Longitudinal beam profile monitor at CTF3 based on Coherent Diffraction Radiation

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Outline

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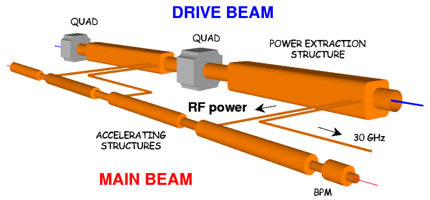
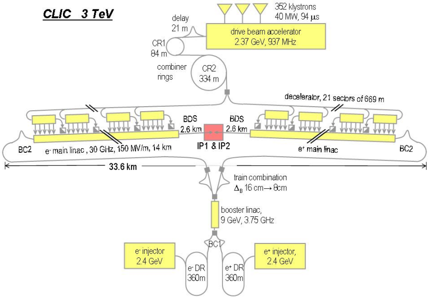
What is CLIC?

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.



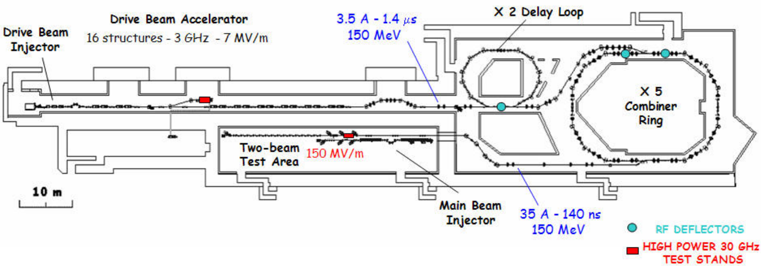


What is CTF3?

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 ⇒ Coherent Diffraction Radiation



Outline

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 form 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

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

$$E^l_{x,y} = \frac{1}{4\pi^2} \iint E^i_{x,y}\left(x_s, y_s\right) \frac{e^{i\varphi}}{r} dy_s dx_s \tag{1}$$

- Need to substitute for the amplitude $E^i_{x,y}$ of every point source:

$$E^i_{x,y}(x_s, y_s) = \frac{iek}{\pi\gamma} \begin{pmatrix} \cos\psi_s \\ \sin\psi_s \end{pmatrix} K_1\left(\frac{k}{\gamma}\rho_s\right) \tag{2}$$

  - $\rho_s = \sqrt{x_s^2 + y_s^2}$, $x_s = \rho_s \sin\psi_s$, and $y_s = \rho_s \cos\psi_s$ $[(x_s, y_s) \Longleftrightarrow (\rho_s, \psi_s)]$
  - $k = 2\pi/\lambda$ is the radiation wave vector, λ is the Backward DR (BDR) wavelength, γ 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:

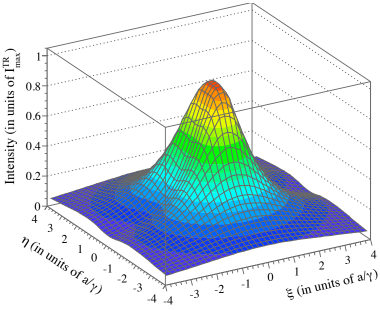
$$\frac{e^{i\varphi}}{|\vec{r}|} = \frac{e^{ika}}{a} \exp\left[\frac{ik}{2a}\left(x_s^2 + y_s^2\right) - \frac{ik}{a}\left(x_s\xi + y_s\eta\right) + \frac{ik}{2a}\left(\xi^2 + \eta^2\right)\right] \tag{3}$$

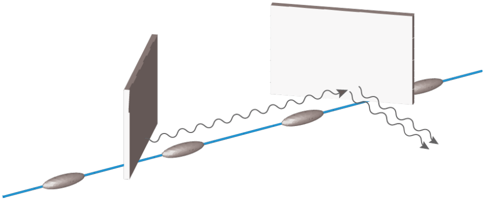
Simulation studies

Diffraction radiation simulations

Diffraction radiation spatial distribution from a semi-halfplate

- $$\frac{d^2W^{DR}}{d\omega d\Omega} = 4\pi^2 k^2 a^2 \left[\left| E_x^{DR} \right|^2 + \left| E_y^{DR} \right|^2 \right]$$
  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 $40(60) \times 40\, mm$
  - Beam energy $\gamma = 235$
  - Distance from target to detector $a =\sim 2\, m$
  - Wavelength λ depending on the detector





