SIMULATIONS OF A CORRUGATED BEAM PIPE FOR THE CHIRP COMPENSATION IN SWISSFEL

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Abstract

In short wavelength FEL designs, bunch compression is obtained by making the beam passing through a magnetic chicane with an energy chirp typically of a percent level. At SwissFEL, before injection into the undulator it is foreseen to remove the residual chirp using the wakes in the C-band accelerating structures of the linac. This scheme works well for the hard X-ray undulator line, which includes the largest accumulation of wakefields, but it leaves a residual chirp in the other undulator line for the soft X-ray beam line, midway in the main linac. Another possibility to remove the residual chirp consists in using the longitudinal wakefields generated by a corrugated beam pipe, as recently proposed by G. Stupakov et al. Before planning a dechirper section in a FEL, an experimental verification of the analytical formulae describing the wakefields is crucial. The SwissFEL injector test facility (SITF) fulfils all the necessary criteria to perform such a proof of principle. We are investigating the technical implementation to perform an experiment in SITF in the second half of 2014. In this paper we present the tracking studies performed to optimize the experiment layout.

INTRODUCTION

In the SwissFEL design two undulator lines are foreseen: Aramis to produce hard X-rays (wavelengths from 1 to 7 Angstrom) and Athos for the soft X-rays (wavelengths from 7 to 70 Angstrom) [1]. The bunch will be compressed up to a factor 150 by means of two compression stages. This process leaves a bunch energy chirp, which has to be removed before the lasing process in the undulator lines. For Aramis the wakes generated by the C-band structures in the main linac are enough to cancel it, whereas for Athos, midway in the main linac, they are not sufficient. A possible solution to this problem would be to use the longitudinal wakes generated by a corrugated beam surface or dechirper, as recently proposed by Stupakov and Bane for NGLS [2]. This idea is very attractive for all short wavelength FELs and several labs are interested to include it in their designs. In the PAL design the use of the corrugated beam pipe has been studied [3] and some experiments have been already performed [4]. A reasonable set of parameters for a possible experiment to verify the validity of the theoretical formulae which describe the wakefield in a corrugated beam pipe have been identified by NGLS and published in summer 2012 [5]:

- Bunch charge > 150 pC;
- Transverse slice emittance < 3 μm;
- A tuneable bunch length in the 4 ps to 8 ps FWHM range;
- A sub-ps resolution RF deflector;
- Energy resolution < 0.05%;
- Space to install the corrugated beam pipe (requested 1 m at least).

The SwissFEL Injector Test Facility [6] fulfils all these conditions and an experiment is planned for the second half of 2014 in the shadow of the U15 prototype undulator test [7].

We optimized the bunch properties, the machine operating point and the geometry of the dechirper we plan to install on the undulator by doing tracking studies to maximize the effect of the energy chirp compensation by the dechirper.

The Longitudinal Wakefields

The longitudinal point-charge wake function generated by a corrugated beam pipe *w(s)* is given by [2]:

$$w(s) \approx \frac{Z_0 c}{\pi a^2} H(s) \cos\left(2\pi/_{\lambda}\, s\right) \tag{1}$$

where Z_0, c are the free space impedance, the vacuum speed of light and $H(s)$ is the unit step function. The other parameters define the geometry of the corrugation, with reference to Fig. 1.

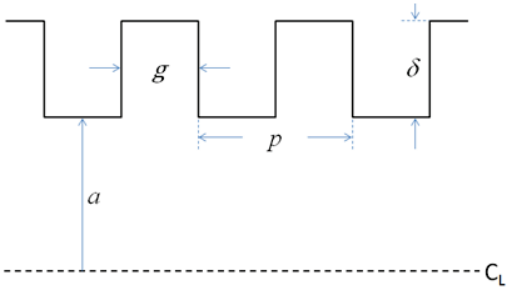

Figure 1: Schematic view of the corrugated beam pipe geometry [5].

The wavelength of the *w(s)* function is defined by the geometry of the corrugation and the semi-aperture as:

$$\lambda \equiv 2\pi\sqrt{\frac{a\delta g}{2p}} \tag{2}$$

The expression in Eq. (1) is valid only under the following assumptions:

$$\begin{aligned} &\bullet\ \delta,\ p << a \\ &\bullet\ \delta \geq p \end{aligned} \tag{3}$$

The effect of the wake on the beam, given by the convolution of the bunch temporal profile and *w(s)*, is maximized if the bunch length σ_z is smaller than the wakefield wavelength, i.e. if the condition

$2\pi\sigma_z < \lambda$ is satisfied. In all the following optimizations this will give a constraint on the wavelength and the bunch length for the chirp cancellation.

