Longitudinal beam profile monitor at CTF3 based on Coherent Diffraction Radiation

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Outline

1. Introduction
2. Theory & Simulation
3. Setup & Hardware
4. Experimental results
5. Conclusion & Outlook
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What is CLIC?
Brief overview and description of CLIC

Compact Linear Collider (CLIC)

- Study of future $e^+e^-$-collider based on room temperature acceleration scheme
- Coupled RF cavities transfer the power from a low energy, high current drive beam to a high energy, low current probe beam (i.e. a 30 km long "klystron").
- Would potentially allow for higher accelerating gradient and proposed Centre-of-Mass energy of 3 – 5 TeV.
What is CTF3?
Brief description of CTF3 and its purpose

CLIC Test Facility 3

- Test accelerator at CERN to demonstrate the feasibility of the CLIC concept
- Test PETS (Power and Extraction Structures) at the nominal gradient and pulse length (100 MV/m for 70 ns)
- Generation of high charge, high frequency electron bunch trains by beam combination in a ring using transverse deflectors
- Diagnostics tools needed for CLIC \( \Rightarrow \) Coherent Diffraction Radiation
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Coherent Radiation

Coherent Radiation can be used to obtain the longitudinal bunch profile

Coherent Radiation

- In particle accelerators, this is mostly Coherent Synchrotron Radiation (CSR), Coherent Transition Radiation (CTR) and Coherent Diffraction Radiation (CDR)

\[ S(\omega) = [N_e + N_e(N_e - 1) F(\omega)] S_e(\omega) \]

- \(N_e S_e(\omega)\) is the incoherent part
- \(N_e(N_e - 1) F(\omega) S_e(\omega)\) is the coherent part

- \(S(\omega)\) is the signal, known from the experiment
  - This can be obtained by using an interferometer

- \(S_e(\omega)\) is the single electron radiation, which should be predictable from theory
- \(N_e\) is the number of electrons, known from the experiment
  - Can be measured using the charge reading of a beam position monitor

- \(F(\omega)\) is the longitudinal bunch form factor, which is the measurement purpose.
  - The bunch form factor is just the Fourier transform of the spatial charge distribution if the transverse size is smaller than \(\frac{\gamma \lambda}{2\pi}\) (which is the case for CDR setup at CTF3).

- The longitudinal bunch profile can therefore be reconstructed
- Phase information can be obtained by Kramers-Kronig reconstruction analysis
Introduction  Theory & Simulation  Setup & Hardware  Experimental results  Conclusion & Outlook

Diffraction radiation theory

Scattering of pseudo-photons

- Electromagnetic field of the moving charged particle considered as pseudo photons
- The DR field (at some distance from the target) is a superposition of the real photons created on the target surface

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

(1)

- Need to substitute for the amplitude \(E_{x,y}^i\) of every point source:

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

(2)

- \(\rho_s = \sqrt{x_s^2 + y_s^2}, x_s = \rho_s \sin \psi_s, and y_s = \rho_s \cos \psi_s [(x_s, y_s) \leftrightarrow (\rho_s, \psi_s)]\)
- \(k = 2\pi/\lambda\) is the radiation wave vector, \(\lambda\) is the Backward DR (BDR) wavelength, \(\gamma\) is the charged particle Lorentz-factor, \(K_1\) is the first order McDonald function, and \(e\) is the electron charge
- \(h = m_e = c = 1\)

- From a geometrical argument:

\[
e^{i\varphi} \frac{1}{|r^a|} = \frac{e^{ika}}{a} \exp \left[ \frac{ik}{2a} \left( x_s^2 + y_s^2 \right) - \frac{ik}{a} (x_s \xi + y_s \eta) + \frac{ik}{2a} \left( \xi^2 + \eta^2 \right) \right]
\]

(3)
Simulation studies

Diffraction radiation simulations

Diffraction radiation spatial distribution from a semi-halfplate

\[
\frac{d^2 W^{DR}}{d\omega d\Omega} = 4\pi^2 k^2 a^2 \left[ |E_x^{DR}|^2 + |E_y^{DR}|^2 \right]
\]

where \( E_x^{DR} \) and \( E_y^{DR} \) are the \( x \)- and \( y \)-polarisation components of DR.