Future target configuration

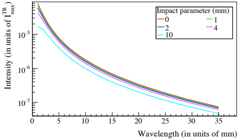
- Second target will be added in 2010
- Simulations will be carried out to account for the second target

Simulation studies

Diffraction radiation simulations

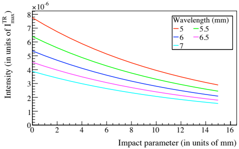
Diffraction radiation spectra with $I^{TR}_{max} = \frac{\alpha\gamma^2}{4\pi^2}$

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



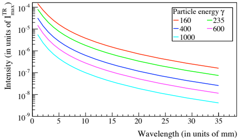
Intensity dependence on impact parameter ($\gamma = 235$)

- 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

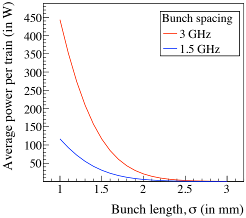


Simulation studies

Power estimation of CDR produced

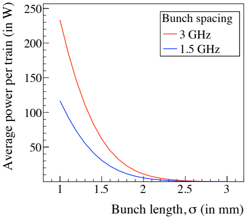
Average power emitted per train by DR for DXP19 and zero impact parameter (h=0)

- Bunch separation of 0.33ns and 0.66ns
- For a 2mm Gaussian beam the energy emitted into the detector is $6.8 \times 10^{-9}\ J$
- The average power per train is 10.3W and 22.7W for 1.5GHz and 3GHZ operation
- For 2.5×10^{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 $3.6 \times 10^{-9}\ J$
- The average power per train is 5.5W and 11.0W for 1.5GHz and 3GHZ operation
- For 2.5×10^{10} electrons per bunch the energy contribution per electron is 0.9eV



Kramers-Kronig analysis

Kramers-Kronig analysis

Kramers-Kronig

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

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

- The complex form factor can be expressed as:

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

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:

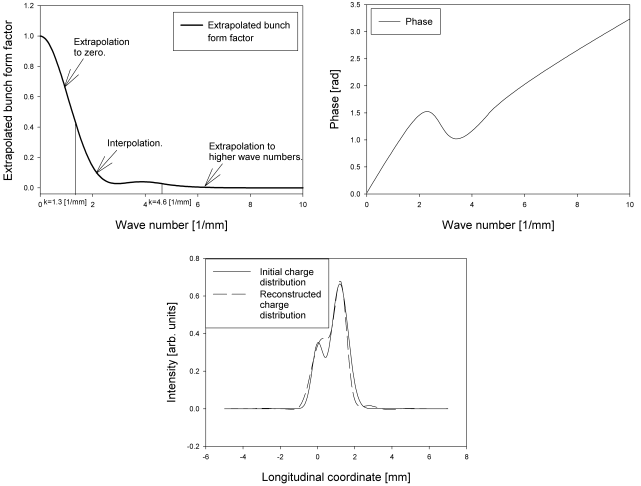
$$\psi(\omega) = -\frac{2\omega}{\pi} \int_0^\infty dx \frac{\ln\left(\rho(x)/\rho(\omega)\right)}{x^2 - \omega^2} \tag{6}$$

- The normalized bunch distribution function can be determined as:

$$S(z) = \frac{1}{\pi c} \int_0^\infty d\omega \rho(\omega) \cos\left(\psi(\omega) - \frac{\omega z}{c}\right) \tag{7}$$

