BUNCH COMPRESSION LAYOUT AND LONGITUDINAL OPERATION MODES FOR THE SwissFEL ARAMIS LINE

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

Abstract

The SwissFEL Aramis Undulator line will produce SASE photon pulses covering a wavelength range from 0.07 nm to 0.7 nm. The facility will consists of an S-band RF-gun and booster, an X-band lineariser, and a C-band main linac, which accelerates the beam up to 5.8 GeV. Two compression chicanes at about 330 MeV and 2.1 GeV will provide a nominal peak current up to 3 kA. It is foreseen to deliver electron pulses between 3 and 19 fs length to the undulator. This is done by adjusting the charge between 10 and 200 pC. Longitudinal wakes in the C-band linac are used to remove the chirp to deliver small bandwidth radiation. A special mode uses these wakes to increase the energy chirp to deliver a photon bandwidth on the percent level for special applications like single shot spectroscopy. In addition a fully compressed 10 pC beam is used as a source of sub femto-second pulses. An iterative semi-analytic procedure was used to setup and optimise the setup efficiently. In this paper these optimised operation modes are presented and discussed.

OVERVIEW

The setup of a global compression scenario for the SwissFEL [1][2] hard-x-ray line has to fulfil certain boundary conditions. Besides a sufficiently high peak current with tolerable low slice emittance, the shape of the current profile, namely the homogeneity of compression, and the overall robustness against parameter jitter are important.

A manual design of such a system is challenging. However, recent work by Zagorodnov and Dohlus [3] offers the possibility for systematic studies and optimisation of longitudinal dynamics setup in a multi-stage bunch compression linac. Their semi-analytic setup algorithm is implemented and applied for the SwissFEL facility design.

SEMI-ANALYTIC LONGITUDINAL SETUP ALGORITHM

The correlation between longitudinal positions of each particle upstream and downstream of compression chicanes is a convenient method to describe the longitudinal dynamics. These correlation function contains not only information on the compression factor but gives insights on the final bunch shape. Let us write the correlation function as

$$Z_i = \frac{\partial s_i}{\partial s_0} \tag{1}$$

* bolko.beutner@psi.ch

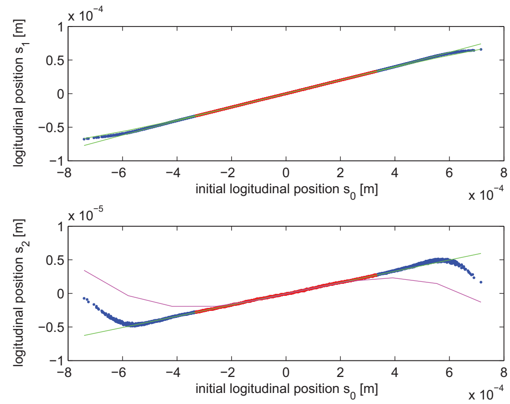

Figure 1: Longitudinal position of each particle are plotted vs. their initial positions for the two compression stages. The compression factor is the inverse of the slope in the central part of the bunch. A polynomial fit is used to quantify this value. Typically a one sigma region in the centre of the bunch (red particles) is considered to avoid complications from the tails.

with i being the number of the compression stage and s the set of longitudinal particle positions- The compression factor is then $C_i = 1/Z_i$. While the value of Z_i corresponds to the compression factor, higher derivatives of Z_i contain information about the general longitudinal shape and the homogeneity of the compression. These parameters Z_i, Z_i', Z_i'' are numerically be calculated by a polynomial fit to the particle distribution (see an example in Fig. 1). In general Z_1' corresponds to the position of the current "peak" along the bunch, while Z_i'' is the overall flatness of the current profile. It can i.e. be increased to suppress "spikes" in the tail regions of the bunch.

