Beam Diagnostics using Coherent Transition Radiation at the CLIC Test Facility

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Abstract

Coherent transition radiation from picosecond electron bunches was observed at the CLIC test facility using a photo-acoustic detector. The spectrum was measured with a series of high pass filters. The decay of the spectrum yields an estimate for the bunch length. The bunch length obtained from the spectra was found to be in good agreement with the one directly measured with a streak camera.

1 Introduction

Transition radiation is produced as charged particles pass through the interface of two materials with different dielectric constants. The radiation will be emitted in forward or backward direction depending on the frequency range of observation and the material of the transition radiator. In either case, the opening angle of the radiation is characterized by γ^{-1} as is typical for relativistic processes. In the frequency range of interest here - well below the plasma frequency of the entry medium - it is the backward radiation that is under observation. By arranging the radiator at an angle of 45^{o} with respect to the electron beam direction, one can seperate the backward transition radiation from the electron beam and make use of it for beam diagnostics.

The total intensity emitted by a bunch of particles can be expressed as

$$I_{tot}(\lambda) = I(\lambda)[N + N(N-1)F(\lambda)] \tag{1}$$

where $I(\lambda)$ is the radiation intensity emitted by a single electron at wavelength λ and N is the number of particles in the bunch. $I(\lambda)$ is constant in the long wavelength regime. The three-dimensional fourier transform of the normalized charge distribution $S(\vec{r})$

$$F(\lambda) = \left| \int_{-\infty}^{+\infty} d\vec{r} S(\vec{r}) e^{\frac{2\pi i(\hat{n}\vec{r})}{\lambda}} \right|^2 \tag{2}$$

can be treated as the bunch form factor. The co-ordinates are chosen such that $\vec{r}$ is the position vector of an electron and $\hat{n}$ is the unit vector directed from the observer to the particle. If the observation direction is along the z-axis and the particle bunch is symmetric in x and y, (2) simplifies to

$$F(\lambda) = \left| \int_{-\infty}^{+\infty} d\vec{z} S(\vec{z}) e^{\frac{2\pi i z}{\lambda}} \right|^2 \tag{3}$$

and the form factor depends only on the longitudinal charge distribution $S(\vec{z})$. Due to the normalization

$$\int_{-\infty}^{+\infty} d\vec{r} S(\vec{r}) = 1 \tag{4}$$

the form factor can have values between 0 and 1. A detailed derivation is given in [1].

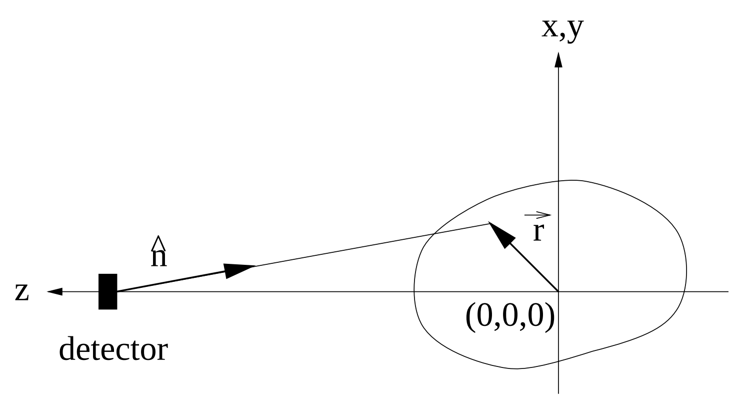

Figure 1: Notation used to derive the formula for the bunch form factor.

For wavelengths shorter than the bunch length, the form factor approaches 0. The emitted transition radiation is then incoherent and its intensity scales with the number of particles N in a bunch. It is characterized by the properties of the individual charges in a bunch and hence can be used for measuring these. In particular, the visible part of the spectrum can be used for transverse beam profile measurement, emittance measurement and energy measurement [2].

For wavelengths equal to the bunch length and longer, the form factor approaches 1. At sufficiently long wavelenghts, the whole bunch appears as one single particle ('macro-electron') with charge Ne. The emitted transition radiation is then coherent and its intensity scales with N^2. The coherent part of the spectrum carries information about the collective properties of the bunch. In particular, one can obtain from it information about the longitudinal charge distribution as $F(\lambda)$ undergoes the transition from 0 to 1. In addition, the long wavelength radiation is much more intense than the incoherent one.

