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SIMULATION AND OPTIMIZATION OF THE TRANSPORT BEAMLINE FOR THE NOVOFEL RF GUN

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Abstract

A new low-frequency CW RF gun was developed and tested at Budker Institute of Nuclear Physics recently. We plan to use it to upgrade the ERL of the Novosibirsk FEL facility. It will allow increasing the average beam current (due to higher beam repetition rate) and thus increasing the average radiation power. The transport beamline for the RF gun uses the ninety-degree achromatic bend. It is designed in a way that keeps an option to operate with the old electrostatic gun as well. Due to the low beam energy (290 keV) the beam dynamics is strongly influenced by space-charge forces. The paper describes results of simulation and optimization of the RF gun transport beamline. Space-charge forces were taken into account with the code ASTRA. Main sources of emittance degradation were considered in order to decrease their influence during the optimization. In addition, the RF gun output beam parameters were measured for various RF gun emission phases. These experiments were simulated, and the results were compared. The resulting beam parameters meets requirements of the Novosibirsk FEL facility ERL.

INTRODUCTION

Injector of the Novosibirsk FEL [1] now uses static electron gun. In near future it is planned to be supplemented with new low-frequency CW RF gun [2]. It will allow increasing the maximum of the average beam current from 30 mA to 100 mA and more due to higher beam repetition rate. The cathode grid assembly of the RF gun is the same as the static gun one. Basic RF gun parameters are listed in Table 1.

Increasing of the average beam current should lead to increasing of the average radiation power. It requires accurate simulation and optimization of beamline magnetic optics in order to reduce losses of high current beam, and consequently to prevent vacuum chamber heating and vacuum breakdown.

Table 1: Basic RF Gun Parameters

Parameter	Value	Unit
Average Current	≤ 100	mA
Electron Energy	240-300	keV
Bunch Charge	≤ 2.0	nC
Bunch Length (FWHM)	1.0	ns
Peak Current	15	A
Beam repetition rate	0.002 – 90.2	MHz

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TRANSPORT BEAMLINE FOR THE RF GUN

Beamline Scheme

The scheme of the Novosibirsk FEL injector is illustrated in Fig. 1. A 300 kV static electron gun, a bunching RF resonator and two RF cavities are in operation now. A beam is generated in the static electron gun. Then it is bunched and accelerated up to an electron energy of 1.8 MeV. At the injector output the beam normalized emittance is 30 mm·mrad.

The RF gun will be connected to the injector by the ninety-degree achromatic bend (as shown in Fig. 1) in order to keep an option to operate it with the static gun. The working regime of the RF gun is around 40° from the phase of the maximum beam acceleration. So, the bunching resonator is not required for the RF gun beamline.

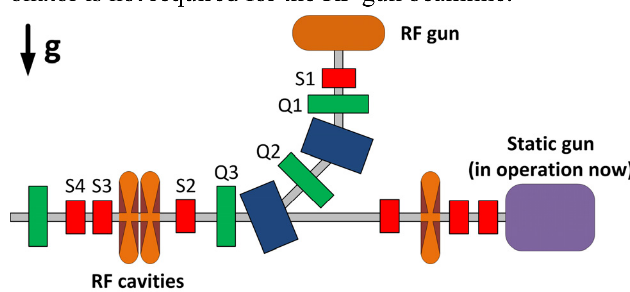

Figure 1: A scheme of the NovoFEL injector with the new RF gun: red – solenoids, green – quadrupoles.

Simulation

Simulations of beam dynamics in the injector are performed with the code ASTRA [3] by the following reasons: taking into account space-charge forces and a possibility of defining 1D and 3D electromagnetic field distribution of magnet and accelerator elements.

The simulation starts from the cathode. The cathode grid assembly and anode focusing is considered.