A straightforward calculation of the longitudinal dynamics to first order is symbolically summarised as $\mathbf{A_0}$. Assuming a set of RF parameters (phase and amplitude) denoted by $\mathbf{x_0}$ we can write the beam parameters $\mathbf{f_0}$, consisting of energies E_i and Z_i, Z_i', and Z_i'', as

$$\mathbf{A_0}(\mathbf{x_0}) = \mathbf{f_0} \tag{2}$$

with $\mathbf{f_0} = (\mathbf{E_i}, \mathbf{Z_i}, \mathbf{Z_i'}, \mathbf{Z_i''})$. A symbolic inversion of $\mathbf{A_0}$ is possible and explicitly calculated for linear beam transport in [3], such that

$$\mathbf{x_0} = \mathbf{A_0^{-1}}(\mathbf{f_0}). \tag{3}$$

This makes it possible to determine the required RF setup $\mathbf{x_0}$ to achieve the required parameters $\mathbf{f_0}$.

In order to include nonlinear effects an expansion of this method is required. Let us denote a nonlinear particle transport (i.e. particle tracking codes like elegant [4]) with the

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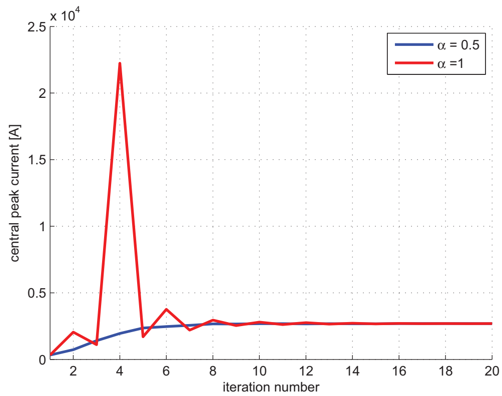

Figure 2: For an example case the convergence of the final peak current is compared for values of α 50% and 100%. In this case the peak current in the first iteration is too low compared to the requested value of 2.7kA. This is because of the longitudinal wakes, which are not included in the simple linear model, reduce the chirp and therefore the compression factor. While both iteration converge to approximately the same value the convergence is more smooth and slightly faster for $\alpha = 50\%$.

symbolic operator $\mathbf{A_x}$ analog to the linear transport $\mathbf{A_0}$. We can now use the results from the idealised calculation $\mathbf{x_0}$ as an initial guess to set up a "real" model. The deviation from the linear model is than used together with $\mathbf{A_0}$ in an iterative loop

$$\mathbf{x_n} = \mathbf{A_0^{-1}}\left[\mathbf{A_0}(\mathbf{x_{n-1}}) + \mathbf{f_0} - \mathbf{A_x}(\mathbf{x_{n-1}})\right] \quad (4)$$

$$\mathbf{x_0} = \mathbf{A_0^{-1}}(\mathbf{f_0}). \quad (5)$$

for $n > 0$. Typically this loop converges after about 10 integrations. In general this converges to stable setup is reached. We can improve the convergence behaviour by applying only a fraction α of the correction term, as in

$$\mathbf{x_n} = \mathbf{A_0^{-1}}\left[\mathbf{A_0}(\mathbf{x_{n-1}}) + \alpha(\mathbf{f_0} - \mathbf{A_x}(\mathbf{x_{n-1}}))\right]. \quad (6)$$

An example is given in Fig. 2.

Using this iterative semi-analytic procedure we can generate RF configurations of a multi stage bunch compression system to generate a specific final bunch profile. It is i.e. possible to vary only the compression factor without changing the shape of the bunch. This is illustrated in Fig. 3.

Another aspect is that we can keep the final bunch constant while varying intermediate parameters like the energy at the first chicane or the compression factor of the first chicane. This allows us to find a set of equivalent machines in terms of FEL performance but different behaviour in terms of i.e. RF stability requirements. Therefore systematic optimisations of linac layouts are possible.

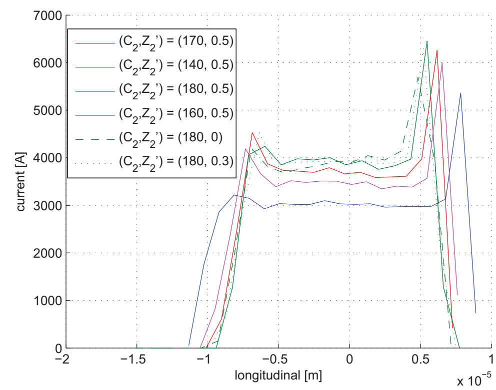

Figure 3: A series of longitudinal bunch profiles (head is to the right). It is shown how the final bunch profile varies if $\mathbf{f_0}$ is changed. In this example especially the total compression factor is varied to scale the current from 3kA to 4kA while keeping the overall shape as similar as possible. All results are the outcome of a global reoptimisation of the whole linac setup. In general the corresponding RF settings are different in all cavities.

