LONGITUDINAL DESIGN AND RF STABILITY REQUIREMENTS FOR THE SwissFEL FACILITY

Bolko Beutner*, Paul Scherrer Institute, 5232 Villigen PSI, Switzerland

Abstract

The SwissFEL facility will produce coherent, bright, and short photon pulses covering a wavelength range down to an angstrom, requiring an emittance between 0.18 and 0.43 mm mrad at bunch charges between 10 pC and 200 pC. In nominal operation continuous changes in this range will be offered to the users to allow an individual trade-off between photon power and pulse length. The facility consists of S-band RF gun and booster, followed by a C-band main linac, which accelerates the beam up to 5.8 GeV. Two compression chicanes will provide a nominal peak current of about 1 to 3 kA depending on the charge. The stability of RF systems is a key design issue for stable compression schemes at reliable user facilities. In this paper the foreseen standard operation modes are presented and discussed.

INTRODUCTION

The design of SwissFEL was discussed in [1] and [2]. Important for the following discussion is the S-band booster upstream of the first chicane (BC1) at 330 MeV and the C-band linac between the first and second chicane (BC2) at 2.1 GeV. Downstream of BC2 a C-band linac accelerates the beam up to 5.8 GeV. Phase space linearisation is achieved by an X-band system.

In standard operation of SwissFEL the electron bunch charge varies between 10 pC and 200 pC. The compression of the bunches is adapted to keep the SASE gain length similar. Such an operation allows a trade-off between photon number and pulse length to address different user requirements. The configuration of the compression is done in an iterative semi-analytical procedure first described by I. Zagorodnov and M. Dohlus, which allows for an efficient compression setup [3, 4]. Using this procedure we design flat-top current profiles at the undulator which optimises the SASE efficiency.

In the standard operation it is foreseen to take advantage of the longitudinal wake fields in the C-band linacs to remove the energy chirp generated for the compression system to reduce the FEL bandwidth. Matching the wake field effects to compensate the energy chirp imposes additional boundary conditions on the compression setup.

STANDARD OPERATION MODES

Bunch charges between 200 pC to 10 pC are foreseen, the upper limit given by beam degrading self-field effects and the lower limit given by the diagnostics systems. The photo-injector laser profile is optimised for each working point. Namely the transverse spot size and the longitudinal pulse length are adapted to optimise the emittance for each charge value. For the design charge range the FWHM pulse length varies from 9.9 ps to 3.7 ps, which corresponds to peak currents from 22 A to 3 A downstream of the injector [5]. Bunch compression is set up to keep the value of $\Gamma = I_{\text{peak}}/\sqrt{\varepsilon_x \varepsilon_y}$ at the undulator at about 10^4 [A/mm mrad].

As mentioned above an iterative procedure is used to generate RF settings based on the desired compression factors, energies at the chicanes, and longitudinal shape parameters. We used *elegant* for particle tracking, including collective effects such as longitudinal space charge, wakefields, and CSR [6]. In our design the energy of the chicanes as well as the desired bunch shape are fixed while the compression factors of each chicane is a free parameter for optimisation (more details in [4]).

Chirp Compensation

The removal of the energy chirp in the last C-band linac is an optimisation problem. If we choose the chirp used for compression as small as possible to ease the subsequent removal the compression might not be sufficient. This might increase the required longitudinal dispersion R_{56} and thus CSR effects. However, higher compression early on in the machine increases the energy chirp and the integrated longitudinal wake field effect on the beam leading to stronger chirp reduction.

In practice we choose to vary the compression factor of the first chicane C_1 but the total compression factor from the gun to downstream of the second chicane C_2 is kept constant. As a result we get a set of working points which share the final current profile but have a different evolution of energy spread along the electron beamline.

In Fig. 1 we summarise the results for the 200 pC case. We obtained the same compression for all cases, the slice emittances are comparable and within design, while the energy chirp varies. As a result we chose the compression factor in the first chicane to be 12 while maintaining a total compression factor of 140 to obtain minimum energy spread and thus optimum FEL bandwidth.

