BEAM DIAGNOSTICS AND RF SYSTEMS REQUIREMENTS FOR THE SwissFEL FACILITY

Y. Kim*, B. Beutner, H. Braun, A. Citterio, M. Dehler, A. Falone, R. Ganter, T. Garvey, S. Hunziker, R. Ischebeck, B. Keil, M. Pedrozzi, S. Reiche, T. Schilcher, V. Schlott, B. Steffen
Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

Abstract

In this paper, we describe four very different operating modes of the SwissFEL facility, the requirements of the challenging beam diagnostics and ultra-stable RF systems needed for two special operating modes with 10 pC, and current developments of beam diagnostics and RF systems for the PSI 250 MeV injector test facility.

INTRODUCTION

SwissFEL will supply coherent, ultra-bright, and ultra-fast XFEL photon beams covering the wavelength range from 0.1 nm to 7 nm. To build the whole facility within about 800 m, PSI will use a 2.5 cell S-band RF gun, a 530 m long normal conducting RF linac, and a 70 m long in-vacuum undulator using the NdFeB with diffused Dy for the hard X-ray beamline and a 70 m long Apple-II type undulator for the polarization controllable soft X-ray beamline [1–3]. SwissFEL will be operated with four very different operating modes according to the overall electron bunch length compression factor, which determines RF jitter tolerances. To begin with, SwissFEL will be operated with a compression factor of 75. After improving the RF systems and beam diagnostics step by step, the facility could be operated with a compression factor of about 2400 to supply a fully coherent single spike XFEL photon pulse. In this paper, we review the requirements of the beam diagnostics and RF systems for two highly challenging operating modes with 10 pC, which have compression factors of 240 and 2400, respectively.

MODES & REQUIREMENTS

To begin with, SwissFEL will be operated with three nominal modes with 10 pC and 200 pC, which have compression factors of 75, 125, and 240 [1]. In the nominal operating modes, a higher single bunch charge of 200 pC will be used to supply more photons per pulse, and a lower single bunch charge of 10 pC will be used to supply shorter photon pulses [1, 3]. For one upgraded mode with 10 pC, RF systems and beam diagnostics will be greatly improved, and attosecond XFEL photon pulses can be generated by increasing the compression factor up to about 2400. For the upgraded operating mode with 10 pC, the soft X-ray beamline will supply transversely as well as longitudinally coherent 250 as (rms) long single spike photon pulses in a range of wavelengths from 0.7 nm to 7 nm, while the hard X-ray beamline will supply transversely coherent 250 as (rms) long multiple spike photon pulses in a range of wavelengths from 0.1 nm to 0.7 nm. Detailed information on the four different operating modes and minimum required and expected beam parameters are summarized in Table 1 [1,3].

Table 1: Parameters of the SwissFEL Project.

Operating Mode		Nominal		Upgraded
Parameters	unit	long pulse	short pulse	atto pulse
beam energy E	GeV	5.8	5.8	5.8 / 3.4
single bunch charge	pC	200	10	10
core-slice emittance	μm	0.43 / 0.38	0.18	0.25
slice rms E-spread	MeV	0.35 / 0.25	0.25	1.00
peak current	kA	2.7 / 1.6	0.7	7
projected emittance	μm	0.65	0.25	0.45
rms bunch length	fs	31 / 47	6.2	2.4
compression factor	·	125 / 75	240	2400
undulator period	mm	15	15	15 / 40
undulator parameter	·	1.2	1.2	1.2 / 1.05
saturation length	m	48 / 55	50	30 / 25
shortest wavelength	nm	0.1	0.1	0.1 / 0.7
rms photon length	fs	12 / 19	2.3	0.25
number of photon	10^9	31 / 32	1.7	3.2 / 31
rms bandwidth	%	0.03 / 0.03	0.035	0.05 / 0.35
single spike pulse	·	no / no	no / no	no / yes
longitudinal coherence	·	no / no	no / no	no / yes
transverse coherence	·	yes / yes	yes / yes	yes / yes

To check the beam quality at the entrance of the undulator for two highly challenging operating modes with 10 pC, we have optimized linac layouts for SwissFEL with the ASTRA and ELEGANT codes, and performed start-to-end (S2E) simulations as summarized in Fig. 1. Here, all key beam dilution effects such as space charge effects up to 150 MeV, short-range transverse and longitudinal wakefields in all linac structures, incoherent synchrotron radiation (ISR) and coherent synchrotron radiation (CSR) in the BC dipoles, and fringe-field and chromatic effects in all magnets are considered. From those S2E simulations, we realized that the lower charge operating modes with 10 pC can supply much better beam quality than the minimum required beam qualities, which are summarized in Table 1.

