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RECENT EXPERIMENTS ON THE EFFECT OF COHERENT SYNCHROTRON RADIATION ON THE ELECTRON BEAM EFFECT OF CTF II

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Abstract

The drive beam of CTF II can provide single electron bunches with charges of more than 15 nC and rms lengths of less than 0.13 mm. If the bunches are bent in the dipoles of a magnetic bunch compressor, they emit coherent synchrotron radiation with strongly enhanced intensity with respect to incoherent synchrotron radiation. Here we report on the experimental and theoretical study of the effect of this coherent radiation emission on the distribution of the electrons in the six-dimensional phase space. Transverse emittances, bunch lengths, and energy spectra were measured for constant bunch compression ratios but different horizontal beam sizes in the bunch compressor. Further, the shielding effect of the finite vacuum chamber height on the mean beam energy loss was investigated by using two vacuum chambers of different heights in a four-magnet chicane. The results are compared with simulations using TraFiC^4 and ELEGANT.

1 INTRODUCTION

The second Compact Linear Collider Test Facility CTF II [1] was built to demonstrate the two-beam acceleration scheme at 30 GHz. The efficiency of RF-power production at 30 GHz decreases as the bunch length increases. Therefore bunch compression is achieved by introducing a longitudinal correlation within the bunch via off-crest acceleration, in connection with a bunch compressor chicane [2]. Particles at the tail of the bunch have a higher energy than particles at the head of the bunch. The compressor introduces an energy-dependent path length difference of $R_{56} = ds/(dp/p)$ allowing particles at the bunch tail to catch up the head particles. For short bunch lengths, the low frequency part of synchrotron radiation induced by a dipole of curvature ρ becomes coherent, resulting in a considerable enhancement of the radiated power [3] by

$$\Delta P_{coh} \approx 0.028 \cdot N^2 \frac{c\, e^2}{\epsilon_0\, \rho^{2/3}\, \sigma_l^{4/3}}, \qquad (1)$$

where a Gaussian distribution of the N particles and a constant rms bunch length σ_l along the trajectory are assumed. The emission of coherent synchrotron radiation (CSR) is independent of the particles' energy for $\gamma \gg 1$. CSR affects the distribution in the six-dimensional phase space and can lead to emittance growth. The emission of CSR should be suppressed [3] by parallel conducting plates with a vertical separation of $h_c \leq 1.2\,(\rho\,\sigma_l^2)^{1/3}$. In previous experiments at CTF II [4, 5] the CSR-introduced transverse emittance growth and mean beam energy loss was measured as a function of the bunch compression parameter R_{56}. This paper reports experiments concerning the dependence of CSR effects on the horizontal beam size and the shielding environment.

2 EXPERIMENTAL SETUP

The experiments were performed with the drive beam of CTF II (Fig. 1). The first chicane in the beam line comprising three dipoles will be called the 'compressor' and was used for the experiments on the transverse emittance growth as a function of the horizontal beta-function in its central dipole. After these experiments, an additional four-magnet chicane was installed downstream of the compressor for the measurements on the shielding effect, and this will be called the 'shielding chicane'. The corresponding vacuum chamber can be exchanged within five hours. In the experiments, two stainless-steel chambers with total heights of 50 mm and 15 mm were used.

Beam energy spectra can be recorded by using the first compressor magnet as spectrometer. A second spectrometer at the end of the beam line is used to record the spectra after the beam has passed the compressor and the chicane. The beam intensity is measured with two wall current monitors, one before the compressor and one before the end of line spectrometer. The bunch lengths are measured after the shielding chicane by analysing the mm-wave spectra, excited by the bunch passing an RF-waveguide connected to the vacuum chamber [6]. An optical transition radiation (OTR) screen viewed with a camera is used to record transverse beam profiles after the shielding chicane. Transverse emittances are measured simultaneously by applying the quadrupole scanning technique to each magnet of a triplet.

3 EMITTANCE GROWTH AS FUNCTION OF HORIZONTAL BEAM SIZE

The first set of measurements concerns the CSR-induced growth of the normalized horizontal emittance as a function of the horizontal beam size. It was performed with the compressor. Prior to the emittance measurements the compressor was set to minimum R_{56}. Energy spectra were recorded with and without longitudinal correlation, and the transverse Twiss parameters were measured. Afterwards, the R_{56} of the compressor was varied and rms bunch lengths were measured to determine the longitudinal Twiss para-

