OPERATION MODES AND LONGITUDINAL LAYOUT FOR THE SwissFEL HARD X-RAY FACILITY

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Abstract

The SwissFEL facility will produce coherent, ultra-bright, and ultra-short photon pulses covering a wavelength range from 0.1 nm to 7 nm, requiring an emittance between 0.18 to 0.43 mm mrad at bunch charges between 10 pC and 200 pC. In nominal operation continuous changes between these two bunch charges will be offered to the users as a tradeoff between photon power and pulse length depending on their requirements. The facility consists of an S-band RF-gun and booster and 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 1–3 kA depending on the charge. In addition special operation setups for ultra short single mode photon pulses and large bandwidth will be available to users. In this paper different operation modes including nominal operation as well as special modes are presented and discussed in terms of machine stability requirements.

OPERATION MODES

The SwissFEL user facility will provide various operation modes to the users. A hard- and a soft-X-ray line will be available available[2, 4]. In this paper we will discuss the operation modes of the hard-X-ray line. Standard operation will utilize bunches of 10 pC to 200 pC. 10 pC is the lower limit for diagnostics reasons. At 200 pC the self-field effects, mainly the longitudinal wake fields, limit user operation. A choice of the bunch charge within these limits allows a tradeoff between photon number and photon pulse length thus increasing the flexibility for the user groups.

In addition to the standard operation mode two specialized modes are offered to the users. The attosecond mode is based on a 10 pC bunch in full compression and offers a single-spike SASE spectrum at 1Ångstrom wavelength with an RMS pulse length of 60 as. The other unique operation mode offers a large spectral bandwidth of the photon pulse at the percent level. It uses a 200 pC bunch in an over-compression configuration utilizing longitudinal wake fields in the C-band structures to increase the energy chirp. The longitudinal phase spaces of the different modes are shown in Fig. 1 and Fig. 2. More details on these modes are summarized in [2].

The SwissFEL injector consists of an RF-gun followed by two S-band structures. Downstream of this booster linac a laser heater system and four more S-band structures are foreseen. These structures generate the energy chirp for compression, which together with the following X-band system provide the main control of the overall compression layout. Three C-band linac sections provide the total beam energy of up to 5.8 GeV. Bunch compressor chicanes are located upstream and downstream of C-band linac 1. More details on the layout of the SwissFEL are presented in [2].

Beam Stability

Of special interest in an FEL User facility is the stability of the delivered photon pulses. Stability and tolerance studies for the standard 200 pC mode of SwissFEL have been discussed earlier [3]. We will follow the same strategy as in the previous discussion but extend it to the other operation modes.

The basic idea of this study is that the Jacobian matrix of the system is determined in *elegant* tracking runs [5]. Variations of single machine parameters and their response are obtained and the linear term of a polynomial fit is used as the matrix element. The varied parameters are machine elements like the RF system phase offset and amplitude, or initial beam parameters like the initial bunch charge. These variations act on beam properties at the undulator entrance, namely the beam energy, the arrival time, and the peak current.

The matrix elements are called *sensitivities*. From the sensitivities we calculate the expected performance of the total machine. This is the quadratic sum of all sensitivities multiplied by the expected machine jitter (summarized in Table 1) normalized with the square root of the number of independent sources.

The stability goals of the machine are difficult to define from a user point of view since the community is heterogeneous. We decide to use a beam dynamics definition of these limits. The arrival time stability should not exceed the bunch length, and the energy fluctuations should be within the bandwidth of the undulator. From the intrinsic fluctuations of the SASE we obtain a fluctuation limit on the peak current, in the sense that a peak current more stable than the FEL power fluctuations would not stabilize the system any further. This is the tightest goal which makes sense from the beam dynamics point of view – user requirements are in general more relaxed. The goals are summarized in Table 2.

The expected beam performance obtained from the sensitivities are summarized in Figs. 3 and 4. The results for the standard 200 pC mode were presented in [3]. The new numbers include updated data on machine performance and a change in the RF configuration of the S-band linac. In the present layout the four S-band structures downstream of the laser heater are powered by two klystrons in contrast to four in the previous design.

