LINEAR ACCELERATOR FOR THE PSI-XFEL FEL3 BEAMLINE

Y. Kim*, A. Adelmann, B. Beutner, M. Dehler, R. Ganter, R. Ischebeck, T. Garvey
M. Pedrozzi, J.-Y. Raguin, S. Reiche, L. Rivkin, V. Schlott, A. Streun, and A. F. Wrulich
Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland

Abstract

To supply coherent, ultra-bright, and ultra-short XFEL photon beams covering a wide wavelength range from 0.1 nm to 7 nm, three FEL beamlines will be constructed in the planned PSI-XFEL facility. The FEL1 beamline will use a 6 GeV normal conducting S-band linac to generate hard X-rays from 0.1 nm to 0.7 nm, while the FEL2 beamline will use a 3.4 GeV linac to supply X-rays from 0.7 nm to 2.8 nm. However, the FEL3 beamline is designed to supply spatially as well as temporally coherent soft X-rays from 1.8 nm to 7 nm with the High-order Harmonic Generation (HHG) based seeded High Gain Harmonic Generation (HGHG) scheme. In this paper, we describe an injector, bunch compressors, beam diagnostic sections, and linacs for the FEL3 beamline, which is based on a 2.5 cell S-band RF gun and a 2.1 GeV linac.

INTRODUCTION

Since 2003, the Paul Scherrer Institute (PSI) has been developing two key technologies to realize the advanced and compact PSI-XFEL facility within about 930 m long space [1]. One is the high voltage pulser based advanced Low Emittance Gun (LEG), and the other is the Cryogenic Permanent Magnet in-vacuum Undulator (CPMU) with a small gap of about 5 mm and a short period of about 15 mm [2]. A prototype CPMU will be installed at the Swiss Light Source in 2011. Since required slice beam parameters for FEL1 and FEL2 beamlines are challenging, we have been concentrating our efforts to develop the advanced LEG [1]. In 2007, a 500 kV pulser based LEG test facility was constructed at PSI, and recently, we have performed various machine studies there [1–3]. In parallel, a 250 MeV injector test facility will be constructed by the end of 2009 to develop advanced accelerator technologies for the future 6 GeV PSI-XFEL project [1, 4]. In the first phase of the 250 MeV injector test facility, a CTF3 RF gun based photoinjector will be tested, and in its second phase, a 1 MV pulser based advanced LEG will be tested. Additionally, an upgrade of the HHG based seeding with a CPMU in the 250 MeV injector test facility is under discussion. To saturate the FEL3 beamline effectively, a low slice energy spread is more important than a low slice beam emittance. Due to a much lower overall bunch length compression factor, the CTF3 RF gun is expected to supply a lower slice energy spread than the advanced LEG. Therefore the RF gun will be used as a dedicated gun to drive the FEL3 beamline. However, the advanced LEG will be used to drive the FEL1 and FEL2 beamlines, where a low slice emittance is the most critical beam parameter to get saturation with 60 m long undulators. In this paper, we describe the CTF3 RF gun based linac to drive the PSI-XFEL FEL3 beamline.

OPTIMIZATION OF DRIVING LINAC

From our recent thermal emittance measurements at the LEG test facility, we find that the thermal emittance of a diamond turned copper cathode is about 0.2 μm for an rms laser spotsize on the cathode of about 330 μm at 40 MV/m [2, 3]. To optimize the CTF3 RF gun based injector, we used the measured value. Since the thermal emittance depends on the rms laser spotsize and the gradient on the cathode by the Schottky effect, the thermal emittance in the CTF3 RF gun was re-scaled to about 0.2 μm by choosing a smaller rms laser spotsize of about 270 μm at 100 MV/m [2, 4]. To compensate the projected emittance growth due to the linear space charge force in a drift space between the gun and the booster linac and to satisfy two special conditions for the invariant envelope matching in the booster, we have optimized the gradient of the RF gun, the magnetic field of the main gun solenoid, and gradients of the booster linac [4,5]. Details on the optimization of the CTF3 RF gun based injector are described in reference [4], and its optimized beam parameters are summarized in Table 1 where all emittances are normalized rms values, and all energy spreads are rms ones. According to ASTRA simulations, the optimized normalized projected and central slice emittance before the first bunch compressor (BC1) are about 0.35 μm and 0.32 μm, respectively.

