the beam out of the gun, and the distance from the buncher to the cryounit is increased to meet the optimum bunching requirement.

The specifications for our FEL injector is summarized in Table 1. The optimized performance of the baseline design is shown in Table 2. Various distributions of the bunch are shown in Fig. 3. The right bunching using the chicane was accomplished with $+2.5^\circ$ off zero-crossing phase for the buncher, -40° off crest phase for the first SRF cavity and -38° off crest phase for the second SRF cavity. With this set of parameters, $f_{56} = -9.57$ cm at the exit of the second SRF cavity and -9.15 cm at the entrance to the chicane, which is close to $R_{56} = -8.5$ cm of the chicane. This is a typical case indicating that the right chicane bunching would happen.

Fig. 3 Various distributions of 1000 superparticles at the exit of the chicane, showing the optimized baseline design performance listed in Table 2. *upper left* : longitudinal phase space distribution (W - energy; $\Delta\phi$ - relative phase); *upper middle* : phase profile; *upper right* : energy profile; *lower left* : horizontal trace space distribution (x - horizontal position; θ_x - horizontal divergence angle); *lower middle* : cross-sectional distribution; *lower right* : horizontal snapshot.

Table 1 FEL Injector Specifications

Energy	10 MeV
Charge per bunch	120 pC
Bunch length ($4\sigma_t$)	2 ps
Energy spread ($4\sigma_E$)	400 keV
Normalized rms emittance (ϵ_n)	15 mm mrad
Average beam current	900 μ A
Repetition frequency	7.677 MHz

Table 2 Performance of the Baseline Design

Bunch charge	120 pC
Bunch length ($4\sigma_t$)	0.96 ps
Energy spread ($4\sigma_E$)	290 keV
Mean energy (E_m)	9.492 MeV
Norm. rms emit. ($\epsilon_{nx}/\epsilon_{ny}$)	4.44/4.73 (mm mrad)

b) Robustness of the Baseline Design

The robustness of the baseline design has been investigated against the laser intensity fluctuation and consequently the bunch charge fluctuation. A series of integrated simulations were conducted with all the system parameters fixed while the bunch charge was varied from 120 pC to 160 pC. The variations of the bunch performance at the exit of the chicane are listed in Table 3, where δE_m and $\delta\phi_m$ represent the mean energy shift and the phase shift of the bunch centroid. The units are pC for bunch charge, ps for bunch length, keV for energy spread, mm mrad for emittance, keV and degree for centroidal energy and phase shifts throughout the paper. It is seen that the mean energy shift and the phase shift of the bunch centroid caused by the charge fluctuations are negligible.

Table 3 Robustness of the Baseline Design

Q	$4\sigma_t$	$4\sigma_E$	$\epsilon_{nx}/\epsilon_{ny}$	δE_m	$\delta\phi_m$
120	0.96	290	4.44/4.73	0	0 (base)
140	1.04	281	4.99/5.31	-1	-0.0048
150	1.11	277	5.25/5.58	-1	-0.0075
155	1.17	275	5.37/5.71	-2	-0.0092
160	1.21	273	5.50/5.84	-2	-0.0092

c) Sensitivity of the Baseline Design

The sensitivity of the baseline design has been investigated on the basis of $\delta\phi = \pm 2^\circ$ for the RF phase change and $\delta E/E = \pm 2\%$ for the RF amplitude change in the buncher and the two RF cavities in the cryounit. For each case only one parameter was varied with all the others being the same as for the optimized baseline design stated in Table 2. The results are listed in Table 4. It is found that the most sensitive performance is the bunch length. The most sensitive system parameters, in sequence, are the RF phase of the second SRF cavity, the RF amplitude

of the second SRF cavity, the RF amplitude of the first SRF cavity and the RF phase of the first SRF cavity. The sensitivity comes from the resultant mean energy shift of the particles and the small value of R_{56} of the chicane. However, the rf requirements are readily achieved.