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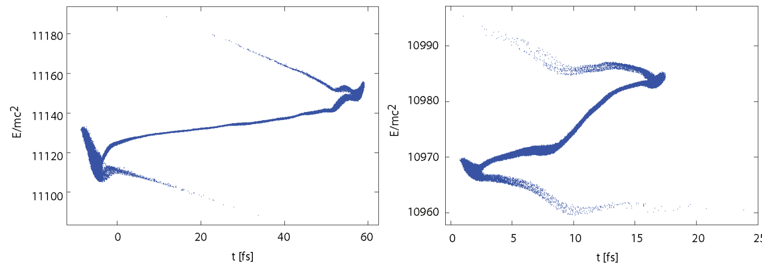

Figure 1: Longitudinal phase-space distributions at the entrance of the hard-X-ray undulator for the standard operation modes, with bunch charge 200 pC (left) and 10 pC (right). These examples represent the two extreme cases, every bunch charge in between will be made available to the users allowing for a continuous trade-off between photon number and pulse duration.

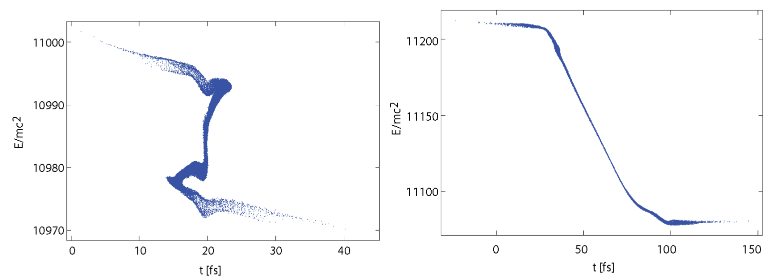

Figure 2: Longitudinal phase-space distributions of the special operation modes: 10 pC attosecond mode in full compression (left) and large bandwidth mode, obtained by over compression in BC2 and influence from the longitudinal wakes in the C-band linac 2 and 3 (right).

