Development of a Bunch-Length Monitor with Sub-Picosecond Time Resolution and Single-Shot Capability*

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Abstract

A bunch-length monitor with single-shot capability is under development at the 100 MeV pre-injector LINAC of the Swiss Light Source (SLS). It is based on the electro-optical (EO) effect in a ZnTe crystal induced by coherent transition radiation (CTR). A spatial auto-correlation of the CTR in the EO-crystal rotates the polarisation of a mode-locked Nd:YAG laser to produce an image on an array detector representing the Fourier components of the CTR spectrum. Up to now a theoretical model for the emission of transition radiation has been developed in order to design optics allowing efficient transport of the CTR onto the EO-crystal. The frequency dependency of the CTR due to the finite size of the target screen has been measured in the sub-THz regime at the SLS LINAC. The results strongly support the theoretical descriptions of the radiation source. By expanding the intensity pattern in higher-order Laguerre-Gaussian modes, the transmission through the optical transfer system is calculated.

EO AUTO-CORRELATION

The electro-optical effect provides the potential to measure electron bunch lengths with sub-ps time resolution. A number of experiments have already been performed using the coincidence of fs-laser pulses with coherent radiation emitted from short electron bunches [1]. At the SLS, a novel bunch length monitor is under development, which uses an actively mode-locked Nd:YAG laser to analyse the spatial auto-correlation of CTR in an EO-crystal. A schematic set-up of the monitor is shown in fig. 1.

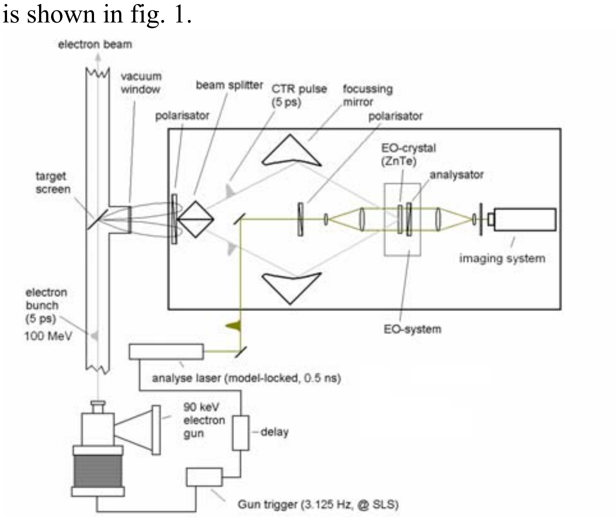

Figure 1: Schematic setup for EO-auto-correlation.

In this experiment, the synchronization of the laser with the CTR from the electron beam is not considered as critical due to the relatively long pulses of the Nd:YAG laser (< 500 ps), however the signal to noise ratio needs to be addressed more carefully.

The interference pattern produced by the auto-correlation of CTR in the EO-crystal can be expressed as:

$$I(\vec{r},\omega) = 2I(\omega)\left[1+Cos\left[2Sin(\theta)\frac{\omega}{c}r_1\right]\right] \qquad (1),$$

where θ is the incident angle between the wave vector k and the normal vector n on the EO-crystal.

The power of the analyse laser is therefore modulated by the EO-crystal according to

$$I^{out} \approx I_{Laser}\left(\frac{\pi d}{V_{\lambda/2}}\right)^2 E_{CTR}^{\,2} \ . \qquad (2)$$

$V_{\lambda/2}$ is the so-called half wave voltage necessary to rotate the laser polarisation by π/2:

$$V_{\lambda/2} = \frac{\lambda}{2n^3 r_{41}} \ . \qquad (3)$$

For ZnTe the half wave voltage is 3.8 kV. Assuming a thickness of the electro-optical crystal of 0.5 mm the laser power modulated by a field of 1 kV/cm is $2\cdot10^{-3}\,I_{Laser}$.

Background intensity $B_{Background}$ and noise contributions have to be considered as well. According to eq. (1), the incoherent background is in the same order of magnitude as the signal itself. The most dominant noise sources, which contribute during the entire duration of the laser pulse (≈ 500 ps), are: the stray light scattered into the detector due to the limited extinction of the polarizer, the limited polarisation state of the laser beam and the strain induced birefringence of the electro-optical crystal. The weighted contributions are given by $\varepsilon_{Polariser}$, ε_{Laser} and ε_{Strain}. Although polarisers with $\varepsilon_{Polariser} < 10^{-5}$ are available, the experimentally achievable total extinction $\varepsilon_{Total} = \varepsilon_{Polariser} + \varepsilon_{Laser} + \varepsilon_{Strain}$ may thus not be better than 10^{-4}.

