UNCORRELATED EMITTANCE GROWTH IN THE TTF-FEL BUNCH COMPRESSION SECTIONS DUE TO COHERENT SYNCHROTRON RADIATION AND SPACE CHARGE EFFECTS

M. Dohlus, A. Kabel, T. Limberg
Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, D-22607 Hamburg

Abstract

In the bunch compressing sections of the Tesla Test Facility Free Electron Laser[1] (TTF FEL), short bunches travel on trajectories with small bending radii. Thus, coherent synchrotron radiation (CSR) will play a significant role in beam dynamics. The energy loss of the bunch will vary longitudinally as well as transversally across the bunch and will induce an emittance growth. The occuring transversal forces, especially the so-called "Talman force" ([3]) and its effects on emittance have been treated before analytically for some specialized arrangements ([2, 4]).

The emittance growth will affect the projective as well as the slice emittance (i.e., the emittance of sub-ensembles of particles with equal longitudinal position). The computer simulation code **TraFiC^4** calculates the fields in the bunch from first principles, thus taking into account radiative as well as space charge effects, which are inseparable on curved trajectories. In addition to dealing with longitudinal dynamics [5], this code has now been extended to handle the transversal dynamics of the bunch. We use it to study the behavior of the fields across the beam and the resulting slice and projective emittance growth. We study its dependence on bunch parameters such as charge and shape and investigate possible cures by shielding.

1 INTRODUCTION

For the operation of an Self Amplified Spontaneous Emission Free Electron Laser (SASE FEL), beam quality is crucial. As the SASE FEL process will involve particles within the longitudinal extension of the so-called *slippage length*, which is about 10μm in the TTF FEL case, the *slice emittance* (the transversal emittance of particles within a longitudinal slice of a particular length of about the slippage length) as opposed to the *projective emittance* (the summed-up emittance of the whole bunch) is the quantity of interest to judge beam quality.

In the TESLA/FEL project, a bunch compression system consisting of two magnetic chicanes operating at different energies will be used to reach the high peak current necessary to operate an FEL. In this paper, we will consider Bunch Compressor II, which will operate at an energy of ≈130 MeV and consists of four bending magnets with signature $[+l - L - l+]$, each having a bending angle of $\frac{\pi}{10}$ and a projected length of 0.5m. They are separated by drift spaces of length $l = 0.5$m and $L = 1.3$m. Bunch Compressor II has been designed to compress a bunch of charge 10^{-9}As and length ≈ 1mm down to 250μm. We also consider the case of half charge and half compressed length, giving the same peak current.

In the bent trajectory sections of a magnetic chicane, the radiation emitted by the tail of a bunch of length σ may overtake the head if the path length exceeds the *overtaking length* $L_o = (\sigma R^2)^{\frac{1}{3}}$. Collective effects on the bunch are expected to take place in this case. For the TESLA/TTF BCII, it is typically $L_o \approx 0.15$m, which is of the order of magnitude of the magnet length. Thus, one cannot expect the longitudinal fields inside the bends to reach a steady state over the full length of the bend, and beam dynamics in the chicane will be influenced by transient effects.

The self-field of the bunch will cause emittance dilution by two effects: (1) Transversal forces will cause angular kicks on the particles, causing emittance growth by their nonlinear dependence on x. (2) Longitudinal fields will cause energy changes, which lead to emittance growth in the dispersive sections.

2 THE SIMULATION CODE TraFiC^4

TraFiC^4 stands for "**Tra**ck and **Fi**eld of **C**ontinuous **C**harges in **C**artesian **C**oordinates". It calculates the effects of space charge forces and coherent synchrotron radiation on bunches of moving charges on curved trajectories. It calculates from first principles the fields acting on the particles as they travel along on the beamline. Retardation effects are handled correctly by the code.

To determine the retarded fields, the history of the beam has to be stored, and for reasons of manageability, Cartesian coordinates are used to do that.

Modelling bunches by clouds of point particles doesn't work for the class of problems **TraFiC^4** is intended for. Instead, small overlapping one- or two-dimensional continuous Gaussian sub-bunches are used to model the bunch for the purpose of field calculation. The bunch causing the fields will be called the "generating bunch" in the sequel.

To calculate the effects of the fields, however, point particles may be used. They are tracked under the influence of the fields generated by the generating bunch. This bunch of point particles will be called the "sampling bunch". It is used to calculate such things as transversal emittance growth and distortion of optical parameters. The ability to handle transversal effects is a major improvement over the code's predecessor, **WAKE**, which calculated the projective centroid emittance [5].