Optimization

The program package ASTRA has a lack of optimization features, except scanning or optimizing by one parameter in predefined value range. Thus, it has been decided to write a script for automatic calculations of beamline regimes with ASTRA that would be easily used with external optimization modules. The program language Python was chosen due to powerful open-source mathematical libraries.

Two Python scripts AstraTools.py and AstraProc.py were written that make the simulation as a calculation of fitness function. It works the following way as it described in Fig. 2. Module AstraTools.py takes a vector of parameters (any parameters defining by ASTRA input file), changes values of corresponding parameters in the pattern input file and saves this as a new one. Then the module launches the simulation in Astra.exe with modified file. When the simulation finishes AstraProc.py script starts processing output data and calculating fitness function. It is possible to define the function as any combination of ASTRA parameters.

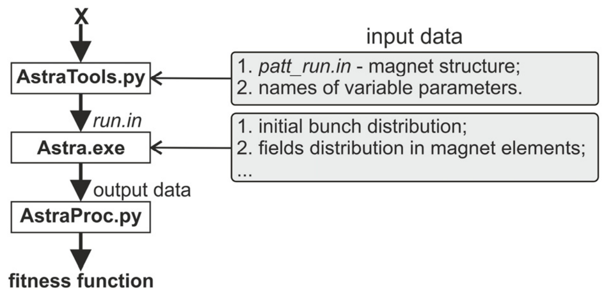

Figure 2: Python scripts make a simulation of magnet optics regime as a calculation fitness function.

Using these scripts, the RF gun beamline regime was optimized. Figure 1 demonstrates free parameters for optimization: currents in elements S1-S4 and Q1-Q3. However, the strength of quadrupole Q2 is determined so as to get an achromatic bend. The bunch is not round after the bend so currents in solenoids S2-S4 are defined by Eq. (1) in order to suppress coupling of transverse betatron oscillations

$$\phi(S2)+\phi(S3)+\phi(S4)=0 \tag{1}$$

where ϕ is an angle of beam rotation in the plane XY in solenoid

$$\phi=\frac{e}{2pc}\int_{-\infty}^{\infty} B_Z(z)dz \tag{2}$$

where B_z is the longitudinal magnet field of solenoid on its axis. Solenoid S3 and S4 currents are chosen equally to decrease their focusing strength. Thus, there are only four variable parameters boundary constrained: currents of Q1 and Q3 are in range -3…3 A, and S1 and S2 are in range 0…10 A.

In this paper two algorithms of optimization were used: differential evolution (DE) algorithm [4] and Nelder–Mead method [5]. The first one is for global optimization of a function that satisfies boundary constraints (in our case: currents in magnet elements), and the second one is for further faster but local optimum solution search.

In order to minimize transverse emittances and to keep beta function to around 1 m the fitness function was defined by the relation

$$f=0.5\left[10^6\left(\varepsilon_X+\varepsilon_Y\right)+10^3\left(\sigma_X+\sigma_Y\right)\right] \tag{3}$$

where $\varepsilon_{x,y}$ – normalized emittance and $\sigma_{x,y}$ – rms beam size (both in meters).

The process of global optimization with DE algorithm is illustrated in Fig. 3. A size of the population is 45, maximum number of iterations is 450.

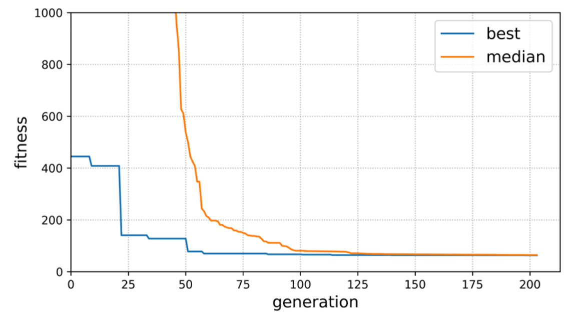

Figure 3: The process of optimization with DE algorithm.