The resulting signal dynamic is given by

$$d_S = 10Log_{10}\left(\frac{I_{Signal}}{I_{Signal}+B_{Background}+\varepsilon_{Total}}\right) \qquad (4).$$

With an assumed bunch length of 5 ps (at the SLS pre-injector LINAC) the signal dynamic is –8 dB. Assuming a detection system with a dynamic range d_N of about 30 dB (commercial CCD-camera) a signal to noise ratio defined as $d_{S/N} = d_N + d_S$ of > 20 dB is achievable for electric field strengths of more than 1 kV/cm.

EMISSION CHARACTERISTIC OF CTR

Although EO auto-correlation can be performed with different kind of coherent radiation sources, we are intending to use transition radiation (TR) in our experiments, since TR diagnostics ports, which are commonly used for the measurement of transverse beam parameters, are widely available in linear accelerators.

In general, TR is emitted when, uniformly moving charged particles cross the boundary between two media with different electric properties (dielectric constants). For the transition from vacuum ($\varepsilon = 1$) to metal the TR intensity for a single electron is given by:

$$\frac{d^2 I}{d\omega d\Omega} = \frac{e^2 \beta^2}{4\pi^3 \varepsilon_0 c} \frac{Sin(\theta)^2}{(1-\beta^2 Cos(\theta)^2)^2}. \qquad (5)$$

The well known formula above has been derived by Ginzburg and Frank [2] and is valid for OTR only, as the target screen is assumed to be large compared to the wavelength of the emitted radiation. The CTR spectrum for electron bunches in the SLS pre-injector LINAC is settled in the frequency range below 1 THz. Therefore, the description of Ginzburg and Frank may prove to be insufficient. Hence, we apply a model for the emission characteristics of transition radiation, taking the finite target screen into account. For a relativistic electron travelling along the z-axis we define the longitudinal fourier transform by:

$$\hat{A}(\omega) := \int_{-\infty}^{\infty} A(\eta) e^{-i\eta\omega} d\eta = e^{-i\frac{z}{\beta c}\omega} \int_{-\infty}^{\infty} A(t) e^{-it\omega} dt \qquad (6)$$

where $\eta := t - z/v = t - z/\beta c$.

The fourier components of the magnetic field [3] are proportional to $\hat{\vec{B}}_0(r,\omega) \propto \frac{\omega}{c\gamma} K_1(\frac{\omega}{\beta c\gamma} r)$. (7)

The magnetic field is inducing currents j in the metallic target screen: $\hat{\vec{j}}(r,k) = \vec{n} \times \hat{\vec{B}}_0$ where n is the normal vector on the target screen. These currents are acting as elementary electrical dipoles, which generate a vector potential calculated by the following expression

$$d\hat{\vec{A}} = \frac{1}{4\pi} \hat{I} d\vec{r} \frac{e^{ikR(r,\varphi)}}{R(r,\varphi)}, \text{ where } \hat{I} = d\varphi \cdot \vec{r} \cdot \hat{\vec{j}}. \qquad (8)$$

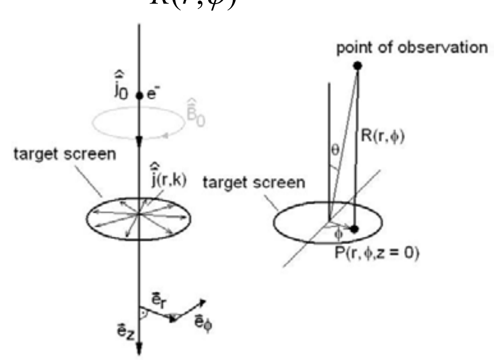

Figure 2: Left side: the magnetic field inducing currents. Right side: observation of radiation in the farfield.

For a single electron with normal incidence on a circular target screen the resulting intensity in the farfield is proportional to

$$\frac{d^2 I}{d\omega d\Omega} \propto \left| \frac{\omega^2}{c^2 \gamma} \int_0^{Radius} r K_1(\frac{\omega}{\beta c \gamma} r) J_1(\frac{\omega}{c} Sin(\theta) r) dr \right|^2 \qquad (9)$$

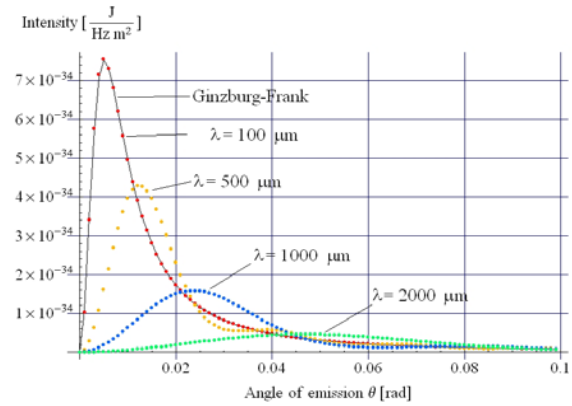

Figure 3: Emission characteristic of CTR for a single electron with normal incidence on a circular target screen of radius 19 mm. For wavelengths of < 100 µm the characteristic agrees well with the expression (5) given by Ginzburg and Frank.