For applying the resulting kicks to the sampling bunch, the beamline is divided into slices. The position $\vec{x}$, the direction of motion $\vec{e}$ and the relativistic factor γ are used to describe the particle state. At each slice, the forces resulting from the retarded fields are calculated and the particles are advanced according to the prescription

$$\vec{x}' = \vec{e}, \vec{e}' = \frac{\vec{F}_\perp}{m\beta^2\gamma}, \gamma' = \frac{F_{||}}{m}, \tag{1}$$

where $\vec{F} = e(\vec{E} + \beta\vec{e} \times \vec{B})$. The resulting change of β is taken into account in the tracking procedure, so the code could also be applied to the non-ultrarelativistic regime. The slices' lengths have to be chosen to be significantly smaller than the overtaking length in the respective beamline section.

3 CALCULATIONS

For our emittance growth calculations, we start out with a generating bunch populated with gaussian sub-bunches smeared in the s direction. To avoid singularities, we also smear them in the direction perpendicular to the plane of motion, though this has shown to have only small influence on the outcome of the calculations. To account for bunch widening and narrowing, we also use multiple layers of sub-bunches transversally. This, too, has proven to have little effect for our class of problems. In general, sub-bunches of the generating bunch are distributed equidistantly parallel the base axes of the correlation matrix given by the Twiss parameters.

The sampling bunch consists of point particles spread at random according to the initial Twiss parameters, but having equal l and $\delta = \frac{\delta p}{p}$ parameters.

Their planar distribution gets distorted as travelling through the chicane, but their final longitudinal distribution is $< 10\mu$m rms, and thus their statistical normalized emittance remains a useful quantity.

4 RESULTS

This setup was used for different set of bunch parameters. We used the case of 1nC bunch charge and 250μm final length and 0.5nC charge and 125μm final length.

Both cases were calculated both with and without shielding. Shielding is considered in **TraFiC^4** by enclosing the plane of motion between two infinitely extended conducting plates parallel to the plane of motion. The fields of the images charges (and their image charges, up to a certain limit) of the physical charges are added up to give the resulting fields.

In Bunch Compressor II at TTF, there is the possibility to run at either 8mm or 20mm vacuum chamber height. The latter case was taken to be the shielding-free case in our calculations, which is a good approximation for the bunch lengths used.

Figure 1 shows the resulting transversal energy spreads induced in the central slice of the bunch. The shielding loses much of its efficiency for the case of shorter bunch lengths. For the 250μm case, however, the energy spread is reduced by a factor of > 2.

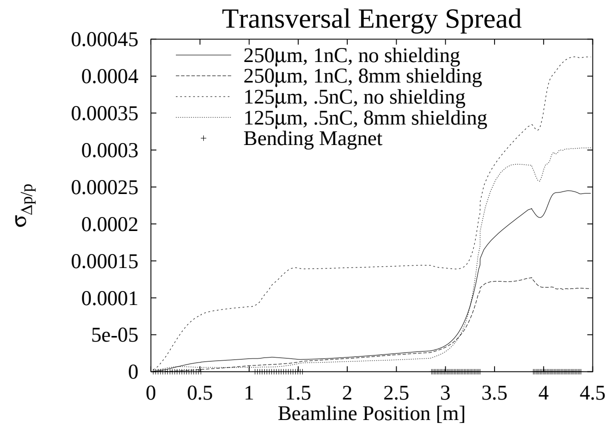

Figure 1: Induced transversal rms energy spreads for different parameter sets

As the particles lose or gain energy in the dispersive section, their emittance changes due to dispersion mismatch. Figure 2 shows the emittance growth along the beamline.

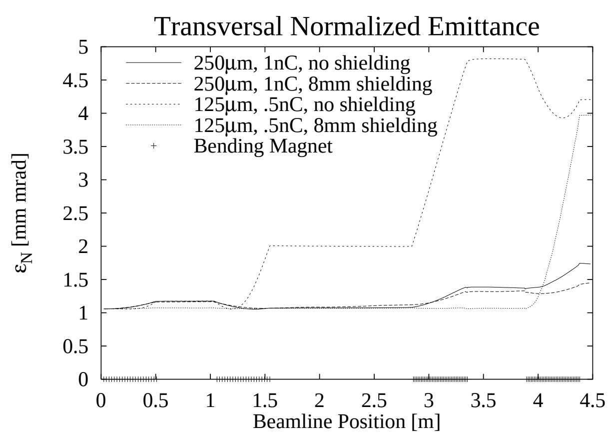

Figure 2: Normalized transversal statistical slice emittance for different parameter sets

Note that the dispersion is not subtracted from the coordinates, so the emittance growth in the dispersive section is spurious. In the case of purely linear transformations, it is spurious and vanishes as soon as the dispersive region is left. In our case, however, an s-dependent transversal energy spread is induced in the dispersive regions, and the emittance growths and reductions fail to compensate. The main contribution stems from the 3rd bending magnet, where the energy spread grows significantly.

