NATIONAL HIGH MAGNETIC FIELD LABORATORY FEL INJECTOR DESIGN CONSIDERATION

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Abstract

A numerical study of beam dynamics was performed for two injector systems for the proposed National High Magnetic Field Laboratory at the Florida State University (FSU) Free Electron Laser (FEL) facility. The first considered a system consisting of a thermionic DC gun, two buncher cavities operated at 260 MHz and 1.3 GHz and two TESLA type cavities, and is very similar to the injector of the ELBE Radiation Source. The second system we studied uses a DC photogun (a copy of JLab FEL electron gun), one buncher cavity operated at 1.3 GHz and two TESLA type cavities. The study is based on PARMELA simulations and takes into account operational experience of both the JLab FEL and the Radiation Source ELBE. The simulations predict the second system will have a much smaller longitudinal emittance. For this reason the DC photo gun based injector is preferred for the proposed FSU FEL facility.

INTRODUCTION

Construction of an IR FEL user facility is under consideration at the National High Magnetic Field Laboratory at Florida State University. Since ease of operation and availability are essential, we favour a design based on accelerator components that have demonstrated reliable operation delivering beam with the necessary parameters. The required electron beam parameters are the following: beam energy up to 60 MeV, transverse normalized RMS emittance 20 mm·mrad, pulse length from 0.5 ps through 20 ps, peak current 45 A, average beam current 1 mA, and RMS energy spread 0.3 %.

Using PARMELA simulations we have made a systematic study of the beam parameter dependence on the accelerator settings. We have calculated the dependence of the bunch length, energy spread, longitudinal and transverse emittances as well as betatron functions at the end of the second TESLA cavity as a function of phases and gradients of the RF elements of the injector. The study shows that the injector can provide a beam quality satisfying the requirements imposed by the IR FEL complex.

INJECTOR OPTIONS

We have considered two options for the injector for the FSU-NHMFL FEL. The first option is very similar to one used at the radiation source ELBE [1]. Such an injector utilizes a thermionic DC gun operated at 250 kV, two normal-conducting buncher cavities, and an ELBE accelerating module consisting of two TESLA type SRF cavities. For a bunch charge of 77 pC a transverse emittance of about 10 mm·mrad and a longitudinal emittance of about 50 keV·ps were measured [2]. In our PARMELA simulations of the system we did not include the beam dynamics in the gun itself, and have assumed the 10 mm·mrad transverse emittance at the exit of the gun. PARMELA simulations of the beam dynamics for such a bunch through the injector, while optimizing the system for both transverse and longitudinal emittance, predict the longitudinal emittance at the exit of the second SRF cavity to be about 50 keV·ps, the transverse emittance has no significant growth.

Using the coherent synchrotron radiation in the THz part of the spectrum is an important part of the developing user program for the FSU-NHMFL FEL [3]. It is very desirable to extend the THz radiation spectrum to a frequency as high as 5 THz or as close as possible to that. This requires generation of the electron buncher shorter than 100 fs RMS and therefore extremely small longitudinal emittance. The minimum bunch length achieved as ELBE was about 1.5 ps RMS [2].

The JLab FEL routinely operates with the bunch length of about 150 fs RMS with a bunch charge of 135 pC. The requirement to extend the THz spectrum to higher frequency has prompted us to consider the second option for an injector based on a DC photo gun. An injector based on a DC photogun and utilizing an ELBE accelerating module has been designed previously for the ERLP [4]. Thus we have done PARMELA simulations of the beam dynamics of the system consisting of the JLab FEL DC photo gun, a normal conducting buncher cavity operating at 1.3 GHz, two TESLA type cavities and two solenoids placed between the gun and the buncher and between the buncher and the first SRF cavity.

SYSTEM OPTIMIZATION AND PREDICTED BEAM PARAMETERS

Using PARMELA simulations we attempted to optimize the injector to minimize both the transverse and longitudinal emittance. We start with a Gaussian longitudinal distribution of the bunch with an RMS width of 5 deg of 1.3 GHz (~10 ps), cut at ±10 deg. The initial transverse distribution is an axisymmetric Gaussian with σ_r=2 mm truncated at radius of 4 mm.