2 Experimental Setup

2.1 The CLIC Test Facility

At the CLIC test facility, transition radiation is produced by moving thin, polished aluminum plates into the beam line. Transition radiators are distributed along the machine for production of optical transition radiation (OTR) [3]. The backward transition radiation is directed out of the vacuum chamber through sapphire windows. The measurements reported here were carried out after the bunch compressor at a beam energy of 12 MeV. The machine was operated with bunch trains at a repetition rate of 10 Hz. The number of bunches per train and the individual bunch charge could be varied.

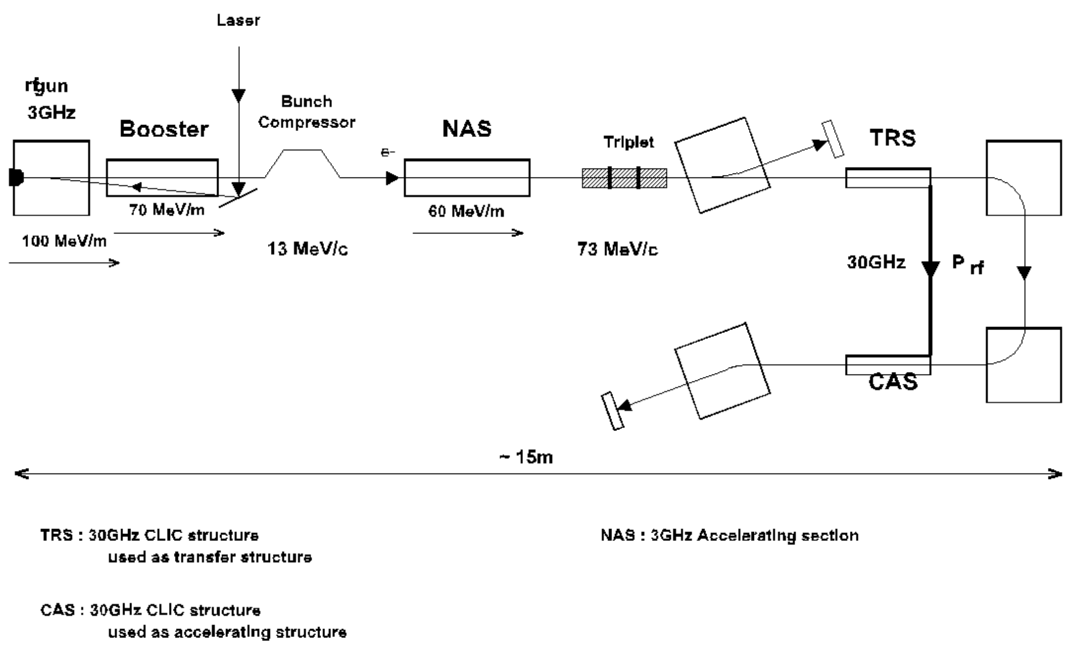

Figure 2: Schematic view of the CLIC test facility.

2.2 Detector

Since the bunch length at the CLIC test facility is supposed to be in the picosecond range, coherent transition radiation is expected at wavelengths of a millimeter and longer. For the observation of millimeter waves, a photo-acoustic detector was chosen [4]. It has a flat response for frequencies from 3 THz to 30 GHz. The detector head consists of a thin metal foil within a gas volume. The metal foil absorbs 50% of the radiation. Heating of the foil causes a change of pressure in the gas volume that is read out by a microphone.

2.3 Thick Grid Filters

Measurement of the coherent transition radiation spectrum yields information about the bunch length. One possibility to determine the spectrum is the use of long wavelength high pass filters together with a broadband detector as described before. A series of high pass filters was manufactured by drilling patterns of holes into brass plates of various thickness [5], [6]. These holes act as waveguides. Their transmission T is given by

$$T = exp(-2\gamma t) \tag{5}$$

with

$$\gamma = \begin{cases} 0 & \text{for k} > k_c \\ 2\pi\sqrt{{k_c}^2 - k^2} & \text{for k} < \text{k}_c \end{cases} \tag{6}$$

where k_c is the cutoff wavenumber and t is the thickness of the brass plate. For the TE_{11} mode, the cutoff wavenumber is given by

$$k_c = \frac{0.586}{d} \tag{7}$$

where d is the diameter of the holes. The thickness of the brass plate is chosen at twice the diameter of the holes in oder to cut off large wavelengths sufficiently. Figure 3 shows the geometry of a filter and Tab. 1 gives the calculated filter dimensions for specific cutoff wavenumbers. The transmission of the filters was specified to 85% for a given wavenumber. Lower frequencies are cut off sharply. The transmission of the filters was measured. Figure 4 shows the normalized transmission versus wavenumber for the filters with cutoff wavenumber k_c=2.49 cm^{-1} and k_c=5.86 cm^{-1}.