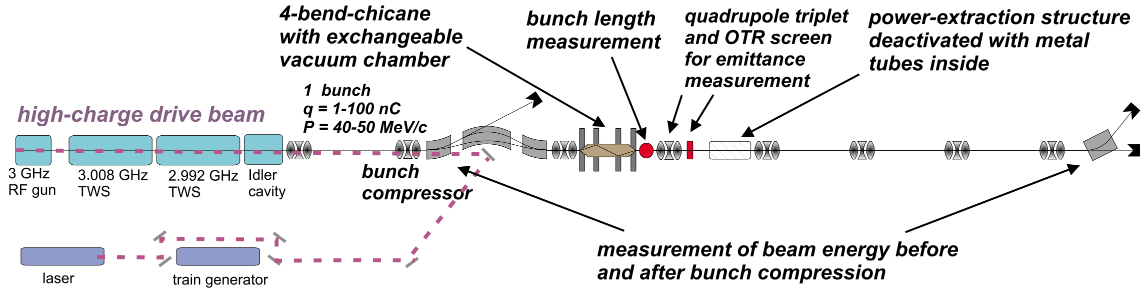

Figure 1: The drive beam of the second CLIC Test Facility CTF II.

meters at the entrance of the compressor. Then R_{56} was set for sufficient compression and deflection to observe horizontal emittance growth due to CSR emission. The quadrupole triplets before and after the compressor were used to set the desired horizontal beta-function in the mid-plane of the compressor. For all settings, a beam waist was kept at this position in both transverse planes with a vertical beta-function of about 1 m. According to theory the horizontal emittance growth is due to a dispersion mismatch in the last dipole of the compressor for particles which changed energy due to CSR emission in a dispersive section. The growth should increase for larger beta-functions [7]. The result of a first experiment on horizontal emittance growth for different horizontal beta-functions in the compressor is shown in Fig. 2. The measured horizon-

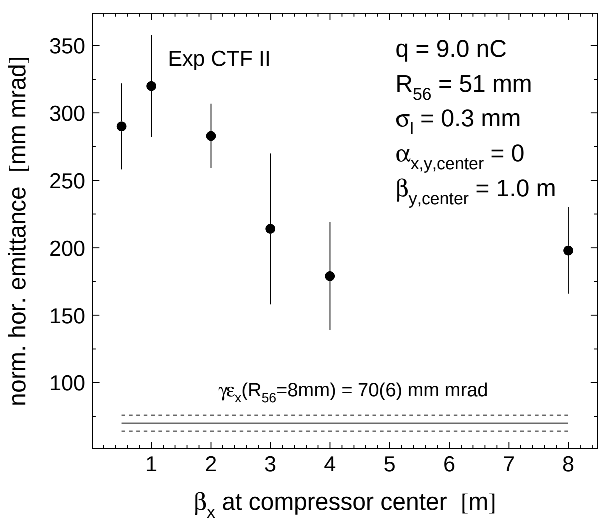

Figure 2: The normalized horizontal emittance measured after the compressor as a function of the horizontal beta-function in the compressor mid-plane for $R_{56} = 51$ mm. The initial emittance measured at $R_{56} = 8$ mm is indicated.

tal emittance growth is increased for small horizontal beta-functions contrary to theoretical expectations. In this first experiment the initial six-dimensional phase space was not determined completely and therefore no simulations were performed. The surprising experimental observation was confirmed by another set of measurements using a different R_{56} in the compressor. Figure 3 shows the measured horizontal emittances together with the results of simulations

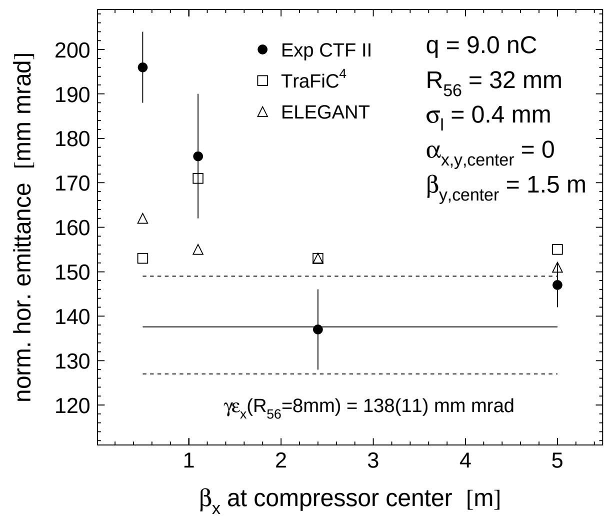

Figure 3: The normalized horizontal emittance measured after the compressor as a function of the horizontal beta-function in the compressor mid-plane for $R_{56} = 32$ mm. The initial emittance measured at $R_{56} = 8$ mm is indicated.

