START-TO-END SIMULATIONS OF THE PSI 250 MeV INJECTOR TEST FACILITY

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Abstract

Since 2003, PSI has been investigating an advanced Low Emittance Gun (LEG) based XFEL facility to supply coherent, ultra-bright, and ultra-short photon beams covering the wavelengths from 0.1 nm to 10 nm. To build the facility within a length of 800 m, challenging beam parameters are required at the entrance of the undulators. For the first two FEL beamlines (FEL1 and FEL2), the required normalized slice emittance, slice energy spread, and peak current are about 0.2 μm, 0.6 MeV, and 1.5 kA respectively. However, the required beam parameters for the third FEL beamline (FEL3), covering 1 nm to 10 nm, are somewhat flexible. Therefore we are developing two different gun technologies. The 1 MV high gradient pulsed diode and field emission based advanced LEG will be used for the first two FEL beamlines, while a CTF3 gun based RF photoinjector will be used for the third FEL beamline. To test these two injector technologies, a 250 MeV injector test facility will be constructed at PSI from 2008. In this paper, we describe beam dynamics for two different injector optimizations of the CTF3 RF gun based injector test facility.

INTRODUCTION

To develop technologies for an advanced low emittance gun (LEG) for the PSI-XFEL project, we have built a 500 kV pulsed diode based LEG test facility [1, 2]. In addition, a new 250 MeV injector test facility will be built at PSI from 2008 to study following things; slice and projected emittance transportation along the injector, invariant envelope matching and emittance damping in a bootster linac, bunch compression and Coherent Synchrotron Radiation (CSR) effects in a chicane, slice and projected beam parameter diagnostics with two transverse deflecting structures (TDSs) and three FODO cells, ultra-stable RF low level system, and timing and synchronization. In the first phase of the 250 MeV facility, a CTF3 type V gun RF photoinjector will be used. In the second phase, a 1 MV pulsed diode based advanced LEG will be tested. Details on the advanced LEG and its recent progress, the LEG based 250 MeV facility, and information on the PSI-XFEL project can be found in references [1–3]. Since FEL3 will supply soft X-rays from 1 nm to 10 nm, the requirements on electron beam quality are somewhat softer than those for the first two FEL beamlines. Therefore, after optimizing the RF photoinjector parameters on the 250 MeV injector, the RF gun will be used as a dedicated gun for the FEL3 beamline. For this beamline, we will use High-order Harmonic Generation (HHG) based seeded HGHG scheme to supply spatially as well as temporally coherent soft X-rays. To obtain low and uniform slice emittance and slice energy spread, we optimized the gun and the bunch compressor (BC) for different values of the maximum gradient in the gun cavity and the pulse length of the gun drive laser. In this paper, we describe beam dynamics and start-to-end (S2E) simulations for the two different optimizations of the CTF3 RF gun based 250 MeV injector test facility.

TWO INJECTOR OPTIMIZATIONS

Originally, the 2.5 cell CTF3 type V gun was designed to compensate beam loading effects during multi-bunch operation at the CLIC Test Facility (CTF) [4]. Since a high gradient of 100 MV/m has been already reached with a forward power of 22 MW during an RF test of the gun at CERN, we optimized the gun for a maximum gradient of 100 MV/m as shown in Fig. 1(top). However, the gun was originally designed to be operated at 120 MV/m with 25 MW. Therefore we also optimized the gun for a gradient of 120 MV/m as shown in Fig. 1(bottom).

Optimization of the CTF3 RF Gun

Generally, a lower bunch charge is preferred to generate high brightness electron beams for XFEL projects due to various beam dilution effects such as space charge forces at low energy, wakefields in the linac and undulator, and CSR in BCs and dog-legs. After considering the thermal emittance, beam diagnostics requirements, and the number of XFEL photons per bunch, we chose 0.2 nC as the nominal single bunch charge for the PSI-XFEL project.

Generally, we can obtain a lower thermal emittance and a lower slice emittance by choosing a smaller laser beam spotsize on the cathode. Due to transverse and longitudinal space charge effects, however, there are restrictions in the choice of the laser spotsize and the longitudinal bunch length, for a given maximum gradient on the cathode. Therefore the slice emittance, peak current, and the available maximum gradient in the gun should be considered together in optimizing the spotsize and the pulse length of the gun drive laser. If the transverse laser spotsize $\sigma_{x,y}$ is 270 μm, the thermal emittance becomes smaller than 0.2 μm assuming an average kinetic energy of emitted electrons of 0.4 eV as shown in Fig. 1. In that case, the pulse length of the optimized gun drive laser becomes