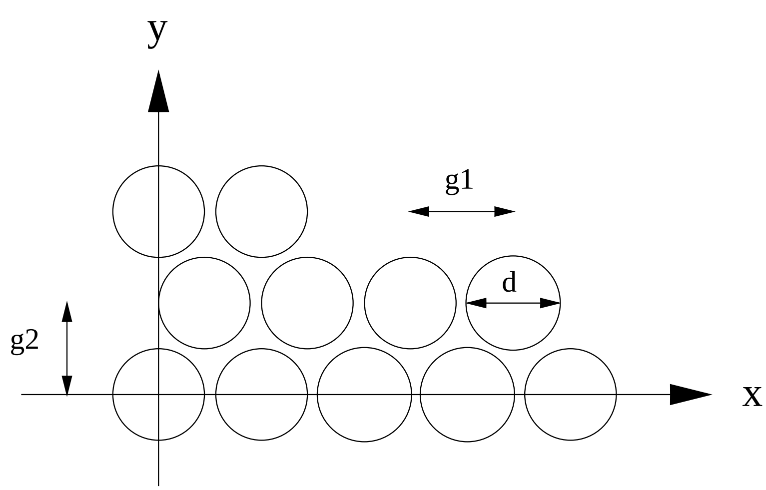

Figure 3: Geometry of a high pass filter.

d[mm]	k_c [cm^{-}1]	g1[mm]	g2[mm]	t [mm]	T[0...1]
0.30	19.50	0.353	0.306	0.60	0.85
0.35	16.75	0.411	0.356	0.70	0.85
0.40	14.65	0.470	0.407	0.80	0.85
0.45	13.02	0.530	0.459	0.90	0.85
0.50	11.72	0.588	0.510	1.00	0.85
0.55	10.65	0.647	0.560	1.10	0.85
0.60	9.67	0.706	0.611	1.20	0.85
0.65	9.01	0.765	0.662	1.30	0.85
0.70	8.37	0.823	0.713	1.40	0.85
0.75	7.81	0.882	0.764	1.50	0.85
0.80	7.32	0.941	0.815	1.60	0.85
0.90	6.51	1.059	0.917	1.80	0.85
1.00	5.86	1.176	1.018	2.00	0.85
1.15	5.10	1.353	1.172	2.30	0.85
1.30	4.51	1.523	1.319	2.60	0.85
1.50	3.91	1.765	1.529	3.00	0.85
1.70	3.45	2.000	1.732	3.40	0.85
2.00	2.93	2.353	2.038	4.00	0.85
2.35	2.49	2.765	2.395	4.70	0.85
2.90	2.02	3.412	2.955	5.80	0.85
3.90	1.50	4.588	3.973	7.80	0.85
5.85	1.00	6.882	5.960	11.70	0.85

Table 1: Dimensions of high pass filters: d is the hole diameter, k_c the cutoff wavenumber, g1 the horizontal spacing, g2 the vertical spacing, t the thickness and T the transmission.

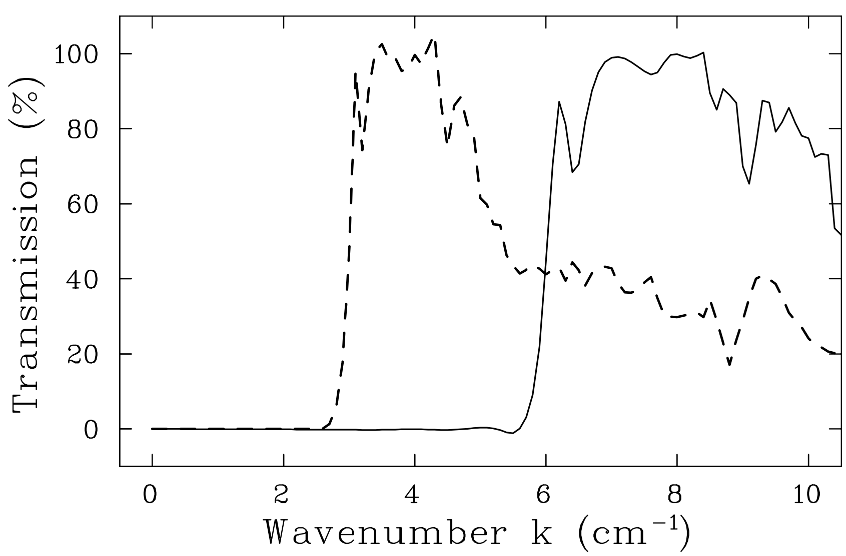

Figure 4: Measured transmission of thick grid filters versus wavenumber. The plots for the filters with cutoff wavenumber 2.49 cm^{-1} (dashed line) and 5.86 cm^{-1} (solid line) are shown.

