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EMITTANCE GROWTH AND ENERGY LOSS DUE TO COHERENT SYNCHROTRON RADIATION IN THE BUNCH COMPRESSOR OF THE CLIC TEST FACILITY (CTF II)

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Bunches of high charge (10 nC) are compressed in length in the CTF II bunch compressor from 1.2 mm rms to less than 0.4 mm. The short bunches start to radiate coherently, thus affecting the horizontal and longitudinal phase spaces of the beam. This paper reports the results of measurements and simulations concerning the increase of the beam emittance and the impact on the energy distribution. Beam emittances were measured for different bunch compression factors and bunch charges. For each compressor setting, the energy spectrum of the beam was recorded in order to measure the energy loss due to coherent synchrotron radiation. For bunch charges of 10 nC a maximum increase of the horizontal emittance of 50% was observed at full compression, while the mean beam energy decreased by 5% from 39 MeV to 37 MeV. Both effects were correlated with an increase of the energy spread from 2.3% to 8.5% rms. The experimental results are compared with simulations.

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Bunches of high charge (10 nC) are compressed in length in the CTF II bunch compressor from 1.2 mm rms to less than 0.4 mm. The short bunches start to radiate coherently, thus affecting the horizontal and longitudinal phase spaces of the beam. This paper reports the results of measurements and simulations concerning the increase of the beam emittance and the impact on the energy distribution. Beam emittances were measured for different bunch compression factors and bunch charges. For each compressor setting, the energy spectrum of the beam was recorded in order to measure the energy loss due to coherent synchrotron radiation. For bunch charges of 10 nC a maximum increase of the horizontal emittance of 50% was observed at full compression, while the mean beam energy decreased by 5% from 39 MeV to 37 MeV. Both effects were correlated with an increase of the energy spread from 2.3% to 8.5% rms. The experimental results are compared with simulations.

1 INTRODUCTION

The second Compact Linear Collider Test Facility CTF II [1] was built to demonstrate the feasibility of two-beam acceleration at 30 GHz (Fig. 1). The RF power at 30 GHz created by the drive beam decreases with the bunch-length. Bunch compression is achieved by acceleration off-crest, such that particles at the tail of the bunch have higher energies with respect to those at the head of the bunch, in combination with a subsequent magnetic chicane comprising three rectangular dipoles. In the first dipole the design orbit can be deflected from an angle of 3.7° to 14° introducing an energy dependence of the orbit length $R_{56} = ds/(dE/E)$ from 6 mm to 90 mm in the chicane. Due to the construction of the vacuum chamber, the chicane cannot be switched off completely. However, using this scheme, rms bunch lengths of less than 0.4 mm can by achieved for bunch charges of 10 nC. For short bunch lengths the synchrotron radiation induced by a dipole of curvature ρ becomes coherent, resulting in an considerable enhancement of the radiated power [2] 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 bunch length σ_l along the curved trajectory are assumed. The coherent synchrotron radiation (CSR) affects the distribution of the particles in the longitudinal and transverse phase space. In a previous work [3] the increase of the horizontal and vertical beam emittances as a function of the deflection angle in the chicane was measured. Here we present the experimental results on the impact of CSR on the transverse beam emittances and the energy spectrum. The results of simulations using the code TraFiC^4 [4] are reported for comparison.

2 EXPERIMENTAL SETUP

The experiments were performed using the drive beam of CTF II with shielded power-extracting transfer structures (Fig. 1). Beam energies were measured at the entrance to the chicane by switching off the last two chicane magnets and using the first one as a spectrometer. A second spectrometer at the end of the line permits the measurement of the spectra of the beam after passing the chicane. Two wall-current monitors placed in front of the chicane and in front of the second spectrometer measured the beam intensities. The bunch lengths were detected behind the chicane by analysis of mm-wave spectra, excited by the beam passing an RF-waveguide connected to the vacuum chamber [5]. Transverse beam profiles were recorded after the chicane using an optical transition radiation (OTR) screen and a camera. The horizontal and vertical emittances were measured simultaneously by applying the quadrupole scanning technique. In order to cover the full range of phase advance from 0° to 180° in both transverse planes the quadrupole strengths of a bipolar triplet were varied independently. For accurate determination of the beam widths, only those profiles were selected which fitted well on the OTR screen. In the experiments the bunch length, the horizontal and vertical emittance, and the energy spectrum after passing the compressor chicane, were measured as function of R_{56} for bunch charges of 5 nC and 10 nC. The range of chicane settings was selected in order to achieve over-compression to the initial bunch length, thus covering a sufficient range of longitudinal phase advances.