As shown in Fig. 1(top), in the case of the nominal mode with 10 pC, the rms transverse beam size, the normalized rms projected emittance, and the normalized core-slice emittance at the entrance of an undulator are about 8.5 μm,

* Mail : Yujong.Kim@PSI.ch

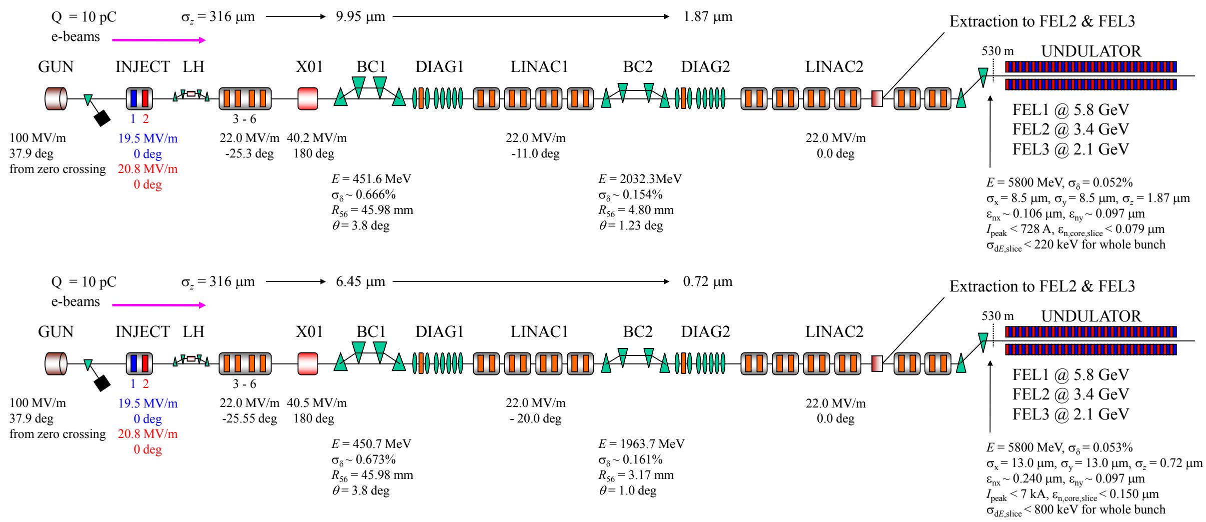

Figure 1: Two special operating modes with 10 pC: nominal mode (top) and upgraded mode (bottom).

0.11 μm, and 0.08 μm, respectively. Since the beam size and emittances are very small in this operating mode, the resolution of the beam based alignment (BBA) or the offset between the ideal design orbit and quadrupole (QM) in the linac should be smaller than 2 μm (rms) to keep emittance growth in the linac smaller than 2% (rms) [1]. Since the transverse rms beam size at the entrance of an undulator is about 8.5 μm (rms), the BPM resolution for undulators should be smaller than 1 μm (rms) to maintain a good overlap between photon beams and electron beams for lasing. Additionally, the resolution of OTR screens in the linac should be smaller than 2 μm (zero-to-peak *i.e.*, z-to-p) to detect 5% projected emittance growth in the linac. Even though the peak current is only 728 A, the photon beam power can be saturated within 50 m of undulator due to the ultra-low core-slice emittance. The requirements for the nominal operating mode with 10 pC are summarized in Table 2. Here, we assume that the repetition rate is 100 Hz, and six S-band klystrons and two X-band klystrons will be used in the injector linac [1]. To determine RF tolerances for the nominal mode with 10 pC, we assume that an active orbit feedback system is working in front of the undulator beamline, and we used the following four criteria on XFEL performance; beam arrival time error $\triangle T_{arrival} \leq 30$ fs (z-to-p), saturation power error $\triangle P_{sat}/P_{sat} \leq 30\%$ (z-to-p), central wavelength error $\triangle\lambda_0/\lambda_0 \leq 0.001\%$ (z-to-p), and power saturation length error $\triangle L_{sat}/L_{sat} \leq 15\%$ (z-to-p) from 80% core slices for 60 seconds.

