Investigation of Coherent Diffraction Radiation from a Dual Target system at CTF3.

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Abstract. A Coherent Diffraction Radiation (CDR) experiment was built at the CLIC Test Facility 3 at CERN. Two silicon wafers are positioned on one side of the beam and the CDR radiation originating from them is translated towards the Michelson Interferometer. We have demonstrated that the first target cuts off the backgrounds, generated by the beam from upstream of the experimental setup. The results of the theoretical and experimental investigations of the CDR from the two targets and a work towards longitudinal diagnostics of sub-picosecond electron bunches is presented. The radiation spatial distribution measurements were performed and compared with the theory. A capability to obtain interferometric measurements of CDR at the experimental setup was proven. Bunch shape instabilities at CTF3 were investigated, as well.

1. Introduction
A novel scheme for the drive beam generation has been proposed for the future Compact Linear Collider (CLIC), in which a long bunch train with a low bunch repetition frequency will be accelerated with a low RF frequency and, then, recombined to increase the bunch repetition frequency from 1.5 GHz to 12 GHz. The optimisation and monitoring of the longitudinal charge distribution in the bunch is crucial for an optimal performance of the CLIC drive beam as well as for maximization of the luminosity at the CLIC interaction point [1].

Diffraction Radiation (DR) is a physical phenomenon occurring when a charged particle moves in the vicinity of a conducting screen. The coulomb field of the particle interacts with the screen and surface currents are produced, which become a source of the DR. The first theoretical approach to the DR was developed in 1950s, however, the first experimental investigations were performed only in 1995 by Shibata et al. [2]. Using an electron beam with the energy of 150 Mev, the DR was generated by a circular aperture in millimetre and submillimetre wavelength regions.

The DR generated from conducting screens has been experimentally investigated in the last 15 years [3, 4, 5] and it was proven to be very promising tool for the longitudinal [6, 7] and transverse [8, 9] diagnostics of electron beams. The main advantage of DR compared to transition radiation, for instance, that it does not affect the beam. Other important property of this physical phenomenon is instantaneous emission, which makes it possible to perform single shot, time resolved measurements. Experiment-wise, one is interested in observation of the Coherent
Diffraction Radiation (CDR), which is $N$ times more intensive than incoherent radiation, where $N$ is the number of particles in the beam. The coherence of the effect is achieved when electrons in a bunch radiate in phase, i.e. the wavelength of radiation is comparable or larger than the bunch length.

At the CLIC Test Facility 3 we have built an experimental setup based on the CDR from a dual target system. Two silicon wafers, coated with aluminium, are positioned on one side of the beam and the radiation, generated from them, is transferred towards the Michelson interferometer. The upstream target serves as a barrier for the Coherent Synchrotron Radiation (CSR) backgrounds coming from upstream of the experimental setup (see figure 1). The ultimate goal of the experiment is to reconstruct longitudinal parameters of the bunch from the spectral measurements obtained at the Michelson interferometer. In the current configuration of the setup ultra-fast Schottky Barrier Diode (SBD) detectors are used for the spectral measurements. The intensity of the CDR is defined by the following equation:

$$S(\omega) = S_e(\omega)N^2F(\omega),$$

where $S(\omega)$ is the measured spectrum, $S_e(\omega)$ is the single electron spectrum which has to be predicted precisely, $N$ is the number of electrons in the bunch, $F(\omega)$ (the goal of the measurements) is the bunch form factor which contains information about the longitudinal distribution of electrons in the bunch.

![Figure 1. Schematic layout of the Dual Target System at CTF3. FDR - Forward Diffraction Radiation; BDR - Backward Diffraction Radiation; CSR - Coherent Synchrotron Radiation.](image)

In this paper we concentrate on the investigation of the CDR from a dual target configuration. A theoretical model, based on the Classical Diffraction Radiation theory, was developed to investigate a geometry of the DR spatial distribution generated by a single electron while interacting with the targets. The CDR spatial distributions were obtained using the two SBD detectors and the measurements were compared with the theory. In order to understand the background contribution in the experimental data better, the dedicated measurement of the CSR reflection from the downstream target was performed. A capability to obtain interferometric measurements of CDR at the experimental setup was proven. Bunch shape instabilities at CTF3 were also investigated.

