

IMPACT OF OPTICS ON CSR-RELATED EMITTANCE GROWTH IN BUNCH COMPRESSOR CHICANES

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Abstract

The dependence of emittance growth due to Coherent Synchrotron Radiation (CSR) in bunch compressor chicanes on optics has been noticed and empirically studied in the past. We revisit the subject, suggesting a model to explain slice emittance growth dependence on chicane optics.

A simplified model to calculate projected emittance growth when it is mainly caused by transverse slice centroid offsets is presented. It is then used to find optimal compensation of centroid kicks in the single chicanes of a two-stage compression system by adjusting the phase advance of the transport in between and the ratio of the compression factors.

INTRODUCTION

In a previous paper [1], we published a 2D scan of the incoming Twiss parameters into the compressor chicane of the TTF, calculating the resulting horizontal slice emittance. According to this scan, a beam waist close to the 4th bending magnet was necessary to keep slice emittance growth small.

Since this is a severe restriction for the optics design around bunch compressors, we repeated the calculation with the code CSRtrack, using a better modelling of the transverse phase space as previously possible for 3D calculations of CSR fields. In addition, we did a scan where the waist position is kept constant, but its β -function is varied.

It has been pointed out [2,3] that in the case of a bunch compression system using two magnet chicanes, the phase advance between the chicanes can be optimized to reduce projected emittance growth.

We developed a fast method to estimate and optimize projected emittance. The method uses the projected or 1D model for the particle dynamics in bunch compressors in combination with perturbation theory. The longitudinal charge profile for any position in the bunch compressor is calculated without self forces and used to compute the ‘renormalized’ longitudinal field [4,5]. This perturbation of the equation of motion is integrated in a second step.

A further simplification estimates the charge profile by a linear compression of the initial shape. It is used here to determine the centroid positions of individual slices at the exit of the bunch compressor. In cases like the European XFEL, where space charge effects are negligible, the growth of projected emittance is essentially caused by the individual offset of slices.

SLICE EMITTANCE

For the calculations in this chapter, we use the ‘Zeuthen chicane’ a benchmark case available on the web where a

bunch of 1 nC charge compressed to reach a peak current of 6 kA at a beam energy of 500 MeV [6].

Fig. 1 shows a few of the different optics used for the calculations, the dotted lines mark the bending magnets. The earlier result was confirmed. An optics with a divergent beam like the one shown with initial Twiss parameters $\alpha = -0.8$ and $\beta = 15$ m leads to slice emittance growth by a factor of 10, while a convergent beam with a narrow waist increases it by just a few per cent. Fig. 2 shows the results for different β -functions at the waist; the waist position is kept at the 4th bending magnet.

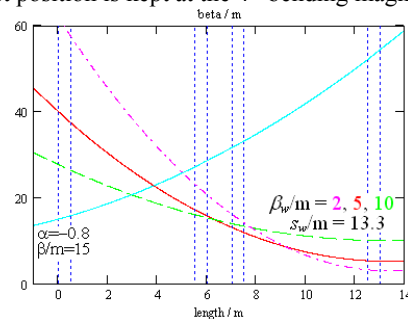


Figure 1: β -functions through the chicane. The dotted lines mark the bending magnets. β_w and s_w are β -function and position at the waist.

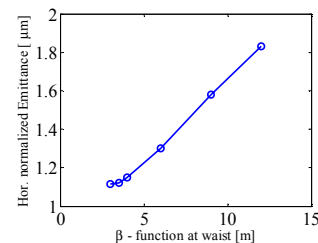


Figure 2: Horizontal slice emittance at the chicane exit for different β -functions at the waist

Transverse slice emittance growth can be caused by two effects: non-linearly varying CSR forces for different transverse positions and directions of particles in the same slice on one hand and different longitudinal positions of particles that are initially (and approximately finally) in the same slice on the other.

The longitudinal spread is shown in Fig. 3. We plot the length of the projection on the bunch center trajectory for an ensemble of particles which start in an infinitesimally short slice at the chicane entry. In linear optics, it is given by:

$$\sigma_{proj} = \sqrt{\varepsilon \beta_w} \sqrt{\left(\frac{r_{52}^2 - s_w r_{51}}{\beta_w} \right)^2 + r_{51}^2}$$

β_w is the β -function at the beam waist, r_{51} and r_{52} are the elements of the linear transport matrix from the entry of

the chicane to the point of interest, coupling initial horizontal offsets and angles to longitudinal deviations at this position.

For a 4-dipole chicane, the term $(r_{32}^2 - s_w r_{51})/\beta_w$ is almost zero at the waist if it is placed close to the entry of the 4th magnet. Further reduction of projected slice length and subsequent slice emittance growth is possible by minimizing β_w . The slice emittance growth at the chicane exit scales indeed roughly quadratically with σ_{proj} in the vicinity of the end of the 3rd and beginning of the 4th magnet, where the CSR forces have maximum strength.