At lower bunch charges setting up the compression is more challenging since the wakefields are weaker. In calculations for the 10 pC mode we learn that the gradient requirements in the S-band booster linac rise above the tolerable limit of 16 MV/m. In this case we are limited to use the compression factors of 5 and 300 in the first chicane and in total respectively. Because of the gradient limitation we cannot completely remove the energy chirp however we are able to reduce the peak-to-peak energy spread in the lasing part of the bunch to a level of about 5 MeV which is an

* bolko.beutner@psi.ch

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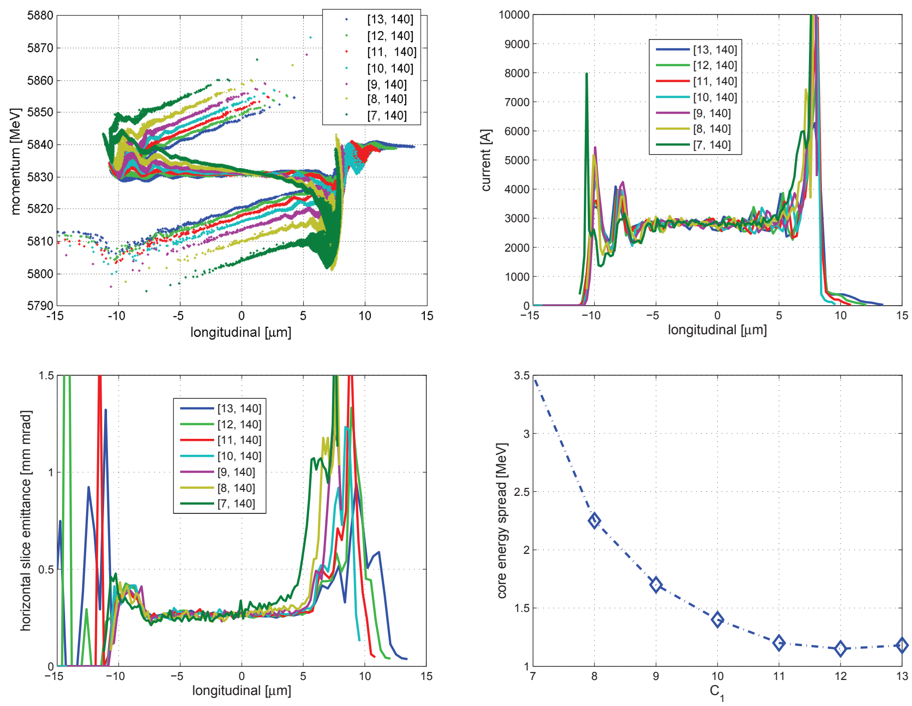

Figure 1: Summary of possible configurations for 200 pC at the undulator entrance. The compression factor in BC1 is varied from 7 to 13 while the total compression is kept constant at 140. The longitudinal phase spaces (upper left plot), as well as the current profiles (upper right plot), and the horizontal slice emittances (lower left plot) are plotted. The absolute core energy spread (lower right plot) has its minimum at a value of $C_1 = 12$. The bunch head is at the right hand side of the figures.

improvement of about a factor of three compared to our previous design (compare [4]).

For all studies presented the bending angles, and thus the momentum compaction factor R_{56}, in the chicanes were kept constant for the bending angles $\alpha_{\mathrm{BC1}} = 3.82°$ and $\alpha_{\mathrm{BC2}} = 2.15°$. We could increase the bending angle in the first chicane to lower the required gradients for the 10 pC case to overcome the gradient limitation. However, balancing the gain in gradient requirements with the increased beam quality degradation (dominated by slice energy spread increase) leads, in our case, to negligible improvements.

Using the described procedure we established working points for the different bunch charges, which are summarised in Tab. 1.

Stability

The longitudinal shot-to-shot stability of the 10 and 200 pC setups are determined and summarised in Fig. 3. A detailed description of the calculation procedure is given in [7].

The total fluctuations of beam arrival time at the undulator are estimated to be on the order of 10 fs. Peak current jitter is expected to range from about 10% to 20% depending on the charge. Energy stability is within 0.01% to 0.02%. These estimated performances are well within tolerable limits.

Table 1: A selection of optimised working points. The values correspond to the presented 10 pC and 200 pC setups (compare Fig. 1 and Fig. 2). Beam properties of the central slice (denoted by a subscript zero) are used to calculate Γ. This summary is concluded by the RMS bunch length and projected relative energy spread.

