Longitudinal beam profile monitor at CTF3 based on Coherent Diffraction Radiation

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Abstract. A setup for the investigation of Coherent Diffraction Radiation (CDR) from a conducting screen as a tool for non-invasive longitudinal electron beam profile diagnostics has been designed and installed in the Combiner Ring Measurement (CRM) line of the CLIC Test Facility (CTF3, CERN). In parallel, the investigation of Coherent Synchrotron Radiation (CSR) generated mostly in the last bending magnet of the combiner ring is foreseen. The first measurements of CDR and CSR are obtained. In this paper we present the status of the experiment and future plans.

1. Introduction
The longitudinal electron bunch profile is one of the parameters which need to be monitored closely. The optimisation and detailed control of the longitudinal electron distribution in the bunch is crucial for the maximisation of the luminosity in future linear colliders. Close monitoring can prevent luminosity losses due to the hour-glass effect if the bunches are too long, and losses due to the pinch effect if the bunches are too short [1].

The monitoring of the longitudinal bunch profile will also be very important for the Compact Linear Collider (CLIC) [2]. For an optimal performance of the CLIC drive beam, the longitudinal beam profile must be controlled after it has been stretched for injection into the combiner rings and after it has been extracted and compressed. The power extraction in the so-called Power Extraction and Transfer Structures (PETS) also depends on the longitudinal beam profile, a good knowledge of which is highly desirable. According to the last CLIC Instrumentation Workshop more than 200 bunch length measurement stations are required for optimal performance of the machine [3].

Coherent radiation is a widely used tool for monitoring the longitudinal bunch profile. Coherent radiation occurs at wavelengths comparable to, or longer than, the bunch length, when all electrons in the bunch irradiate more or less in phase. The intensity of coherent radiation is proportional to the square of the beam current. The spectral distribution of the coherent radiation contains the information about the electron distribution in the bunch [4, 5]. Coherent Diffraction Radiation (CDR) was suggested as a mechanism for coherent radiation generation due to its non-invasive nature [6, 7, 8].
2. Theoretical background

CDR arises when a charged particle beam passes by in the vicinity of a target. In this case the effect of the beam interaction with the target material is minimal and a smaller perturbation to the beam is produced compared with other diagnostics, such as coherent transition radiation (CTR).

When considering Diffraction Radiation (DR) theory the analogy between the processes of radiation and light scattering is used. The electromagnetic field of a uniformly moving particle represented as a sum of pseudo-photons. Hence, the processes of radiation are reduced to those of the scattering of pseudo-photons off a metal screen [9, 10].

Assuming an electron is traveling along the positive z-direction and the vacuum-metal interface is in the x-y-plane, the DR field is simply a superposition of the real photons created on the target surface and can be described by

\[
E_{x,y}^i(x_s, y_s) = \frac{1}{4\pi^2} \int\int E_{x,y}^i(x_s, y_s) \frac{e^{i\varphi}}{r} dy_s dx_s
\]

where \(E_{x,y}^i\) is the amplitude of the x- and y-polarisation components of DR, respectively, and the integration is performed over the target surface. \(E_{x,y}^i\) is the amplitude originating from an elementary radiation source on the target at a position \((x_s, y_s)\), \(\varphi\) is the phase advance of the photons and \(r\) is the distance from an arbitrary point on the target surface to the observation point with Cartesian coordinates \(\xi\) and \(\eta\).

The amplitude \(E_{x,y}^i\) one needs to substitute into Eq. 1 is just [9, 10]

\[
E_{x,y}^i(x_s, y_s) = \frac{ie k}{\pi \gamma} \left( \frac{\cos \psi_s}{\sin \psi_s} \right) K_1 \left( \frac{k}{\gamma} \rho_s \right)
\]

where \(\rho_s = \sqrt{x_s^2 + y_s^2}\). \(k = 2\pi / \lambda\) is the radiation wave vector, \(\lambda\) is the radiation wavelength, \(\gamma\) is the charged particle Lorentz-factor, \(K_1\) is the first order McDonald function, and \(e\) is the electron charge. A natural unit system is also used, where \(h = m_e = c = 1\) [10].

