SUPERCONDUCTING RF INJECTOR FOR HIGH-POWER FREE-ELECTRON LASERS (FEL)*,

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Abstract

A key technology issue on the path to high-power FEL operation is the demonstration of reliable, high-brightness, photo-cathode injector operation. The physics and engineering conceptual design of a high-current superconducting RF injector has been completed and will be presented. The system, which is an outgrowth of the existing injector on the Jefferson Lab IR FEL[1], consists of an integrated room temperature DC photocathode gun and a 500 MHz superconducting RF accelerator. The device is compact and produces high-brightness beams. After DC acceleration in the gun, emittance compensation techniques are utilized to reduce the rms normalized emittance by over a factor of two to ~ 2 π mm-mrad at the output of the RF accelerator. The design is based upon the existing geometry of the Jefferson Lab DC gun and will be capable of operation at 100 mA average beam current.

1 INTRODUCTION

Linear accelerators utilizing superconducting radio frequency (SRF) cavities are the natural choice when high average beam currents are to be accelerated to high energies. SRF linacs can transport the highest average currents, minimize emittance growth, minimize beam spill because of the large inter-cavity apertures that can be used, lead to better phase and amplitude stability because of the high stored energy of the cavities, and can support the highest "real-estate" accelerating gradients. This leads to the brightest, most efficient and most compact accelerator systems for the given applications. The Thomas Jefferson National Accelerator Facility (JLab) has clearly demonstrated the viability and reliability of using SRF linacs to deliver high-quality, high-energy, continuous electron beams in the CEBAF ring[2].

The key issue for high-brightness SRF technology is the source that is used to generate the electrons. The approach that we are investigating is to generate the electrons in a DC gun and then transport them, using emittance compensation techniques[3], to the first superconducting cavity. This approach will be shown to lead to a high power electron source with low emittance at relatively high per bunch charge.

Our simulations have shown that this injector system is capable of producing up to 100 mA at 10 MeV with a normalized transverse emittance below 2 πmm-mr. With further optimization we expect this emittance to improve.

The high brightness, high power beam produced by this injector makes it suitable for use in high efficiency IR FEL systems[4], high power UV FEL's[5], and energy recovery linac based light sources[6].

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2 SYSTEM DESCRIPTION

The system that we have chosen as having one of the highest potentials for achieving the required beam parameters begins with the Jefferson Lab design of a 500 kV DC gun. This gun will ultimately be illuminated with a 500 MHz mode locked laser, generating 200 pC per bunch. The RF will also be operated at 500 MHz. Thus, with every RF bucket filled, the average current is 100 mA.

At the output of the DC gun, an emittance compensating solenoid captures the electron beam and transports it to the first superconducting accelerating cavity. In the present design this is a single cell cavity that accelerates the beam to an intermediate energy. A second solenoid transports the beam into the final accelerating cavity. At the end of this cavity, the energy is 10 MeV.

Such a split system allows some latitude in adjusting the longitudinal phase space through different phase relationships between the first and second cavities.

The target parameters for this system are summarized in Table 1. Note that all emittances shown in this paper are rms normalized values.

Table 1: Target Parameters

Parameter	Value	Units
Frequency	500	MHz
Micropulse Rep. Rate	500	MHz
Duty Factor	CW	
Bunch Charge	200	pC
Transverse Emittance	<2	π mm-mrad
Longitudinal Emittance	<30	π keV-deg
Energy	10	MeV

3 SYSTEM SIMULATIONS

Simulations of the system were carried out using the POISSON/SUPERFISH[7] group of codes and PARMELA[8]. At this point, only single bunch simulations were carried out. Multi-bunch effects were not addressed. However, recent work[9] has estimated the Beam-Breakup Instability threshold to be 200 mA or higher at 1300 MHz. Since this threshold increases as the frequency drops, there should be a healthy margin at 100 mA and 500 MHz.

3.1 Simulation Configuration

The system as described in Section 2 was simulated in PARMELA in order to determine its potential performance. The first step in the simulation was to obtain the electric fields in the DC gun. These were obtained from POISSON simulations. A cathode voltage of 500 kV was used with a very conservative anode to cathode spacing. A closer anode to cathode spacing is certainly possible and will be explored in the next phase. It is expected that improved performance will be found under this circumstance.

The PARMELA model started with the gun fields generated by POISSON. The electrons are generated with a uniform transverse profile and a gaussian longitudinal profile. The initial electron beam parameters are shown in Table 2.

After an additional short drift space beyond the anode, a solenoid is positioned. This solenoid begins the emittance compensation process and focuses the beam into the first cavity. The rest of the system, as described previously, then follows. The superconducting cavities were simulated in SUPERFISH utilizing a standard cell shape. The SUPERFISH output was processed to obtain the field input necessary for PARMELA. The solenoid fields were generated using one of PARMELA'a built-in routines.

Table 2: Initial Beam Conditions

Parameter	Value	Units
Beam radius (uniform)	3	mm
Pulse length (truncated Gaussian)	44	ps (full width)
Bunch charge	220	pC

3.2 Simulation Results

No attempt was made to fully optimize the performance of the system. Efforts were geared toward satisfying the mechanical constraints while still achieving the desired beam performance level. Figure 1 shows the rms radius and emittance of the bunch as it propagates down the system from the gun through the end of the four-cell cavity.

