# OPTIMIZED BUNCH COMPRESSION SYSTEM FOR THE EUROPEAN XFEL

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*Abstract*

The European XFEL [1] bunch compressor system has been optimized for greater flexibility in parameter space. Operation beyond the XFEL design parameters is discussed in two directions: achieving the uppermost number of photons in a single pulse on one hand and reaching the necessary peak current for lasing with a pulse as short as possible on the other.

Results of simulation calculations including 3D-CSR effects, space charge forces and the impact of wake fields demonstrate the potential of the XFEL for further improvement or, respectively, its safety margin for operation at design values.

## INTRODUCTION

The new lay-out of the bunch compression system is sketched in Fig.1: The bunch is compressed in two magnetic chicanes by factors of 20 and 5, respectively. Details about the chicanes proper can be found in [2].

The energy chirp injected by running off-crest in the RF upstream of the first chicane is about 10 MeV, compensating the energy contribution by the longitudinal wake fields of all linac RF structures.

A 3rd harmonic RF system is used to optimize the final longitudinal charge distribution. Slice emittance and other parameters which vary along the longitudinal position in the bunch can be measured with a vertically deflecting RF system after the first chicane. After the second chicane, the longitudinal bunch profile is measured with the optical replica method [3]. Behind both chicanes, wire scanners control projected emittance and optics.

## TRANSVERSE SPACE CHARGE EFFECTS

In low-emittance, high-current electron beams, space charge forces can cause growth of slice emittance and mismatch of slice Twiss parameters with respect to the design (zero current) optics. Slice emittance growth directly degrades the performance of the SASE-FEL. The generated mismatch significantly complicates accelerator operations because of projected emittance increase and the dependence of transverse dynamics on beam current.

Extensive numerical studies were done using the TrackFMN code [4]. This program has the possibility to model transverse space charge forces via a particle-in-cell (PIC) approach. The numerical method employed is symplectic integration of Hamiltonian equations of motion (split-operator method).

The results present the (normalized) slice emittance and the mismatch envelopes:

$$\lambda_{x,y} = M_{x,y} + \sqrt{M_{x,y}^2 - 1},$$

where $M_{x,y}$ is the usual mismatch parameter. The contribution of the space charge non-linearities was

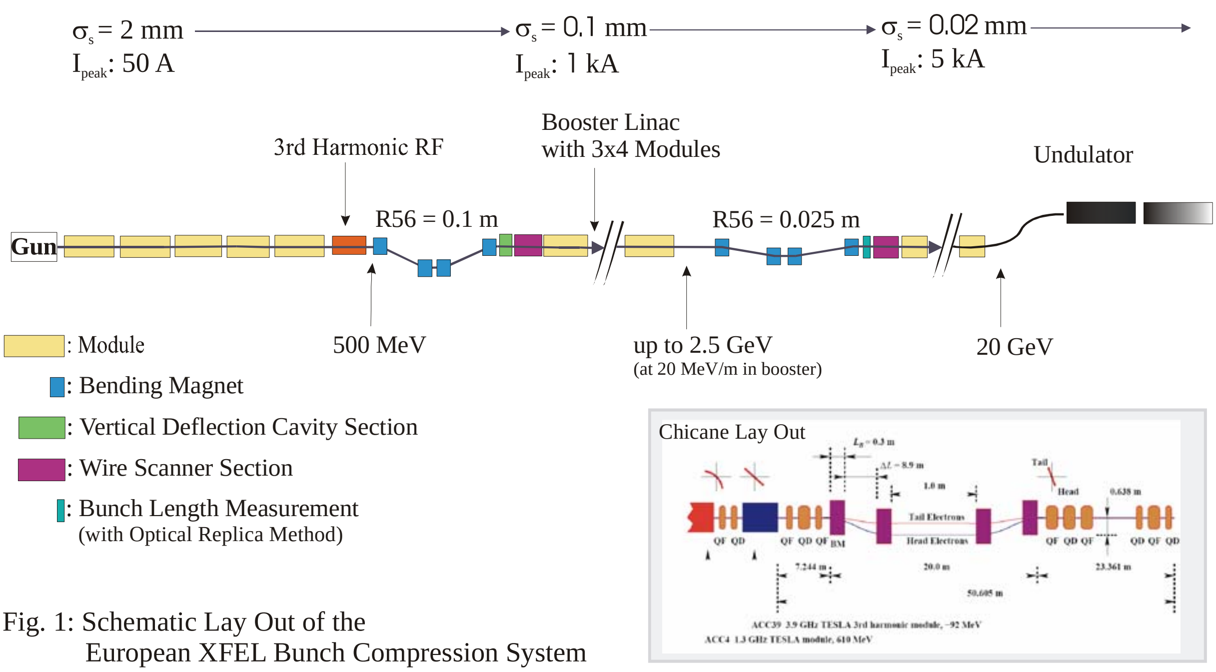


Fig. 1: Schematic Lay Out of the European XFEL Bunch Compression System

estimated using momentum invariants of fully coupled 2D linear motion [5].