2. Calculation of Coherent Diffraction Radiation from the dual target system

A detailed description of the theoretical model was presented in [10]. In this section the model and the key dependences, used for the comparison with our experiment, are shown. For the calculations we shall use a classical theory of Diffraction Radiation, based on Huygens principle of plane wave diffraction. In reality the classical DR theory describes backward DR only. However, for a metallic foil and millimetre wavelengths we can use an ideal conductor approximation. In this case backward DR (BDR) characteristics coincide with forward DR (FDR) ones. A particle...
field is introduced as a superposition of its pseudo-photons and when they are scattered off a target surface, they are converted into the real ones and propagate either in the direction of a specular reflection (BDR) or along the particle trajectory (FDR).

Consider an electron moving along the z-axis. Each point of the target surface can be represented as an elementary source of the radiation. Two polarization components of the DR can be represented as a superposition of the waves from all elementary sources at a distance r from the target [11]:

\[
E_{r,\text{DR}}(x, y) = \frac{1}{4\pi^2} \iiint E'(x', y') \frac{e^{ik|r|}}{r} dx' dy'.
\]  

(2)

\(E'(x, y)\) is the amplitude of the radiation source positioned on the target surface, \((x, y)\) are the coordinates of the radiation source on the target surface, \(r\) is the distance from the radiation source at the target to the observation point and \(k\) is the wavenumber.

The process of the CDR emission is considered in two main steps: firstly, propagation of the FDR from the first target towards the second one, diffraction at the second target and propagation towards the observation plane, and secondly, propagation of the BDR from the second target towards the observation plane (see figure 1). The DR spatial distribution in general form can be written as:

\[
d^2W_{\text{DR}} = \frac{4\pi^2 k^2 a^2}{4\pi^2} \left( |E_{x,\text{DR}}|^2 + |E_{y,\text{DR}}|^2 \right),
\]  

(3)

where \(E_{x,\text{DR}}\) and \(E_{y,\text{DR}}\) are the horizontal and vertical polarisation components of \(E_{r,\text{DR}}\), respectively.

Once the two radiation components are obtained, we can derive the DR distribution from the two targets. We observe interference between the BDR from the second target and the FDR from the first target, therefore the following formula for the radiation spatial distribution is applied:

\[
d^2W_{\text{DR}} = \frac{4\pi^2 k^2 a^2}{4\pi^2} \left[ \left( ReE_{r,\text{1}} - Re \left[ E_{r,\text{2}} \exp \left( \frac{ikd}{\beta} \right) \right] \right)^2 
+ \left( ImE_{r,\text{1}} - Im \left[ E_{r,\text{2}} \exp \left( \frac{ikd}{\beta} \right) \right] \right)^2 \right],
\]  

(4)

where \(E_{r,\text{1}}\) is the FDR from the first target diffracted from the second one and \(E_{r,\text{2}}\) is the BDR from the second target, \(r_1, r_2\) are the surfaces of the targets, \(\beta = v/c\) is the speed of an electric charge in terms of the speed of light, the exp \((ikd/\beta)\) defines the phase delay due to the particle moving from the first target to the second one, \(a\) is the distance from the second target to the observation plane and \(d\) is the distance between the targets.

Understanding of the radiation distribution geometry is crucially important for the optimisation of the experimental setup. In the current configuration the two targets are positioned on one side of the beam, therefore the fields of the DR interfere with each other. The CDR distributions as functions of the second target impact parameter and the horizontal coordinate at the observation plane were calculated for the two main configurations of the experiment. In the first configuration the impact parameter of the first (upstream) target is at 30 mm from the beam and the second target impact parameter is variable in the region of 10 to 30 mm. In the second configuration the first target impact parameter is 10mm and, as in the first configuration, the second target impact parameter is variable in the region of 10 to 30 mm.

In figures 2 and 3 the vertical polarisation component of the CDR spatial distribution is presented for the two main configurations of the setup, the distributions were calculated for the parameters shown in table 1. In figure 2 the radiation distribution was calculated for the first
configuration of the targets as a function of the second target rotation and impact parameter. In figure 3 the CDR distribution was calculated for the second configuration of the targets as a function of the second target rotation and impact parameter. Zero degree rotation in the figures corresponds to the mirror reflection from the downstream target. The distributions have a single mode nature and the radiation intensity decreases while the second target is gradually lifted up, i.e. $h_2$ increases. In figure 3 the maximum intensity is suppressed by approximately 50% due to the destructive interference between the targets.