3 RESULTS AND DISCUSSION

The measured bunch lengths and emittances after passing the chicane as function of R_{56} are plotted in Fig. 2. For

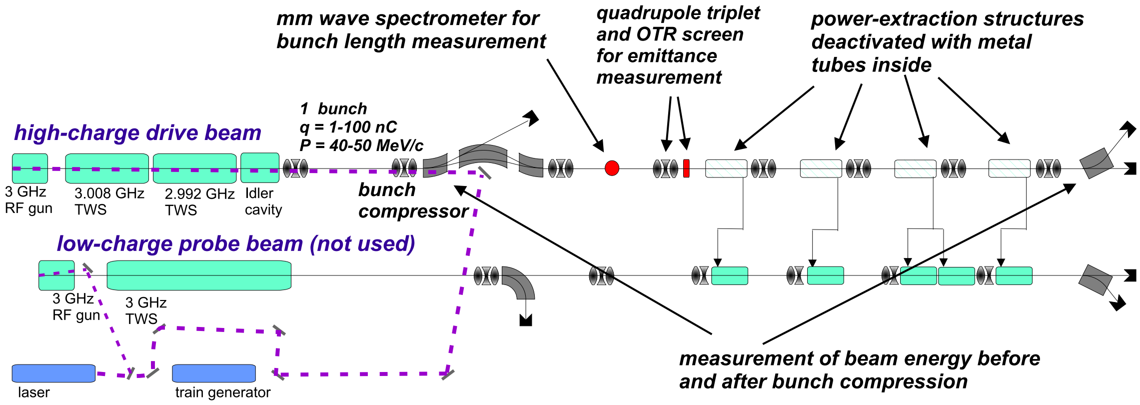

Figure 1: The second CLIC Test Facility CTF II. The CSR experiments were performed on the drive beam (upper part).

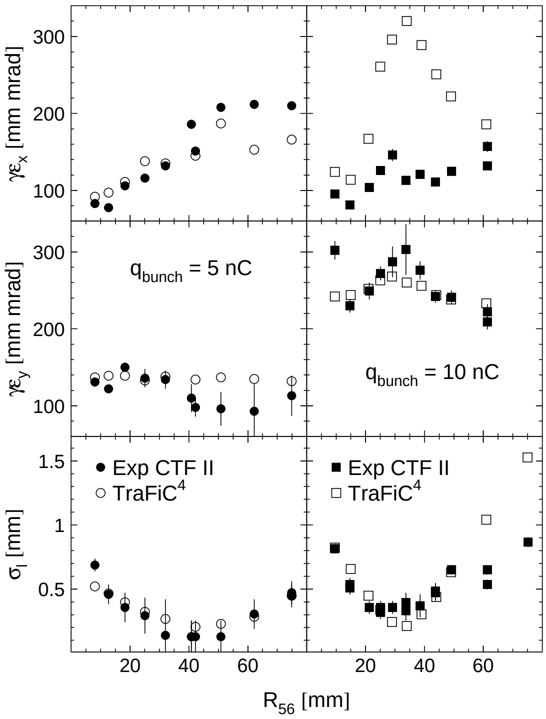

Figure 2: Measured and calculated rms bunch lengths and transverse beam emittances as function of R_{56} for bunch charges of 5 nC (left part) and 10 nC (right part).

5 nC the dependence of the measured bunch length on R_{56} shows a symmetric shape as expected from linear longitudinal dynamics. On the other hand, the asymmetric shape of the corresponding curve for 10 nC indicates a strong impact of CSR on the longitudinal properties for R_{56}>20 mm. The measured horizontal emittances (Fig. 2) increase until full compression. For 5 nC a saturation occurs after full compression. The four highest values seem to be shifted with respect to the lower values. This shift might be due to dispersion at the beam profile monitor caused by a mismatch of the last chicane dipole strength with respect to the strengths of the first and second dipole of the chicane. The four points were recorded after switching off the last two magnets of the chicane in order to measure the beam energy at the entrance to the chicane. For 10 nC the data points scatter after over-compression thus not allowing meaningful conclusions. The measured vertical emittances for 5 nC are constant within the error bars but reveal a maximum at full compression at 10 nC.

The impact of CSR on the energy spectrum of the bunch is shown in Fig. 3. Since the spectrometer at the end of the beam line consists of a deflecting dipole it also represents a source of CSR, and the resulting spectra show the sum of the CSR effects in the compressor chicane and in the spectrometer. As the bunches are compressed

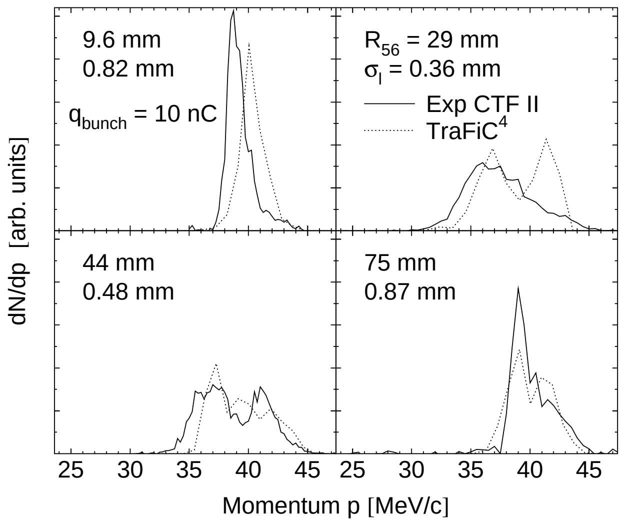

Figure 3: Measured and calculated energy spectra behind the compressor chicane for different compressor settings R_{56} (upper values) and measured bunch lengths (lower values). The bunch charge was 10 nC.

the spectrum broadens especially at the high energy side, and develops two maxima for R_{56}, slightly higher than for full compression. During over-compression the spectrum narrows again and a high-energy tail remains. For 5 nC the spectrum broadens as well until full compression, and narrows afterwards. However, no splitting of the maximum occurs at 5 nC.