At full compression to 5 kA at 500 MeV with normalized emittance of 1 mm-mrad, the slice emittance growth in the downstream diagnostic section and following accelerating modules was as large as 40%, the maximum optical mismatch parameter was six.

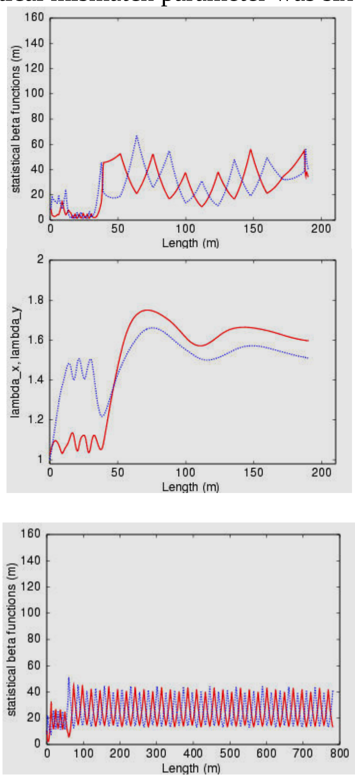


Figure 2: Space charge effects of 1 kA peak curent on optics downstream of compressor chicanes. Upper two pictures: optics and mismatch parameter downstream of 1st chicane (1 kA peak current, 500 MeV beam energy). Lower Picture: No effect downstream of 2nd chicane (5 kA peak current at 2.5 GeV). The red curves show parameters in the horizontal plane, the blue one in the vertical.

When the second compression stage was shifted to 2.5 GeV beam energy and the optics of the beam line sections downstream of the compressor chicanes was optimized, the slice emittance growth (again, at design parameters) due to transverse space charge is negligible (not more than 1%) and the optical mismatch is limited to $\lambda_{x,y}=1.5$.

## COHERENT SYNCHROTRON RADIATION EFFECTS

### *Parameter Scans*

The impact of Coherent Synchrotron Radiation (CSR) fields on beam emittance in the compressor chicanes was calculated for different parameter sets with the code CSRtrack [6]. First, the energy of the second compressor chicane was raised in steps to explore possible limitations due to the increasing R56. For the energy of choice the 2nd chicane bending magnet strength was then varied. In the first scan, the final peak current is increased while the bunch charge is kept constant. In the other scan, the charge is reduced but the peak current is kept at 5 kA.

### *Energy Scan*

If the 2nd compressor stage is shifted towards higher beam energy to reach a working point where space charge forces are negligible even for peak currents above design values, its longitudinal dispersion R56 has to scale with energy. Otherwise, the compensation between the RF induced energy chirp for compression and the correlated energy offset impressed on the bunch by the RF structure wake fields (see Fig. 6) is lost. The result of the CSRtrack calculations for the projected horizontal emittance is shown in Fig. 3, the slice emittance growth is of the order of a percent for all energies.

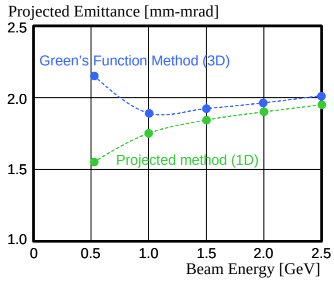


Figure 3: Projected emittance vs. beam energy (Strength of 2nd chicane bending magnets scales with energy)

The increase of projected emittance at the 500 MeV point is due to the longitudinal position dependent optics mismatch caused by space charge forces which are neglected by the 1D method.

### *Peak Current*

Figure 4 shows the horizontal emittance, if the peak current is raised by increasing the bending magnet strength in the 2nd compressor chicane. The resulting energy spread in a longitudinal slice located in the bunch core varies between 0.4 and 2 MeV.

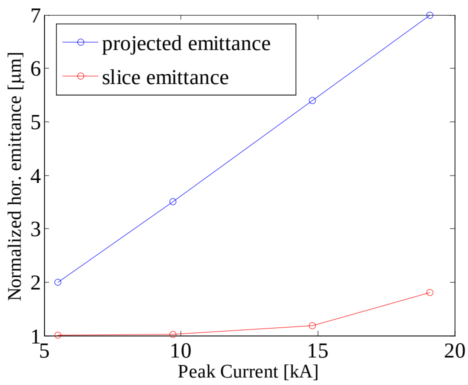


Figure 4: Normalized horizontal emittance vs. different peak currents due to different settings of the 2nd bunch compression chicane

### *Lower Bunch Charge*

Lowering the bunch charge and increase the R56 of the second chicane to keep the 5 kA peak current at the bunch compressor exit has two (potential) rewards: The FEL pulse gets shorter and at even smaller transverse emittance and shorter wave lengths might be achievable.