We have used the following sequence for the system setup and optimization. The first solenoid is set to have the beam waist in the buncher cavity or as close as

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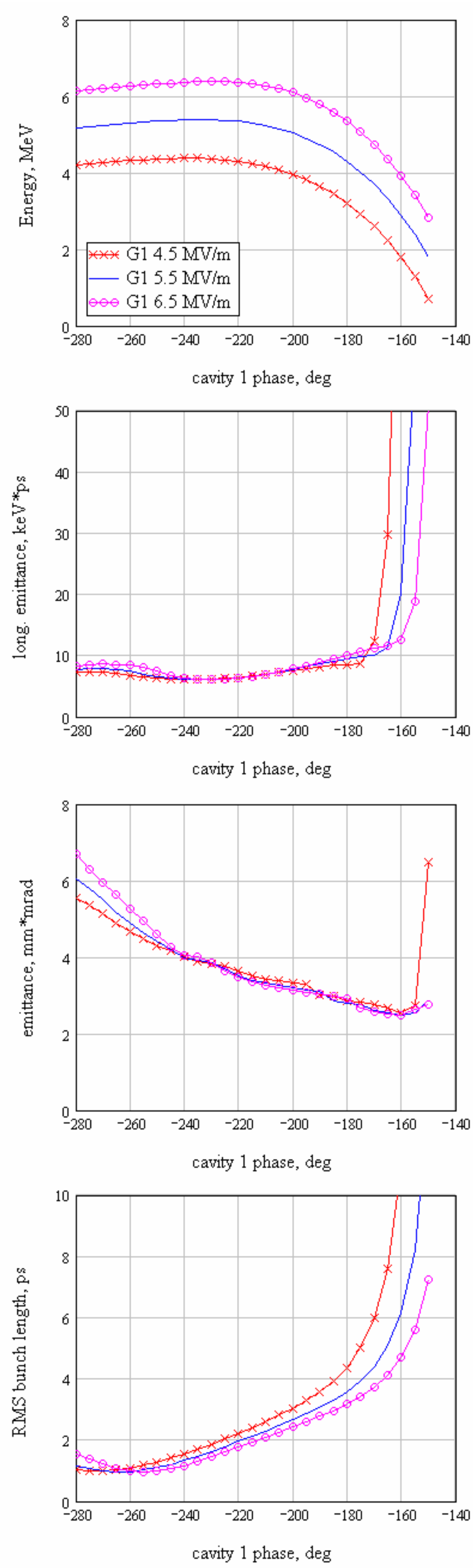

Figure 1: Beam parameters at the exit of the C1.

possible to it; at the same time we made sure that the decreasing the transverse beam size does not lead to emittance growth, either transverse or longitudinal. The second step is to set the buncher gradient to achieve shortest bunch length possible without degradation of the transverse and longitudinal emittance at the entrance of the first SRF cavity (C1). The complication at this stage is that the appropriate buncher gradient depends on the second solenoid setting defining the transverse beam size at the entrance to C1. Because of the relatively low energy of the beam and already relatively short bunch, the space change force couples strongly the longitudinal and transverse bunch properties. Thus the settings of the buncher gradient and the second solenoid are compromised in the following way. On one side the longitudinal and transverse emittances do not grow significantly due to the space charge force prior entering C1. On the other side the bunch length and the transverse beam size entering C1 have to be small enough to prevent the emittance growth in the C1 due to the time variation of the accelerating field and an excessive focusing of the beam by the field magnetic component. Once such a setting of the buncher and second solenoid are found we explore the C1 influence on the beam parameters.

We calculate the bunch properties at the exit of C1 as a function of the C1 phase for different accelerating gradients. The target energy for the injector is ~ 9 MeV, to keep the energy of the decelerated beam under the neutron production threshold. We evaluated the bunch properties for gradients of C1 of 4.5 MV/m, 5.5 MV/m and 6.5 MV/m. Figure 1 shows dependence of the beam energy, longitudinal end transverse emittance and the bunch length at the exit of first SRF cavity as a function of the cavity phase for different gradients of the cavity field. This set of data combined with the requirement of electron beam transmission to be 100 % defines the range of the C1 phase variation. For this particular case the C1 phase maybe changed from -300 deg to -200 deg.

As a next step we explore the effect of the second SRF cavity (C2) on beam properties. The gradient of C1 was chosen to be fixed at 5.5 MV/m; the phase of C1 is also fixed in the above mentioned range. The three cavity 2 phase scans are made then. That is, we calculate the beam parameters at the exit of C2 as a function of the C2 phase for three different values of the C2 gradient; these are 4 MV/m, 5 MV/m and 6 MV/m. The phase of the second cavity changes in the range of ±60 deg from crest. Such three cavity 2 phase scans are made for different phases of cavity 1. The results of such triple cavity 2 phase scans for the case of C1 phase equals -215 deg are shown in Fig. 2. The case corresponds to cavity 1 at approximately 20 degrees off crest.