The Transverse Wakefields

The kick experienced by an off-axis bunch in a corrugated beam pipe can be expressed as [2]:

$$w_\perp \approx \frac{z_0 c \lambda_\perp}{\pi^2 a^4} H(s) \sin\left(2\pi\big/_{\lambda_\perp} s\right) \tag{4}$$

where the wavelength $\lambda_\perp$ is about the same defined in Eq. (2). In case of uniform temporal charge distribution, where s is the head-tail distance, Q is the bunch charge, Δs is the full width bunch length, the transverse kick is given by:

$$\Delta y' \approx \frac{Z_0 c Q L \Delta y}{\pi a^4 \Delta s E_0} s^2 \tag{5}$$

The strong dependence of the function $w_\perp(s)$ on the inverse of the fourth power of the aperture fixes the minimum aperture we can accept.

THE EXPERIMENTAL LAYOUT IN SITF

In next year a 4 m SwissFEL full scale variable gap undulator (U15) will be installed in SITF to test the alignment procedure and to measure the orbit kick inside the undulators [7]. The SITF layout has been modified to install the device between the Transverse Deflecting Cavity (TDC) and the high energy spectrometer, as schematically shown in Fig. 2.

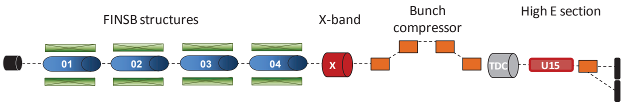

Figure 2: Schematic layout of SITF. The dechirper will be installed at the U15 position.

The option of mounting the corrugated surface on the plates of the U15 gap is very attracting for several reasons. First of all such a solution would allow varying the semi-aperture almost continuously and with a range from several hundreds of micrometers up to some millimetres. Furthermore the location of the corrugated plates will permit to measure the longitudinal phase space in the following high energy spectrometer using the TDC and the spectrometer bend. A drawback is that in this configuration the strength of the longitudinal wake would be reduced with respect to the circular beam pipe by a factor $\pi^2/16$ [8-9]. In any case this will be more than compensated by the pipe length (about 4 m), compared to the suggested length of 1 m discussed in [5].

THE OPTIMIZATION IN SITF

The optimal configuration for this experiment is to have the maximum possible energy chirp at the entrance of the corrugated plates and to be able to compensate it with the longitudinal wakes of the dechirper. A small semi-aperture would be beneficial to realize this condition, but, due to Eq. (4) we have a constraint on the minimum aperture imposed by the transverse wakes. At the same time we tried to ease and to make as much as possible robust the manufacturing of the corrugation by selecting a configuration keeping p/g ratio of about 2 and δ below 1 mm.

To optimize the experiment in SITF we performed start-to-end simulations using Astra [10], from the gun to the exit of the second FINSB structure, and Elegant [11] from that point up to the high energy section.

According to Eq. (1) the strength of the longitudinal wake is controlled by only the semi-aperture a, whereas the wavelength depends also on the geometry of the corrugation. Fixed the semi-aperture, therefore, the wake depends in the same way only on the three geometrical parameters p, g and δ. A variation of any of them is then completely equivalent to the same variation of one of the other two from the beam dynamics point of view. It looks hence reasonable to vary one of these parameters, fix the other two and for each case vary a to eliminate the energy chirp. For all the cases presented in this paper we arbitrarily fixed p and g (to 1.1 mm and 0.5 mm respectively) as a starting condition for the optimizations and we varied δ. Only once we had a good configuration we found a collection of infinite equivalent geometries by varying p, g and δ at fixed a to have a constant wavelength, neglecting the cases which don't satisfy the conditions in Eq. (3).

As laser pulse we assumed the SITF nominal one [6] with the exception of the length, which we varied from 3 ps to 9.9 ps FWHM and we present in this paper the 200 pC charge cases.

To maximize the effect of the wake on the bunch the beam energy at the entrance of the corrugated plates must be as low as possible compatibly with a reasonable beam setup in terms of emittance, RF curvature and bunch elongation. The optimal layout for the experiment is to keep the nominal settings of the gun and the first FINSB structure, to stay as close as possible to the design emittance and energy spread, switching off the second FINSB cavity to reduce the energy. In this setup the bunch travels through the dechirper at about 100 MeV energy, being away from the space charge regime with moderate compression factors. The transverse emittance is kept well below 1 μm. The third and the fourth FINSB structures are used to generate the chirp, and the compression is finally linearized by the X-band cavity. After that the bunch is compressed and enters in the dechirper. For the compression setup we assumed, if not differently specified, 25 MV voltage and -37 degrees off-crest in the third and fourth FINSB structures and a 4.071 degrees as a bending angle in the bunch compressor.