A cooling aperture at the center of the bend was considered so as to decrease bunch energy distribution. In the result, an optimal regime with beam propagation of 81% and normalized transverse emittances of 27 mm·mrad was achieved. A distribution of beam transverse rms sizes along the beamline is shown in Fig. 4. More output beam parameters are listed in Table 2.

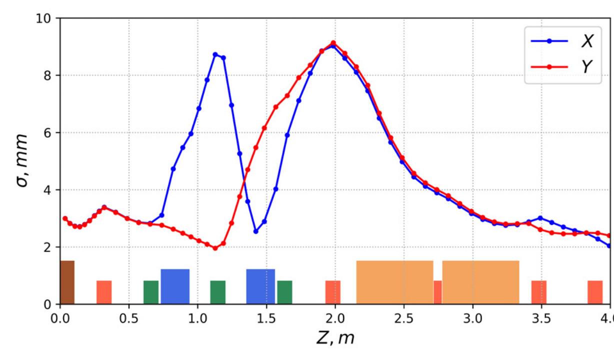

Figure 4: The optimized beam sizes for the RF gun beamline.

Table 2: Optimized Regime: Electron Beam Parameters at the Output of RF Gun Beamline Bend

Parameter	X	Y
Propagation	0.81	
Normalized Emittance, mm·mrad	27.6	27.0
Average Local Norm. Emittance, mm·mrad	13	20
Beta Function (β), m	0.39	0.82
Alpha Function (α)	-0.092	0.017
Longitudinal Size, ps	42	
Kinetic Energy of Electrons, MeV	1.356	
Energy distribution, σ_p/p_0	0.008	

MEASUREMENTS OF THE RF GUN BEAM PARAMETERS

In order to verify a model of the RF gun measurements of beam parameters were performed. The RF gun is testing at the stand now. The scheme of the test stand is shown in Fig. 5. It consists the RF gun, a solenoid, a quadrupole lens,

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a bend dipole magnet and an optical transition radiation (OTR) monitor.

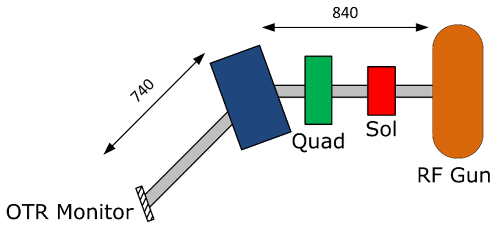

Figure 5: The scheme of the RF gun test stand.

A bend magnet in the scheme allows measuring an energy distribution of the beam from the RF gun. The experiment was conducted in the following way: the solenoid was turned off and the quadrupole strength was chosen so that the horizontal beta function was a minimal. Thus, the best energy resolution is achieved

$$\frac{\delta p}{p_0} \approx \frac{\sqrt{\varepsilon\beta}}{\eta} \tag{4}$$

where p_0 and δp is an average of electron impulse and its deviation, ε is the emittance, η and β – are the dispersion and the beta function at the OTR monitor position. The result of measurements of transverse horizontal beam density is shown in Fig. 6, which demonstrates good agreement between the simulation with ASTRA code and the experimental data. However, the deviation is more as the RF gun phase is far from the phase of maximum acceleration (0°). We assume that it the result of less the peak current in the simulation than in the experiment, which we can see because of the acceleration at the slope and a time-longitude dependence.