As summarized in Table 1 and as shown in Fig. 1(bottom), the 250 as (rms) long photon pulses can be generated by compressing the electron bunch length down to about 2.4 fs (rms). For the upgraded operating mode with 10 pC, the longitudinal beam diagnostic systems, the RF reference timing distribution system, and the RF low level systems are extremely challenging due to the ultra-short electron bunch and the photon pulse length as summarized in Table 3. Here, we assume that

Table 2: Requirements of Nominal Mode with 10 pC.

Parameters	Tolerances
gun laser arrival time error	$\leq$ 5 fs (rms)
single bunch charge error	$\leq$ 1% (rms)
INJECT S-band $\triangle\phi_s$ per klystron (total six)	$\leq$ 0.01 deg (rms)
INJECT S-band $\triangle V_s/V_s$ per klystron (total six)	$\leq$ 0.01% (rms)
X-band $\triangle\phi_x$ per klystron (total two)	$\leq$ 0.06 deg (rms)
X-band $\triangle V_x/V_x$ error per klystron (total two)	$\leq$ 0.06% (rms)
gun solenoid misalignment after BBA	$\leq$ 20 μm (z-to-p)
S-band structure misalignment after BBA	$\leq$ 100 μm (z-to-p)
S-band solenoid misalignment after BBA	$\leq$ 50 μm (z-to-p)
X-band structure misalignment after BBA	$\leq$ 50 μm (z-to-p)
BC dipole misalignment after BBA	$\leq$ 50 μm (z-to-p)
BC dipole roll error after BBA	$\leq$ 25 μrad (z-to-p)
BBA resolution	$\leq$ 2 μm (rms)
screen resolution to detect 5% emittance growth	$\leq$ 2 μm (z-to-p)
gun solenoid power supply error $\triangle I_{sol}/I_{sol}$	$\leq$ 10 ppm (rms)
BC dipole power supply error $\triangle I_{bc}/I_{bc}$	$\leq$ 10 ppm (rms)
QM power supply error $\triangle I_{qm}/I_{qm}$	$\leq$ 10 ppm (rms)
steerer power supply error $\triangle I_{st}/I_{st}$	$\leq$ 10 ppm (rms)
girder vibration amplitude from 2 Hz to 200 Hz	$\leq$ 50 nm (rms)
undulator BPM resolution	$\leq$ 0.85 μm (rms)

six S-band klystrons and six X-band klystrons will be used in the injector linac to operate SwissFEL facility at 400 Hz [1]. Due to a much stronger power fluctuation, a much higher uncorrelated energy spread, and a much shorter photon pulse, we have used four somewhat different criteria to determine RF tolerances for the single spike operating mode with 10 pC; $\triangle T_{arrival} \leq 5$ fs (z-to-p), $\triangle P_{sat}/P_{sat} \leq 100\%$ (z-to-p), $\triangle\lambda_0/\lambda_0 \leq 0.01\%$ (z-to-p), $\triangle L_{sat}/L_{sat} \leq 15\%$ (z-to-p) from 80% core slices for 60 seconds. Here we also assume that an active orbit feedback system is working in front of the undulator beamline. For the upgraded operating mode, the other

Table 3: Requirements of Upgraded Mode with 10 pC.

Parameters	Tolerances
gun laser arrival time error	$\leq$ 1 fs (rms)
single bunch charge error	$\leq$ 1% (rms)
INJECT S-band $\triangle\phi_s$ per klystron (total six)	≤ 0.005 deg (rms)
INJECT S-band $\triangle V_s/V_s$ per klystron (total six)	$\leq 0.005\%$ (rms)
X-band $\triangle\phi_x$ per klystron (total six)	≤ 0.005 deg (rms)
X-band $\triangle V_x/V_x$ per klystron (total six)	$\leq 0.025\%$ (rms)
BC1 dipole power supply error $\triangle I_{bc1}/I_{bc1}$	≤ 7.5 ppm (rms)
LINAC1 $\triangle\phi_1$ per klystron	≤ 0.015 deg (rms)
LINAC1 $\triangle V_1/V_1$ per klystron	$\leq 0.010\%$ (rms)
BC2 dipole power supply error $\triangle I_{bc2}/I_{bc2}$	≤ 7.5 ppm (rms)
LINAC2 $\triangle\phi_2$ per klystron	≤ 0.017 deg (rms)
LINAC2 $\triangle V_2/V_2$ per klystron	$\leq 0.011\%$ (rms)

requirements which are not shown in Table 3 are the same as those for the nominal mode with 10 pC in Table 2.