3 Results

3.1 Observation of Coherent Transition Radiation

The detector head was placed directly on the sapphire window of a transition radiation setup. It was carefully shielded against electromagnetic noise, acoustic noise and vibrations. The signal was transmitted to the control room via a coaxial cable and measured with an oscilloscope. Figure 5 shows the detector signal observed from a train of 24 bunches with a bunch spacing of 333 ps. The detector cannot resolve the time structure of the bunch train. One can clearly see its temporal behaviour: the foil warms up quickly as the train passes. The decay then takes several milliseconds. The oscilloscope was triggered on the beam and averaged over 32 single measurements. The same procedure was repeated with the transition radiator moved out of the beam as a background measurement. The background was then subtracted to obtain the pure coherent transition radiation signal. The lower curve in Fig. 5 is the total signal, whereas the upper curve is the signal after background subtraction.

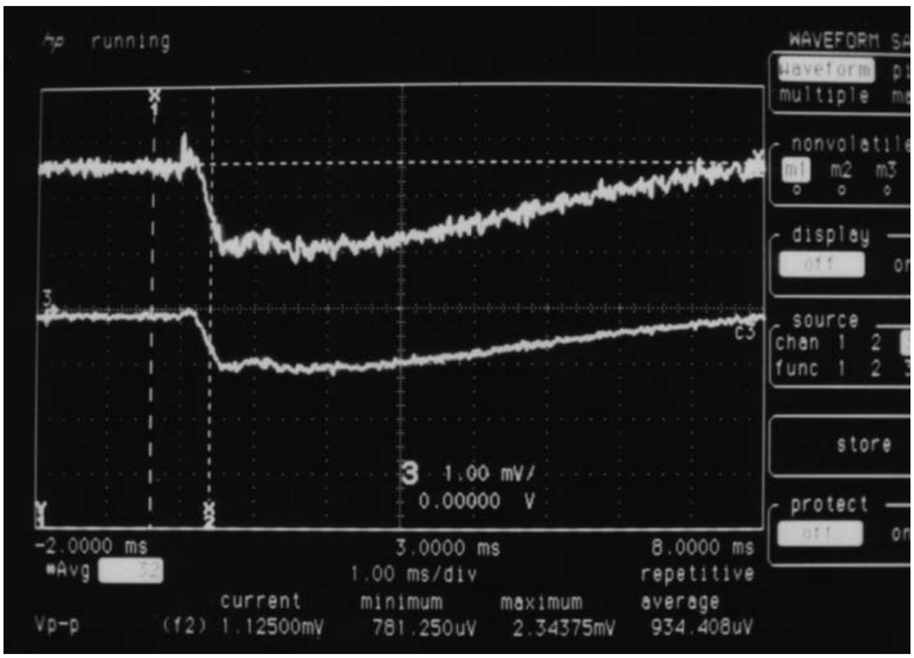

Figure 5: Detector output from a train of 24 bunches; the oscilloscope shows voltage versus time. The total time axis is 10 ms. The lower curve represents the total signal whereas the upper curve is the pure transition radiation signal after background subtraction.

Changing the number of particles per bunch results in a drastical change of the radiation power according to (1). Changing the bunch length, on the other hand, will shift the onset of the coherence effect. For a short bunch, a larger part of the coherent spectrum will be found within the spectral limits of the detector than for a long bunch. This will also result in a change of the detector output and hence can be used for optimizing the machine to short bunches.

The CTF machine was optimized using the detector output. With the bunch compressor switched off, no coherent transition radiation could be observed. We have found one setting of the bunch compressor where the detector output could be maximized. For comparison with this optimized machine setting a second - non optimized - setting was used with the bunch compressor in a slightly different operation mode.

The number of the bunches per train was increased, leaving the single bunch charge constant. Theory predicts a linear increase of the signal, since adding bunches does not lead to a coherence effect. Figure 6 shows signal versus charge for different numbers of bunches in the train. The first value refers to one single bunch. Then, bunches are added successively until the train consists of twelve bunches. The detector signal increases linearly with the charge.