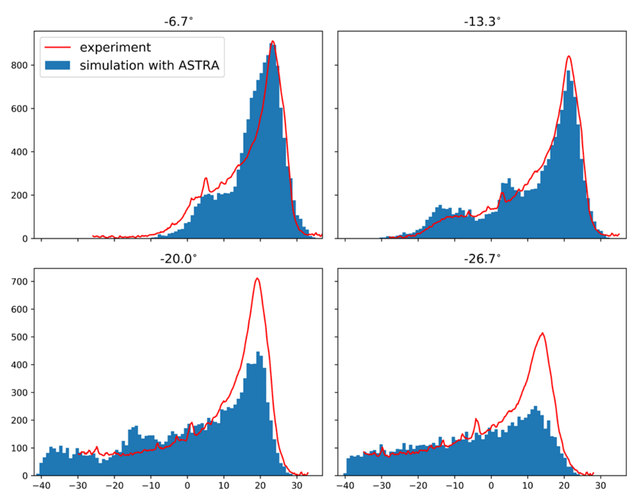

Figure 6: Transverse horizontal beam density distribution at the monitor for several RF gun injection phases (0° - the phase of the maximum acceleration).

Also, dependence of vertical beam size at the monitor on the strength of the quadrupole focusing was measured and compared with the simulation. The result is demonstrated in Fig. 7. The simulation and the experimental data are equivalent to a shear along the abscissa axis. Possibly, some focusing (e.g. the anode one) is calculated wrong or is not taken into account.

The vertical normalized emittance in the simulations is 18.5 and 16.0 mm·mrad for the solenoid current of 0.0 and 4.0 A, respectively. Figure 8 illustrates typical beam image and its vertical distribution fitting during the experiment.

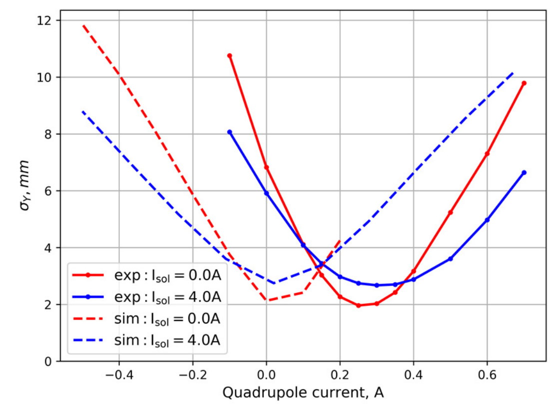

Figure 7: Dependence of vertical beam size at the monitor on quadrupole strength for two currents of solenoid (measurements and simulation).

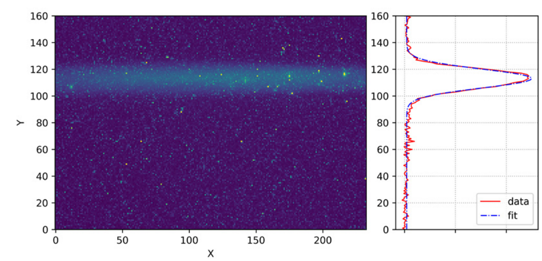

Figure 8: The example of beam image in a quadrupole strength variation experiment.

CONCLUSION

The simulation model of the RF gun is in a good agreement with the experimental data. The regime for the new RF gun beamline was optimized. Results will be applied when the beamline is commissioned.

REFERENCES

[1] O. A. Shevchenko *et al.*, "Novosibirsk Free Electron Laser: Recent Achievements and Future Prospects," *Radiophys. Quantum Electron.*, vol. 59, no. 8–9, pp. 605–612, Jan. 2017. doi:10.1007/s11141-017-9727-9

[2] V. Volkov *et al.*, "Thermocathode radio-frequency gun for the Budker Institute of Nuclear Physics free-electron laser," *Phys. Part. Nucl. Lett.*, vol. 13, no. 7, pp. 796–799, Dec. 2016. doi:10.1134/S1547477116070517

[3] K. Floettmann, ASTRA – A Space Charge Tracking Algorithm, http://www.desy.de/~mpyflo

[4] K. Price, R. M. Storn, and J. A. Lampinen, *Differential Evolution*, Springer-Verlag Berlin Heidelberg, 2005.

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[5] J. A. Nelder and R. Mead, "A Simplex Method for Function Minimization," *Comput. J.*, vol. 7, no. 4, pp. 308–313, Jan. 1965. doi:10.1093/comjnl/7.4.308