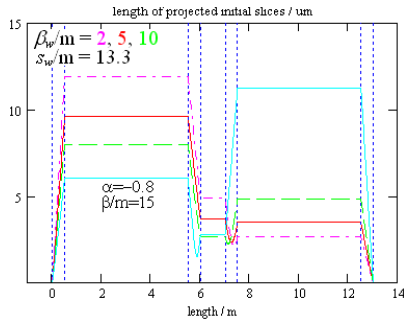


Figure 3: Length of slice projection through the magnet chicane. The dotted lines mark the bending magnets.

PROJECTED EMITTANCE

Even if the slice emittance is preserved, the projected emittance can change significantly due to variation of the optics along the bunch or slice centroid shifts caused for example by longitudinally varying fields. Fig. 4 shows the horizontal phase space distribution of a bunch at the exit of a test chicane. The parameters for that calculation are listed in Table 1.

Table 1: Parameters for Test Chicane calculations

Magnet Length	0.3 m
Drift Length	8.9 m
Beam Energy	0.5 – 2.5 GeV
Compression	100μm → 20μm
$\alpha, \beta_{initial}$	1.8, 48 m
Normalized beam emittance	1 mm-mrad

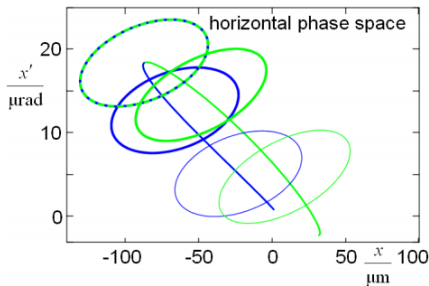


Figure 4: 1- σ ellipses and centroid at the exit of a bunch compressor (2.5 GeV).

For this example the size and shape is in agreement with linear optics, but the shifted centroids increase the projected emittance. The slice emittance is increased by only about 1%, but the projected emittance calculated with CSRtrack (using its Green's functions method and projected method) is nearly doubled [5,7]. Both calculation methods are approximately in agreement for energies above 1 GeV, but for lower energies the approximations of the 1D method (neglect space charge effects, transverse forces and transverse dependence of forces) are insufficient (see Fig. 5).

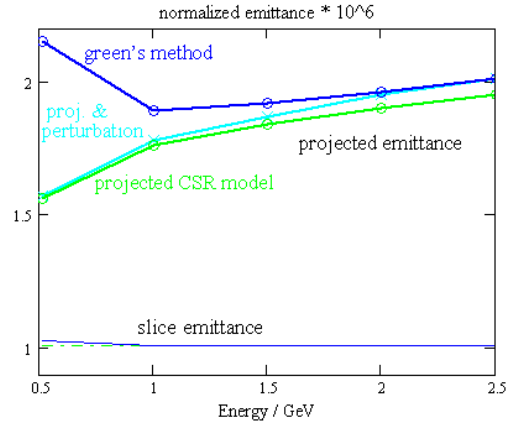


Figure 5: Emittance growth in test chicane.

Simplified Calculation of Projected Emittance

Supposed the shift of the slice centroids is the main reason for an increased projected emittance, this effect can be estimated by the computation of the centroid curve x_c, x'_c . The first and second momenta of x and x' are

$$\bar{x} = \int x \psi(x - x_c(s), x' - x'_c(s)) \lambda(s) ds dx dx'$$

$$\bar{x}' = \int x' \psi(x - x_c(s), x' - x'_c(s)) \lambda(s) ds dx dx'$$

$$\overline{xx} = \int (x - \bar{x})(x - \bar{x}) \psi(\dots) \lambda(s) ds dx dx'$$

$$\overline{xx'} = \int (x - \bar{x})(x' - \bar{x}') \psi(\dots) \lambda(s) ds dx dx'$$

$$\overline{x'x'} = \int (x' - \bar{x}')(x' - \bar{x}') \psi(\dots) \lambda(s) ds dx dx'$$

with $\psi(x, x')$ calculated by linear optics and $\lambda(s)$ the longitudinal profile. These momenta can be expressed as superposition

$$\overline{xx} = \overline{x_c x_c} + \epsilon \beta, \quad \overline{xx'} = \overline{x_c x'_c} - \epsilon \alpha, \quad \overline{x'x'} = \overline{x'_c x'_c} + \epsilon \gamma$$

of second momenta of the centroids, e.g.,:

$$\overline{x_c x_c} = \int (x_c(s) - \bar{x}_c)^2 \lambda(s) ds$$

and second momenta of the original distribution that are determined by the Twiss parameters $\alpha, \beta, \gamma, \epsilon$ of the unperturbed optic. The projected emittance is

$$\epsilon_p = \sqrt{\overline{xx} \cdot \overline{x'x'} - \overline{xx'}^2}$$

To solve the equation of motion

$$x_c'' + K^2 x_c = \frac{K \Delta E}{E}$$

for the centroids, the longitudinal electrical field E_{CSR} has to be calculated for all positions S along the trajectory. ($K(S)$ is the curvature radius of the trajectory, E the beam energy and $\Delta E = q \int E_{CSR} dS$.) This can be done with low numerical effort for the unperturbed and linearly compressed bunch profile $\lambda(s, S) = C(S)\lambda(s \cdot C(S))$ with $C(S)$ the compression ratio. The comparison of this estimation with CSRtrack calculations can be seen in Fig. 5.