The mean energies and rms widths of the measured spectra as function of R_{56} are plotted in Fig. 4. For 5 nC, no

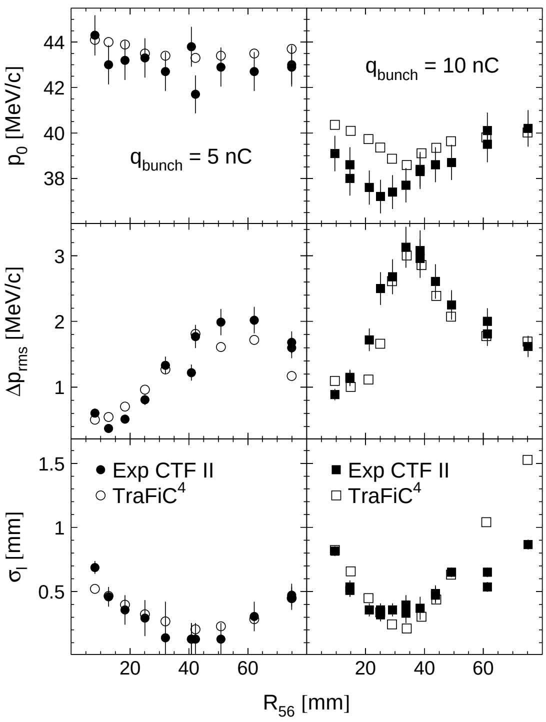

Figure 4: Measured and calculated rms bunch lengths, centre of mass momenta and rms widths as function of R_{56} for bunch charges of 5 nC (left part) and 10 nC (right part).

change of the mean beam energy was observed, although the energy spread increased by a factor four at full compression with respect to the initial spread, and decreased at over-compression. For charges of 10 nC, a decrease of the mean energy by 2 MeV, i.e. 5% of the beam energy, was measured at full compression. The energy spread shows the same behaviour as described for 5 nC. The increase of the energy spread also affects the accuracy of the emittance measurements and contributes to the error bars and the scattering of the data points.

The measured data points at R_{56} <20 mm, in connection with the energy spectra recorded at the entrance to the chicane, were used to deduce the initial longitudinal and transverse phase space distribution for the simulations, assuming that the CSR effects can be neglected for small R_{56}. As already mentioned above, this assumption seems not to be justified for charges of 10 nC and R_{56}>20 mm. Accordingly the input parameters for the 10 nC measurements are known with less accuracy. Using the program TraFiC^4 the bunch consisted of 500 macro particles and was tracked from the entrance to the chicane to the end of line spectrometer dipole. At each step, the sum of fields resulting from the beam focusing, space charge and wake fields was applied to the macro particles. The resulting bunch lengths, emittances and energy spectra are shown in Figs. 2-4. In the case of 5 nC the dependence of the observables on R_{56} was reproduced well. However, for 10 nC the calculated bunch lengths fit the measured ones until full compression, but the asymmetric shape of the bunch length curve was not reproduced. The huge growth of the horizontal emittance found in the simulations was not found experimentally, but for the qualitative dependences of the vertical emittance on R_{56} the simulations and the experiment agree. The amount of energy loss for 10 nC was calculated correctly, but the experimental and theoretical curves are shifted with respect to each other, indicating different initial longitudinal beam parameters in the experiments and the simulations. On the other hand, a very good matching of the measured and calculated energy spreads was found. The simulations show that the splitting of the maxima in the spectra for 10 nC is due to CSR in the chicane, but the broadening of the spectra is caused by space charge during the drift to the spectrometer. Comparing the energy spreads and calculated horizontal emittances shows that in the simulations the emittance growth is due to chromaticity for 5 nC and 10 nC. Although the rms widths are well calculated, the measured and simulated energy spectra for 10 nC have different shapes. The formation of two maxima occurs at smaller R_{56} in the simulations. In the case of 5 nC the simulations reveal no splitting of the maximum and the shapes of the spectra agree well.

4 CONCLUSIONS AND OUTLOOK

The impact of CSR on the transverse and longitudinal phase space distribution was measured and compared with simulations. Good agreement was found for all observables except the emittance growth for bunches of 10 nC, which is not yet understood. After successful qualitative measurements of the impact of CSR on the beam parameters, future experiments aim at experimental investigation of shielding the CSR by horizontal parallel plates. Short bunches will be passed through a four-magnet chicane designed for large deflection angles and small dispersion functions, i.e. small R_{56}. Three vacuum chambers of different height will be used providing different shielding environments.

5 REFERENCES

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