Kramers-Kronig analysis

Reconstruction of a bunch with a double Gaussian charge distribution



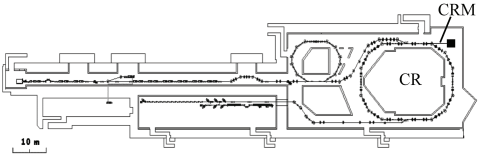
Outline

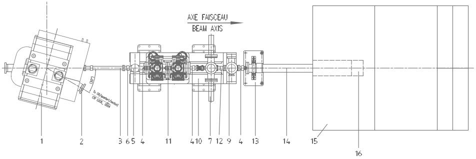
CDR Installation location

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



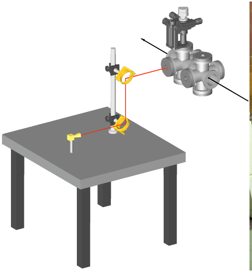


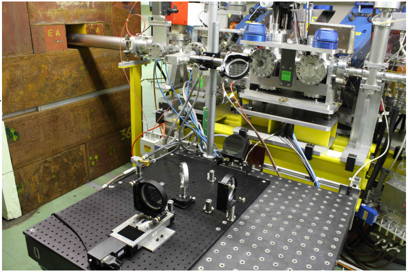
CDR in the CRM Line

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



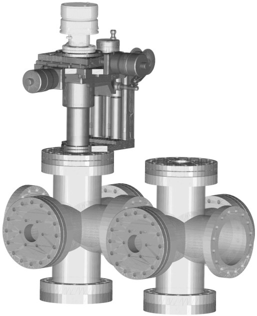


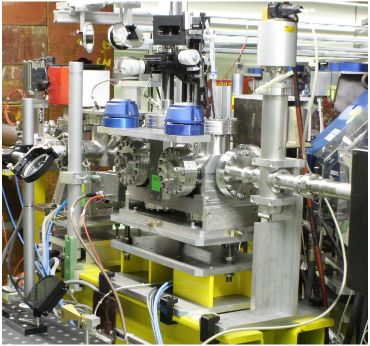
CDR UHV hardware

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



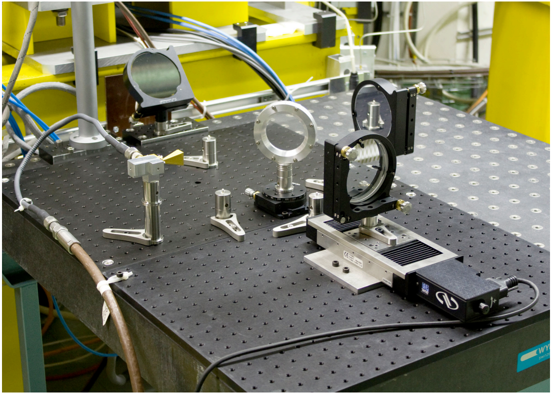


Interferometer system

The interferometer of the CDR experiment

Interferometer

- 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($<0.3\,\mu$m precision)
- Schottky Barrier Diode detector



Schottky Barrier Diode detector and DAQ

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

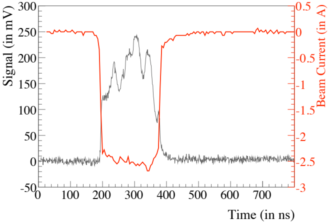
Detector properties

Property	Value		Unit
Detector	DXP08	DXP12	
Frequency range	90 - 140	60 - 90	GHz
Wavelength	2.14 - 3.33	3.33 - 5	mm
Sensitivity (freq. dep.)	1530 - 400	$\sim$700	mV/mW
Horn Antenna Gain	22.42 - 23.69	$\sim$24	dB
Time response (FWHM)	$\sim$250	$\sim$250	ps

Example CDR signal with BPM current reading

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

$\Rightarrow$ Suggests bunch length changes throughout the train



Beam splitter

Calculations of the efficiency of Mylar and Kapton optical films

Efficiency calculations

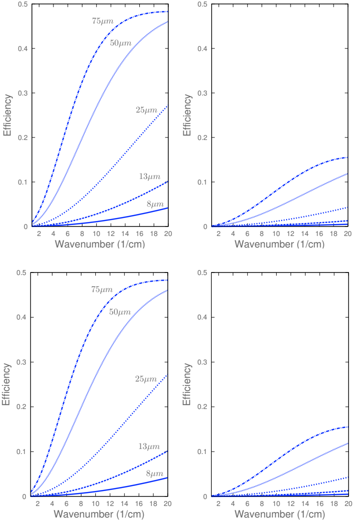
- $E = 2R_0T_0 = \dfrac{2ART^2\left(1 + A^2 - 2Acos\delta\right)}{\left(1 + A^2R^2 - 2ARcos\delta\right)^2}$
- $R_s = \left(\dfrac{cos\theta_i - n_1\sqrt{1 - \left(\frac{1}{n1}sin\theta_i\right)^2}}{cos\theta_i + n_1\sqrt{1 - \left(\frac{1}{n1}sin\theta_i\right)^2}}\right)^2$
- $R_p = \left(\dfrac{\sqrt{1 - \left(\frac{1}{n1}sin\theta_i\right)^2} - n_1cos\theta_i}{\sqrt{1 - \left(\frac{1}{n1}sin\theta_i\right)^2} + n_1cos\theta_i}\right)^2$
- $A = exp(-Kh/cos\theta_1)$