In the next sections the results of the simulations will be discussed, focusing on the one finally selected for the experiment in SITF.

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5 ps Initial Bunch Length

The most convenient configuration for the experiment came out to be the one corresponding to the initial laser pulse length of 5 ps. For this initial pulse we introduced ±0.5%, ±1% and ±2% chirps by changing the gradients of the last two FINSB structures.

In Fig. 3 the (t,p) space of the bunch upstream the corrugated plates for the ±2% chirp is shown.

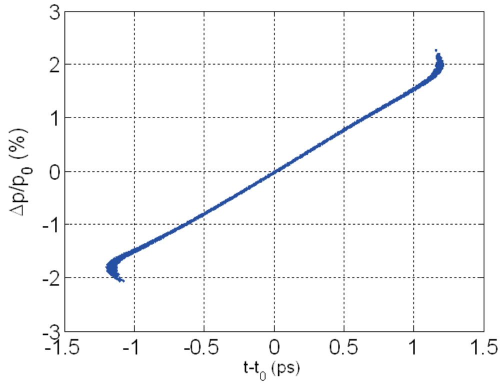

Figure 3: Longitudinal phase space upstream the corrugated plates for the ±2% case.

As anticipated, we kept constant p and g and we did a 2D scan of the semi-aperture a and δ in steps of 0.1 mm to determine the configuration which corresponds to the best chirp compensation. As optimal case we obtained a configuration corresponding to a = 2.25 mm and δ = 0.6 mm, as shown in Fig. 4.

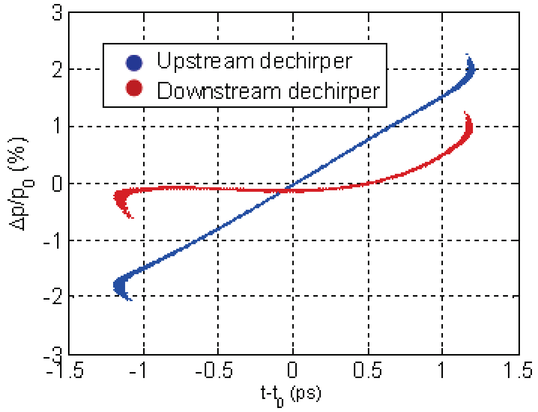

Figure 4: Longitudinal phase space upstream and downstream the corrugated plates for the ±2% case.

Once we identified the best (a,δ) for the chirp compensation we varied a and δ with finer steps around that point and we applied a polynomial fit to the final (t,p) distributions to refine the result. From this it came out that the best parameters for the chirp compensation in this configuration are δ = 0.535 mm and a = 2.25 mm, corresponding to λ = 3.29 mm.

As pointed out in the previous section this is only one of the infinite equivalent geometries. Fixed a, different combinations of p, g and δ with the same wavelength are completely equivalent to this one. Fig. 5 shows a collection of possible equivalent p, g, δ parameters corresponding to this case.

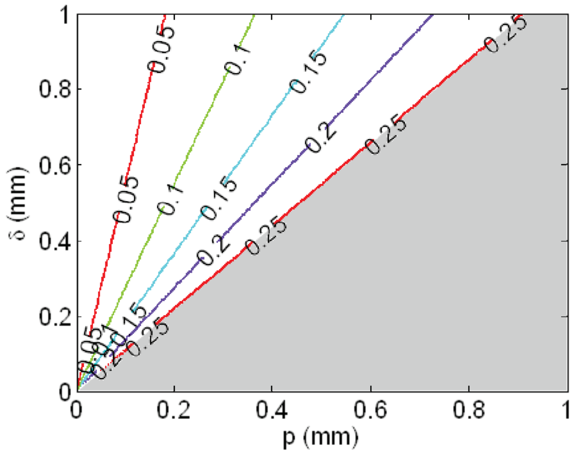

Figure 5: Combinations of the geometrical parameters of the corrugation of the equivalent geometries to compensate the chirp of Fig. 3 at constant semi-aperture (i.e. at constant wavelength). The grey region corresponds to cases which don't satisfy the Eq. (3) conditions.

Among these possible solutions we selected geometry sketched in Fig. 6.