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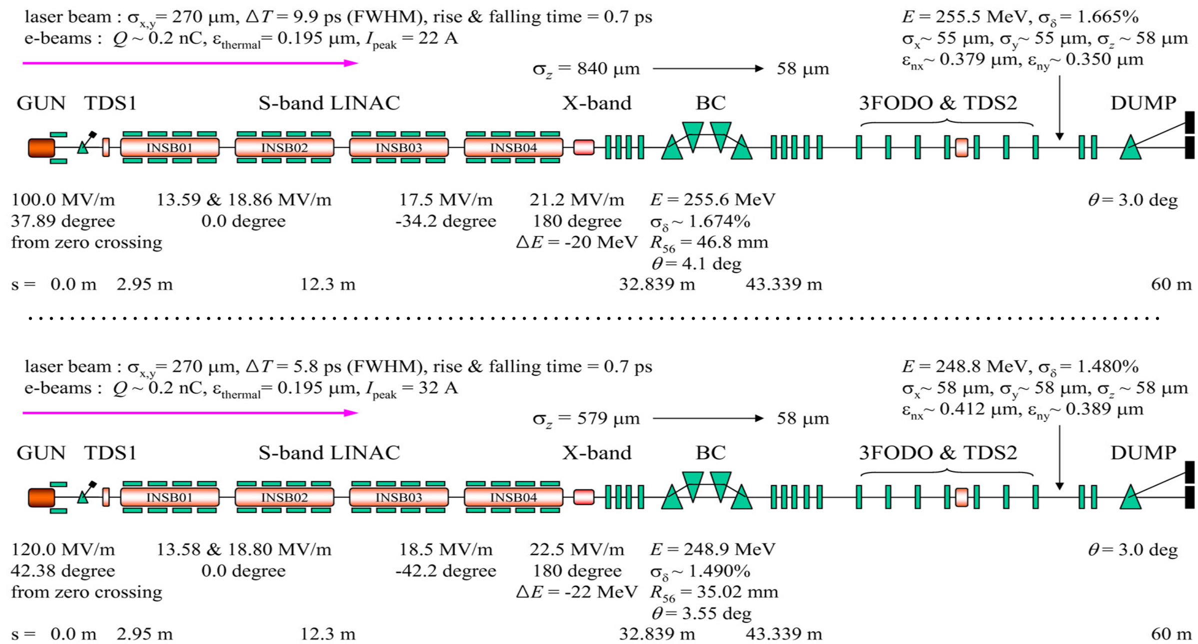

Figure 1: Two optimized layouts of the CTF3 RF gun based 250 MeV injector test facility for the PSI-XFEL project. Here the maximum gradients in the gun cavity are 100 MV/m (top) and 120 MV/m (bottom).

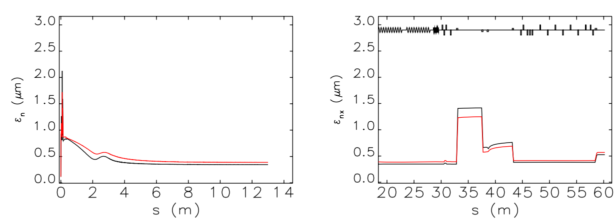

Figure 2: Projected normalized rms emittance from the cathode to the booster linac obtained from ASTRA simulations (left). Projected normalized rms horizontal emittance from the end of the booster linac to the beam dump obtained from ASTRA and ELEGANT S2E simulations (right). Here black and red lines indicate the projected emittances for the 100 MV/m and 120 MV/m cases.

9.9 ps (FWHM) and the peak current at the exit of the gun becomes 22 A for a maximum gradient in the gun of 100 MV/m. However with a higher maximum gradient of 120 MV/m, the pulse length of the gun drive laser can be reduced to 5.8 ps (FWHM), which gives a much higher peak current of 32 A at the exit of the gun.

The gun cavity gradient, magnetic field of the gun solenoid, and gradient of the booster linac (INSB01 and INSB02) were optimized to compensate the projected emittance growth due to the linear space charge force and to satisfy two conditions of the invariant envelope matching in the booster linac, which were experimentally demonstrated at the FLASH facility in 2005 [5, 6]. By matching the invariant envelope to the booster linac, the projected emittance as well as the slice emittance were effectively damped

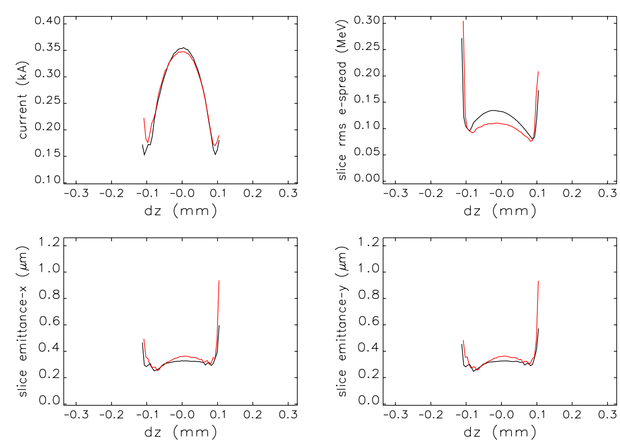

Figure 3: Peak current and slice beam parameters right before the dump dipole for two different gun optimizations. Here black and red lines indicate corresponding beam parameters for the 100 MV/m and 120 MV/m cases.

along the booster as shown in Fig. 2(left) and as described in references [5] and [6]. At the end of the booster linac (INSB02), the optimized projected emittance and central slice emittance are about 0.345 μm and 0.320 μm for a maximum gradient of 100 MV/m. Those emittances are 0.388 μm and 0.360 μm for the 120 MV/m case as shown in Figs. 2(left) and 3(bottom). Here we assumed that the longitudinal profile of the gun drive laser is a flat-top shape with a rise and fall time of 0.7 ps, and its transverse profile is homogeneous. Since slice emittance growth at the BC is negligible, the central slice emittances at the end of the booster are almost the same as those in Fig. 3(bottom).