Mylar beam splitter (top plots - E_s & E_p)

- Best compromise between efficiency and linearity $\Rightarrow$ 50 μm thick film

Kapton beam splitter (bottom plots - E_s & E_p)

- Best compromise between efficiency and linearity $\Rightarrow$ 50 μm thick film



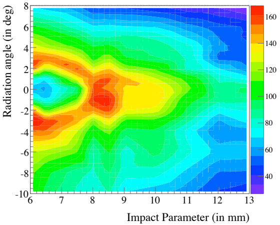
Outline

DR & SR 2D Distributions

CDR and CSR signal dependences obtained with 2D (translational & rotational) scans

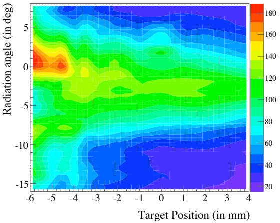
CDR signal dependence (horizontal polarization)

- 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

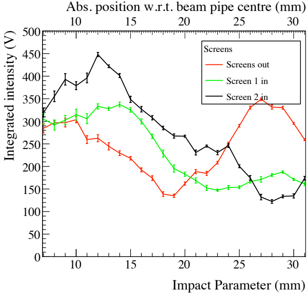


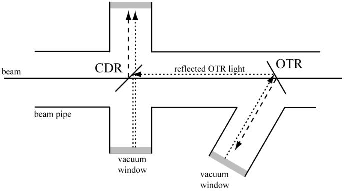
Beam based backgrounds

Backgrounds from downstream OTR screen and beam dump detected in the CRM line

Background at CDR

- Observed a large background from the OTR screen behind the setup
- High reflecting screen gives higher background (photon yield ∝ 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





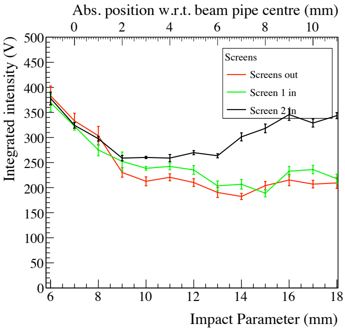
Beam based backgrounds

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)



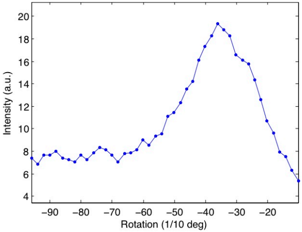
First preliminary measurements with the upgraded system

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)

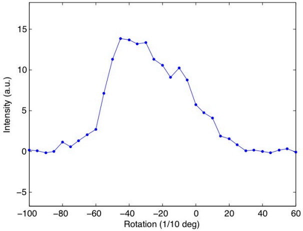
$\Rightarrow$ Single peak as expected



Rotation scan of CDR

- Vertical polarisation
- DXP08 detector (2.14 - 3 mm)
- Impact parameter of 10 mm

$\Rightarrow$ Single peak as expected

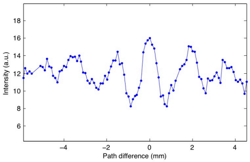


First preliminary interferometric measurements

First CSR interferometric measurements taken after the interferometer has been installed

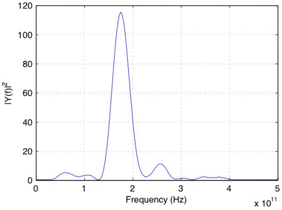
Interferometric measurements of CSR

- 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



Outline

Conclusion & Outlooks

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 ?

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