Adding charge to each single bunch and leaving the number of bunches constant, however, will lead to a quadratic increase in power. Figure 7 shows signal versus charge for a train of twelve bunches. The charge per single bunch is increased, and the signal increases quadratically with the charge. The experimental results are in good agreement with the theoretical prediction. The beam optics was not changed during the experiments reported above.

3.2 Measurement of the Coherent Spectrum

The spectrum of the coherent transition radiation was measured using the thick grid filters. Therefore, the filters were placed directly between the sapphire window and the detector head. Since the filters are transparent above their specific cutoff wavenumber, one obtains an integrated spectrum. Calculating the difference between the detector output for two successive filters yields the power spectrum. From its form and decay, the bunch length can be obtained. The spectrum was measured for both the optimized and non-optimized bunch compressor setting. Various filters were used according to Tab. 1. Figure 8 shows the power spectrum for the non-optimized machine setting and Fig. 9 for the optimized machine setting. The data are corrected for the bunch charge. The measured transmission curves of the filters are taken into account. The sapphire window is transparent in the wavelength range of interest [7].

Taking into account the limited resolution of the measurements and the fact, that the data are more reliable for low wavenumbers than for larger ones, the following procedure was chosen to obtain the bunch length. For low wavenumbers, the spectrum as a function of k is dominated by a parabolic term. These parabolas are fitted to the measured spectra. From the rms-sigma of the parabolas, the full width of a rectangular pulse form can be obtained. This procedure yields a pulse length of 6.4 ps full width for the non-optimized setting and a pulse length of 5.6 ps full width for the optimized machine setting. This is consistent with results obtained from PARMELA simulations [8].

3.3 Streak Camera Measurements

The bunch length obtained from the coherent transition radiation spectra was compared with the one directly measured with a streak camera. Therefore, Čerenkov radiation in the visible frequency range was directed on a streak camera. A series of measurements was performed for both machine settings. The single shot measurements were superimposed for comparison with the integrating measurements of the coherent spectra. Figure 10 shows the streak camera measurements for the two machine settings. A fit yields a bunch length of 7.1 ps and 5.2 ps respectively.

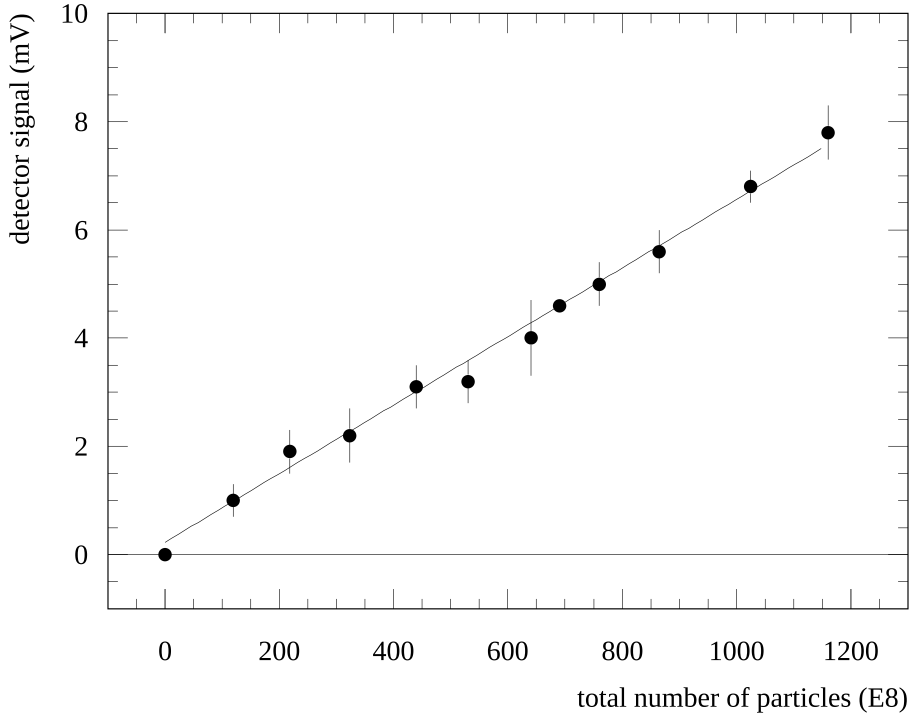

Figure 6: Signal for different numbers of bunches in a train. The first value is taken with one single bunch, then bunches are added successively until the train consists of 12 bunches.