CURRENT DEVELOPMENTS

As discussed in the previous section, challenging transverse beam diagnostic systems are required for the nominal operating mode with 10 pC due to its small beamsize and the low emittance, and highly challenging longitudinal beam diagnostic systems, RF reference timing distribution system, and RF low level systems are required for the upgraded operating mode with 10 pC due to its short electron bunch length. To develop these diagnostic systems and RF systems, PSI is constructing a 250 MeV injector test facility, and its first commissioning will start at the end of 2009 [5]. Accelerator design concepts and two advanced beam diagnostic sections of the 250 MeV injector test facility are described in references [1, 4, 5].

Here we give some examples of current developments of beam diagnostics and RF systems for the 250 MeV injector. Further details can be found from references [1,5–13]. The 250 MeV injector will use two different technologies to distribute the RF reference timing. One is an electrical timing distribution system with a temperature controlled coaxial cable. The other is an optical timing distribution system with a mode locked laser (MLL) based optical master oscillator. At the moment, an ultra-low timing jitter of 3.3 fs (rms) for 1 kHz to 10 MHz has been demonstrated with the latter technology [6]. To get a wide dynamic range from 10 pC to 200 pC, the injector test facility will use various screen methods which are all attached on a ladder actuator [7]. To measure the projected emittance in the presence of coherent optical transition radiation (COTR) emission, a wire scanner will be installed on the ladder. Additionally, we are testing a cooled CCD camera to improve the signal-to-noise ratio during 10 pC operation as well as a fast gated CCD camera to obtain an individual beam image during two or three bunch operation [7]. The injector test facility will test two different BPMs. The first one is the resonant stripline BPM with a required resolution of about 10 μm (rms) for 10 pC and 200 pC, and the second one is an RF cavity BPM with a sub-micron rms resolution [8, 9]. To minimize the projected emittance growth due to transverse wakefields in an X-band linac structure, the injector test facility will use a HOM coupler based structure alignment system, which can align tilts, bends, offset, and cell-to-cell misalignment of the X-band structure within a few μrad or μm (rms) [10]. For the single-shot measurement of electron longitudinal profile or bunch length with a resolution of 100 fs (rms), the injector will use an electro-optical (EO) crystal based compact bunch length monitor [11]. To measure electron bunch length with a much higher resolution, the injector will use two transverse deflecting structures (TDSs). At the gun region, there is a single cell deflecting structure (TDS1) to measure the slice emittance, the bunch length, and the longitudinal phase space [12]. Its expected time resolution is about 42 fs (rms) for 10 pC electron beams. Without changing any optics, to measure various parameters such as electron bunch length, slice emittance, slice energy spread, longitudinal phase space, beam arrival time jitter, projected emittance, Twiss parameters, and optics matching, the injector has an advanced beam diagnostic section after the bunch compressor [1,5,13]. In the advanced diagnostic section, there are specially designed asymmetric three and half FODO cells and a five cell deflecting structure (TDS2) to measure bunch length with a time resolution of about 11 fs (rms) for 10 pC [1, 5].

SUMMARY

Due to two low charge, 10 pC operating modes, the requirements on beam diagnostic systems, the RF reference timing distribution system, and the RF low level system are highly challenging for stable operation of the SwissFEL facility. To develop these required technologies for SwissFEL, the PSI 250 MeV injector test facility is under construction. Since there are strong random orbit fluctuations in undulators due to CSR kick and RF jitters, we are also investigating its impact on the orbit feedback system and XFEL performance during the upgraded mode.

REFERENCES

[1] Y. Kim *et al.*, in *Proc. FEL2009*, Liverpool, UK.
[2] T. Schmidt *et al.*, in *Proc. FEL2009*, Liverpool, UK.
[3] S. Reiche *et al.*, in *Proc. FEL2009*, Liverpool, UK.
[4] Y. Kim *et al.*, in *Proc. EPAC2008*, Genoa, Italy.
[5] M. Pedrozzi *et al.*, in *Proc. FEL2009*, Liverpool, UK.
[6] S. Hunziker *et al.*, in these proceedings.
[7] R. Ischebeck *et al.*, in these proceedings.
[8] A. Citterio *et al.*, in these proceedings.
[9] B. Keil *et al.*, in these proceedings.
[10] M. Dehler *et al.*, in these proceedings.
[11] B. Steffen *et al.*, in these proceedings.
[12] A. Falone *et al.*, in *Proc. PAC2009*, Vancouver, Canada.
[13] B. Beutner *et al.*, in *Proc. FEL2009*, Liverpool, UK.