- Simulations done for one single half target
- Parameters for the setup at CTF3 are used:
  - Target dimension \( 40(60) \times 40 \text{ mm} \)
  - Beam energy \( \gamma = 235 \)
  - Distance from target to detector \( a \approx 2 \text{ m} \)
  - Wavelength \( \lambda \) depending on the detector

Future target configuration

- Second target will be added in 2010
- Simulations will be carried out to account for the second target
Simulation studies

Diffraction radiation simulations

### Diffraction radiation spectra with $I_{\text{max}}^{TR} = \frac{\alpha \gamma^2}{4\pi^2}$

- Needed in the de-convolution of the spectral information
- $S(\omega) = N_e^2 F(\omega) S_e(\omega)$

### Intensity dependence on impact parameter ($\gamma = 235$)

- At a considerable distance from the beam the signal level is still high
- **non-invasive measurements**

### Diffraction radiation spectra for different beam energies

- Zero-impact parameter
- For higher beam energies the intensity increases
Simulation studies
Power estimation of CDR produced

**Average power emitted per train by DR for DXP19 and zero impact parameter (h=0)**

- Bunch separation of 0.33ns and 0.66ns
- For a 2mm Gaussian beam the energy emitted into the detector is $6.8 \times 10^{-9} \text{ J}$
- The average power per train is 10.3W and 22.7W for 1.5GHz and 3GHz operation
- For $2.5 \times 10^{10}$ electrons per bunch the energy contribution per electron is 1.7eV

**Average power emitted per train by DR for DXP19 and a non-zero impact parameter (h=10 mm)**

- For a 2mm Gaussian beam the energy emitted into the detector is $3.6 \times 10^{-9} \text{ J}$
- The average power per train is 5.5W and 11.0W for 1.5GHz and 3GHz operation
- For $2.5 \times 10^{10}$ electrons per bunch the energy contribution per electron is 0.9eV
Kramers-Kronig analysis

The form factor obtained from the experiment gives directly the magnitude of the form factor amplitude $\rho(\omega)$:

$$F(\omega) = \hat{S}(\omega)\hat{S}^*(\omega) = \rho^2(\omega)$$  (4)

The complex form factor can be expressed as:

$$\ln \hat{S}(\omega) = \ln \rho(\omega) + i\psi(\omega)$$  (5)

where $\rho(\omega)$ is the form factor amplitude and $\psi(\omega)$ is the phase factor.

The phase factor $\psi(\omega)$ can be obtained using Kramers-Kronig relation:

$$\psi(\omega) = -\frac{2\omega}{\pi} \int_0^\infty dx \frac{\ln (\rho(x)/\rho(\omega))}{x^2 - \omega^2}$$  (6)

The normalized bunch distribution function can be determined as:

$$S(z) = \frac{1}{\pi c} \int_0^\infty d\omega \rho(\omega) \cos \left(\psi(\omega) - \frac{\omega z}{c}\right)$$  (7)
Kramers-Kronig analysis
Reconstruction of a bunch with a double Gaussian charge distribution
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CDR Installation location
The CDR setup is installed in the Combiner Ring Measurement (CRM) line

- **Installation location in CTF3**
  - Layout of CTF3 with the CRM line (schematic layout at the top)
  - Top view of the CRM line with the CDR setup (Device 11) installed (schematic layout at the bottom)
  - Locations allows to measure **CDR and CSR** (CSR: Combiner Ring (CR) dipole on - beam in CR, CDR: dipole off - beam in CRM line)
  - For CSR insert target completely and use the screen as a mirror
CDR in the CRM Line
CDR assembly in the CRM line

View of the entire CRM line including the CDR setup

- Schematic drawing of the CDR setup (Stage 1) in the CRM line (on the left)
- Picture of the CRM line including the CDR setup (on the right)
  - Vacuum valve to the right of the CDR setup
  - OTR screen behind (to the left of) the setup
- Installation was done in 2 stages:
  - Stage 1: Simply observed the radiation originating from the target
  - Stage 2: Installed the interferometer
CDR UHV hardware

UHV hardware installed in the CRM line

CDR Vacuum hardware

- CDR UHV hardware (on the left):
  - 2 six-way crosses containing the target(s) (2nd six-way cross for the 2nd target in 2010)
  - 4D UHV manipulator to precisely rotate and translate the aluminised silicon target
  - Quartz fused silica UHV window with a viewing diameter of 40 mm through which the radiation is detected
Interferometer system
The interferometer of the CDR experiment

- Installed the interferometer on the optical table earlier this year
- Using a Kapton optical film beam splitter at the moment
- 4” aluminised broadband mirrors
- High precision translation stage (<0.3 µm precision)
- Schottky Barrier Diode detector
Schottky Barrier Diode detector and DAQ

Schottky Barrier Diode detector used to detect the radiation originating from the target.