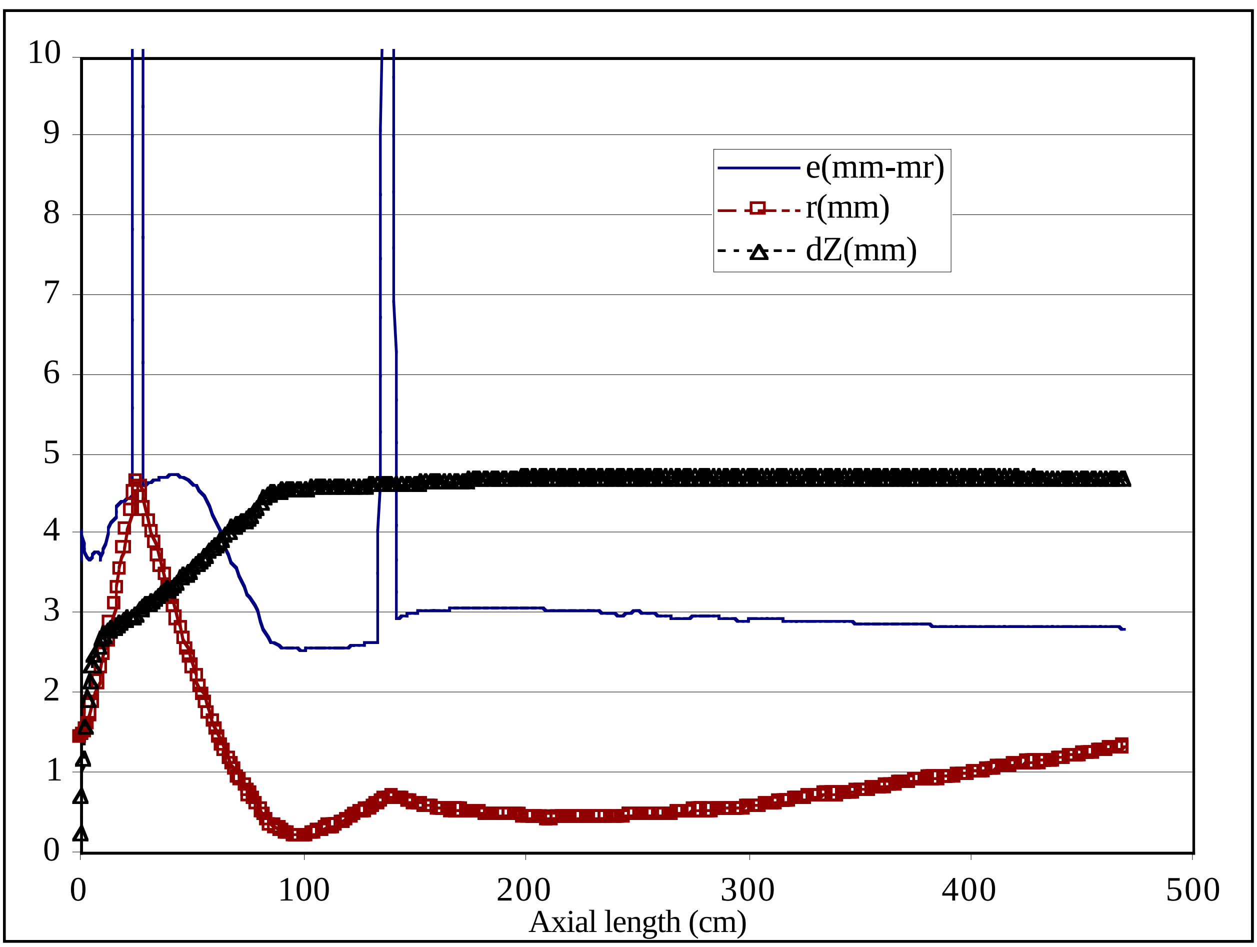

Figure 1: RMS beam properties through simulation plotted on the same vertical scale. The numbers shown in the plot include the beam halo. The halo has been removed to obtain the numbers given in Table 3.

Emittance compensation is clearly evident between roughly 50 and 100 on the longitudinal axis where the normalized transverse emittance reaches a peak of about 4.75 and declines to a minimum of around 2.6. It is important to note that the beam represented in Figure 1 is the full beam. The rms emittance of the full beam has a large contribution from a small percentage of the particles that constitute the halo. When these halo particles are discounted, a dramatically improved emittance is evident. The effect of this is shown in Table 3.

Table 3: Simulation Results-RMS Beam Parameters

Parameter	**Value (w/halo)**	**Value (w/o halo)**	**Units**
Bunch Charge	220	204	pC
Radius	1.85	1.17	mm
Transverse Emittance	2.84	1.79	mm-mrad
Longitudinal Emittance	35.6	29.0	keV-deg
Energy Spread	0.33	0.31	%
Energy	10.1	10.1	MeV

The halo particles were removed at the end of the simulation by use of a small diameter drift. This is not necessarily the ideal position to perform the scraping and finding the optimal position to remove the halo should result in an even larger improvement between the two cases.

4 CONCLUSIONS

A preliminary design for a very high power, high brightness, 10 MeV electron beam source has been completed. In comparing Tables 1 and 3 it is seen that the source satisfies all of the target parameters. With this level of performance, this injector can form the basis for a high efficiency, infrared free electron laser. It is also a suitable source for a high power ultra-violet free electron laser, and is an excellent candidate as the injector for an energy recovery linac based light source. It is expected that with careful optimization and adjustment of some of the gradients that the performance can be significantly improved beyond that which has been obtained in this study [10].

5 FUTURE WORK

We have proposed to build, in collaboration with Jefferson Lab, a test stand for the injector whose design is described in this paper. This test stand will include everything up to the end of the first accelerating cavity. In addition, the laser repetition rate will be reduced initially, in order to match the beam power to the available RF power. This test stand will allow us to measure the single bunch performance of the emittance compensated, DC gun/superconducting cavity injector combination. Upon comparison with simulations, this should provide an excellent measure of the ultimate single bunch performance for the full injector. Multi-bunch effects also need to be studied with respect to the injector described here.

6 REFERENCES

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