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Summer Student Program '09

— DESY —

Project:
Bunch Compression for a Free Electron Laser

Accelerator Group
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Motivation and Basic Concept

Short bunches of electrons are required by the contemporary free electron lasers to produce high brilliant radiation in the range of nm. Since these bunches of less then μm lengths reach currents of several kilo Amperes, the space charge forces make it impossible to produce them at the early stage of beam injection at the gun. The idea is to produce low intensity bunches, accelerate them and use the $\frac{1}{\gamma^2}$ decrease of of the space charge forces to enable high compression rates in dispersive beam lines. These beam lines are curved magnetic chicanes which result in a deviation of the particles path length due to the momentum/energy spread in one bunch. In such a beam line the tail is able to catch up with the head of the bunch, since the bending angle within a dipole due to Lorentz force depends on the particles individual energy.

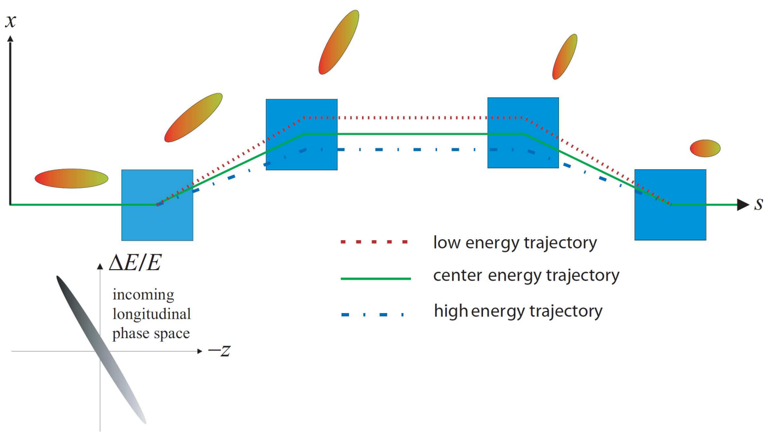

Figure 1: "Longitudinal bunch compression in a simple 4-bending-magnet chicane" [4]

This leads to a rotation of the bunch in the phase space and is the key to an effective reduction of the bunch length.

The Project

The aim of this project is to use the computer code ELEGANT by M. Borland[2] for a simulation and design improvement of such a magnetic chicane. The approach is step by step. Every new (unintended) side effect, caused by a part of the beam line, has to be treated with just another fine tuning or element, correcting the adverse impact of the preceding one. Therefore the final setup, to achieve a compression of $\frac{1}{10}$ of the initial bunch length, is a compromise of all possible setups.

Elegant

Elegant is a code package written in *C* used to simulate electron bunches in all kinds of accelerators or storage rings. The abbreviation stands for "ELEctron Generation ANd Tracking". Consequently the program tracks the particles in the 6-dimensional phase space $(x, x', y, y', s, \delta)$, while the output data can, in the most cases, be interpreted with the SDDS Toolkit[1]. Both packages can be downloaded at *www.anl.gov.*

First Compression

To accelerate the injected bunch of 10000 particles, three radio frequncy (rf) cavities with a length of 1 m, a frequency of 1.3 GHz and a peak gradient of 21 $\frac{\mathrm{MV}}{\mathrm{m}}$ each – much like the TESLA cavities used for the XFEL – are placed in front of the first magnet. Additionally there are drifts in between the bending magnets of 6 m length and one as well after the acceleration track in front of the chicane itself. All these parameters are used in the furthers simulations. Via the acceleration a so called energy "chirp" is created as shown in figure 2. This chirp is used to perform the phase space rotation and create a compressed bunch. The phase resulting in the highest bunch compression can be theoretically calculated by several equations given in [4], the phase of a cavity is defined with maximum acceleration realized at $\varphi = 0$. But close to the ideal value, little effects have a huge impact. Therefore the concept of try and error is often used in the following setups to determine a stable solution for a given task. In this case a phase of 34.5° in the cavities leads to a longitudinal reduction of the bunch from the initial 2.00 mm to about 666 μm:

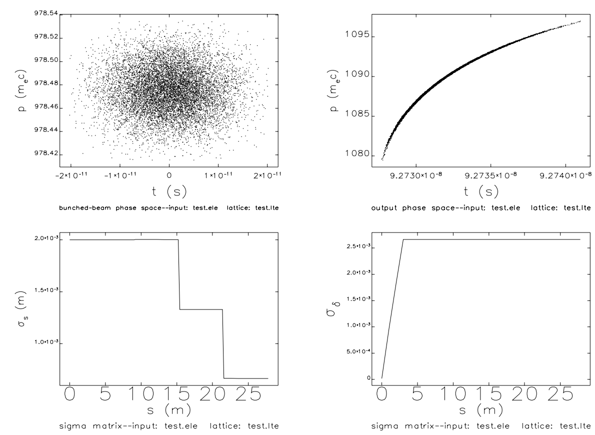

Figure 2: **Plot 1**: Particle bunch before acceleration $(p(t))$ **Plot 2:** Particle bunch after acceleration, before the magnetic chicane **Plot 3**: Length of the bunch $\sigma_s(s)$ **Plot 4**: Energy spread $\sigma_\delta(s)$

Third harmonic RF Cavity

In plot 2 of picture 2 one can already see the non-linearity of the chirp. This is motivated by the shape of the accelerating curvature inside the rf cavity. This effect limits the possibility to compress the bunch and should be compensated. A common trick to overcome the curved nature of this chirp is to add an extra RF cavity of a *higher* harmonic order and *lower* gradient to the beam line. The effect of the interference of the different orders is visualized in the following figure:

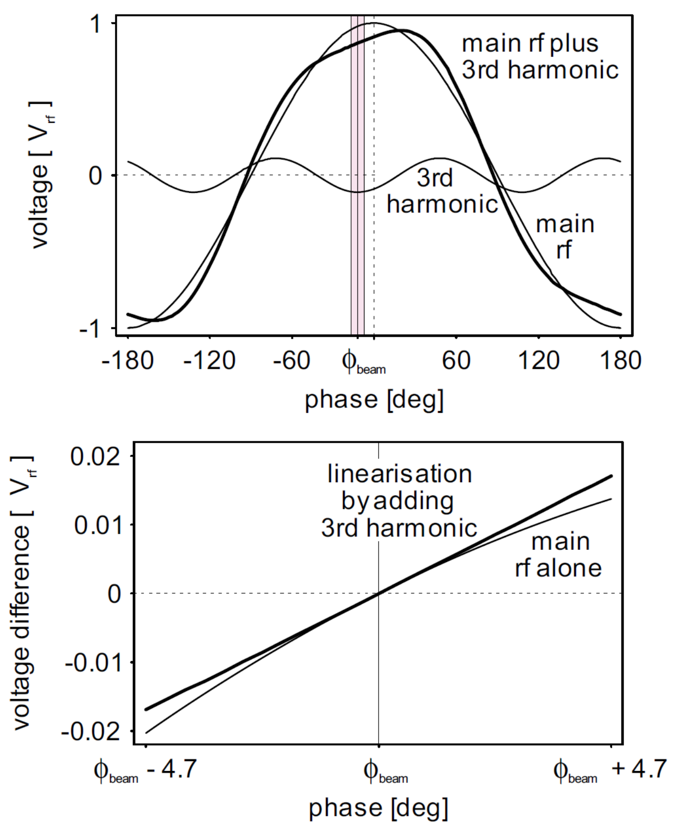

Figure 3: Linearisation of the chirp with a higher order cavity [3]

This is planed for FLASH at DESY [3]. An appropriate module has been designed at Fermilab and was recently shipped to Hamburg where it is going to be installed soon. Within the ELEGANT simulation the same setup can be applied. The third harmonic RF cavity is installed after the three standard cavities and runs with a frequency of 3.9 Ghz, a gradient of 7 $\frac{\text{MV}}{\text{m}}$ and with a phaseshift of 180° to the other cavities' phase. The result is a very linear chirp for the bunch compressor and a loss in the energy spread σ_δ due to the paraphase of the third harmonic rf cavity:

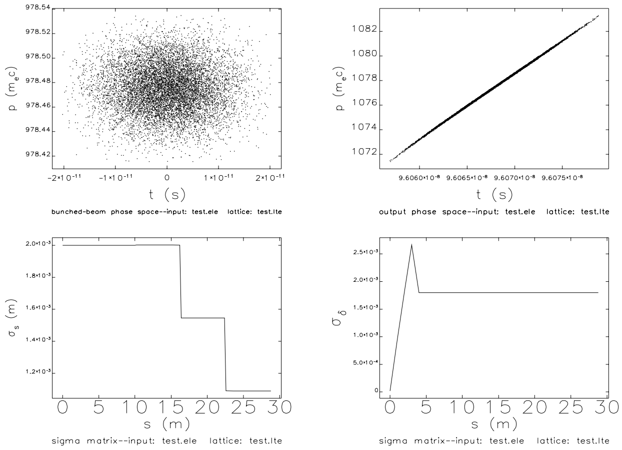

Figure 4: Linearisation of the chirp and compression by a factor of 2

Coherent Synchrotron Radiation

An additional problem inside the bending magnets of the bunch compressor is the upcoming effect of coherent synchrotron radiation for very short bunches. The particles inside the bunch may even form sub-bunches and generate self amplified stimulated emission – SASE. So far this effect has been neglected by the code, but as we reach bunch dimensions of a few hundred μm this drawback has to be taken into account. For the simulation this can simply be done by replacing elements in ELEGANT, the "CDBEND"s in the beam line are replaced by "CSRCSBEND"s to switch on the CSR tracking. The result for a compression of the achieved $\frac{1}{10}$ is a "dip" in the middle and at the end of the bunch:

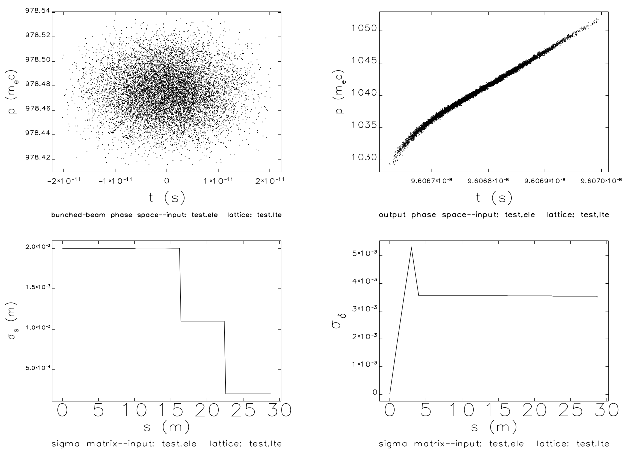

Figure 5: Initial mean bunch length 2.00 mm; final mean length 200 μm (plot 3); the result is a strong impact of the CSR on the energy chirp in plot 2

Horizontal Emittance

Another parameter gains importance and is a further disadvantage, the horizontal emittance. The magnetic chicane uses a path deviation to compress the bunch. This path deviation takes place in the horizontal plane. As the particles may form micro bunches within the bending magnets and lose energy via coherent synchrotron radiation, depending on their position within the bunch, the horizontal emittance increases. This produces a very unrewarding outcome of the bunch compressor. To give an example: For the compression shown in figure 5 the horizontal emittance increases from the initial value of $1\,\mu$m to $2.32\,\mu$m at the end of the beam line.

It's very tricky to fight these effects and to decrease the emittance without losing in compression. There are two "control knobs" which can be used for this task. One is to use an S-chicane as shown in figure 6 to compensate some of the effects with a deflection of the beam in the opposite direction. The other one is to modify the β and α functions of the betatron oscillations with a FODO line in front of the compressor. Both parts have been applied to improve the beam's emittance.

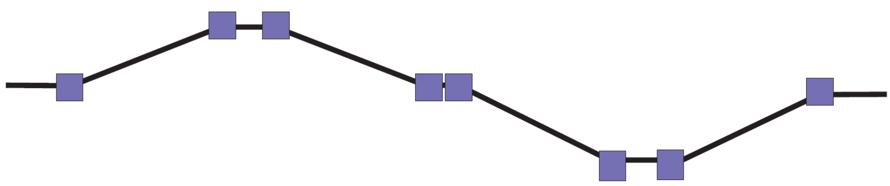

Figure 6: A functional schematic of an S-chicane

The fine tuning of the $K1$ values (the focusing strength of the quadrupoles) in the FODO part of the beam line, turnes out to be a rather time-consuming process. Since the built-in optimization routines of elegant seems to be highly dependent on the choice of the initial values. With the help of another script in MATLAB a surface plot of the horizontal emittance in dependence of the two $K1$ values can be produced, shown in figure 7.

Using these results for the start values of the ELEGANT optimization routines within the maximum value of $5\,\frac{1}{\mathrm{m}^2}$ for each quadrupole, a minimum for the horizontal emittance ε_x is found for the following constellation; a defocussing quadrupole of $K1 = -3.9\,\frac{1}{\mathrm{m}^2}$, a three meter drift and a focussing quadrupole with a $K1$ value of $1.9\bar{3}\,\frac{1}{\mathrm{m}^2}$. The so created beta-function is thus increased by the first magnet, while the second reduces its amplitude down to a minimum close the the end of the second chicane as shown in figure 8.