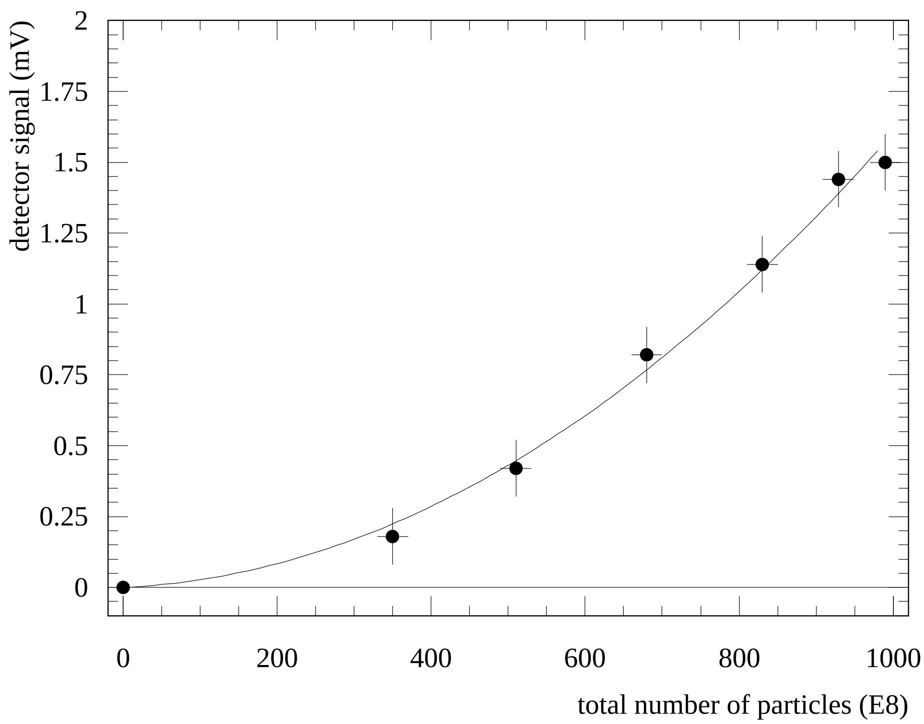

Figure 7: Detector signal for increasing single bunch charge. The number of bunches in the train is kept constant to 12.

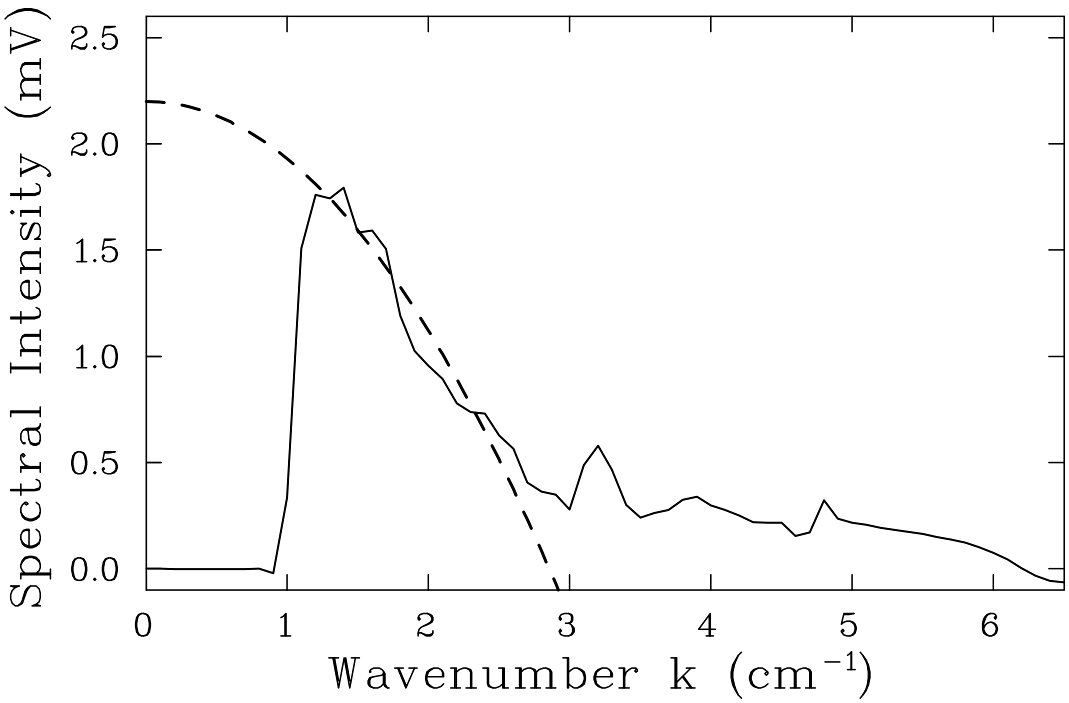

Figure 8: Spectral intensity versus wavenumber for non-optimized machine setting (solid line). A fit yields the form factor for a 6.4 *ps* (full width) rectangular shaped charge distribution (dashed line).

