BEAM DYNAMICS STUDIES ON THE INJECTOR OF THE IHEP ERL TEST FACILITY*

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Abstract

In this paper we present the beam dynamics studies with the Impact-T program on the injector of the ERL test facility in the Institute of High Energy Physics, Beijing. Variable parameters, including driven-laser beam size, solenoid strengths and positions, RF cavity strengths, positions and phases, are varied to optimize the beam quality at the end of the injector.

INTRODUCTION

The energy recovery linac (ERL) and free electron laser (FEL) are considered to be candidates of the fourth generation light sources, and have received much attention worldwide. Since both of them are based on linac technologies, it is possible to combine FEL into an ERL facility, resulting in a compact two-purpose light source. A test facility, named energy recovery linac test facility (ERL-TF), was proposed at the Institute of High Energy Physics (IHEP), Beijing, to verify this principle [1]. Physical design of the ERL-TF started a few years ago and is well in progress [2-4]. It is worth mentioning that we thoroughly studied the beam breakup effect in such a two-purpose machine. It is found that two effects emerge as a result of the introduction of FEL beams: a reduction in the threshold current and a central orbit fluctuation for ERL current under threshold. Due to the fact that the repetition rate of FEL bunches is much smaller than that of ERL, the introduction of FEL beam does not have a fatal effect on the threshold current. As for the orbit fluctuation, we gave a simple model and found a resonance relation between the voltage spread and the ratio of HOM frequency to the FEL repetition rate. By choosing an appropriate FEL frequency, the amplitude of the orbit fluctuation can be kept small [4].

The layout of the facility is presented in Fig. 1. The nominal energy of the electron beam in the radiator is 35 MeV and beam current is 10 mA. Among the components of the facility, one extremely important device dominating the machine performance is the photo-injector. The injector, including a 500-kV photocathode direct-current (DC) gun equipped with a GaAs cathode, a 1.3 GHz normal conducting RF buncher, two solenoids, and two 2-cell superconducting RF cavities, was designed for the ERL-TF [2], with the layout shown in Fig. 2 and main parameters listed in Table 1. Preliminary optimization of the beam dynamics has been performed, and finally an electron beam with normalized emittance $\varepsilon_{n,x(y)}$ of 1.49 mm.mrad was obtained. In this paper, we optimize the beam dynamics of the injector in both the low-charge operation mode (bunch charge 7.7 pC, rep. rate 1.3 GHz) and the high-charge operation mode (bunch charge 77 pC, rep. rate 130 MHz) using the Impact-T program [5], a fully 3D program to track relativistic particles taking into account space charge force and short-range longitudinal and transverse wake-fields. Study shows that it is feasible to achieve a better beam quality at the end of the injector.

Figure 1: Layout of the ERL test facility.

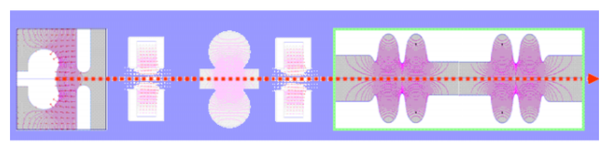

Figure 2: Layout of the ERL-TF injector.

Table 1: IHEP ERL-TF Injector Main Parameters

Parameter	Value	Unit
DC-gun voltage	300-500	kV
Laser power and wavelength	2.3/532	W/nm
Laser rep. rate	130 (or 1300)	MHz
Laser rms trans. size	0.3~1.2	Mm
Laser length	20	Ps
E- ave. kinetic energy	0.2	eV

OPTIMIZATION FOR THE LOW-CHARGE OPERATION MODE

For the low-charge operation mode, a parameter iterative scan program is developed with Matlab which starts several runs of tracking simultaneously. This code can finish the multi-variable scans, which usually contains a few hundred of runs, within an acceptable period of time (e.g. in 2 hours) on a desktop computer.

As the start of the simulation, initial beam distribution is generated according to initial laser parameters listed in Table 1. The normalized emittance $\varepsilon_{n,x(y)}$ is given by

$$\varepsilon_{n,x(y)} = \sigma_{x(y)}\sqrt{\frac{k_B T_\perp}{m_e c^2}}, \qquad (1)$$

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where $\sigma_{x(y)}$ is the horizontal (vertical) rms beam size on the cathode, $m_e c^2$ is the electron rest energy, and $k_B T_\perp$ is the transverse beam thermal energy, which is found depending mainly on the incident laser wavelength [6],

$$k_B T_\perp (meV) = 309.2 - 0.3617\lambda(nm). \quad (2)$$

For the incident 532 nm laser, $k_B T_\perp$ = 116.8 meV and $\varepsilon_{n,x(y)}$ = 0.57 mm.mrad.