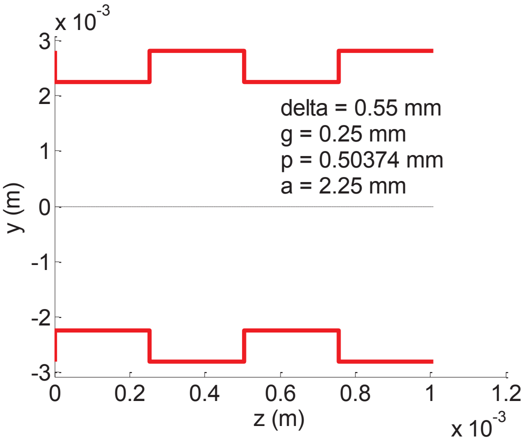

Figure 6: Geometry selected for the dechirper experiment in SITF.

In Table 1 the parameters to define the geometry of the dechirper and the machine setup are summarized in comparison with the ones discussed in [5].

Compared to the NGLS proposal in the SITF setup we could stay at higher beam energy and compensate for a larger linear chirp. Furthermore this configuration allows having a more relaxed geometry for the corrugation. The draw-back of the SITF case is the smaller semi-aperture we need to compensate the chirp. We investigated therefore the possibility of increasing a by reducing the initial chirp to a smaller value.

Table 1: Comparison of the Crucial Parameters for the Dechirper Experiment Discussed in [5] and the One Optimized for SITF

	NGLS [5]	**SITF**
Charge (pC)	200	
Laser pulse length (ps)	5	
Beam energy (MeV)	60	96
Initial chirp (%)	0.2	2
Semi-aperture (mm)	5	2.25
Pipe length (m)	1	4
p (mm)	0.50	0.50
δ (mm)	1.00	0.55
g (mm)	0.25	0.25

In Fig. 7 the chirp at the entrance of the corrugated plates and the case corresponding to the best chirp compensation for the ±1% case are shown.

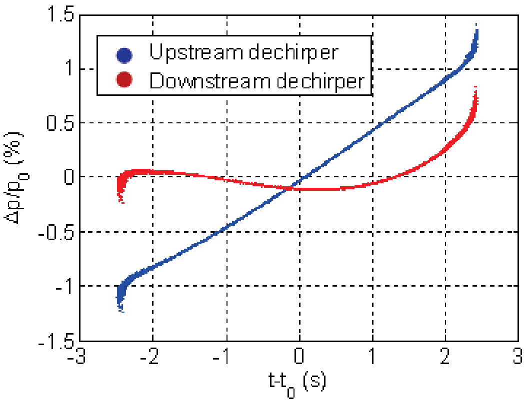

Figure 7: Longitudinal phase space upstream and downstream the corrugated plates to compensate the linear chirp.

The corrugation geometry corresponding to this case is worse than the previous one, because of the larger δ. This goes into the direction of increasing δ or the p/g ratio. The same argument is valid for the configuration corresponding to ±0.5% chirp.

In Table 2 the parameters corresponding to the configurations to compensate the linear chirp in these setups are summarized.

Table 2: Most Important Parameters of the Optimized Layout for Several Initial Chirp Cases with the 5 ps Laser Pulse Length

	±0.5%	**±1%**	**±2%**
Semi-aperture (mm)	4	3	2.25
δ (mm)	1.35	0.85	0.535
FINSB03-04 voltage (MV)	10	15	25
FINSB03-04 phase (°)	-37	-37	-37

For these reasons we selected the configuration corresponding to the ±2% induced chirp compensation for the SITF experiment.

10 ps Initial Bunch Length

We considered also the case of the nominal SwissFEL pulse length of 9.9 ps FWHM.

Following the same procedure of the previous case we determined δ and a, fixed p and g, to compensate the ±2% introduced chirp. We obtained the best compensation for $\delta = 2.85$ mm and $a = 2$ mm, as shown in Fig. 8.

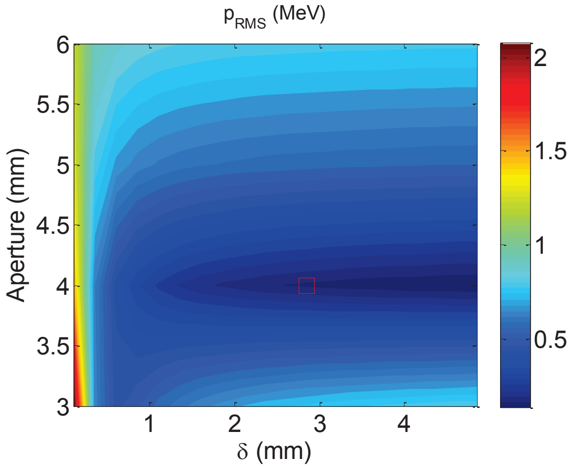

Figure 8: Projected rms momentum downstream the dechirper as a function of the aperture and δ. The solutions at larger d satisfy the condition $2\pi\sigma_z < \lambda$ and they are therefore acceptable. The optimal point is also indicated (square).