	200pC	100pC	10pC
$R_{56,\mathrm{BC1}}$ [m]	-0.055	-0.055	-0.055
$R_{56,\mathrm{BC2}}$ [m]	-0.021	-0.021	-0.021
S-band Grad. [MV/m]	15.32	15.44	15.77
X-band Grad. [MV/m]	15.96	16.84	20.66
C-band Grad. [MV/m]	26.16	25.64	26.40
S-band Phase [deg]	23.58	24.02	24.11
X-band Phase [deg]	-175.94	-174.26	-166.94
C-band Phase [deg]	17.45	13.63	19.44
BC1 Compression C_1	12	13	5
Total Compression C_2	140	200	300
$I_{\mathrm{peak},0}$ [A]	2644.59	2544.46	917.579
$\varepsilon_{x,0}$ [mm mrad]	0.268	0.200	0.144
$\varepsilon_{y,0}$ [mm mrad]	0.260	0.252	0.106
Γ [A/mm mrad]	10036.5	11350.8	7431.5
$\sigma_s[\mu\mathrm{m}]$	5.94	3.23	0.90
$\sigma_\delta[\%]$	0.040	0.044	0.085

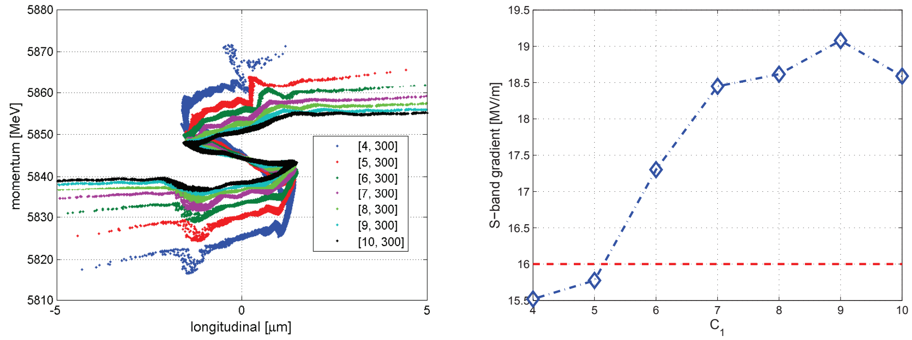

Figure 2: Varying C_1 has a similar effect on the energy chirp in the 10 pC as in the 200 pC mode (see Fig. 1). The maximum gradient of 16 MV/m in the S-band limits the compression in the first stage to 5.

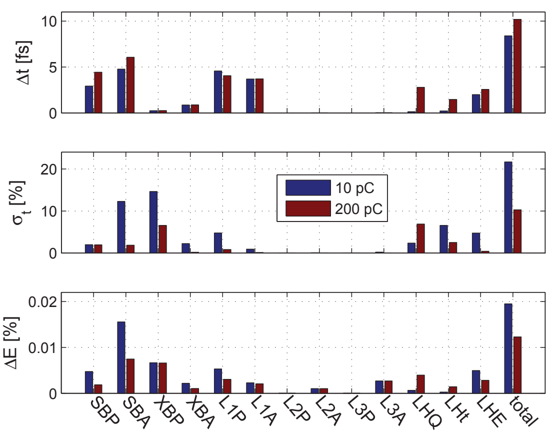

Figure 3: A summary of the longitudinal stability. The estimated arrival time (upper plot), bunch length (middle plot), and the beam energy (lower plot) jitter are presented. Each column represents one jitter source. The phase jitter of the RF systems (SBP, XBP, L1P, . . .) are assumed to be equivalent to 0.018 deg in S-band. We assume an amplitude jitter (SBA, XBA, . . .) of 0.018% for the RF amplitudes. The initial charge, arrival time, and energy jitter (LHQ, LHt, LHE) are expected to be 1%, 30 fs, and 0.01%, respectively. The total jitter is given in the rightmost column.

SUMMARY

We established a procedure, which allows us to generate a longitudinal compression setup for the standard operation modes in the range from 10 pC to 200 pC. For each working point the ratio between the compression is optimised for minimum total energy spread. As an example we presented data for the 10, 100, and 200 pC options with certain compressions. Using the described procedure we can apply the methods to other charge. It is straightforward and fast to generate similar modes for intermediate bunch charges or different choices of Γ.

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