Design Consequences of Coherent Synchrotron Radiation Beam Dynamic Effects on the TTF-FEL Bunch Compression System

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Abstract

The emittance of a coherently radiating electron bunch is increased by self-induced longitudinal and radial wake fields with strong variations along the longitudinal axis[1, 2, 4]. We have written a numerical code which calculates fields and resulting emittance growth in transverse and longitudinal phase space. In this paper, we describe parameter optimization for the Tesla Test Facility FEL[3] bunch compression system to minimize emittance growth. The induced longitudinal wake potential in the center of a gaussian line charge of length σ_s on a circular trajectory with radius R scales with

$$W_{\|} \propto \frac{1}{\sigma_s^{4/3} R^{2/3}}$$

and the 'critical height' of the vacuum chamber where shielding sets in is given by

$$h_c = 4\sqrt{3}(\sigma_s \sqrt{R})^{2/3},$$

so larger bending radii will alleviate emittance growth but will considerably lengthen the compression sections. Thus, numerical calculations taking into account the three-dimensional bunch shape, transition regions going into bending magnets and shielding effects are needed.

1 Introduction

The TTF-FEL requires a single bunch peak current of 2500 Amperes for the SASE process. This is achieved by compressing the bunches longitudinally to 50μm length. This compression is done in 'bunch compressors': magnet chicanes where particles of different energy have different path lengths so that the bunch length can be adjusted by inducing a longitudinal energy gradient.

The bunch compression in the TTF-FEL is done in stages. A first rather small bunch compressor (BC1) ensures that the bunch length is at the required 0.8 mm at the 20 MeV point. At an energy of ca. 150 MeV, the bunch is compressed from 0.8 mm to 0.25 mm in bunch compressor 2. Both these bunch compressors are already frozen where length and bending radii are concerned. The third bunch compressor at a beam energy of about 500 MeV where the final compression to 50μm takes place, has a length restriction of around 25 meters total but is still in the design phase.

The induced correlated energy spread is at least partly transformed into non-correlated energy spread by the compression process. Since the tolerable energy spread at the entrance of the TTF-FEL wiggler is only 0.1%, the path length difference per particle energy offset must be sufficient. That, given overall length limitations, makes the use of strong bending magnets with relatively small bending radii (of the order of meters) attractive.

The first effect to put a lower limit on bending radii R over a length L in a beam line is energy spread and emittance growth due to incoherent synchrotron radiation. The energy spread at a beam of energy of $E = \gamma m_e c^2$ is increased by:

$$\sigma_E \approx 1.94 \cdot 10^{-14}\mathrm{MeVm}\sqrt{\frac{\gamma^7 L}{R^3}}$$

while transverse emittance increases as:

$$\Delta(\varepsilon\gamma) \approx 4.04\ 10^{-8}\frac{\mathrm{m}^2}{\mathrm{GeV}^6}\ E^6\frac{L}{R^3}\ H \qquad (1)$$

with

$$H = \frac{1}{L}\int_0^L \frac{1}{\beta(s)}\left(D(s)^2 + \left(\beta(s)D(s)' + \alpha(s)D(s)\right)^2\right) ds \qquad (2)$$

and β the beam envelope function, α its derivative and D the dispersion function. These effects would limit the bending radii for bunch compressor 3 to one meter (to keep transverse emittance growth below 1%). That would fit a symmetric chicane for a required longitudinal compression factor $R_{56} = 0.15$ within three meters.

However, if short bunches travel along trajectories with small bending radii a simple geometrical condition permits strong longitudinal and radial wake fields to act on the bunch: electro magnetic fields emitted by a particle can 'overtake' on a shorter straight trajectory and interact with particles which are ahead in the bunch. The bunch then starts to radiate coherently.

The longitudinal variation of the wake fields causes a correlated bunch deformation in longitudinal-transversal phase space. We will call that in this paper 'correlated emittance' growth. For moderate growth (¡25%), this leads to an increase of the size of the photon cone. Since the cooperation length is short compared with the bunch length, the laser power is to first order not effected. For larger deformation, the coherent betatron oscillations in the undulato of the bunch regions with big transverse offsets disturb the overlap of radiated field and particle trajectory which is necessary for the SASE process. So parts of the bunch will not lase, overall power will drop. The transverse variation of the wake acts on the bunch like any non-linear field and causes non-correlated emittance growth inside the bunch slices. This emittance growth directly influences the SASE process.