Fig. 6 shows the projected emittance for different initial parameters α and β . With an initial β -function of 100 m and stronger focussing ($\alpha = 3.5$), the projected emittance is reduced to a value below $1.6 \mu\text{m}$. The beam waist is positioned a few meters after the compressor end.

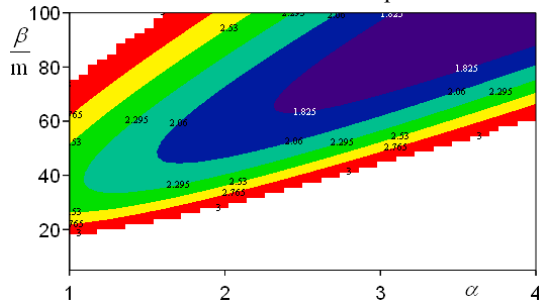


Figure 6: Projected Emittance (normalized, $\times 10^6$) for different Twiss parameters at the entrance, $E = 2.5 \text{ GeV}$.

Two Stage Bunch Compression System

In the following, we will demonstrate that a compensation of CSR effects in a two stage bunch compression can be utilized to reduce the projected emittance without increasing the β function.

A two stage bunch compression system is proposed for the European XFEL to decrease the initial rms length of about 2 mm down to $20 \mu\text{m}$ [8]. Both chicanes have the same geometry as the test chicane. BC1 is operated at 500 MeV and the second compression takes place at energies between 2 GeV and 2.5 GeV. The absolute energy chirp of 10 MeV/rms-length is the same in both compressors as well as the optics at the entrance ($\beta = 48\text{m}$, $\alpha = 1.8$) that is chosen to maintain the slice emittance.

There are only two degrees of freedom in the characterization of the system: the compression per stage (with $C_1 C_2 = 100$) and the phase advance μ of the transport between the chicanes. The simplified calculation of the projected emittance described above was used to explore this two dimensional parameter space. Fig. 7 shows the centroid curves after BC2 for the optimal setting $C_1 = 20$, $C_2 = 5$ and $\mu = 1.4$. For comparison the centroid positions are calculated with CSR forces in one of the two chicanes as well as the $1-\sigma$ ellipse according to linear optics. It can be seen that the CSR effects of both compressors compensate each other so that the estimated projected emittance is only slightly increased.

This result was verified with CSRtrack calculations (ideal particle distribution at entrance of BC1, transport

exit BC1 to entrance BC2 by transport matrix). It is found that the cancellation of the centroid shifts is less perfect than predicted by the simplified model but significant (normalized slice emittance increased by few %, normalized projected emittance $1.4 \mu\text{m}$) and that the working point is nearly optimal (projected emittance increases for other compression ratios and phase advance).

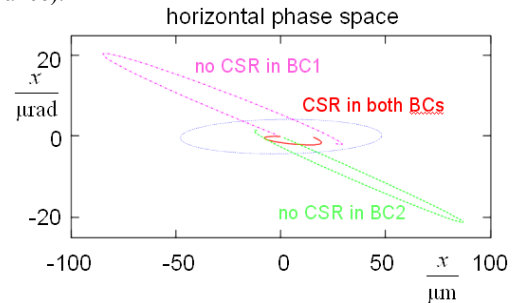


Figure 7: Centroid curves after two stage bunch compression.

SHIELDING, RESISTIVE WALLS

All CSR fields have been calculated for free space conditions. The assumption that shielding effects are negligible has to be reviewed: a bunch (with length σ) on a circular trajectory (with radius R) between conducting planes radiates the same power as in free space if the gap g between the planes is large compared to $\sqrt[3]{R\sigma^2}$. For g of the order of centimeters this condition is violated in BC1 but fulfilled in BC2. Usually shielding helps to reduce CSR related emittance growth in a single BC, but it counteracts to the compensation of effects in a two stage system as described above. Furthermore, it has to be mentioned that the criterion for the gap width holds for circular motion but not for chicanes with long drifts. The conducting planes build a waveguide system with cut-off effects, reduced group velocity and wall losses. Therefore the bunch escapes from CSR fields if the drift is long compared to $2g^2/(\pi^2\sigma)$, but it builds up a resistive wall field. Shielding and resistive wall effects have to be investigated.

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