Optimization of the Bunch Compressor

The operational principle and the design concept of the bunch compressor can be found in references [7] and [8]. To reduce the projected emittance growth due to CSR, we used the following methods to optimize the bunch compressor for the 250 MeV facility:

Firstly, after considering the total allowed length of 10.5 m for the BC chicane and the required length for beam diagnostics at the center of the chicane, we chose long drifts of $\Delta L = 4.375$ m between first two dipoles and last two dipoles as shown in Fig. 4. In that case, the required magnitude of R_{56} for bunch compression can be obtained with a BC dipole bending angle of only a few degrees [8].

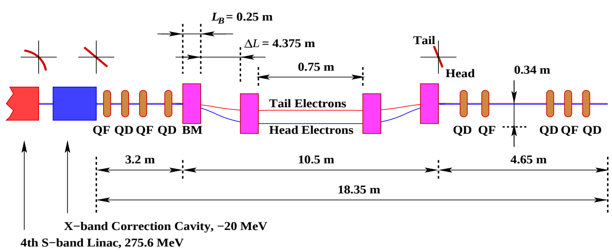

Figure 4: BC layout of the 250 MeV injector test facility.

Secondly, the strength of the chicane or R_{56} was reduced further by choosing a somewhat large rms relative energy spread at the BC. For the 100 MV/m case, the initial bunch length of 840 μm is much longer than the initial bunch length of 579 μm for the 120 MV/m case. However, by increasing the energy spread from 1.490% to 1.674%, the much longer initial bunch length of 840 μm was also compressed to 58 μm without serious emittance dilution as shown in Figs. 1, 2(right), and 3. Although we can choose a much larger energy spread to reduce CSR effects, we have kept it smaller than 1.7% to avoid excessive projected emittance dilution due to chromatic effects [8].

Thirdly, we have reduced CSR wakefields further by installing a higher harmonic X-band cavity upstream of the BC. As shown in Fig. 4, the X-band cavity compensates various non-linearities in the longitudinal phase space such as the second order non-linearity due to the RF curvature of the S-band linac, the second order path dependence on the beam energy in the chicane T_{566}, the short-range longitudinal wakefield in the linac, and non-linearity due to the longitudinal space charge force [8]. However the beam energy is reduced by about 20 MeV in the X-band cavity.

Fourthly, we can control the projected emittance growth by choosing strong focusing optics around the BC, which makes a beam waist at the exit of the fourth dipole [8].

Start-To-End Simulations

After optimizing the RF gun and the BC, we have performed S2E simulations from the cathode to the beam dump to compare the performance of the two optimizations. Here all positions of machine components are the same for both cases, but their settings and the optics are re-optimized to get a high peak current of 350 A after the BC as shown in Figs. 1 and 3(top left). S2E simulation results with ASTRA and ELEGANT codes are shown in Figs. 2 and 3. The ASTRA code was used from the cathode to the end of the booster linac to take account of space charge effects. The ASTRA output was then directly converted to input for the ELEGANT code and was tracked up to the beam dump. All key emittance dilution effects such as space charge effects up to 150 MeV, short-range transverse and longitudinal wakefields in all linac structures, CSR and Incoherent Synchrotron Radiation (ISR) in the BC and the dump dipole, and fringe-field and chromatic effects in all magnets were considered in these S2E simulations. As shown in Figs. 1, 2, and 3, the final peak current of about 350 A is the same for both cases although their projected and slice beam parameters after the BC are somewhat different. For a gradient of 100 MV/m, the optimized projected emittance and central slice emittance after the BC are about 0.379 μm and 0.320 μm while those emittances are 0.412 μm and 0.360 μm for a gradient of 120 MV/m. In the case of the optimization with 100 MV/m, the projected emittance was increased by 8% in the BC due to the stronger CSR while it was increased by 6% for the case of the optimization with 120 MV/m as shown in Fig. 2(right). Note that the slice emittance growth in the BC is negligible in both cases. However, for the 100 MV/m case, the slice energy spread was somewhat further increased in the central region of the bunch due to the higher compression factor of 14.5 as shown in Fig. 3(top right). This may dilute the FEL lasing process in the undulator.

SUMMARY

The CTF3 gun based 250 MeV injector test facility for the PSI-XFEL project was optimized for two different maximum gradients in the gun cavity. Although the final peak current of about 350 A is the same for both optimizations, the projected and slice beam parameters after the BC are somewhat different. However all slice beam parameters are acceptable after the BC. Therefore we expect that both optimizations with the CTF3 gun can supply sufficient slice beam parameters for the FEL3 beamline in the PSI-XFEL facility. To measure the slice emittance with TDS2 without changing optics, we are studying a new optics for the beam diagnostics section after the BC.

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