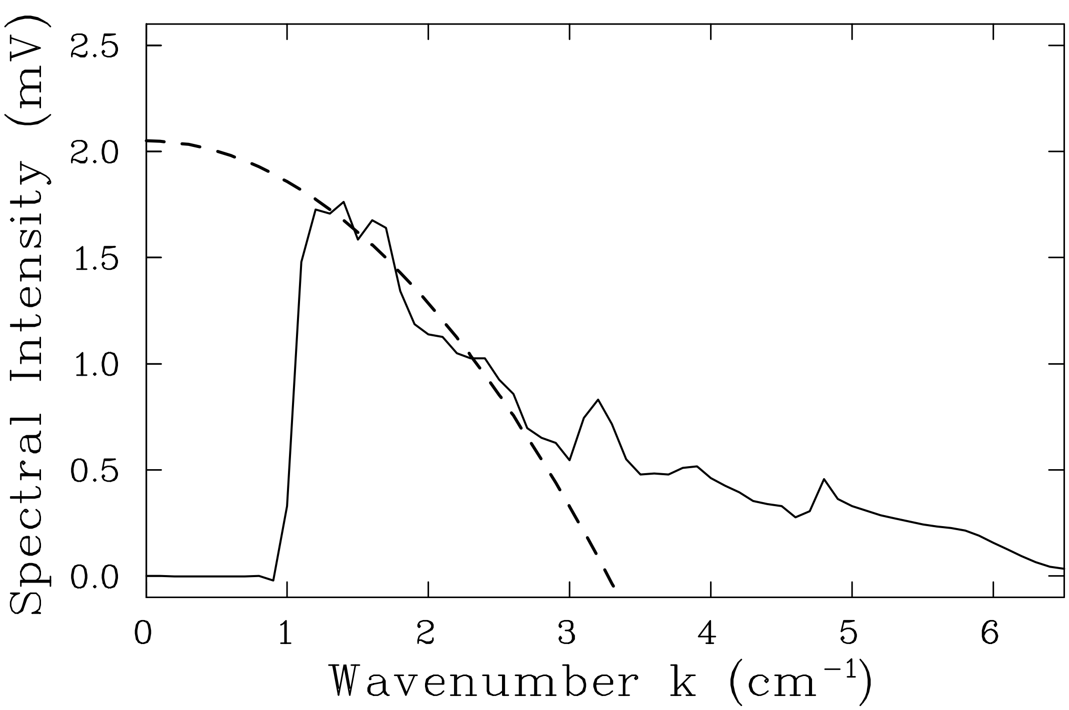

Figure 9: Spectral intensity for optimized machine setting (solid line). A fit yields the form factor for a 5.6 *ps* (full width) rectangular shaped charge distribution (dashed line).