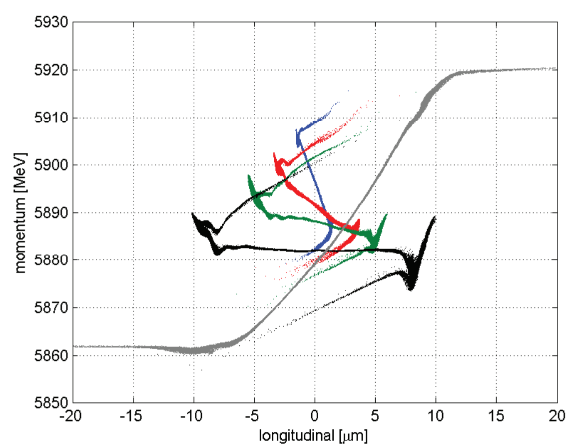

Figure 4: A comparison of the longitudinal phase spaces for the different modes. Colour code as in Fig. 5. Please note that the large bandwidth mode is overcompressed in BC2.

OPTIMISED OPERATION MODES FOR THE SWISSFEL HARD X-RAY LINE

We used the above methods to optimise the overall SwissFEL compression layout with respect to the earlier versions presented in [5][6]. The main goal was the homogeneity of the compression (a "flat" current profile) and the relaxation of RF stability requirements.

We present a summary of the final states of these optimisations in Fig. 4 and 5. All these operation modes are foreseen to have a comparable SASE gain, we quantified this by keeping the number $\Gamma = I_{\text{peak}}/\sqrt{\varepsilon_{x,0}\varepsilon_{y,0}}$ about constant at 10^4.

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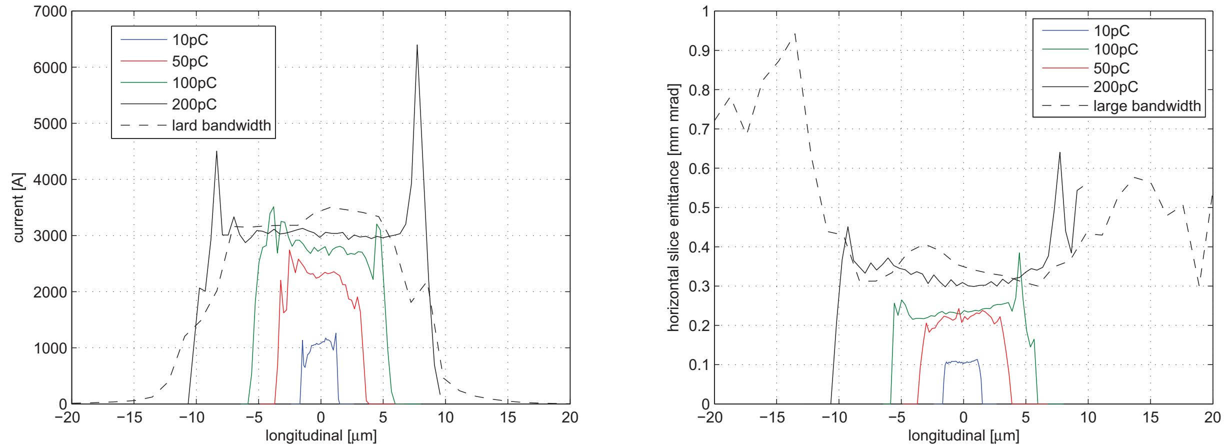

Figure 5: An overview over different operation modes of the SwissFEL Hard-X-Ray line. The longitudinal charge density profile, and the horizontal slice emittance are compared. In the lower plot the colour code is as in the two upper plots. The current profiles are homogenous compressed for all the modes, while the slice emittance is within acceptable limits. The corresponding parameters are given in Tab. 1