2 Coherent Synchrotron Radiation in the Compression System of the TTF-FEL

2.1 Bunch compressor 2

Bunch compressor 2 had to be fit into a five meter long space while providing a longitudinal compression factor regime of $0.12 < R_{56} < 0.24$ [6]. Calculation on the effect of coherent synchrotron radiation wake fields were done at a setting of $R_{56} = 0.14$ and a corresponding bending radius of 1.6 meters[4]. It was shown that in order to keep correlated emittance growth small, the coherent radiation has to be shielded with a narrow gap vacuum chamber of 8 mm height. Without any shielding, the correlated emittance reaches more than five times the incoming transverse emittance of 1mm-mrad normalized. The observed increase in transverse emittance due to radial variations of the fields was found less than a few percent.

Besides introducing an aperture inconvenient for machine operation, the narrow gap vacuum chamber also excites wake fields due to the necessary steps to lower the chamber profile from the L-Band iris diameter into the chamber and to open it up again. For the BC2 we have calculated these fields with a simple model of stepping in and out of an iris and find the induced correlated energy spread is comparable or less than the nonlinearity of the RF (and of opposite sign) and is not going to disturb the bunching process[7].

2.2 Bunch compressor 3

2.2.1 Shielding and Longitudinal Compression

The longitudinal compression factor (R_{56}) of a symmetric chicane is given by

$$R_{56} = 2 \cdot (\frac{L}{R})^2 \cdot (\Delta L + \frac{2}{3} \cdot L)$$

where L is the bending magnet length, R the bending radius and ΔL the drift length in between bending magnets. To shield coherent synchrotron radiation effectively for a bunch of length σ_s, the vacuum chamber hight must be less than

$$h_c = 4\sqrt{3}(\sigma_s\sqrt{R})^{2/3},$$

where the fields are reduced by a factor between two and four [5]. To keep h_c at a reasonable size so that no severe aperture limitation is introduced to the beam line sets a lower limit for the bending radius R. The total length of a symmetric chicane scales then quadratically with the necessary h_c for a fixed R_{56}:

$$L_{Total} = (\frac{3}{10}R_{56})^{1/3} \cdot \frac{h_c^2}{(3.7 \cdot \sigma_s)^{4/3}}$$

For bunch compressor 3, total chicane length and bending radius are plotted in Fig.1 vs. h_c for a longitudinal compression factor $R_{56} = 0.15$, the uppermost to be required from the compression system design. For that case, a total length of 20 m is needed.

2.2.2 Emittance growth calculations

In the following calculations, bunch compressor 3 is a symmetric chicane with 3 m long bending magnets with deflection angles of 5.9 degrees (corresponding to a bending radius of 29.4 m) and 3 m long straight sections between the bending magnets. A linear correlated energy spread of $1.9 \cdot 10^{-3}$ compresses an incoming bunch with $\sigma_s = 250\mu$m length to $\sigma_s = 50\mu$m.

For the calculation of correlated emittance growth, the bunch is represented by 51 sub-bunches, each being a two-dimensional Gaussian charge distribution (horizontal and longitudinal). At the compressor entrance, the sub-bunches are lined up longitudinally over a range of $\pm 3\sigma_s$, modeling an incoming straight bunch.

The sub-bunches are then tracked through the bunch compressor, simulating the compression process in the dispersive section. The generated wake-fields are calculated and applied to the sub-bunch trajectories. Tracking is still not self-consistent, i.e., the fields are not re-calculated using the perturbed trajectories and then re-applied and so forth.

Fig.4 shows this distribution in phase space weighted with the relative bunch charge. In the core region, horizontal position and angle are strongly correlated. This optical mismatch has to be compensated for by the subsequent beam line optics. At the compressor end, the RMS-sizes of the distribution of the sub-bunch centers are $\sigma_{x,correlated} = 190\mu$m and $\sigma_{x',correlated} = 37\mu$rad which compare with the sub-bunch sizes of $\sigma_x = 113\mu$m and $\sigma_{x'} = 13\mu$rad at a β-function of 10 meters.

The situation is altered significantly as soon as shielding is introduced. The simulations described above were also done with a vacuum chamber, consisting of a pair of conductive plates 8mm apart, parallel to each other and to the plane of motion.