In the upper part of the plot of Fig. 8 the strength of the wakes is not enough to compensate the chirp, whereas in the bottom part the chirp is overcompensated.

We excluded this case, because it corresponds again to δ larger (due to the longer bunch length) than the limit coming from the mechanics (maximum 1 mm), as stated before.

3 ps Initial Bunch Length

We investigated the case corresponding to 3 ps initial laser pulse length. We obtained in this configuration the ±1% chirp compensation for $\delta = 0.8$ mm and $a = 2.5$ mm. This configuration is more favourable for the mechanics, because of the smaller value of the parameter δ. Furthermore from the dynamics point of view we can make the chirp smaller compared keeping the same final bunch length. This implies that we can satisfy the condition $2\pi\sigma_z < \lambda$ with smaller δ maintaining a constant p/g ratio and that we can reduce the induced chirp, and, therefore, the necessary compensation a is larger, being beneficial for the transverse wakes.

In despite of these arguments the emittance is about a factor 3 larger than the previous case, because of the longitudinal space charge in the low energy section. In addition for this configuration it can be very tough to produce the 200 pC charge we assumed in the simulations. A careful analysis of the ablation limit of the copper cathode and of the energy from the laser and the quantum efficiency has also to be done.

For all these reasons we decided to select at the present status the 5 ps laser pulse length configuration and to move to the 3 ps one after verifying that the laser-cathode system can provide the necessary setup for the experiment.

The Transverse Dimension

In all the calculations discussed so far we considered a bunch passing on-axis in the corrugated plate. The transverse wakes, described in Eq. (4), may generate quite a strong bunch deformation especially for the small aperture we obtained for the chosen configuration for the experiment in SITF.

To evaluate this effect we vertically misaligned the beam at the entrance of the dechirper and we tracked it up to the high energy section. In Fig. 9 the deformation of the bunch and the emittance in the plane of the misalignment on the high energy screen with the spectrometer bend and the TDC switched off assuming several offsets is shown.

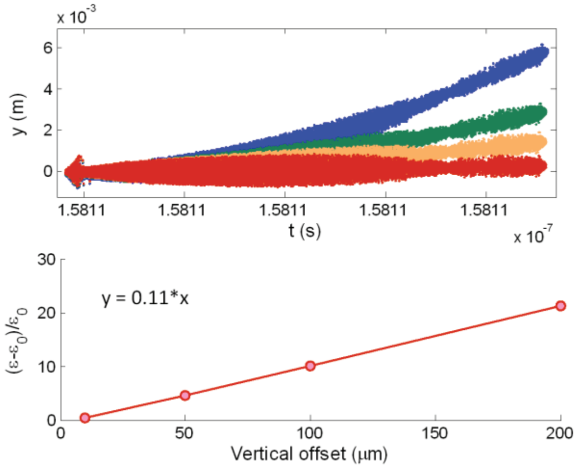

Figure 9: Vertical deformation along the bunch and emittance degradation on the high energy screen (spectrometer bend and TDC off) for misalignment from 10 μm to 200 μm (from red to blue) vertical offset at the entrance of the dechirper.

One of the outcomes of the U15 test is the experimental demonstration of orbit control below 100 μm, so we can assume that this will be our starting alignment, but this value is still critical in terms of normalized projected emittance, which would be about 5 μm.

The strategy to overcome this problem is given by the fact that the aperture of the dechirper will be adjustable in a very large range. The strategy will be to minimize the beam size on the high energy screen with TDC and bend switched off by means of closed orbit bumps in the corrugated plates. After that we will further reduce the aperture of the dechirper and we will repeat the same procedure. This process iterated several times should be enough to perform the experiment.

CONCLUSIONS

The longitudinal wakefields induced by a dechirper structure could be used in short wavelength FELs to compensate the residual linear energy chirp coming from the magnetic bunch compressions, allowing also an variable chirp compensation for the different compression settings. In SwissFEL this option would be very useful especially for the Athos line, midway in the main linac, where the wakes of the C-band structures are not enough.

We presented tracking simulations to optimize the layout for an experiment feasible in SITF next year. We optimized the machine setup, to be as sensitive as possible to the longitudinal wakes effect, the induced energy chirp, to maximize the effect of the dechirper and the bunch length after the compression to ease and make more robust the manufacturing of the corrugation. At the present status we identified as the optimal setup the one corresponding to the 5 ps laser pulse length with a compression of factor 3, which should allow compensating ±2% energy chirp at almost 100 MeV.

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