From a geometrical discussion, \(\frac{e^{i\varphi}}{r}\) can be represented as [10]

\[
\frac{e^{i\varphi}}{r} = \frac{e^{ika}}{a} \exp \left[ \frac{ik}{2a} (x_s^2 + y_s^2) - i k \left( x_s \xi + y_s \eta \right) \right]
\]

Substituting Eq. (3) and Eq. (2) into Eq. (1) one obtains equations for the correct amplitudes and the DR spatial-spectral distribution can be calculated using

\[
\frac{d^2 W^{DR}}{d\omega du} = 4\pi^2 k^2 \left[ |E_{x}^{DR}|^2 + |E_{y}^{DR}|^2 \right]
\]

where \(E_{x}^{DR}\) and \(E_{y}^{DR}\) are the x- and y-polarisation components of DR, and \(du = d\xi d\eta\) is the detector aperture element.

Simulation studies are performed where the target is placed to one side of the electron beam with impact parameter \(h\). The single electron spectrum \(S(\omega)\) for a given target size, particle energy, impact parameter, and detector aperture can be determined by integrating Eq. 4 over the detector aperture.

The integration limits used for this integration are the dimensions of the detector opening along the x and y axis, i.e. \(\xi_{\text{detector}} = 46 \text{ mm}\) and \(\eta_{\text{detector}} = 35 \text{ mm}\). The distance between the detector and the target, \(a = 2 \text{ m}\), and the target size was taken into account, which in the case at the CLIC Test Facility (CTF3) is just \(40 \times 40 \text{ mm}\), which is a projection of the target surface onto the plane perpendicular to the beam trajectory.
A plot of the DR spectra for different particle beam energies and an impact parameter of $h = 20\, \text{mm}$ can be seen in Fig. 1(a). Another investigation is the change of intensity with impact parameter for fixed wavelength, which is shown in Fig. 1(b). It is interesting to note that the intensity for a $15\, \text{mm}$ impact parameter only decreases by a factor of 2 compared to a zero impact parameter. This means that one does not have to worry about the signal levels when keeping the target at a distance from the electron beam. Therefore a working point at $h = 15\, \text{mm}$ is perfectly acceptable for accelerator operation. The spectra calculated by this model will be used for data analysis at a later stage.

Kramers-Kronig relation will be used to derive the longitudinal particle distribution in a bunch [11] from the experimentally obtained form factor

$$\rho^2(k) = \frac{S(k)}{N_e S_e(k)}$$

where $S(k)$ is the experimentally measured coherent diffraction radiation spectrum, $N_e$ is the number of particles in a bunch, $S_e(k)$ is the single electron spectrum calculated in Section 2 and $k = \frac{2\pi}{\lambda}$ is the wavenumber, where $\lambda$ is the wavelength of emitted radiation.

Since $\rho(k)$ is a Fourier transform of the longitudinal particle distribution in a bunch, the normalised bunch distribution function can be determined as

$$S(z) = \frac{1}{\pi} \int_0^\infty dk \rho(k) \cos(\psi(k) - zk)$$

where $z$ is the longitudinal coordinate. The phase factor $\psi(k)$ and the form factor amplitude $\rho(k)$ in Eq. (6) are related by Kramers-Kronig relation so that if the form factor $\rho^2(k)$ is measured at all wave numbers, then the phase factor can be obtained as [11, 12]

$$\psi(k) = -\frac{2c}{\pi} \int_0^\infty dx \frac{\ln(\rho(x)/\rho(k))}{x^2 - k^2}$$

where $x$ is the integration variable in the wave number domain.

Realistically, measuring of $\rho^2(k)$ over the entire wave number interval is practically impossible, therefore it is necessary to extrapolate. At first we replace the integration by summation over the chosen wave number domain, as in the experiment we will have a number of discrete
spectral points. We suggested the longitudinal charge distribution, \( S_{\text{ideal}}(z) = \frac{\exp\left(-\frac{z^2}{2\sigma_1^2}\right)}{4\sqrt{2\pi}\sigma_1} + \frac{3\exp\left(-\frac{(z-z_0)^2}{2\sigma_2^2}\right)}{4\sqrt{2\pi}\sigma_2} \), where \( z_0 = 1.2 \text{ mm} \), \( \sigma_1 = 0.3 \text{ mm} \), and \( \sigma_2 = 0.45 \text{ mm} \). The calculated form factor \( \rho^2_{\text{calc}}(k) \) is presented in Fig.2(a). The data area confined within the two vertical lines was assumed to be a given data set (from 1.3 to 4.6 \( \text{mm}^{-1} \)). For the interpolation between the form factor data points the following function was applied:

\[
\rho^2_{\text{int}}(k) = \sum_{n=0}^{N} \rho^2(k_n) \exp\left(-\frac{(k_n - k)^2}{2\sigma^2}\right)
\]

where \( \rho^2(k_n) \) is the form factor data and \( \sigma \) is the smoothing parameter for the reconstruction presented in Fig.2. To avoid significant smoothing of the data, \( \sigma \) was chosen to be \( \frac{\Delta k_n}{3} \), where \( \Delta k_n = k_n - k_{n-1} \).

For the low wave number extrapolation the following extrapolation function was used [13]:

\[
\rho^2_{\text{low}}(k) = \rho^2_{\text{int}}(k_0) \exp(-ak^2 + bk + c)
\]

with \( a = (\ln \rho^2_{\text{int}}(k_0) - k_0^2) \frac{s}{\rho^2_{\text{int}}(k_0)} \frac{1}{k_0^2} \), \( b = \frac{s}{\rho^2_{\text{int}}(k_0)} + 2ak_0 \), \( c = -\ln \rho^2_{\text{int}}(k_0) \), where \( \rho^2_{\text{int}}(k_0) \) is the interpolation function value corresponding to the lowest wave number, \( k_0 \) is the lowest wave number and \( s \) is the slope derived from the interpolation function: \( s = \frac{\rho^2_{\text{int}}(k_4) - \rho^2_{\text{int}}(k_0)}{k_4 - k_0} \).

The following function was used to extrapolate towards large wavenumbers:

\[
\rho^2_{\text{large}}(k) = \exp(-\beta k^2 + \gamma k + \delta)
\]

where \( \beta, \gamma, \delta \) are chosen to smoothly join the larger wave numbers. \( \rho^2_{\text{large}} \) should match the data at the largest wave number and both the first and second derivatives of \( \rho^2_{\text{large}} \) should match the first and second derivatives of \( \rho^2_{\text{int}} \) at the largest wave number.

Figure 2. (a) Calculated bunch form factor, when interpolation and extrapolation functions were applied. (b) Phase reconstruction. (c) Initial and reconstructed longitudinal charge distributions.

The bunch profile and the phase reconstruction are presented in Fig.2(c) and Fig. 2(b), respectively, when extrapolation procedures to lower and larger wave numbers, as shown in Fig.2(a), were applied. A comparison of the reconstructed bunch profile with the initial bunch profile provides information about the accuracy of the extrapolation methods. As seen from
Fig. 2(c), the reconstructed bunch length and the amplitude agree fairly well with the original distribution, even though the method is not completely sensitive to the left non-dominant peak of the initial pulse.

It is worth noting, that a sufficiently large spectral detector coverage is very important when we want to apply extrapolation. If the spectral range is too short, especially towards larger wave numbers, the method does not reconstruct the minimal phase accurately enough to be able to detail the trailing structures that follow the dominant peak.

3. Experimental setup

The CDR setup is installed in CTF3 [2]. CTF3 aims to demonstrate the feasibility of the CLIC two-beam acceleration scheme and other necessary components including non-invasive bunch length measurements. CTF3, as seen in Fig. 3(a), consists of a linac producing a 125 MeV electron beam, a Delay Loop (DL), a Combiner Ring (CR) and the CLIC Experimental Area (CLEX) where measurements are carried out to prove the feasibility of CLIC. The DL and CR are used to interleave and combine the electron beam to produce a high current electron beam with a bunch sequence frequency of 12 GHz. For the CDR setup, the DL after the linac is bypassed and the beam is injected into the CR. After the first bending magnet in the CR, an extended straight section can be found, which is the CR Measurements (CRM) line. A schematic layout of the CRM line with a section of the CR can be seen in Fig. 3(b).