Table 4 Sensitivity of the Baseline Design

Element	$\delta\phi$	$\delta E/E$	$4\sigma_t$	$4\sigma_E$	$\epsilon_{nz}/\epsilon_{ny}$	δE_m	$\delta\phi_m$
(Baseline)	0.0	0.0	0.96	290	4.44/4.73	0.0	0.0
Buncher	+2	0.0	1.57	306	4.69/4.98	-51	+0.42
Buncher	-2	0.0	1.37	261	4.23/4.50	+56	-0.47
Buncher	0.0	+2	1.05	309	4.52/4.81	-1	+0.03
Buncher	0.0	-2	1.21	257	4.34/4.63	+3	-0.05
1 st cavity	+2	0.0	1.53	260	4.30/4.58	-75	-0.22
1 st cavity	-2	0.0	1.23	306	4.60/4.90	+78	+0.42
1 st cavity	0.0	+2	1.22	296	4.45/4.75	+106	-1.81
1 st cavity	0.0	-2	1.52	269	4.41/4.69	-102	+2.04
2 nd cavity	+2	0.0	1.63	269	4.41/4.70	+114	-1.94
2 nd cavity	-2	0.0	1.89	295	4.45/4.74	-117	+2.33
2 nd cavity	0.0	+2	1.18	288	4.42/4.71	+85	-1.47
2 nd cavity	0.0	-2	1.41	277	4.45/4.73	-84	+1.63

d) Gun Parameter Variations

To evaluate the maximum operational flexibilities, the injector performance under different gun operating conditions has been investigated. These conditions include the voltage V_0 (keV), the field gradient E_0 (MV/m) at the cathode, the laser pulse length $4\sigma_t$ (ps) and the diameter d_0 (mm) of the active cathode area. The corresponding beam parameters at the exit of the chicane are shown in Table 5. The low gradient of 6 MV/m was obtained by increasing the cathode-anode gap while holding the cathode and anode shapes unchanged. Low-gradient operation would be favorable for avoiding vacuum breakdown and cathode poisoning. It is seen that the design will function over a quite wide range of operating conditions.

Table 5 Gun Parameter Variations

V_0	E_0	$4\sigma_t$	d_0	$4\sigma_t$	$4\sigma_E$	$\epsilon_{nz}/\epsilon_{ny}$
500	10	100	3	0.96	290	4.44/4.73 (base)
500	10	60	3	2.00	109	3.65/3.85
500	10	60	5	1.54	118	3.78/3.97
500	10	100	5	0.79	287	4.07/4.44
400	8	100	3	1.24	272	5.32/5.02
400	8	60	5	0.91	260	6.12/6.08
500	6	100	3	0.91	330	6.49/6.12

e) Emission Phase Fluctuations

Emission of electrons is controlled by the laser pulses regularly illuminating the photocathode. Arrival time spread $\delta\phi_0$ (deg.) of the laser pulses will cause bunch-to-bunch energy spread δE_m and bunch-to-bunch centroid phase shift $\delta\phi_m$. As is shown in Table 6, the effects on both mean energy and centroid phase are negligible.

Table 6 Emission Phase Fluctuations

$\delta\phi_0$	$4\sigma_t$	$4\sigma_E$	$\epsilon_{nz}/\epsilon_{ny}$	δE_m	$\delta\phi_m$
0	0.96	290	4.44/4.73	0	0 (base)
+2	1.06	276	4.50/4.80	-14	+0.039
-2	0.94	303	4.32/4.61	+15	-0.029

f) Space Charge Effects

The setup procedure is one of our major concerns. To investigate the possibility of using a low-current beam to guide the injector to its full-charge (120 pC) operation, an integrated simulation was conducted, in which the space charge was simply turned off, in the case of 400-kV gun voltage, 60-ps laser pulse length and 5-mm cathode diameter [12].

In this specific case, the bunch length changes from 0.96 ps with space charge on to 1.92 ps with space charge off. This is because the system parameters are for a matched space-charge-dominated bunch in longitudinal phase space. The normalized rms emittance $\epsilon_{nz}/\epsilon_{ny} = 3.53/3.47$ mm mrad with space charge on or 0.66/0.66 mm mrad with space charge off, at the exit of the gun. $\epsilon_{nz}/\epsilon_{ny} = 6.12/6.08$ mm mrad with space charge on or 2.19/1.83 mm mrad with space charge off, at the exit of the chicane.

Our numerical calculations show that on a step-by-step basis, a lower current beam can be used to guide the injector to its full-charge operation, which will greatly simplify the setup procedures.

IV. SUMMARY

Extensive careful integrated computer simulations have demonstrated that our injector design will perform better than the specifications over a quite wide range of operating conditions. In addition, in view of the fact that the accelerating gradient of the two cell buncher is as low as 0.5 MV/m, we will use a one cell buncher to make the design more cost effective.

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