With the generated initial beam distribution, twelve variables are iteratively scanned to search the optimal parameter setting that results in the lowest $\varepsilon_{n,x(y)}$, small energy spread σ_δ, bunch length σ_z of 2 ~ 4 ps, and kinetic energy E_k of 5 MeV. The optimization starts with the scan of the buncher parameters to realize a σ_z of 2 ~ 4 ps, then incudes the solenoid parameters in the scan to minimize the $\varepsilon_{n,x(y)}$ and the RF cavity parameters to optimize the E_k as well as the σ_δ and σ_z, and finally ends with a global scan of all variables. Finally, with a laser rms transverse size of 0.5 mm is made, an electron beam with E_k of 5 MeV, $\varepsilon_{n,x(y)}$ of 0.40 mm.mrad, σ_z of 0.74 mm and σ_δ of 0.33% is achieved at the end of the injector.

Recently significant progress was made in Cornell University on high-current operation from a photo-injector with a DC-gun [7]. One important technological improvement is to choose the active area off the cathode center, which helps avoiding the damage due to ion back-bombardment and hence providing good operational lifetime. To investigate the impact of the initial offset on the final beam quality, numbers of simulations with different initial offsets are performed. Since the beam distribution is no longer azimuthal symmetry with a nonzero offset, 3D space charge effects are turned on right at the beginning of the tracking. The result is shown in Fig. 3. It shows that a 5-mm offset from the cathode center does not lead to neither large difference between horizontal and vertical emittance nor large beam quality degradation. The emittance increases by about or more than 50%, but is still below 1 mm.mrad.

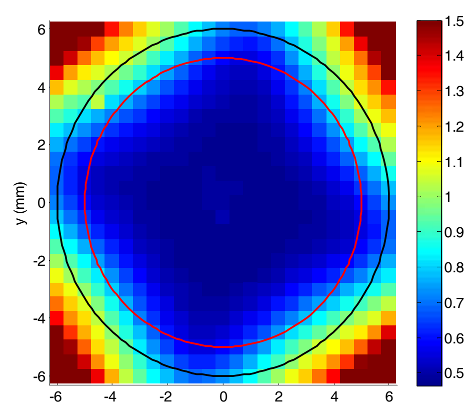

Figure 3: Simulation data of $(\varepsilon_{n,x}^2/2 + \varepsilon_{n,y}^2/2)^{1/2}$ with different initial offset at cathode. The red and black circles represent initial offset of 5 mm and 6 mm from the center, respectively.

To ensure the feasibility of the optimized beam quality in a realistic condition, error tolerance study is necessary and tolerable magnitude of the errors should be determined. For the ERL-TF, both the alignment and rotation errors of each element are considered in the analysis. We first set the amplitude of the alignment error the same as that of the rotation error. In the analysis 1000 random settings of the errors (truncated at 3σ) are added to each element, then tracking with 3D space charge forces is performed, and finally the beam parameters at the end of the injector are recorded. It is found that only the normalized emittance has evident increase due to errors. Therefore statistical analysis is performed only on emittance data. The variation of the average and the maximum emittance growth rates with error amplitude is shown in Fig. 4. Consequently the contributions of different element and different error to emittance growth are analysed. Study shows that only the alignment error of the solenoids (especially the first solenoid) is the main source of the emittance growth. To remain the emttance growth rate below 10%, the element alignment error of the solenoids must be smaller than 0.15 mm, while the other errors should be smaller than 0.3 mm or 0.3 mrad. .

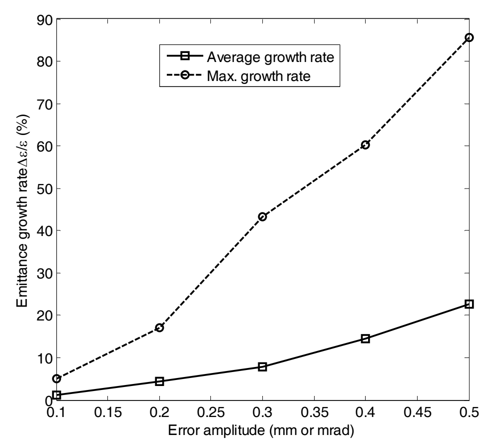

Figure 4: Variation of the emittance growth rate with the alignment and rotation error amplitude.

OPTIMIZATION FOR THE HIGH-CHARGE OPERATION MODE

For the high-charge operation mode, associated with the stronger space charge force compared to that in the low-charge operation mode, unfortunately the iterative scan loses it efficiency in achieving a promising beam qualify at the end of the injector. It is necessary to explore the available minimum emittance with more advanced method, for instance, the multi-objective genetic algorithm (MOGA). This method recently has been widely used in the accelerator designs to optimize the beam optics or the machine performance [e.g., 8]. Here we apply a genetic algorithm, NSGA-II [9] in the optimization.