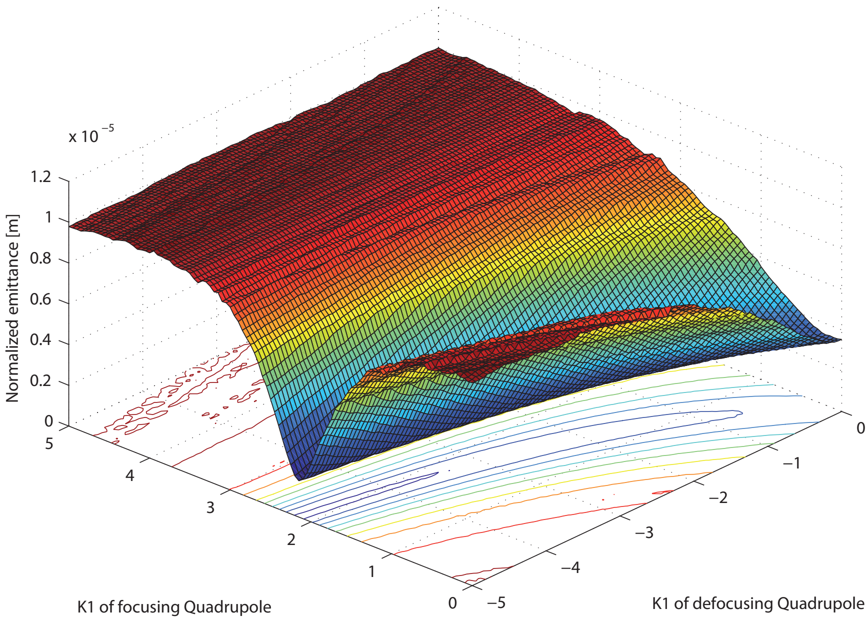

Figure 7: The normalized horizontal emittance ε_x in a range of 0 to 5 $\frac{1}{\mathrm{m}^2}$for the $K1$ values of the two quadrupoles

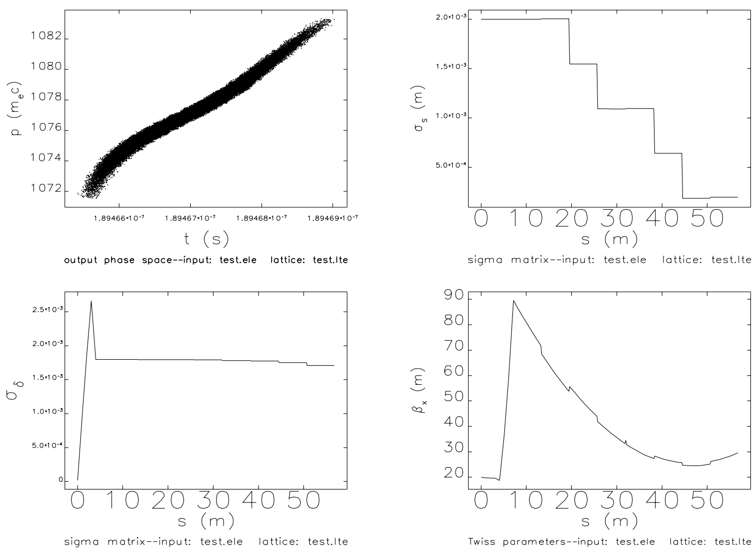

Figure 8: The energy chirp, mean bunch length, energy spread and characteristic beta-function of the final bunch compressor

ELEGANT tracks 100000 electrons with an energy of 500 MeV through this setup and calculates a final horizontal emittance of $1.74\,\mu$m (the initial value is $1\,\mu$m) while the mean bunch length is decreased from the initial value of $2\,$mm to $196\,\mu$m, hence about a factor of $\frac{1}{10}$.

Summary

The concept of a bunch compressor using the "elegant" package has successfully been simulated. Within these simulations often try and error approaches have been made, but also numerical calculations helped a lot to gain efficiency. A parameter study of the necessary properties of a complete bunch compressor has been performed, the "reasonable" results have been presented and can be used for future optimization of the bunch compressor in th XFEL.

References

[1] M. Borland. A self-describing file protocol for simulation integration and shared postprocessors. *Proc. 1995 PAC*, 1995.

[2] M. Borland. *elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation*. Advanced Photon Source LS-287, September 2000.

[3] H. Edwards E. Harms M. Huening K. Jentsch T. Khabiboulline A Matheisen W.-D. Moeller A. Schmidt W. Singer E. Vogel, M. Dohlus. Considerations on the third harmonic rf of the european xfel. *Proceedings of SRF2007*, 2007.

[4] P. Emma M. Dohlus, T.Limberg. Bunch compression for linac-based fels. *Beam Dynamic Newsletter*, 38, December 2005.