PARMELA SIMULATION FOR BNL 704MHZ SRF GUN IN LOW EMITTANCE OPERATION

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Abstract

The BNL 704MHz 0.5 cell SRF gun is designed for an ERL prototype with high bunch charge and high average current, but may ultimately be used to generate a high brightness electron beam for a high power far infrared free electron laser (FEL) without energy recovery. In simulations with the space charge tracking code PARMELA we obtained a transverse normalized beam emittance of 0.22 mm-mrad for a bunch charge of 300 pC. The schematic layout of 704 MHz gun and its preliminary beam dynamics are presented in this paper. The emittance of electron beam was optimized for 300 pC bunch charge, 20 ps bunch length and 20 MeV operations.

INTRODUCTION

A high repetition rate FELs requires an electron beam with an extremely good emittance and operating in CW mode. The transverse normalized emittance of the electron bunch is matched to a FEL beam if

$$\gamma\varepsilon_{x,y} < \frac{1}{4\pi}\gamma\lambda_r$$

where γ is the electron energy and λr is the FEL wavelength. The reduction the transverse emittance from the RF gun and the optimization beam optics are the goals of this paper. To realize the high repetition rate and high average power FEL, the gun has to work in CW mode.

SRF gun combines the high gradients of normal conducting RF gun with the CW mode operation of superconducting RF technology. It is demonstrated to be capable of generating a low emittance beam in CW mode operation. The 704MHz superconducting gun for BNL ERL prototype is commissioned now[1]. As an ERL injector, this gun must accelerate electrons to 2-2.5MeV with bunch charge up to 5nC dependent on the operational parameters. In pervious simulations it was shown that this gun is capable of providing the beams with 1.4μm rms normalized emittance with a bunch charge of 1.4nC.

In our PARMELA simulation we reduced the bunch charge to 300 pC and obtained a normalized transverse emittance of 0.22 mm-mrad after acceleration to energy of 20MeV. The optimization code RTX was used in this work as a wrapper around the PARMELA program. The 2D electric field map of the gun and cavities was obtained with Superfish and passed into PARMELA. The average axial electric field in the gun is assuming 9.4MV/m.

BEAM OPTICS ARRANGEMENT

The layout of the accelerator is shown on Figure 1. The beam energy at half cell SRF gun exit is 2MeV. Then it will be boosted to 20MeV by a 5 cell cavity. Two solenoids are used to maintain the beam size and space charge compensation. A 3rd harmonic cavity is used to reduce the energy spread. A uniform spatial and temporal distributions laser shape was assumed to drive the beam from cathode. The 704MHz cavity shape is shown on Figure 2. The initial beam and accelerator parameters are listed as Table 1.

Multiple parameters including laser spot size, emission phase, beam length, solenoids' field, 3rd harmonic cavity parameters must be optimized.

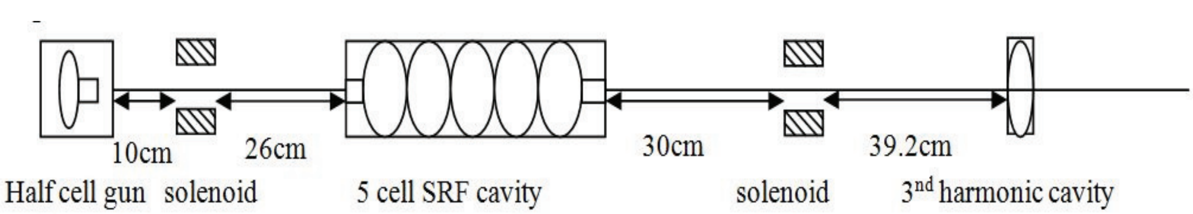

Figure 1: The layout of beam optics. The optimized distance is labelled.

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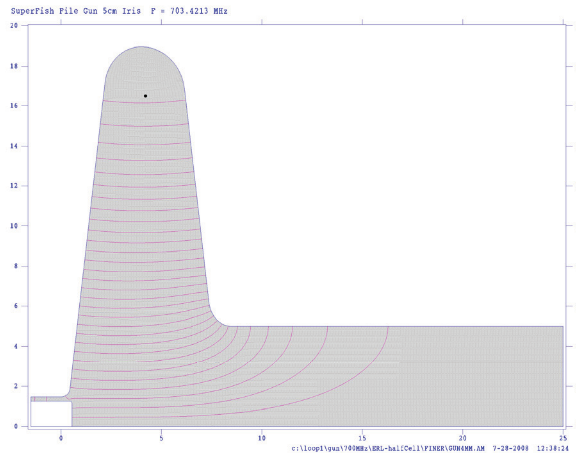

Figure 2: The fundamental mode in the 704Hz SRF gun. The cathode position can be adjusted.

