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The Bunch Compression System at the TESLA Test Facility FEL

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Abstract

A SASE-FEL requires extremely high peak currents which cannot be achieved by electron guns. The bunch length therefore has to be reduced along the accelerating linac, the bunch has to be compressed. In the TTF-FEL this is done with the help of bending magnet chicanes in three stages. We present the lay-out of the scheme as well as first beam dynamics calculations.

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I. Introduction

Space charge effects prevent electron guns from producing bunches considerably shorter than 1mm while maintaining the brightness necessary for a SASE-FEL[1]. A bunch compression system is needed to compress the bunch down to its final length of less than 100 μm , thus providing the necessary high peak intensities at the undulator.

Figure 1 shows the principle of bunch compression in longitudinal phase space. The uncorrelated energy spread of the beam leaving the gun is around 25 keV, its length 2 mm. The SASE process requires less than 1000 keV energy spread at the undulator. The initial longitudinal emittance of around 50 mm·keV is already close to the finally tolerable emittance, so emittance blow up during compression has to be kept small.

In an ideal bunch compressor, a linear correlation between energy and longitudinal position is induced to the bunch for instance by passing a high gradient RF structure at the zero-crossing phase. Then follows a sequence of bending magnets where particles with different energies have different path lengths; mostly because they travel on circles with different radii through the bending magnets with dispersion. The dependence between path length and particle energy is therefore in very good approximation linear and with the right choice of parameters an ideal full compression as shown in Fig. 1 can be achieved. The final bunch length is basically determined by the ratio of initial to induced energy spread.

Compressing the bunch in the TTF-FEL will be done in stages to negotiate two effects limiting the achievable bunch length: On one hand, a long bunch traveling through the whole linac accumulates too much nonlinear although correlated energy spread from the cosine-like accelerating RF field. We looked into compressors with nonlinear dependence between path length and energy spread to compensate for that, but found that introducing these non-linearities gives rise to other non-linear terms like higher order dispersion which then dilute the emittance.

On the other hand, space charge effects scale with $1/\gamma^2$ and prevent bunch compression resulting in very short bunches if the energy is still too low. Also, longitudinal wake field effects get stronger if the bunches are shorter. The following chapter describes the resulting layout of the bunch compression system in the TTF-FEL.

II. Layout of the TTF-FEL Bunch Compression System

As shown in Figure 2, the bunch compression will be done in three stages. The first compressor might be considered part of the electron injector since it is located directly after the first 15 MeV acceleration section and compresses a 2 mm bunch down to a little below 1 mm.

In the next step, after the first RF module, the bunch is further compressed to 0.3 mm at an energy of 144 MeV and the third step reaches the final value of 0.05 mm.

A schematic drawing of bunch compressors two and three is shown in Fig. 3. The stage 1 compressor looks essentially the same but for being half as long. The bending magnets are rectangular magnets which do not have net focusing in the horizontal plane and therefore do not generate higher order dispersion that would increase transverse emittance. They do focus the beam vertically, the focal length being inversely proportional to the tangent of the entrance angle of the beam. For bending (and entrance) angles of more than 30 degrees additional quadrupoles have to be considered between the bending magnets to avoid too densely focused beams in the vertical plane which would cause emittance growth due to space charge effects. For the proposed bunch compression system however, deflection angles of up to 23 degrees are sufficient.

In Figure 4, the maximum horizontal dispersion and the resulting 'longitudinal dispersion' R56 are shown. The path length difference Δl of an off-energy particle is given by

$$\Delta l = -R56 \cdot \Delta E.$$

The choice of the necessary tuning range for the longitudinal dispersion determines the range in deflection angle for the bending magnets and thus the width of bending magnet gaps and vacuum chamber. The aperture in the middle bends and the instrumentation section is given by the sum of the orbit displacement in the magnet due to orbit curvature, the difference in beam orbits due to different dispersion values plus the dispersion dominated beam size of 20 mm (4 sigma of a beam with 1% energy spread at 0.5 m dispersion).

We have designed a bending magnet which allows deflection angles between 17 and 23 degrees at both the 140 and the 500 MeV compressor, resulting in a comfortable R56 tuning range of 0.12–0.24 m. It is a C-type magnet with a gap width of 360 mm and a good field region of 210 mm (relative field strength deviation less than $2 \cdot 10^{-3}$).

The optics through the compressor magnets is adjusted with the quadrupole triplets on both sides of the bending magnets. Their strengths are chosen to match the incoming optics parameters to the outgoing to make the compressor section transparent and keep it symmetric around the mid-plane. Fig. 5 shows horizontal and vertical beam sizes (normalized with respect to transverse emittance) and the dispersion function in the TTF-FEL from the source up to the third compressor stage.