![Figure 2. Vertical polarisation of the CDR distribution for the first configuration of the targets. The first target impact parameter $h_1 = 30$ mm.](image1)

![Figure 3. Vertical polarisation of the CDR distribution for the second configuration of the targets. The first target impact parameter $h_1 = 10$ mm.](image2)

3. Experimental investigation of the CDR from a Dual Target system

3.1. Experimental setup

The experimental setup is located at the Combiner Ring Measurements (CRM) line of the CLIC Test Facility 3 (CTF3). The CRM line is a straight section deviated from the first quarter of the Combiner Ring (figure 4). Once the bending magnet, located at the entrance to the CRM line, is switched off, the beam is directed straight into the beam dump passing the dual target system and the CDR from the targets can be observed. If the bending magnet is switched on, the CSR, generated upstream of the experimental setup, can be reflected by the downstream target and measured by the same detection system.

Two six-way crosses are installed in the CRM line, they contain two targets, which are positioned above the beam at 45deg with respect to the beam propagation direction. The targets are silicon wafers coated with aluminium. They are mounted on the Ultra High Vacuum (UHV) manipulators, which provide the vertical translation and rotation of the second target and a vertical translation of the first target.

The radiation, originated from the targets or reflected from them, is transferred through a CVD diamond window with a viewing diameter of 30 mm. Diamond exhibits a broadband transparency in the far-infrared and millimetre wavelength range. The CVD window has a thickness of 0.5 mm, which is smaller than or comparable to the observation wavelength and, therefore, the viewport absorption and the distortion of the transmitted radiation spectrum due to multiple reflections are minimized. The radiation, originated from the targets, is translated vertically by a periscope towards the floor to avoid X-ray backgrounds from the horizontal particle beam plane. On the optical table a Michelson interferometer is installed (see figure 5).

The polariser (P1) transmits the vertical polarisation component towards the interferometer and reflects the horizontal polarisation component toward the second detector, positioned
Figure 4. Schematic layout of the CLIC Test Facility 3.

Figure 5. Schematic layout of the CDR experiment.

Table 1. CTF3 and CDR experiment parameters.

| Parameter                                      | Value | Unit |
|------------------------------------------------|-------|------|
| Beam energy ($\gamma$)                        | 235   |      |
| Bunch charge                                  | 2.3   | nC   |
| Bunch spacing frequency                       | 3     | GHz  |
| Target dimensions (projected)                 | 40x40 | mm   |
| Observation wavelength ($\lambda$)            | 5     | mm   |
| First target impact parameter ($h_1$) (upper position) | 30   | mm   |
| First target impact parameter ($h_2$) (lower position) | 10   | mm   |
| Second target impact parameter ($h_2$)        | 10    | mm   |
| Distance between the targets ($d$)             | 0.25  | m    |
| Distance from the second target to the observation plane ($a$) | 2    | m    |

beside the interferometer and used for bunch shape instability studies. The parameters of the experimental setup and CTF3 are presented in table 1.

In the experiment the ultra fast Schottky barrier diode (SBD) detectors with a response time less than 1ns are used to measure power in the narrow frequency ranges. The detectors are sensitive in 50 - 75 GHz (DXP15) and 60 - 90 GHz (DXP12). They are polarisation sensitive and only one detector can be used at a time for the interferometric measurements.

Data acquisition is performed using a 10-bit Acqiris DC282 digitiser. The digitiser can provide four channel sampling at up to 2 GS/s, or dual and single-channel sampling at 4 GS/s and 8 Gs/s, respectively. In the current configuration 4 GS/s sampling for two channels is used. An external trigger provides a precise synchronisation with the electron beam. The data is read out for every single bunch train and transferred to the digitiser through high quality RF cables.