The input parameters assumed for the PAMELA simulations are summarized in Table 1.

Table 1: The Optimized Parameter for Low Emittance Operation

Parameter	Value at 40MV/m
Bunch charge at cathode	300pC
Longitudinal charge distribution at cathode	Uniform
Transverse charge distribution at cathode	Uniform
Bunch length at cathode	20ps rms
Thermal emittance, $\varepsilon_{n,th}$	0.23µm
Gun gradient E_0	9.4MV/m
Injection phase	15.3 degrees
Boost gradient E_0	25MV/m

BEAM OPTICS OPTIMIZATION PROCEDURE

RTX code[2] is a beam optics optimization code which uses the Condor optimizer[3] and PARMELA for the calculation of the beam dynamics. The optimization is performed in several steps in order to limit the number of variables and reduce the optimization time:

- Define the gun geometry and calculate the EM fields using Superfish. The recess of the cathode was adjusted in 6 steps and the following optimization steps were executed for each position of the cathode.
- Single electron tracking to optimize the phase of RF gun and linac. The goal is to reach the maximum energy at the exit of the 5 cell cavity and the minimum energy at the exit of the 3rd harmonic cavity.
- With 5000 particles optimize the spot size on the cathode. The goal is to reach the minimum the normalized emittance at the gun exit.
- With 5000 particles find the strength of the solenoid strength and the distance between the solenoid and the 5 cell cavity, minimizing the normalized emittance at the end of the linac.
- With 5000 particles find the strength of the second solenoid, optimizing the emittance at the exit of 3rd harmonic cavity. The improvement in this step is small.
- Optimized the beam energy spread by varying the phase, gradient of 3rd harmonic cavity and the phase of the accelerating cavity.
- With 10000 particles perform a global optimization of spot size, emission phase, cavity phase, solenoids field and components distance.
- Confirm the final result with 100000 particles.

EMITTANCE OPTIMIZATION

The electron beam energy increases as the function of position is shown in Figure 3. The optimized beam injection phase is 15.3 degrees on the cathode.

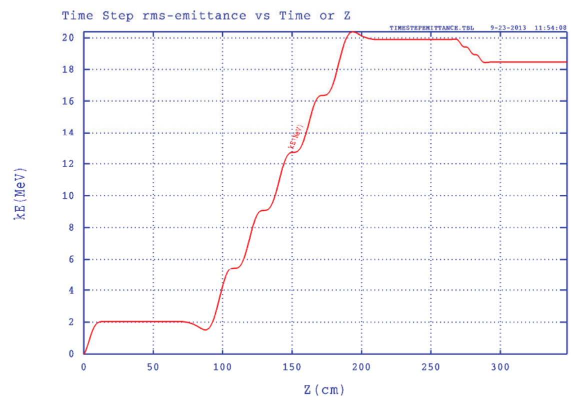

Figure 3: The electron energy as the function of longitudinal position.

The beam emittance from an RF gun is determined by the thermal emittance, the RF emittance and the space charge emittance. It can be written by

$$\varepsilon_n = \sqrt{\varepsilon_{thermal}^2 + \varepsilon_{rf}^2 + \varepsilon_{sc}^2}$$

where the thermal emittance refers to initial beam emittance at cathode emission surface, the RF emittance refers to time dependent focusing of the beam by RF field in the gun cavity and the space charge emittance refers to the repulsive force attributable to space charge cause the emittance to increase. To obtain optimized emittance result in a short time, 5000 particles were used in entire beam line simulation.

A larger laser beam size increases the thermal emittance while a smaller spot size increases the space charge emittance. Therefore varying the beam spot radius can be used to minimize the value of normalized emittance at the exit of gun. The optimized initial beam size is 0.67mm diameter. Here, we assume the beam has a beer can shape, i.e. a uniform transverse and longitudinal distribution.