Figures 3 and 4 correspond to 2 and 5, respectively. The induced energy spread has decreased by a factor of two.

Figure 6 compares the beams' phase-space distributions at the end of the compressor section. The area of the included phase-space has decreased drastically. For the RMS values, we find $\sigma^{shielded}_{x,correlated} = 50\mu$m and $\sigma^{shielded}_{x',correlated} = 37\mu$rad. The phase-space distibution still is highly correlated in the area of high statistical weight.

2.2.3 Vacuum chamber heat load

For the above case of a bunch compressor 3 with a total length of 20 meters, bending radii of ca. 30 meters and a R_{56} of 0.15 the radiated power vs. position is shown in Fig.7. The cw heat load is given by

$$P_{cw} = P_{bunch} \cdot t_{bunch} \cdot \frac{n_{bunch}}{sec}$$

where P_{bunch} is the power radiated by a single bunch and t_{bunch} the bunch length in time. If we take the bunch length to be $100\mu m$ and thus t_{bunch} to be ca. 0.4 ps (FWHM) and the number of bunches n_{bunch} per second as 70000 (ten cycles of 7000 bunches), the average power comes out to be only fractions of a Watt.

3 Conclusion

Correlated emittance growth due to coherent synchrotron radiation determines the choice of the bending radius of the compressor chicane magnets and thus the length of the system. The correlated emittance growth is accompanied by an optical mismatch which has to be compensated by the subsequent beam line optics. The heat load of the vacuum chamber due to coherent synchrotron radiation should be negligible if parameters have been chosen which avoid strong correlated emittance blow up.

References

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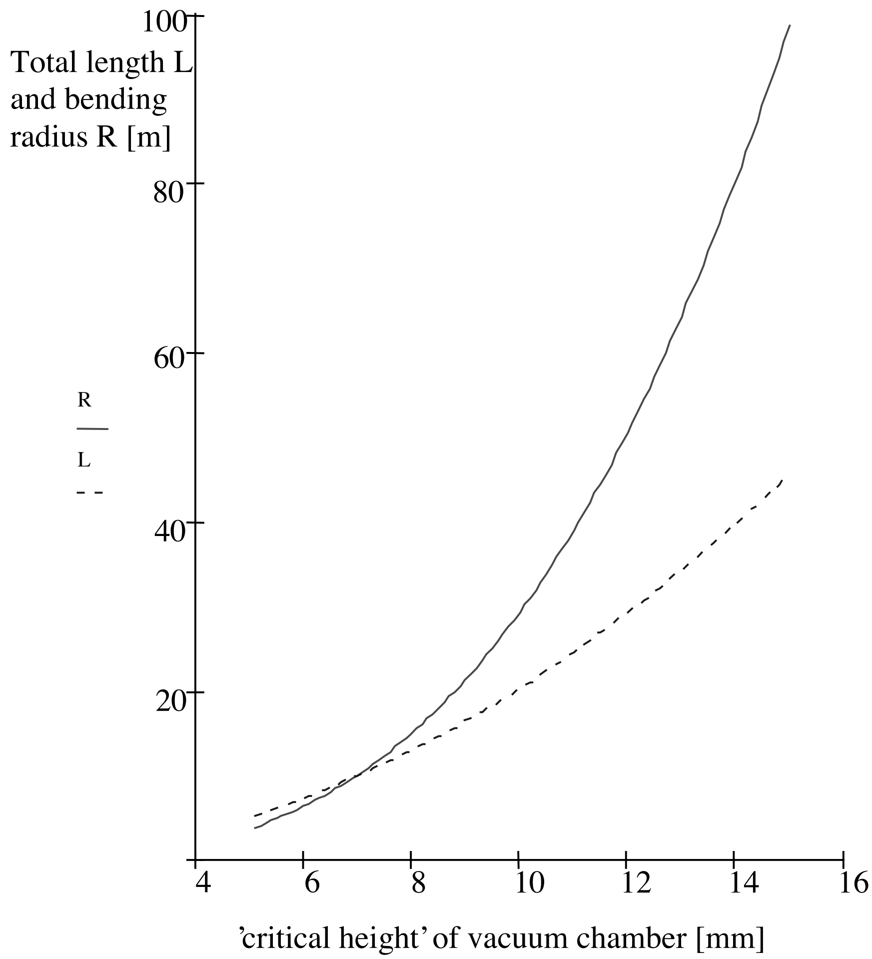