3.2. Measurements of the CDR spatial distribution

In the experimental setup the radiation is transferred through a periscope mirrors towards the optical table where it is split into two polarisation components, the vertical component is translated towards the beam splitter and further on, when recombined, towards the detector in the interferometer. In order to understand the spatial geometry of the radiation detected in the
interferometer, the measurements of the CDR spatial distributions as functions of the second target rotation angle and the impact parameter were performed for the two main configurations of the experimental setup. For the first configuration the first (upstream) target is located 27 mm away from the beam, the second target position is in the range of the discrete points of 7 to 25 mm away from the beam. Later on, the scan is normalized by the current. The similar scan is performed for the second configuration of the setup when the first target is 7 mm away from the beam.

In figure 6 the CDR distribution for the first configuration, measured by the detector sensitive in 50-75 GHz, is presented. The second target travelling range in the horizontal plane is from 7 to 23 mm. It has a single mode shape. The distortions caused by the backgrounds coming from the upstream of the experimental setup are seen in the scan. Figure 8 demonstrates the radiation distribution for the same configuration, but measured using the SBD detector sensitive in 60-90 GHz spectral range. The second target travelling range in the horizontal plane is from 7 to 25 mm. When compared with the distribution in figure 6, the latter scan shows a smoother radiation distribution, most likely due to the milder background conditions at the time of the measurement.

![Figure 6. Vertical polarisation of the CDR distribution measured by DXP15 detector. The first target impact parameter $h_1 = 27$ mm.](image1)

![Figure 7. Vertical polarisation of the CDR distribution measured by DXP15 detector. The first target impact parameter $h_1 = 7$ mm.](image2)

In figures 7 and 9 the first target is positioned 7 mm away from the beam, consequently the intensity of the radiation decreases as a result of destructive interference between the two targets. In this configuration the first target also serves as an obstacle for the coherent backgrounds coming from the upstream.

The distributions for the first and the second target configurations qualitatively agree with the theoretical calculations: figures 6 and 8 correspond to the theoretically calculated distribution in figure 2; figures 7 and 9 can be compared with figure 3. The theoretical CDR distributions were calculated for the wavelength $\lambda = 5$ mm. The detectors in use sensitive and demonstrate a flat frequency response in the following wavelength regions: DXP15(4-6 mm) and DXP12(3.33 - 5 mm). In the region of 3.33 - 6 mm the CDR spatial distribution does not change considerably and, therefore, the radiation distribution calculated for $\lambda = 5$ mm can be compared with the experimental results. All four experimental scans demonstrate a general agreement with the theory: they have a single mode nature, the maximum intensity of the radiation decreases when the first (upstream) target is positioned closer to the beam and the intensity of the CDR gradually decreases while the second target impact parameter increases. However, in figure 6 one may see the asymmetry in the distribution, as compared with the experimental result in
figure 8 and theoretically calculated CDR distribution in figure 2, which is yet to be understood.

Figure 8. Vertical polarisation of the CDR distribution measured by DXP12 detector. The first target impact parameter $h_1 = 27$ mm.

Figure 9. Vertical polarisation of the CDR distribution measured by DXP12 detector. The first target impact parameter $h_1 = 7$ mm.

4. **Coherent Synchrotron Radiation backgrounds**

Coherent backgrounds coming from the upstream of the experimental setup significantly complicate the experimental data interpretation. A dedicated measurement of the Coherent Synchrotron Radiation (CSR) reflection from the downstream target was performed. At a time of the measurement the bending magnet at the entrance to the CRM line was switched on, so the beam circulated in the Combiner Ring and generated CSR, which propagated into the CRM line.

The configuration of the setup makes it possible to measure the reflection of the CSR from the second target. By rotating it one can measure the intensity of the radiation as a function of the rotation angle. When the upstream target is at its highest position, it is far from the center of the six-way cross and does not block the CSR. However, when it is gradually lowered down a portion of the oncoming radiation is cut off and not reflected towards the detector.

In figure 10 the four rotation scans of the CSR reflection are presented. The red curve shows the CSR reflected from the second target when the first target is at its highest position and the second target in the centre of the six-way cross. The green curve corresponds to the configuration of the setup when both targets are at the centre of a six way cross and the maximum CSR suppression should be achieved. It is clearly seen that intensity suppression with the factor 5 achieved by positioning the first target in the centre of the beam pipe, however, some intensity is still observed for this configuration. This might be due to the residual reflections in the coupled six-way crosses. The residual part of the CSR background can be reduced by putting the targets closer together.