Table 1: The Input Parameters $\mathbf{f}_0$ for the Operation Modes Presented in Fig. 5. Please Note that the Last Entry Corresponds to the Large Bandwidth Mode, There is Overcompression in BC2 therefore the Signs of the Compression Correlation is Inverted

q [pC]	C_1	C_2	Z_2'	Z_2''	I_{peak} [kA]	Γ
10	5	300	0	0	1.10	0.93
50	8	250	0	0	2.29	1.12
100	10	200	0.2	0	2.76	1.18
200	10	140	0.5	0	2.98	0.99
200	10	-180	-0.5	0	3.44	1.08

In all the modes the acceleration in the C-band linac downstream of BC2 is done on-crest. Longitudinal wake fields in this linac segment compensate for the chirp lowering the FEL bandwidth (see Fig. 4). This, however, is only perfectly matched for the 200 pC case. In the future either additional wake field sources like corrugated pipes or modifications of the R_{56} are used to optimise the dechirping for all modes.

The presented longitudinal setups are analysed toward their stability performance. We assumed an S-band phase stability of $0.018°$ and $1.8 \cdot 10^{-4}$ amplitude stability, which correspond to measurements at klystron output in the SwissFEL Injector Test Facility. For C-, and X-band systems the expected phase jitter is a multiple of the S-band jitter while the amplitude stability is assumed to be the same as for the S-band systems. The charge is assumed to be stable to 1% after the booster with an arrival time jitter of 30fs, and an energy fluctuation of 10^{-4}. Bending magnets are assumed to have a shot-to-shot field fluctuation on the $5 \cdot 10^{-5}$ level. In the plots Fig. 6 and 7 the jitter contribution from various sources is displayed and added up as RMS values.

SUMMARY

We discussed a semi-analytic modeling technique which allowed us to efficiently set up an multi stage bunch compression system, including an lineariser cavity. This method was successfully used to optimise the present operation modes of SwissFEL.

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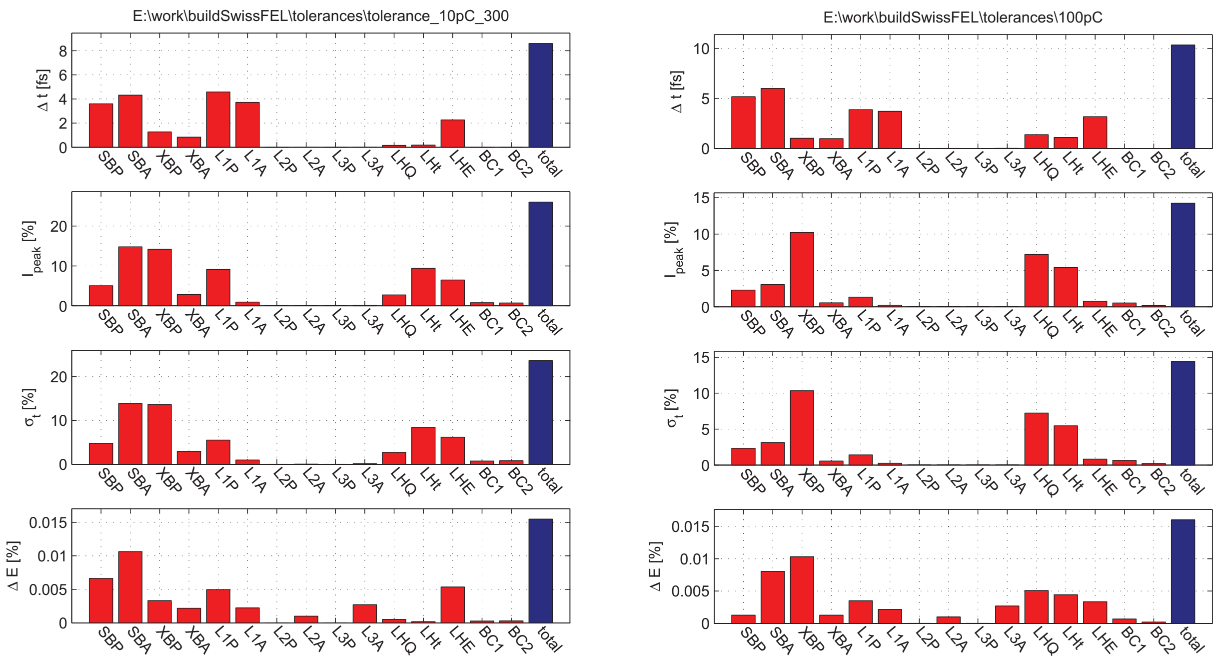