In the gun the electrons in a bunch will experience different RF kicks depending on the longitudinal position along inside the. This will cause the projected emittance to increase[4]. The minimum RF emittance occurs when the bunch experiences the maximum field amplitude. To minimize the RF emittance, the initial emission phase and laser spot size are varied together.

By recessing the cathode we obtain focusing of the beam by creating a radial electric field near the cathode. In a normal conducting gun this is accomplish using magnetic coils outside the copper cavity. This is not possible in a SRF gun. We found the best position of the cathode to be 5.4 mm behind the cavity wall at a peak RF field at the cathode of 40MV/m. Figure 4 shows the transverse normalized emittance as function of distance from cathode with the optimized parameter.

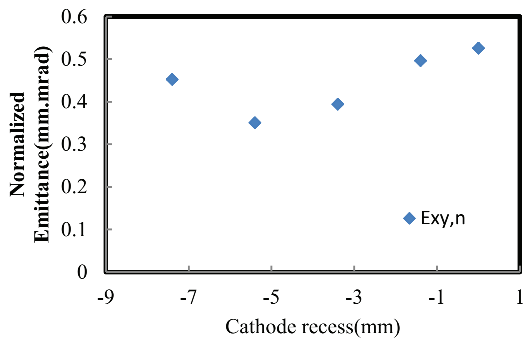

Figure 4: Transverse normalized emittance dependent on cathode insertion position.

The middle section of the bunch usually experiences higher defocusing from space charge forces then the head or tail of the bunch. This results in a bunch rotation in a phase space which is different for beam ends and middle section and increases the projected emittance. A focusing lens in combination with a drift is capable of compensating the overall emittance growth[5]. We place two solenoids to maintain the beam size and compensate emittance increase due to the linear space charge. The first solenoid is placed 10 cm from the gun exit to allow for the space needed for the cryostat. The RF focusing of the booster must match to the beam invariant envelope to damp the emittance oscillations. This matching requires the beam waist is at entrance to the booster linac. The optimized value of B_z is 891G. The optimized position of the booster entrance to the cathode was found to be 46.7 cm,

The beam energy is then boosted to 20 MeV by the 5 cell SRF cavity. A second solenoid is used to optimize the emittance at the end of beam line. A minimum emittance was found when the solenoid field is 197G and the location of the second solenoid entrance is 185.2 cm from the cathode.

As the electrons are accelerated in the 5 cell cavity the particles in the head and tail of the bunch gain less energy than the particles in the centre. This effect can be compensated by deceleration in a 3rd harmonic cavity with a frequency of 2111.1MHz. This cavity is placed downstream of booster cavity. By varying the phase of the 5 cell cavity together with the phase and voltage of the 3rd harmonic cavity we can eliminate the linear and quadratic components of the energy distribution.

At cavity exit, the beam energy spread is 960eV which corresponds to $5 \cdot 10^{-5}$ of full beam energy.

After the separate optimization of the parameters the laser spot size, the strength of both solenoids and the drift length are optimized together. Since the optimization starts close to the final values convergence is quickly reached. Finally, the complete beam line is calculated with 1 million particles to obtain final transverse emittance evolution in the beam line. (shown on Figure 5). A normalized transverse emittance of 0.22 mm-mrad was obtained.

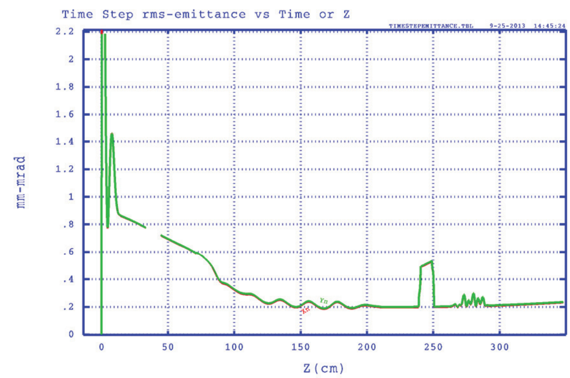

Figure 5: Transverse normalized emittance as function of longitudinal position.

CONCLUSION

We used PARMELA and RTX code to find the best beam optics arrangement for 300pC bunch charge operation of BNL 704MHz gun. 0.22 mm-mrad normalized transverse emittance was obtained. The beam energy spread is minimized to $5 \cdot 10^{-5}$.

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