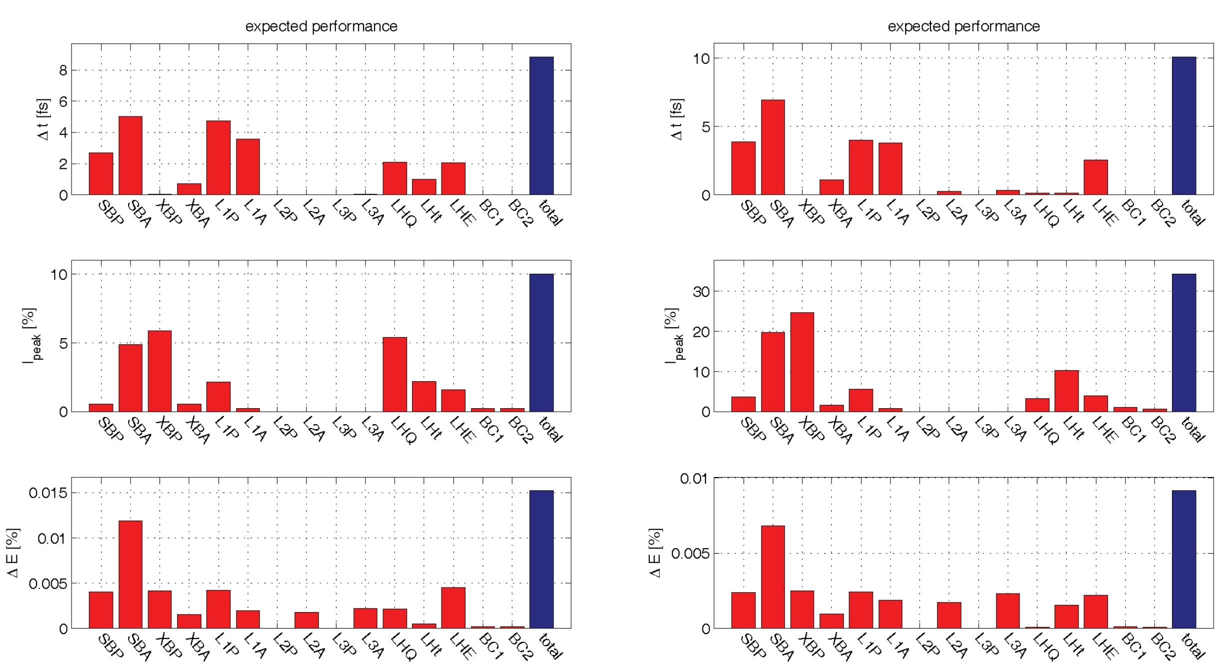

Figure 3: Expected beam performance of the standard operation modes. The red bars indicate the contributions to the RMS jitter caused by different error sources, their total is given by the blue bar. The arrival time (top), peak current (middle), and energy jitter (bottom) is given for the 200 pC (left) and the 10 pC mode (right).

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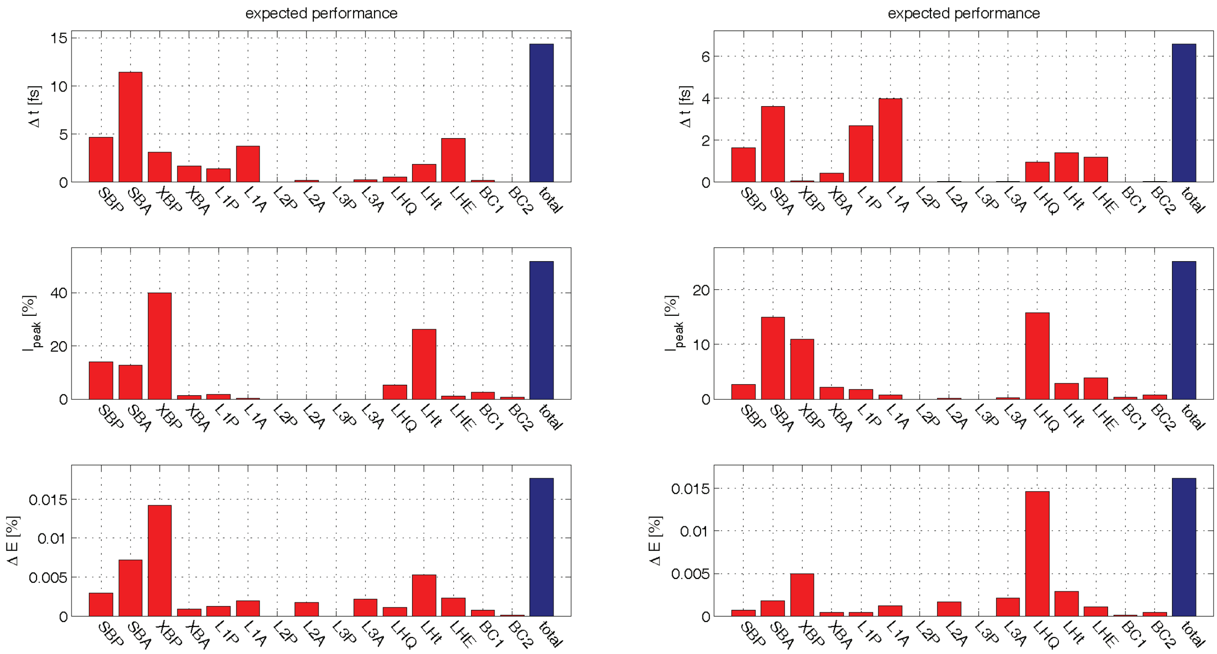

Figure 4: As in Fig. 3, but for the 10 pC attosecond mode (left) and the 200 pC large bandwidth mode (right).

Table 1: Expected RMS Stability Performance of SwissFEL Subsystems. The numbers for S-band are obtained from measurements at the SwissFEL Injector Test Facility. The phase stability of the other RF systems are assumed to be a multiple of that.