Three objectives, such as the final emittance, bunch length (the closer to 3 ps, the better), and the beam kinetic

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energy (the closer to 5 MeV, the better), are used in the optimization. The genetic optimization is rather time consuming. In our case it needs about one month to calculate 100 generations, with 350 random seeds in each generation. Figure 5 shows the pareto front of the objectives after 100th generation in the case that the initial laser beam rms transverse size of 0.5 mm. As expected, the available emittance decreases as the bunch length increases. If only considering the results with final bunch length below 4 ps, i.e., 1.2 mm, the available minimum emittance is about 2.7 mm.mrad.

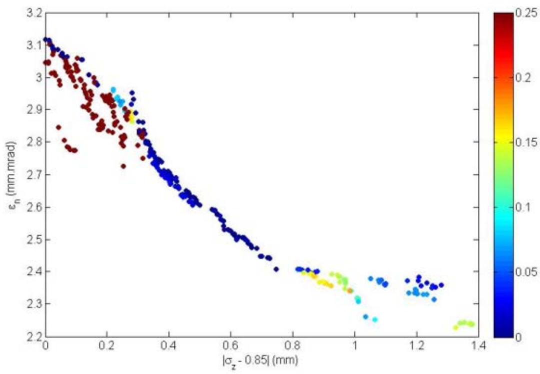

Figure 5: Pareto front of the objectives after 100th generation in the case that the initial laser rms transverse size of 0.5 mm. The colour indicates the difference of beam kinetic energy from 5 MeV.

Similarly, we perform the genetic optimizations for the cases with different initial laser beam rms size (up to 200 generations for each case), and record the result predicting the smallest emittance among those with final bunch length of 2 to 4 ps and kinetic energy of 5MeV. The variation of the minimum emittance with the initial laser beam rms size is presented in Fig. 6. It appears that a relatively large laser beam rms size (1 ~ 1.2 mm) is preferred for achieving a small-emittance electron beam in the high-charge operation mode. Too small or too large an initial laser beam size will lead to a large final emittance, because of the strong space charge effect or the large initial thermal emittance.

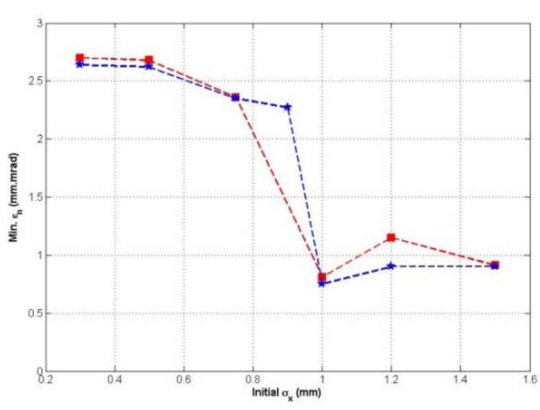

Figure 6: The available minimum emittances (σ_z – 2~4 ps, E_k ~ 5 MeV) with different initial laser beam rms size.

In addition, to demonstrate the efficiency of the iterative scan in the optimization for the low-charge operation mode, genetic optimization is also performed for the low-charge operation mode with initial laser beam rms size of 0.5 mm. The optimal results as well as the result obtained by the iterative scan (signified with a star) are shown in Fig. 7. It shows that the emittance obtained by the iterative scan is very close to the global minimum.

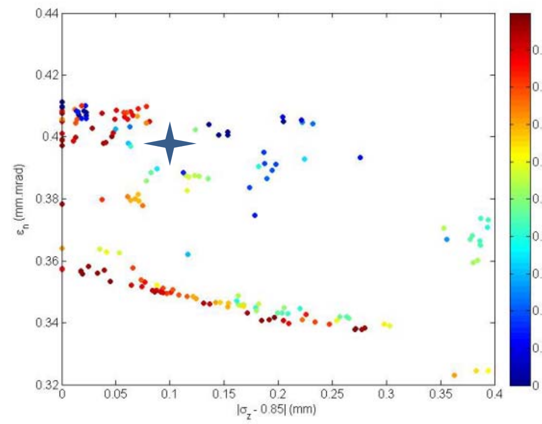

Figure 7: The available minimum emittances (σ_z – 2~4 ps, E_k ~ 5 MeV) with different initial laser beam size.

CONCLUSION

We show the beam dynamics optimization of the ERL-TF injector in both the low-charge and the high-charge operation mode at IHEP with iterative scans and multi-objective genetic algorithm based on simulations with the Impact-T program. The dependency analysis and the error tolerance study are also performed. It appears feasible to achieve a good beam quality at the end of the injector.

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