The overall system behaviour is such that the phase of cavity 1 defines the longitudinal emittance, bunch length, the transverse emittance and beam size at the exit of the injector, whereas the combination of the second cavity gradient and phase can be used to adjust the energy

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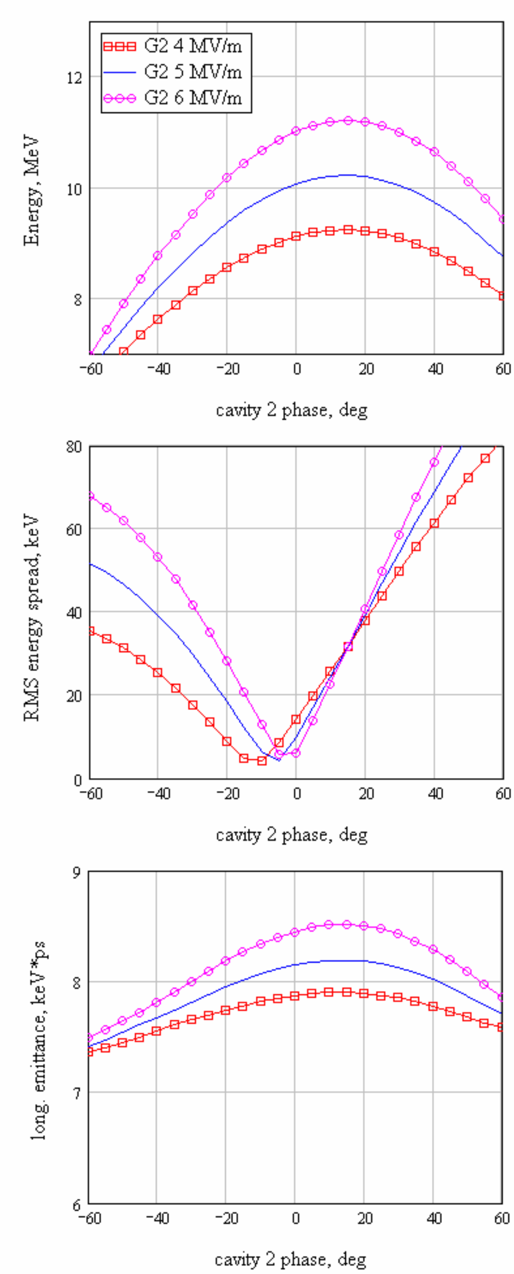

Figure 2: Beam parameters at the exit of the C2.

spread, the longitudinal analogue of the alpha function and energy of the beam. The simulations predict very good beam quality at the exit of the system. A longitudinal RMS emittance of about 8 keV·ps simultaneously with a transverse normalized RMS emittance of 3.5 mm·mrad are achieved in the simulation. Probably most critical point in the design is that the small longitudinal and transverse emittances are achieved simultaneously partially at the expense of transverse beam size. For example, the data set shown in Fig. 2 corresponds to a transverse RMS beam size of about 3 mm. The beam size increases at the exit of the second cavity when the first cavity is set less off crest, and reaches 5 mm RMS size when the first cavity is on crest.

DISCUSSION AND OUTLOOK

The predicted beam parameters would easily satisfy the requirements imposed for the IR FELs and for THz CSR production. One has to realize that such a numerical study implies certain idealization of the system and therefore predicts somewhat better beam parameters that will be achieved in the as-built system. That is why we consider an experimental validation of such a study extremely important. One might find several reasons for optimism here. One of them is that simulations of ELBE-like injector predict beam parameters very close to those experimentally measured. These are transverse emittance of about 10 mm·mrad and longitudinal emittance of 50 keV·ps for the 77 pC bunch charge case. For our simulations it is important that this system uses TESLA type cavities. Second, at the JLab FEL for a bunch charge of 135 pC a transverse emittance of 8 mm·mrad is routinely measured in the injector. An upper limit on the longitudinal emittance, which is very difficult to measure, in the injector is 60 keV·ps. A similar numerical study has predicted these parameters to be 10 mm·mrad and 28 keV·ps [5]. In the study presented here we have assumed use of the same DC photogun.

We would like to point to two idealizations, which might cause PARMELA to predict beam parameters better than can be practically achieved. First is the assumption that the photocathode response is prompt, which is not true for the GaAs photo cathode when it is used with a green drive laser. Second, we assume the system to be perfectly axisymmetric, which is not exactly true for any real system. We are yet to study numerically how big this effect is. We are also planning to make a numerical system tolerances study.

We have studied numerically the performance and system behaviour of an injector for the FSU ERL-based IR FEL. The predicted beam parameters are considerably better than required. The injector under consideration consists of components which were proven to be reliable during operation at existing facilities.

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