Since the initial peak current from the RF gun is about 22 A, the peak current is increased to about 1.6 kA by two bunch compressors (BC1 and BC2) as shown in Figs. 1, 2, 3, and 4(middle left) and as summarized in Table 1. To minimize the projected and slice emittance growth due to the space charge forces, the bunch length is initially compressed from 840 μm to 55 μm by BC1 at 256 MeV. Then the beam is accelerated to a much higher beam energy of about 1469 MeV, where the bunch length is re-compressed down to 14 μm by BC2. To control the emittance growth at BC1 due to Coherent Synchrotron Radiation (CSR), we used special optimization methods which are described in references [4, 6]. Additionally, to control the horizontal emittance growth at BC2 due to CSR, we chose a higher horizontal beta-function of about 65 m in front of BC2 and a strong focusing horizontal beta-function in BC2 to make a beam waist at the end of the fourth dipole as shown in Fig. 2(bottom) [6]. Since the projected energy spread is

* Mail : Yujong.Kim@PSI.ch

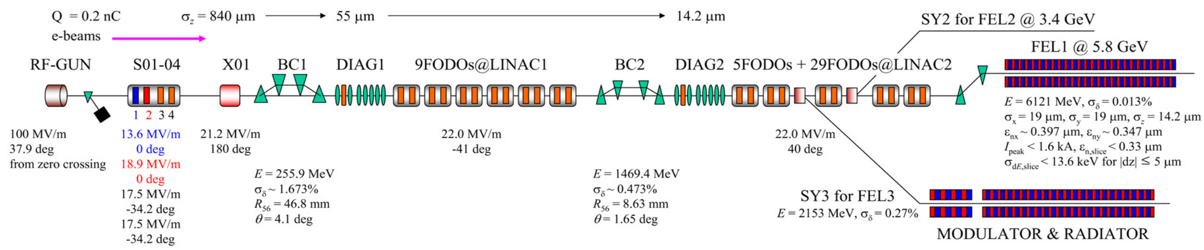

Figure 1: An optimized layout of the CTF3 RF gun based linac for the PSI-XFEL Project.

Table 1: Parameters of an optimized FEL3 driving linac.

Parameter	unit	value
single bunch charge Q	nC	0.2
gun and S-band linac RF frequency	MHz	2998
maximum repetition rate	Hz	100
gun cell number	cell	2.5
rms laser spotsize on cathode σ_{laser}	μm	270
laser pulse length (FWHM)	ps	9.9
laser pulse rising and falling time	ps	0.7
normalized thermal emittance	μm	0.195
gun solenoid max longitudinal field	T	0.206
gun maximum gradient	MV/m	100
gun RF phase from zero crossing	deg	37.9
S01 accelerating gradient	MV/m	13.6
S01 RF phase from on crest	deg	0.0
S02 accelerating gradient	MV/m	18.9
S02 RF phase from on crest	deg	0.0
length per FODO in LINAC1 / LINAC2	m	10.3 / 10.4
phase per FODO in LINAC1 / LINAC2	deg	60 / 60
max β-function in LINAC1 / LINAC2	m	17.3 / 18.8
length of QM in LINAC1 / LINAC2	m	0.15 / 0.2
max QM gradient in LINAC1 / LINAC2	T/m	6.5 / 23.2
projected emittance before BC1 / BC2	μm	0.35 / 0.39
central slice emittance before BC1 / BC2	μm	0.32 / 0.32
rms bunch length before BC1 / BC2	μm	840 / 55
beam energy before BC1 / BC2	MeV	256 / 1469
projected E-spread before BC1 / BC2	%	1.7 / 0.47
central slice E-spread before BC1 / BC2	keV	0.3 / 2.6
full slice E-spread before BC1 / BC2	keV	1.4 / 30.5
projected emittance after BC2 / SY3	μm	0.40 / 0.40
central slice emittance after BC2 / SY3	μm	0.33 / 0.33
rms bunch length after BC2 / SY3	μm	14 / 14
beam energy after BC2 / SY3	GeV	1.469 / 2.153
projected E-spread after BC2 / SY3	%	0.47 / 0.27
projected E-spread after SY2 / SY1	%	0.12 / 0.01
central slice E-spread after BC2 / SY3	keV	13.6 / 13.6
full slice E-spread BC2 / SY3	keV	147.6 / 147.6

about 0.47% and the bunch length is already compressed by BC1, we can avoid the chromatic effects around BC2 though the beta-function is somewhat large. To control CSR and Incoherent Synchrotron Radiation (ISR) effects at BCs effectively, a higher bunch compression factor of about 15 is selected at BC1 where CSR and ISR effects are weaker due to a somewhat longer bunch length and a lower beam energy. Then the bunch length is slightly compressed further with a lower bunch compression factor of about 4 at BC2 where CSR and ISR effects are stronger due to a much shorter bunch length and a higher beam energy.