**Detector properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector</td>
<td>DXP08</td>
<td>DXP12</td>
</tr>
<tr>
<td>Frequency range</td>
<td>90 - 140GHz</td>
<td></td>
</tr>
<tr>
<td>Wavelength</td>
<td>2.14 - 3.33 mm</td>
<td></td>
</tr>
<tr>
<td>Sensitivity (freq. dep.)</td>
<td>1530 - 400 mV/mW</td>
<td></td>
</tr>
<tr>
<td>Horn Antenna Gain</td>
<td>22.42 - 23.69 dB</td>
<td></td>
</tr>
<tr>
<td>Time response (FWHM)</td>
<td>~ 250ps</td>
<td>³ 250ps</td>
</tr>
</tbody>
</table>

**Example CDR signal with BPM current reading**

- Current over the train is fairly constant
- CDR signal shows some variation

⇒ Suggests bunch length changes throughout the train
Beam splitter
Calculations of the efficiency of Mylar and Kapton optical films

Efficiency calculations

\[ E = 2R_0T_0 = \frac{2ART^2 (1 + A^2 - 2Acos\delta)}{(1 + A^2R^2 - 2ARcos\delta)^2} \]

\[ R_s = \left( \frac{\cos\theta_i - n_1 \sqrt{1 - \left( \frac{1}{n_1} \sin\theta_i \right)^2}}{\cos\theta_i + n_1 \sqrt{1 - \left( \frac{1}{n_1} \sin\theta_i \right)^2}} \right)^2 \]

\[ R_p = \left( \frac{\sqrt{1 - \left( \frac{1}{n_1} \sin\theta_i \right)^2 - n_1 \cos\theta_i}}{\sqrt{1 - \left( \frac{1}{n_1} \sin\theta_i \right)^2 + n_1 \cos\theta_i}} \right)^2 \]

\[ A = \exp(-Kh/\cos\theta_1) \]

Mylar beam splitter (top plots - \( E_s \) & \( E_p \))

- Best compromise between efficiency and linearity \( \Rightarrow 50 \mu m \) thick film

Kapton beam splitter (bottom plots - \( E_s \) & \( E_p \))

- Best compromise between efficiency and linearity \( \Rightarrow 50 \mu m \) thick film
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**CDR signal dependence (horizontal polarization)**

- Checked the signal level depending on the target position and orientation
- **Good agreement with expectation** but some distortion
- Distortion can be explained by background caused upstream (wake-fields, CSR, etc.)

**CSR signal dependence (horizontal polarization)**

- Also **good agreement with expectation** but some distortion and additional offset
- Distortion can also be explained by background caused upstream
- Offset can be explained by the offset beam in the bending magnet
Background at CDR

- Observed a large background from the OTR screen behind the setup
- High reflecting screen gives higher background (photon yield $\propto$ reflectivity)
- Low reflecting screen gives a smaller background
- Vacuum window of OTR screen reflects light back towards the CDR setup and reflection of light from our six-way cross
- Possible background from beam dump
Beam based backgrounds
Backgrounds from downstream OTR screen and beam dump detected in the CRM line

Possibility to cut off this background

- Used vertical corrector before the CRM line to lower the position of the beam (by about 8 mm)
- Therefore able to lower the target as well without touching the beam
- Observing a convergence of the signal levels for low impact parameter
- Target starts cutting of the background as it is covering more of the vacuum window

⇒ Off-centre adapter flange, i.e. 15 mm offset (currently manufactured at CERN and installed in October)
First preliminary measurements with the upgraded system
First CSR & CDR measurements taken after the interferometer has been installed

Rotation scan of CSR
- Horizontal polarisation
- DXP08 detector (2.14 - 3 mm)
- Target fully inserted (target edge 7 mm below the beam pipe center)
  ⇒ Single peak as expected

Rotation scan of CDR
- Vertical polarisation
- DXP08 detector (2.14 - 3 mm)
- Impact parameter of 10 mm
  ⇒ Single peak as expected
First preliminary interferometric measurements
First CSR interferometric measurements taken after the interferometer has been installed

Interferometric measurements of CSR
- Horizontal polarisation
- Target full inserted
- 0.05 mm mirror step size

Spectrum of CSR
- Obtained the spectrum from the above interferogram
- Next steps:
  - De-convolute the spectrum by the single electron radiation, the detector spectral response, gain horn spectral gain etc.
  - Extrapolate the spectrum to lower frequencies and higher frequencies to be able to apply Kramers-Kronig relation
  - Use different detectors ⇒ increase spectral coverage
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Conclusion

- Performed simulation studies for CDR setup at CTF3
- Investigations on Kramers-Kronig bunch length reconstruction method
- Carried out beam splitter efficiency calculations for Mylar and Kapton films to find ideal thickness
- Installed the CDR setup in the CRM line
- Executed 2D translation & rotation scans and confirmed working order
- First interferometric measurements of CSR
- First CSR spectrum obtained

Outlook

- CDR interferograms
- Installation of the off-centre flange in October to cut off some of the backgrounds
- Install detectors on translation stage for more flexibility
Questions ?