For our simulation, we take a 1 nC beam distribution at the injector exit and scale the charge. Figure 5 shows results for the normalized horizontal emittance at the end of the compression system. Down to 0.25 nC the slice emittance growth stays within 5%, sufficiently low to profit from smaller emittance at lower bunch charge. The pulse length is reduced to 5 μm.

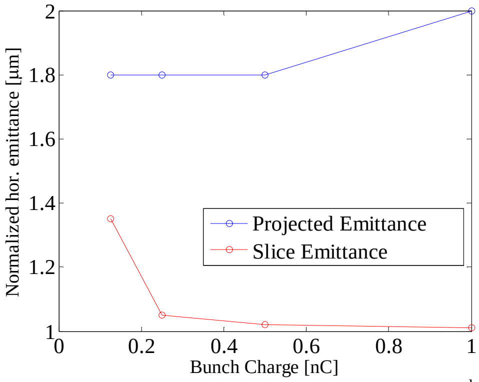


Figure 5: Normalized horizontal emittance after 2nd chicane vs. bunch charge for fixed peak current of 5 kA.

## WAKE FIELDS

Figure 6 shows the longitudinal phase space at the exit of the bunch compression system and at the end of the linac. The calculation was done with the 'elegant' [7] code including the wake fields of all RF structures. Note the compensation of the remaining chirp and the linac RF structure wake fields.

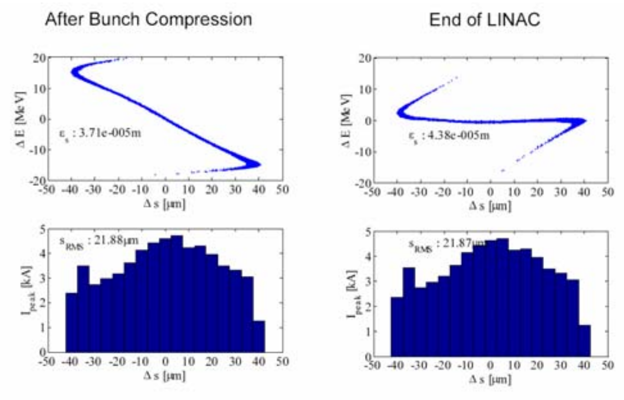


Figure 6: Longitudinal phase space and profile at exit of bunch compression system and end of linac from an 'elegant' calculation including all RF structure wake fields

## CSR INSTABILITY

The gain curves for the CSR driven instability of the longitudinal charge distribution were evaluated with CSRtrack calculations. The drawn curves are results from the 1D model, with a maximum gain of about 8. The 3D Green's function method with its correct model for the transverse particle mixing reduces the gain to about 5.

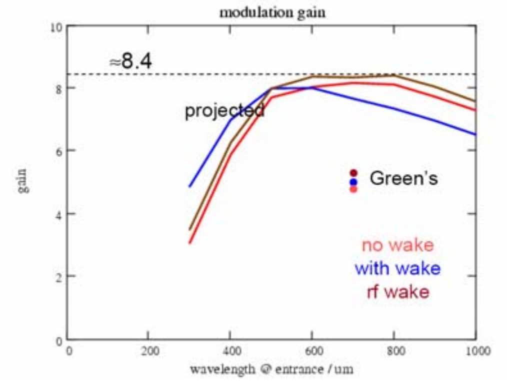


Figure 7: CSR instability gain curve for complete bunch compression system

## SUMMARY AND CONCLUSION

With the 2nd BC stage at higher energy (2-2.5 GeV), space charge effects in the downstream beam line at design parameters (5 kA) are negligible. The charge sensitivity of the section downstream of the 1st chicane is sufficiently reduced – the beta-mismatch parameter is 1.5 if no re-matching is done. For smaller emittance (at least down to 0.5 mm-mrad) and high peak current (up to 15 kA) emittance growth due to space charge effects will be still lower than 10%.

CSR effects present no problem at design parameters and are nearly independent of the beam energy at the 2nd BC stage. At 15 kA peak current (1 nC charge) the slice emittance increase in the bunch center is less than 25%. For bunch lengths down to 5 μm RMS (at 0.25 nC, peak current of 5 kA), this value is below 5%.

Wake fields of booster linac, 3rd harmonic RF and transverse deflecting cavity slightly change settings for phase and amplitude of the RF, but do not disturb the bunch compression.

CSR instability gain curves were calculated for the complete bunch compression system. The overall maximum gain calculated with a 3-dimensional CSR treatment is about five.

## REFERENCES

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