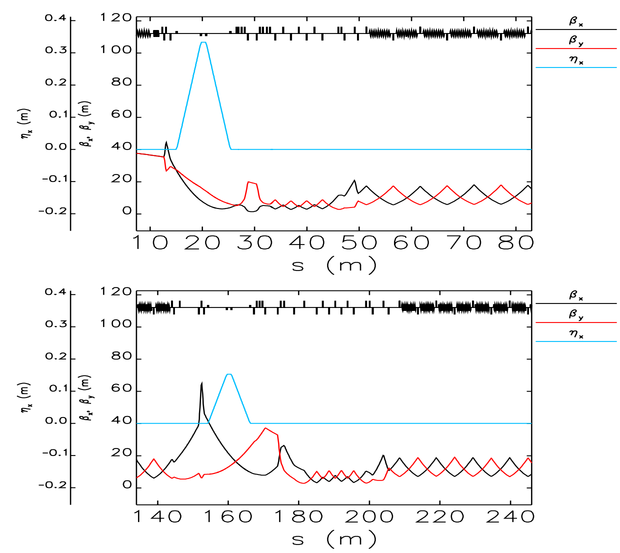

Figure 2: Optics around BC1, DIAG1, and LINAC1 (top), optics around BC2, DIAG2, and LINAC2 (bottom). Here TDSs will be installed at about 30 m and about 170 m.

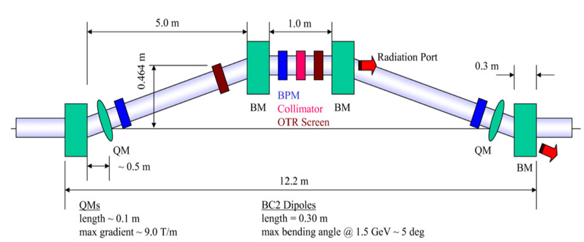

Figure 3: Layout of BC2 for the PSI-XFEL project.

As shown in Figs. 1 and 2, two special diagnostic sections (DIAG1 and DIAG2) are designed after BCs to measure the slice emittance, slice energy spread, bunch length, longitudinal phase space, arrival timing jitter, projected emittance, and Twiss parameters without changing optics during FEL operations. The diagnostic sections consist of five main parts: The first part is the five quadrupoles (QMs) to match optics between BCs and a transverse deflection cavity (TDS). The second part is the TDS to streak beams vertically. The third part is another five quadrupoles to match optics between the TDS and following three FODO cells. The fourth part is three FODO cells with seven quadrupoles to generate a wide-range phase advance along seven OTR screens in the FODO cells. The fifth part is the one dipole magnet after three FODO cells to generate a required dispersion for the longitudinal phase space measurement. To get a high time resolution of about 20 fs (FW), the vertical beta-functions at those TDSs should be high enough as shown in Fig. 2. Additionally, to get a high resolution in slice and projected emittance measurements, an asymmetric optics is used for three FODO cells where the horizontal and vertical phase advances per FODO cell are 55 degree and 25 degree, respectively.

After bunch length compression, the electron beam is accelerated by LINAC1 and LINAC2 as shown in Figs. 1 and 2 and as summarized in Table 1. To avoid any emittance growth due to chromatic effects, LINAC1 and LINAC2 use optimized FODO cells with a phase advance per FODO cell of 60 degree and the maximum beta-function smaller than 20 m. In each FODO cell in LINAC1 and LINAC2, there are two quadrupoles, two 0.7 m long drift spaces to host beam diagnostic components and steerers, and two 4.3 m long S-band tubes as shown in Fig. 2.