Figure 1: Bending radius and total length of magnet chicane vs. critical height of vacuum chamber for the case of TTF-FEL bunch compressor 3 (final bunch length $\sigma_s = 50\mu$m, longitudinal compression factor $R_{56} = 0.15$)

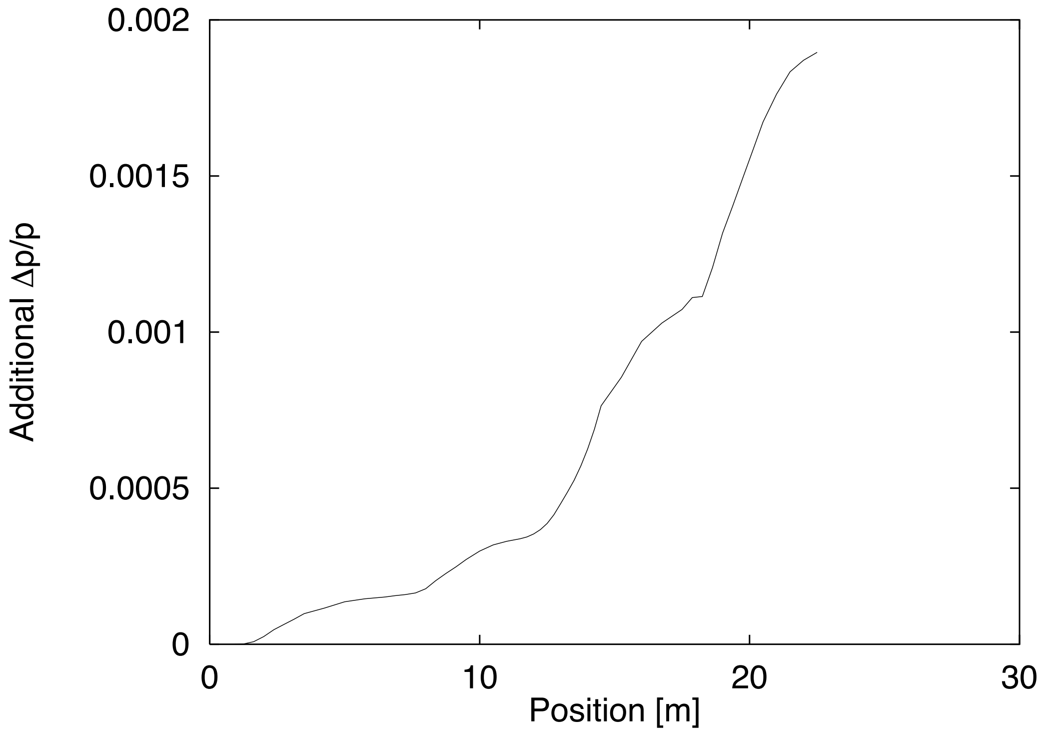

Figure 2: Energy spread gained by a bunch transversing the bunch compressor 3

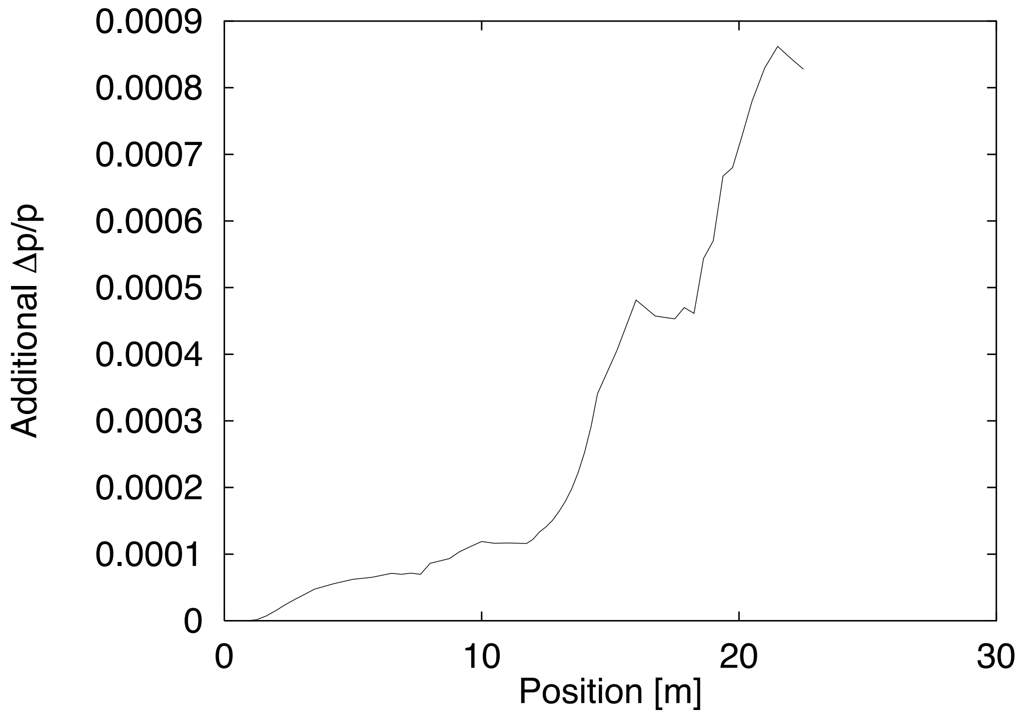