S-band phase [deg]	0.018
S-band amplitude [rel]	0.00018
X-band phase [deg]	0.072
X-band amplitude [rel]	0.00018
C-band 1 phase [deg]	0.036
C-band 1 amplitude [rel]	0.00018
C-band 2 phase [deg]	0.036
C-band 2 amplitude [rel]	0.00018
C-band 3 phase [deg]	0.036
C-band 3 amplitude [rel]	0.00018
initial bunch charge [pC]	1%
initial arrival time [fs]	30
initial beam energy [rel]	0.0001
BC1 dipole [rel]	0.00005
BC2 dipole [rel]	0.00005

EXPECTED PERFORMANCE ANALYTIC AND MONTE-CARLO

The expected beam stability performance was estimated from the Jacobian matrix elements. We verified this approach with a Monte-Carlo study for the standard 200 pC mode. In this study the complete machine with all parameters given in Table 1 was randomized within the expected RMS stability. In Table 3 a summary of 100 randomized machine setups is shown. The numbers are lower than in Table 3, because these calculations were still based on a layout with four klystrons for the S-band linac.

Table 2: Beam Stability Goals of the different Charge Modes

	200 pC modes	10 pC modes
arrival time [fs]	20	5
peak current [%]	5	15
energy jitter [%]	0.05	0.05

Table 3: Comparison Between an Analytic Estimation of Expected Beam Performance and with a Monte-Carlo Approach for the 200 pC Standard Mode

	Monte-Carlo	Jacobian
arrival time [fs]	7.5	7.8
peak current [%]	8.9	9.4
energy jitter [%]	0.014	0.012

OUTLOOK

Recent work by I. Zagorodnov and M. Dohlus provides a good opportunity for the systematic study of longitudinal design optimizations in terms of beam stability [1]. Their semi-analytical technique to calculate RF settings depending on a desired final longitudinal bunch profile allows find-

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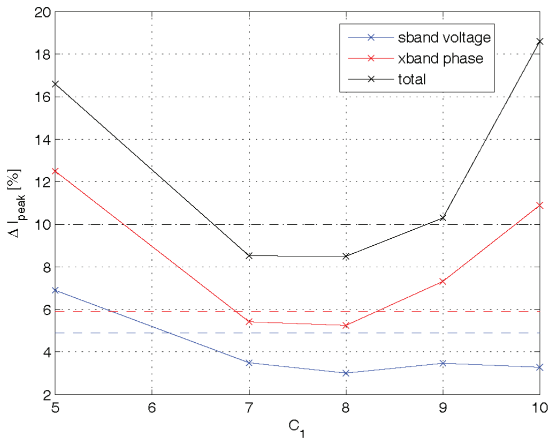

Figure 5: Example of a parameter optimization for the 200 pC standard mode. Solid lines represent the RF setups obtained from the semi-analytical algorithm. The dashed lines correspond to the numbers from Fig. 3 (left). The expected jitter caused by the S-band voltage and the X-band phase as well as the total expected jitter are shown.

ing different sets of machine parameters which share the same final configuration.

In Fig. 5 we present an example of such a stability optimization. The compression factor in the first chicane was varied while the RF setup of the machine was adjusted automatically to keep the final longitudinal bunch configuration, in particular the peak current, constant. The dipole strength was kept constant. For all these settings the performance was calculated as in the previous section. We clearly see that compression factors in BC1 between about 7 and 8 result in an improved stability performance.

This multi-parameter optimization of the whole SwissFEL is work in progress; intermediate results are very promising.

SUMMARY

Compared with the goals from Table 2 the energy jitter is no problem in any mode. Arrival time is an issue for the 10 pC modes. In all the modes the peak current stability goal is not reached. As a consequence the tightest tolerances are driven by the peak current stability.

In all modes the main drivers for beam peak-current jitter are the S-band phase and amplitude and the X-band phase. In addition the bunch charge fluctuations have a strong impact on the large bandwidth mode. This is because of the major role the longitudinal wake fields play in this configuration, which strongly depend on the total charge.

In conclusion, we have outlined a strategy for the optimization of the complete SwissFEL longitudinal compression scheme.

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