Figure 6: Expected beam performance of the standard operation modes. The red bars indicate the contributions to the RMS jitter of i.e. arrival time caused by different error sources. Their total is given by the blue bar. The arrival time (top), peak current (middle), and energy jitter (bottom) is given for the 10 pC (left) and the 100 pC mode (right). The labels denote the source of jitter contributions, S-, and X-band jitter is given as SBP, XBP, SBA, XBA for the phase and amplitude respectively. LnP, LnA, corresponds to the C-band linace 1 to 3. LHQ, LHt, and LHE is the beam charge, arrival time, and energy at the laser heater just downstream of the injector booster. Magnet field variations in the chicane dipoles are labeled as BC1 and BC2.

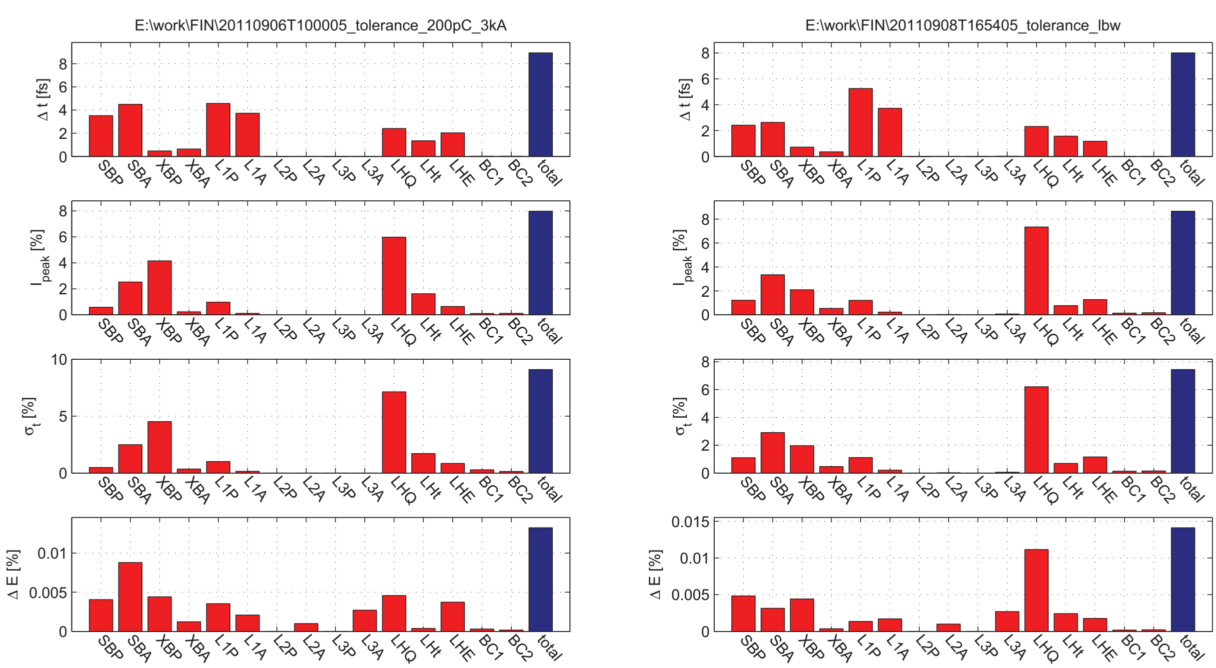

Figure 7: As in Fig. 6, but both modes have 200 pC in standard (left) and in large bandwidt mode configuration (right).

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