OVERALL PERFORMANCE

To check the overall performance of the CTF3 RF gun based FEL driving linac, we have performed start-to-end (S2E) simulations from the cathode to the end of LINAC2 with the ASTRA and ELEGANT codes. Here, all main emittance dilution effects such as space charge effects up to 150 MeV, short-range transverse and longitudinal wakefields in all linac structures, CSR and ISR in BC dipoles, and fringe-field and chromatic effects in all magnets are considered. As summarized in Table 1 and as shown in Figs. 1 and 4, the emittance growth along the whole linac is well suppressed, and the final projected emittance and central slice emittance at a switching yard 3 (SY3) for the FEL3 beamline are about 0.40 μm and 0.33 μm, respectively. Although the projected energy spread is about 0.27% at SY3 and the energy chirp is somewhat large as shown in Fig. 4(top left), its rms slice energy spread is smaller than 150 keV over the whole bunch. In particular, the central rms slice energy spread is only about 14 keV for a 5 μm long central slice. The large linear energy chirp is helpful to reduce the sensitivity of the energy jitter in the seeded FEL3 beamline. As shown in Figs. 1 and 4(top right), by continuously accelerating the electron beam with an off-crest RF phase of 40 degree in LINAC2, the large projected energy spread is effectively damped down to 0.01% by the action of short-range longitudinal wakefield in LINAC2. This ultra-small projected energy spread and ultra-flat energy chirp is helpful to increase the intensity of FEL photon beams and to reduce the bandwidth of the FEL photon beam spectrum in the SASE based FEL1 beamline. Note that the growth of the slice beam parameters along

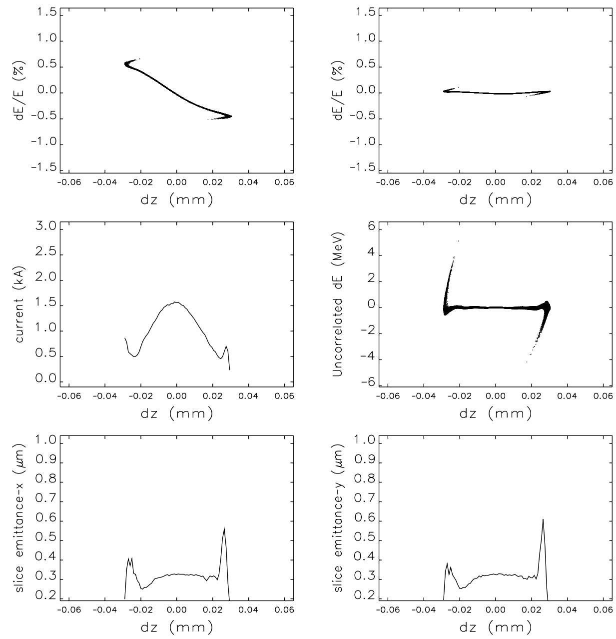

Figure 4: Longitudinal phase space at the FEL3 (top left) and at the FEL1 (top right), peak current (middle left) and slice beam parameters at the FEL1, FEL2, and FEL3 beamlines (middle right and bottom). Here positive dz corresponds to the head part of an electron bunch.

LINAC2 is negligible. Therefore the slice beam parameters at the FEL1 beamline are same as those at the FEL3 beamline.

SUMMARY

The CTF3 RF gun based linac can supply sufficient beam quality to drive the FEL3 beamline with the help of four main optimization methods; compensation of projected and slice emittances with the invariant envelope matching in the booster, careful suppression of CSR and ISR in BCs, reduction of chromatic effects in the LINACs with the optimized FODO cells, and control of energy chirp and energy spread by the action of the short-range longitudinal wakefields in LINAC2. From the full S2E simulations with the ASTRA, ELEGANT and GENESIS codes, we have checked that the power of the FEL1 beamline can be saturated even at 0.1 nm with this optimized beam quality, and a promising spectrum bandwidth of about 0.05% can be obtained by the ultra-flat energy chirp.

REFERENCES

[1] http://fel.web.psi.ch
[2] Y. Kim *et al.*, in *Proc. FEL2008*, Gyeongju, Korea.
[3] M. Pedrozzi *et al.*, in *Proc. EPAC2008*, Genoa, Italy.
[4] Y. Kim *et al.*, in *Proc. EPAC2008*, Genoa, Italy.
[5] Y. Kim *et al.*, in *Proc. LINAC2006*, Knoxville, USA.
[6] Y. Kim *et al.*, *Nucl. Instr. and Meth. A* **528** 421 (2004).