Two ultra-high vacuum (UHV) six-way crosses form our vacuum vessel. The inner diameter of the six-way crosses is 95.7 mm. The target is a 60 mm × 40 mm × 300 µm silicon wafer coated with aluminium and is placed to one side of the electron beam with impact parameter h. The target is attached to the shaft of a 4D UHV manipulator, which is mounted on top of the downstream cross and provides precise remote control of the rotational and vertical translation axis. The manipulator is equipped with stepper motors which provide a single step precision, relating to a 0.004° and 1 µm rotational and translational precision, respectively. The motors are driven and monitored with a BALDOR NextMove e100 motion controller via custom cable connections. The vacuum output window is a fused silica vacuum window, which is transmissive for mm and sub-mm radiation, with a viewing diameter of 40 mm. The adjacent viewport is a standard Kodial window with a viewing diameter of 38 mm and is only used for alignment purposes. Both viewports are attached to the six-way cross through 150-to-70 mm OD adapter flanges.

The radiation originating from the target is translated vertically with a periscope to avoid backgrounds from the horizontal particle beam plane. On an optical table the Michelson...
interferometer is installed and the reference working point is at a height of 5 inch (127 mm) above the table surface.

The mirrors (M1 and M2 in Fig. 3(b)) are broadband aluminium coated mirrors with a diameter of 4 inch (101.6 mm). Two axes of each mirror holder can be controlled with fine adjustment screws, which can potentially be motorised.

Mirror M2 is mounted on top of a translation stage. The translation stage has a travel range of 150 mm, a resolution of 0.1 \( \mu \)m, a minimum incremental motion of 0.3 \( \mu \)m, and a unidirectional repeatability of 1 \( \mu \)m. The translation stage is interfaced with a controller which can be accessed via a RS232 serial connection.

In order to align the interferometer an optical laser alignment procedure is used. A HeNe laser is stably mounted on the adjacent side of the beam line and directed into the six-way cross through the Kodial viewport. The laser then resembles the path of radiation originating from the target. The mirrors are then adjusted locally to obtain circular fringes produced by the interferometer. Even a rough alignment with an optical laser will be nearly perfect for millimetre waves.

![Diagram of interferometer](image)

**Figure 4.** Comparison of efficiencies for different thickness for Kapton films (a,b) and an example CDR signal (c)

A 50 \( \mu \)m Kapton film was used as a splitter. The efficiencies of the splitter are represented in Fig. 4(a) and 4(b). From the studies it was concluded that the best compromise between splitter efficiency and linearity for commercially available films was for a 50 \( \mu \)m Kapton film [14, 15].

The detectors are based on ultra fast Schottky barrier diodes (SBD) (with response time typically around 250 ps). All SBD detectors used are polarisation sensitive and one can only measure one polarisation at a time. High quality RF cables with a bandwidth of 10 GHz are used to transport the signal. The detector used at the moment is sensitive in a wavelength region from 2.14 mm to 3.33 mm (90 - 140 GHz) with an average sensitivity of around 1000 mV/mW. An example signal of DR is shown in Fig. 4(c). It can be seen that for a fairly constant beam current the DR intensity varies significantly. It suggests that the longitudinal electron distribution throughout the train is non-uniform and the detector can be used for machine tuning.

The data acquisition is performed with a 10-bit Acqiris DC282 digitiser. The DC282 offers synchronous four channel sampling at up to 2 GS/s, or interleaved dual- or single-channel sampling at up to 4 and 8 GS/s respectively. The input for an external trigger provides a
precise synchronisation to the electron gun trigger. The internal acquisition memory of the digitiser is 256 kSample/channel and is large enough to theoretically store around 100 bunch trains of 1.4\(\mu\)s length.

4. Experimental results

With the CDR setup in the CRM line, DR and Synchrotron Radiation (SR) can be measured. With the bending magnet turned on and the electron beam circulating in the combiner ring, SR can be observed. The target is therefore lowered and used as a mirror to direct SR into the detector. For DR measurements the magnet is simply turned off. After the CDR setup and the OTR screen, the beam is terminated in the CRM beam dump.

According to theory (cf. Fig. 1(b)) the CDR intensity must decrease monotonically as a function of impact parameter. The impact parameter dependance of the signal for two different beam trajectories was investigated. Fig. 5(a) shows the dependance for the beam on the CRM reference orbit, i.e. the beam is centred in the beam pipe, and Fig. 5(b) illustrates the dependance for the beam lowered by 7 mm in the CRM line by a vertical corrector in the CR.