5. **Interferometric measurements**

The Michelson interferometer is used to perform spectral measurements of the CDR, originated from the targets. The measurements are performed in the following way: a detector in the interferometer registers vertical polarisation component of the radiation; the DAQ system reads out a signal from the detector for each train of bunches; an interferometric scan is performed by moving the mirror M1 (figure. 5) on the translation stage; three to ten signal readouts per position of the M1 are performed to collect statistics. A length of the interferometric scan can
vary and it was limited to the maximum travelling range of the translation stage (100mm for UTS100 stage, which was used in the measurements).

Each point of the interferogram is obtained by calculating an average integrated intensity of the CDR radiation over a number of shots, obtained for each position of the moveable mirror in the Michelson interferometer using the DXP15 detector. The integration for each signal is performed over a narrow slice of the pulse (approximately 25 ns), this was done because the bunch length variation throughout the train is rather severe. A sample interferogram, obtained while both targets are at the same distance from the beam, is presented in figure 11. A sample signal of the detected radiation with the marked integration region is presented in figure 12.

![Figure 10. The rotation scans of the CSR reflection from the second target.](image)

![Figure 11. A sample interferogram obtained for the dual target system: \( h_1 = h_2 = 7 \) mm.](image)

![Figure 12. A sample signal from the DXP15 detector.](image)

The measurement was performed using DXP15 detector when both target were at 7 mm from the beam; the stage traveling range for the measurement was \( x = 30 \) mm which resulted in the path difference of \( z = 2x = 60 \) mm and the corresponding signal delay in the interferometer of \( T = z/c = 200 \) ps. This yields the maximum spectral resolution of 5 GHz. The resulting spectrum is shown in figure 13, where the red line marks a low frequency cut-off, defined by the
detector. The DXP15 detector is sensitive in 50-75 GHz, which gives five spectral data points in this frequency region. Due to a very narrow frequency region where the data were obtained, this measurement has a very limited applicability for a bunch profile reconstruction.

Figure 13. Spectrum obtained from the interferogram in figure 11.

A bunch length stability along the train is a key to successful spectral measurements. When the bunch length vary along the pulse, the CDR is generated at different wavelengths from different parts of the pulse, therefore complicating the result interpretation. Additional problematic issue is instability of a bunch shape. At CTF3 bunch length manipulations are performed before the beam is inserted into the recombination rings and after it is extracted from them. In the linac section of CTF3 the bunch length is in the region of 1 to 7 ps, then the beam is directed through the stretching chicane where the bunches are stretched up to 15 to 20 ps to achieve an effective recombination in the Delay Loop and the Combiner Ring. Later on, the bunches are shortened to 1-2 ps to achieve an effective RF transfer in the Power Extraction and Transfer Structures (figure 4). When the beam goes through the Frascati chicane the bunches can become distorted and micro-bunching structures can occur, which results in distortion of the signals, obtained using the high frequency SBD detectors.

Overall, the experimental setup was proved to be capable of taking interferometric data despite significant bunch shape instabilities and the RF drifts in the machine. An immediate solution of a bunch shape variation problem could be installation of the low frequency detectors, which would be less sensitive to the changes of a bunch shape.

6. Conclusions
In this paper we have presented the results on the investigation of the CDR from the dual target system at CTF3. The theoretical model, based on the Classical Diffraction Radiation theory, was developed to theoretically calculate the radiation spatial distributions. The experimental spatial distributions were measured at the CDR setup and demonstrated a general agreement with the theory. Additional studies of the CSR contribution into the measurements were performed as well. Installation of the second target made it possible to effectively cut off a dominant part of the backgrounds coming from the upstream of the experimental setup.

The ultimate goal of the experiment is to reconstruct longitudinal parameters of the bunch from the interferometric measurements obtained at the Michelson interferometer. The experimental results showed that the interferometric measurements can be performed with
the new two-target configuration. However, limited bandwidth of the detectors in use limits applicability of the spectral measurements for the longitudinal bunch profile reconstruction.

Bunch length and shape instabilities and their influence on the measurements were discussed. A clear understanding of the problematic issues and the hardware constraints was achieved. The ways towards the further development of the experimental setup were identified: firstly, usage of low frequency detectors with a broader bandwidth to suppress the influence of a bunch shape variation and, secondly, as a more long term-solution, shot-by-shot measurements and installation of a grating spectrometer.

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