III. Simulation Calculations

Bunch compression has been simulated in two different ways. A one-dimensional model including the nonlinear RF and longitudinal wake fields was used to do a first optimization of RF phases and the longitudinal dispersion R56 of the compressor sections. To study space charge effects and subsequently re-optimize the compression scheme, three-dimensional calculations using the code PARMELA were done. The dipoles were set to deflection angles of 18 degrees in compressor 2 and 20 degrees in compressor 3.

Calculations with a One-Dimensional Model:

In the one-dimensional model, it was assumed that the bunch leaves the injector with 0.8 mm bunch length and a random energy spread of 25 keV. Figure 6 shows the bunch in longitudinal phase space before and after compressor 2 at a beam energy of 145 MeV. Note that the bunch is not fully compressed to avoid problems with space charge effects. The bunch then passes through three RF modules, where it experiences the non-linear shape of the RF pulse as well as longitudinal wake fields. The phase of the bunch has to be optimized to achieve the best cancellation of both effects. Figure 7 shows the result of such an optimization: the bunch entering the final compression stage 3 has a nearly linear correlation between energy and longitudinal position over a wide range and can therefore be compressed down to 54 μm .

In the last part of the linac, where the bunch is accelerated to 1 GeV, its longitudinal distribution does not change anymore. Its energy spread, however, will be increased by RF non-linearities and wake fields. Here again the RF phase has to be adjusted to minimize growth in energy spread. As to be seen in figure 6.8, the bunch gains another 130 keV of energy spread on its way to the undulator.

3-Dimensional Calculations with PARMELA:

To evaluate space charge effects, the computer code PARMELA was used with a point-to-point algorithm to calculate space charge effects, since inside the compression sections the beam is not cylindrically symmetric. For these calculations all three bunch compressors were modeled with their optical elements. Figure 9 shows a PARMELA run without space charge. The RMS-value for bunch length is 0.075 mm but is dominated by the tails of the distribution. More than 70% of the charge is within a window of ± 0.05 mm, which supplies the necessary peak current.

If space charge effects are included (Figure 10), the distribution broadens, the RMS-value is nearly unchanged, but the charge contained within ± 0.05 mm drops to about 60%, which is still within specifications.

The energy spread in both calculations is of the order of 500 keV, but wake fields are not yet included in these calculations, so it is expected to be closer to 1 MeV like in the one-dimensional calculations.

IV. Conclusion and Outlook

We propose a bunch compression in three stages to avoid longitudinal emittance blow up due to space charge forces on one hand and nonlinear RF energy correlation on the other. We have found optical solutions, transverse and longitudinal, to fit the compressor sections into the TTF linac. A bending magnet has been designed which meets the space requirements and provides a comfortable range of deflection angles. The first simulation calculations show that although space charge forces already increase longitudinal emittance, we still meet the SASE specifications.

We still have to introduce wake fields into the tracking, although the one-dimensional model does not predict a dramatic increase in energy spread. Perhaps more important are the effects of possible coherent synchrotron radiation on the energy distribution in the electron bunch, which are just being analyzed[5].

V. References

- [2] A VUV Free Electron Laser at the TESLA Test Facility at DESY, Conceptual Design Report, DESY Print TESLA-FEL 95-03 (1995)
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Fig. 1: Principle scheme of required bunch compression

Fig. 2: Layout of the TTF-FEL Bunch Compression System

Fig. 3 : Lay Out of the Bunch Compressors at Stage 2 and 3

Fig. 4 Maximum Horizontal Dispersion and Longitudinal Dispersion R56 vs. Bending Magnet Deflection Angle in Bunch Compressors

Fig. 5: Optical Functions in the TTF-Linac with Bunch compression 'on' from Source to 3rd Bunch Compressor

After RF and Wake fields up to Compressor.

After Compressor.

Fig. 6 : Longitudinal Phase Space before and after Bunch Compressors #2

Fig. 7 : Longitudinal Phase Space before and after Bunch Compressors #3

Fig. 8: Longitudinal Phase Space before Undulator

Fig. 9 Longitudinal Phase Space and Longitudinal Bunch Distribution after Bunch Compressor #3 without Space Charge Effects

Fig. 10 Longitudinal Phase Space and Longitudinal Bunch Distribution after Bunch Compressors #3 with Space Charge Effects (bunch charge ≈ 1 nC)