As there are two different screens available in the OTR station behind the CDR setup - a semitransparent silica screen and high-reflective aluminised silica screen - the influence of the two different screens was also studied. For the nominal beam orbit, upon changing the OTR screens behind the setup a change in CDR intensity was observed. The different intensities can be explained by reflections of transition radiation within the UHV hardware as outlined in Fig. 5(c). Transition radiation emitted by the two OTR screens and the aluminium UHV flange of the beam dump contribute to the CDR signal.

![Image](image_url)

(a) Impact parameter dependance for nominal beam operation in the CRM line

(b) Impact parameter dependance for a lowered beam in the CRM line

(c) Schematic drawing explaining the origin of the backgrounds

**Figure 5.** Dependence of the CDR signals on the impact parameter and OTR screens behind for different beam positions in the CRM line.

For low impact parameters and an OTR screen inserted, the contribution to the CDR signal is dominated by the OTR screens. For large impact parameters the contribution is dominated by the beam dump UHV flange when none of the OTR screens are inserted.

For the beam lowered in the CRM line, the impact parameter dependance is shown in Fig. 5(b). When no screen or the semitransparent screen is inserted the signal agrees fairly well with the expected impact parameter dependance. However, the aluminised silica screen shows a contribution to the signal for large impact parameters, which can be explained by the vertical position of the CDR target. For small impact parameters the target is lowered further in the beam line and the reflected TR is simply blocked which manifests itself in the convergence of the signals and a monotonic signal increase for decreasing impact parameters.
To be able to block the reflected background completely we are planning to design and install an off-centre adapter flange, as discussed in Section 5. This upgrade is very important to continue the CDR measurements.

SR measurements were also performed and therefore the target edge is 1 mm below the beam pipe centre. As expected, the CSR distribution is a single peak distribution, as seen in Fig. 6(a). The maximum intensity found during the rotation scan was the mirror reflection direction and the angle of mirror reflection was used as the working point.

The first interferogram is shown in Fig. 6(b). The target was placed at an orientation angle of 34.0° and a vertical position of 0 mm. The CSR signal is integrated over a small part of the bunch train - typically 50 ns - as the longitudinal profile is fluctuating quite significantly throughout the train. For each translation stage position, the arithmetic mean of the integrated CSR intensity is taken over 10 bunch trains. It was chosen to average over 10 bunch trains as this is a good compromise between statistics and the stability of the electron beam.

![Graphs](image)

(a) Rotation dependance  
(b) Interferogram  
(c) Spectrum

Figure 6. a) CSR Interferogram and b) corresponding spectrum

From the interferogram in Fig. 6(b), the corresponding spectrum can be found performing a discrete Fourier transform. As the interferogram is expected to be symmetric about the zero path difference a discrete Cosine transform was performed. The resulting spectrum is shown in Fig. 6(c). One may see that the CSR spectrum is rather narrow. To be able to perform Kramers-Kronig analysis we shall perform measurements using a few SBD detectors in the near future.

5. Conclusion and outlook

In this paper we have presented the status of the CDR longitudinal beam profile monitor development in CTF3 at CERN. We have designed and installed the vacuum hardware, the Michelson interferometer system, and we have also developed the data acquisition and hardware control software. The first CSR and CDR signals were observed using an ultrafast SBD detector. For a fairly flat charge distribution throughout the train, we observed a signal variation which suggests that there is a bunch-by-bunch longitudinal profile fluctuation in the train.

The first CSR interferometric measurements have been performed with the system and the first CSR spectra are obtained. As described above, the spectra need to be normalised with respect to various spectral hardware dependencies and the single electron radiation spectrum. Thereafter the longitudinal bunch profile will be reconstructed using Kramers-Kronig relation. The experience gathered from parasitic synchrotron radiation studies will be transferred to CDR interferometric measurements which are scheduled after an upgrade.

Unfortunately, a significant background in the CRM line did not allow us to perform proper CDR interferometric measurements. To exclude the background the system will be modified. This can be achieved by installing an off-centre adapter flange. As the study of the background
suggests, a vertical off-set of this inner bore by +15 mm would allow for the backgrounds to be minimised while still being able to align the interferometer with a laser through the adjacent viewport. Such an off-centre flange has been designed and manufactured at the CERN workshop, and is due for installation in the near future.

In January/February 2010 we intend to install a second target in order to block the upstream background radiation.

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