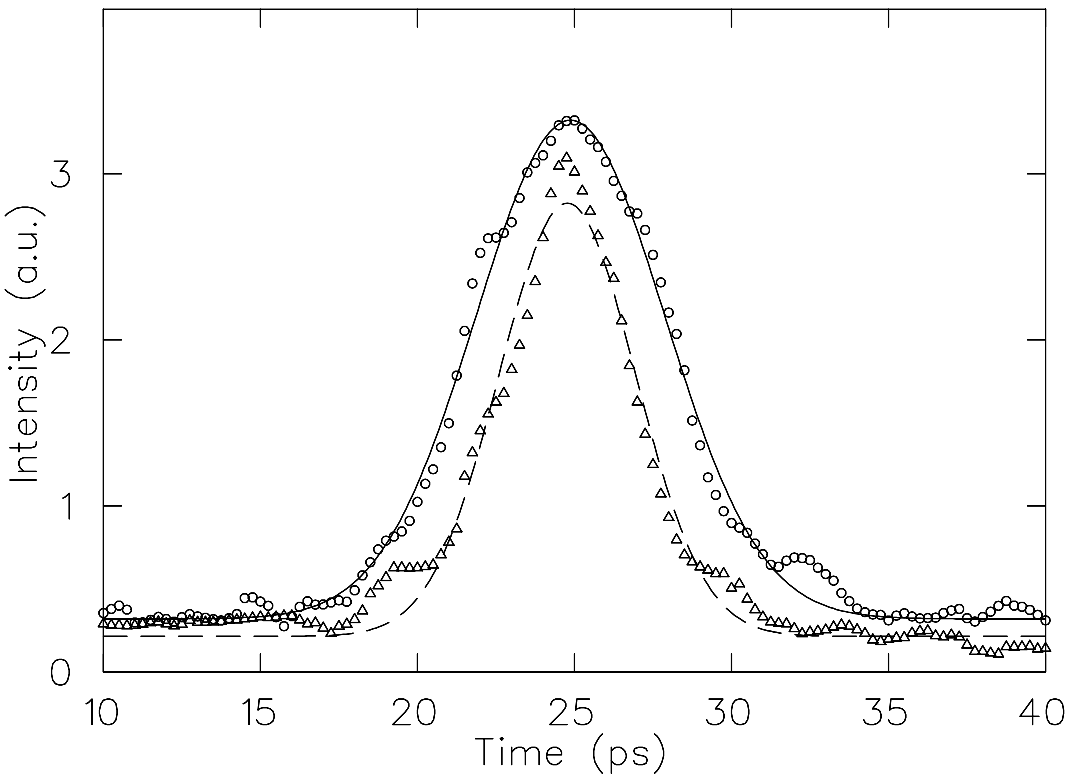

Figure 10: Streak camera measurements for optimized and non-optimized machine setting. The single-shot measurements were superimposed and the rms bunch length determined. A fit yields a bunch length of 7.1 *ps* and 5.2 *ps* respectively.

4 Conclusion and Outlook

Coherent transition radiation from picosecond bunches was observed at the CLIC test facility. Its properties were measured and found to be in good agreement with theoretical predictions.

The bunch length was obtained from the coherent radiation spectra and compared with the one directly measured with a streak camera. The measurements were in good agreement.

For further measurements, a polarizing Michelson Interferometer ('Martin-Puplett Interferometer') was developed at DESY [9]. It has an intrinsic flat characteristic over the whole frequency range of interest. By measuring the autocorrelation function of a pulse, the whole spectrum can be obtained. This will allow to determine both the bunch length and shape [10], [11].

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References

[1] C. J. Hirschmugl, M. Sagurton, G. P. Williams, *Multiparticle coherence calculations for synchrotron-radiation emission* , Phys. Rev. A, **Vol.44** , No 2, pp.1316 (1991).

[2] S. Döbert, R. Eichhorn, H. Genz, H.-D. Gräf, R. Hahn, T. Hampel, H. Loos, M. Reichenbach, A. Richter, V. Schlott, E. Spamer, A. Staschek, M. Thomas, O. Titze, T. Wesp, *Beam diagnostics using transition radiation* , to be published.

[3] S. Battisti, *Measurement of the short bunch length in the CLIC Test Facility (CTF)*, CERN CLIC Note 211 (1993).

[4] Thomas Keating Ltd, *Installation and operating instructions for the TK TeraHertz absolute power/energy meter head.*

[5] A. Roberts, M.L. von Bibra, H.-P. Gemünd, E. Kreysa, *Thick grids with circular apertures: a comparison of theoretical and experimental performance* , Intern. Journal of Infrared and Millimeter Waves, **Vol.15** , No.3, 1994, pp. 505.

[6] F. Keilmann, *Infrared high-pass filter with high contrast* , Intern. Journal of Infrared and Millimeter Waves, **Vol.2** , No.2, 1981, pp.259.

[7] LOT Oriel, data sheet.

[8] F. Chautard, *Le compresseur de paquets d'électrons pour le banc de test du futur collisonneur linéaire compact au CERN* , thesis of the University of Paris 6/070596.

[9] K. Hanke, dissertation, DESY Hamburg, in preparation.

[10] R. Lai, A.J. Sievers, *Determination of a charged-particle-bunch shape from the coherent far infrared spectrum* , Phys. Rev. E, **Vol.50** , No 5, pp. R3342 (1994).

[11] R. Lai, U. Happek, A.J. Sievers, *Measurement of the longitudinal asymmetry of a charged particle bunch from the coherent synchrotron or transition radiation spectrum* , Phys. Rev. E, **Vol.50** , No 6, pp. R4294 (1994).