Figure 3: Energy spread gained by a bunch transversing the shielded bunch compressor 3

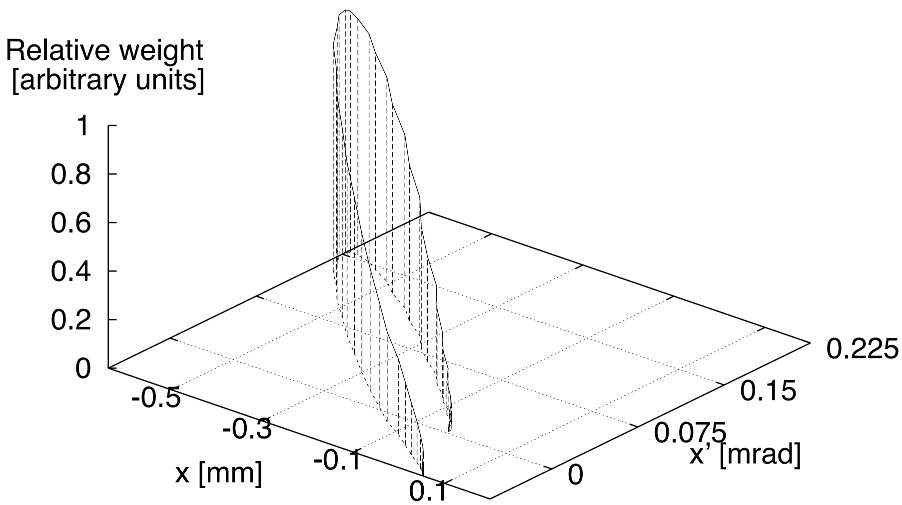

Figure 4: Phase space distribution of sub-bunch centers weighted with charge density of the bunch at the end of bunch compressor 3

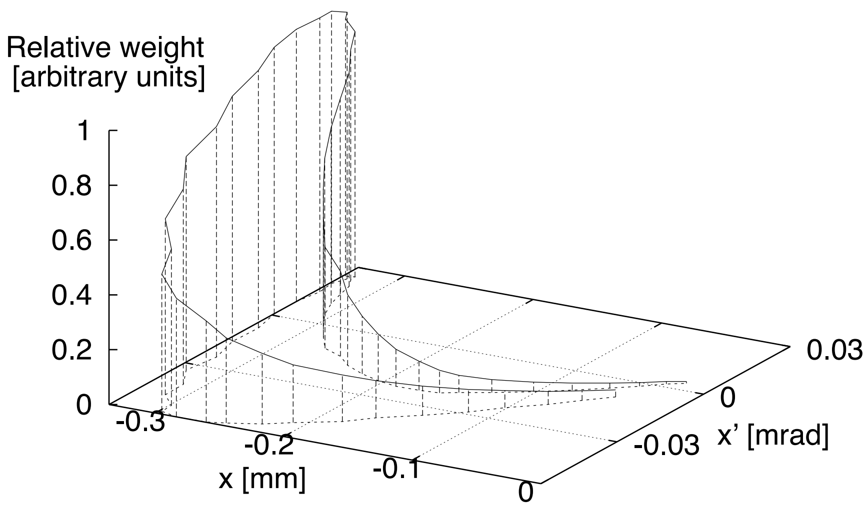

Figure 5: Phase space distribution of sub-bunch centers weighted with charge density of the bunch at the end of bunch compressor 3 for the shielded case