performed with TraFiC^4 [8] and ELEGANT [9]. The simulations show no significant dependence of the emittance growth on the beta-function. In order to verify whether the measured increase for small beta-functions is caused by the different beam focusing settings, the experiment was repeated with the same beam focusing but using acceleration with opposite correlation, i.e. for bunch stretching. In this case no dependence of the emittance growth on the beta-function was observed. To check whether the observed emittance increase is due to enhanced space charge defocusing forces during the emittance measurement, the three-dimensional beam envelope equation including space charge was integrated numerically for the quadrupole scans used for the emittance measurements. This simulation of the emittance measurement did not reveal any influence of space charge forces on the result. Finally, the emittance growth due to uncompensated Talman-forces for short bunches [10] was estimated. It increases with the beam size as well, and cannot explain the observations.

4 EFFECT OF SHIELDING ON BEAM ENERGY LOSS

The shielding experiments were done with the shielding chicane downstream of the compressor. After off-crest acceleration for compression, the transverse and longitudinal Twiss parameters were measured as described in the preceding section. Then the compressor was set to obtain the desired bunch length at the entry of the shielding chicane. Energy spectra were recorded for different R_{56} of the shielding chicane. In a first scan, a vacuum chamber with a height of 50 mm was used, which has no shielding effect for our bunch and chicane parameters. The energy loss due to CSR was deduced from the recorded energy spectra. Comparison with the energy loss calculated with ELEGANT showed an excellent agreement, while the TraFiC^4 simulations overestimated the measurements. In the following scans a flat chamber ($h_c = 15$ mm) was used. It should suppress CSR emission at low frequencies, thus reducing the beam energy loss. Four scans with different initial bunch lengths were performed. The measured energy losses are plotted in Fig. 4. For short bunches and

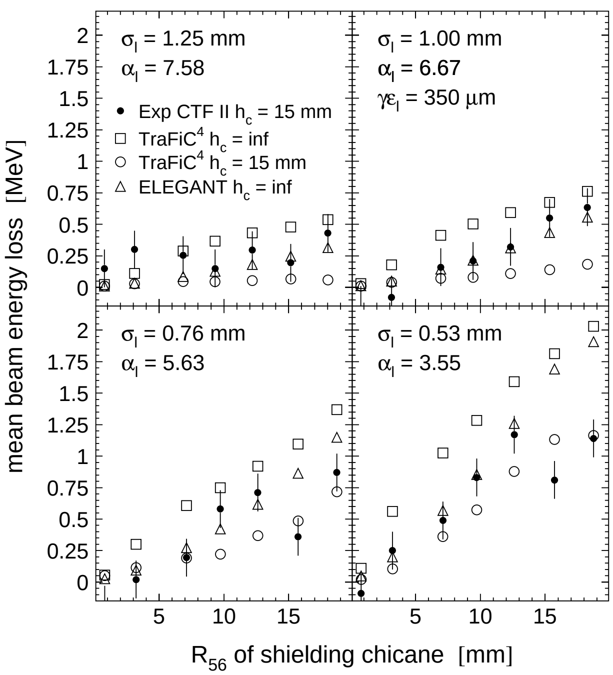

Figure 4: The measured energy loss in the shielding chicane as a function of R_{56} for four different initial bunch lengths and correlations. The chamber height was 15 mm.

high R_{56} transmission losses occurred. This might explain the drop of the measured energy loss. The results of simulations done with TraFiC^4 and ELEGANT are plotted as well. For the free space case the two codes give considerably different results. The ELEGANT simulations done for the free space case fit very well to the experimental points measured in a shielding environment, while the corresponding results of TraFiC^4 overestimate the measurement. The latter underestimate the data if shielding is taken into account in the simulations (Fig. 4). According to the TraFiC^4 simulations the shielding effect of the 15 mm-chamber significantly suppresses the energy loss. The current version of ELEGANT cannot treat shielding cases. Unfortunately, technical problems with the CTF II laser system did not allow the four scans (Fig. 4) to be repeated with the 50 mm-chamber for comparison.

5 CONCLUSION

The measured horizontal emittance shows a significant increase for small horizontal beam sizes in the compressor. This behaviour is not predicted by simulations with TraFiC^4 and ELEGANT nor is it expected from analytical estimates.

The energy loss in a four-bend chicane is consistent with ELEGANT results for free space CSR. This agreement holds for measurements without shielding as well as for measurements where a significant shielding effect is expected. TraFiC^4 predicts for the free space case a considerable higher energy loss than ELEGANT. The simulations with shielding predict a reduction of the energy loss and underestimate the measurements. Further clarification is expected from future measurements using vacuum chambers with different shielding heights for otherwise identical beam conditions.

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