Starting from a normalized emittance of 1.0mm $\cdot$ mrad, the predicted growth rates are

Emittance Growth	250μm	125μm
shielded 8mm	37%	275%
unshielded	64%	446%

which seems to favor clearly the 250μm case. However, the emittance growths can be influenced and possibly improved significantly by the choice of a set of appropriate initial Twiss parameters. Especially, the shielded 125μm case is not too far away in terms of induced energy spread from the unshielded 250μm case, but gives a much larger emittance growth. The possibility of finding an optimized optics setup for this situation is currently being investigated.

TraFiC^4 can output the final transversal phase space which then can be used as an input for other codes simulating the downstream behavior of the bunch. Preliminary calculations with the FEL simulation code **GENESIS** showed that the beam quality in the 250μm case would be sufficient for SASE FEL operation, even if unshielded [1].

Simulations were also carried out for slices outside of the center of the bunch. Figures 3 and 4 show transversal energy spreads and slice emittances for two slices initially ± 1 rms bunch length away from the center (250μm/1nC case). As could be expected, the tail-head interaction leads to a significantly smaller energy spread in the back slice while increasing it for the front slice. Emittance growth for both cases, however, is smaller than for the center slice. The mechanisms leading to this behavior have to be investigated.

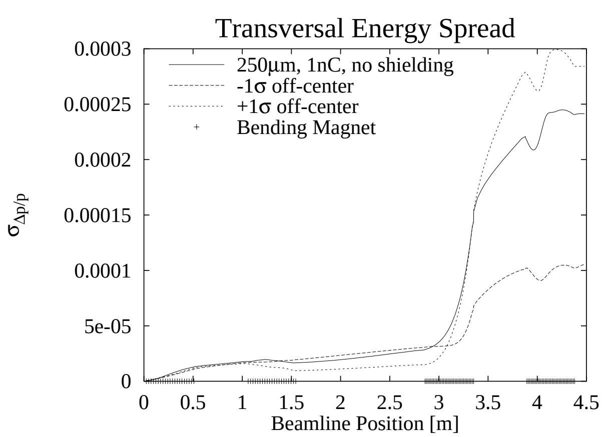

Figure 3: Induced transversal rms energy spreads for different longitudinal positions

5 CONCLUSION AND FUTURE PROSPECTS

We have used the numerical simulation code **TraFiC^4** to calculate collective effects in bunch compressors for different set of parameters.

The results show that the beam quality to be reached with the design parameters for Bunch Compressor II at the TESLA Test Facility is sufficient for SASE FEL operation.

For the simulations demonstrated here, some simplifying assumptions were made. In reality, the charge distributions both longitudinally and transversally are not Gaussian. **TraFiC^4** accepts arbitrary phase space distributions as input, so future calculations will use results from numerical simulations of the upstream beamline section. Integrating **TraFiC^4** into an overall computer simulation of the TTF beamline is a part of the ***TRACK** effort, a collaboration of working groups at Technische Universität Darmstadt and DESY.

The factor currently limiting the usefulness of **TraFiC^4** is, of course, CPU time demand, most of which is related to the field calculation. As the optimization of Twiss parameters for low emittance growth will require a multitude of **TraFiC^4** runs, further efforts therefore will concentrate on efficiency improvement.

[1] S. Reiche, private communication

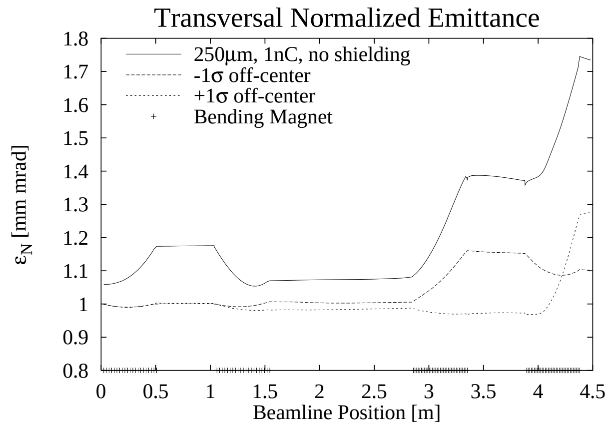

Figure 4: Normalized transversal statistical slice emittance for different longitudinal positions

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