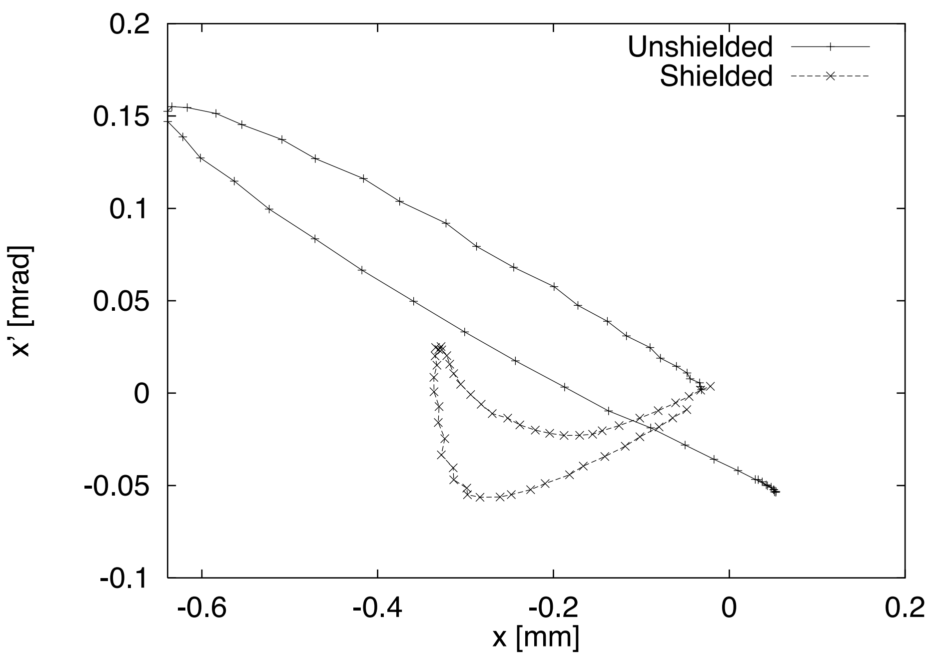

Figure 6: Comparison of phase space distribution at the end of bunch compressor 3 with and without shielding

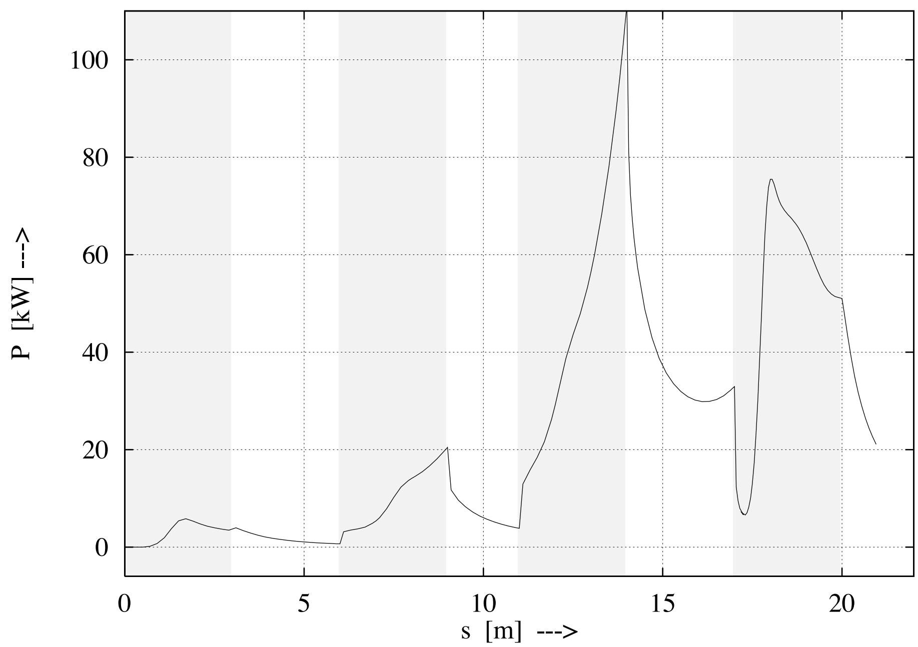

Figure 7: Total power radiated by the bunch during compression in bunch compressor 3 vs. longitudinal position