It can be seen, that the emission angle of TR increases drastically at longer wavelengths, where the coherent part of the emission spectrum from a short electron bunch is to be expected. This effect has to be considered for the design of a preferably efficient transport system to the EO auto-correlation experiment.

EXPERIMENTAL CHARACTERISATION

The emission characteristic of CTR was experimentally investigated at the diagnostic station ALIDI-SM-5 behind the 100 MeV SLS pre-injector LINAC. The transverse intensity distribution was mapped using polarizer grids and a PYE UNICAM golay cell detector, measured to be sensitive up to wavelengths of 1 cm.

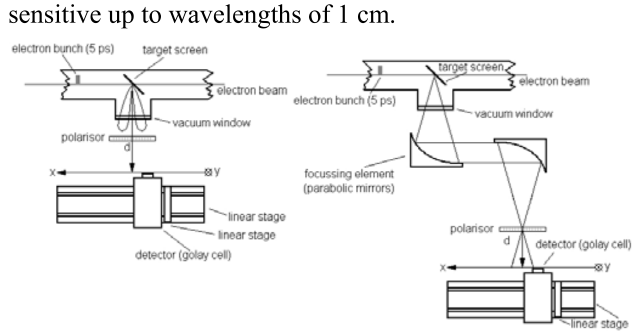

Figure 4: Set-up A (left): Mapping of the CTR farfield at a distance d of 250 mm from the source. Setup B (right): Two parabolic mirrors with focal lengths of 200 mm and 60 mm diameter were used to produce an image of the source. The CTR intensity distribution was then measured at a distance of 70 mm from the focal plane.

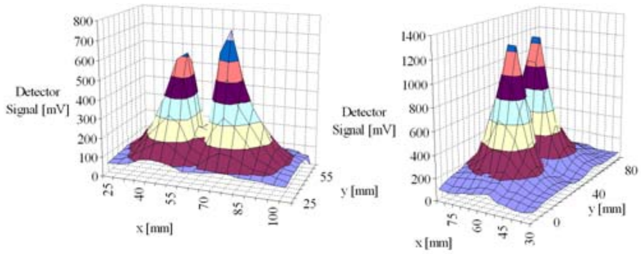

Figure 5: Intensity distribution of the horizontal (left) and vertical (right) polarization of CTR, measured at the SLS LINAC (set-up A). The asymmetry in the horizontal scan is predicted by the model when considering the target screen to be rotated by 45 degree into the electron beam.

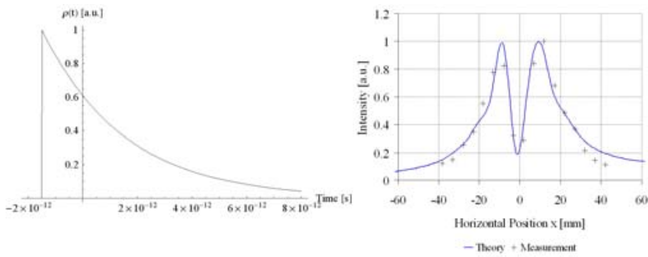

Figure 6: Cut through the horizontally polarized CTR intensity distribution (left side of fig. 5) compared with the theoretical curve for an electron distribution ρ as shown on the left side (3 ps).

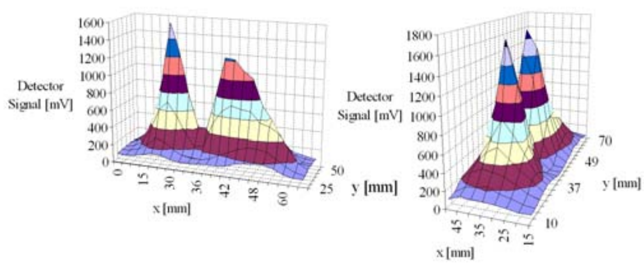

Figure 7: Scans of horizontal respectively vertical polarisation after passing the imaging optics of set-up B. The radial polarisation of CTR is conserved.

The emission angles of CTR as shown in figure 5 are 100 mrad and therefore considerably larger than the 10 mrad predicted by Ginzburg and Frank for an electron beam energy of 100 MeV. According to our theoretical description of CTR emission, the spectrum is dominated by frequencies above 100 GHz. The good agreement of our CTR emission model with the experimental data allows the expansion of the transverse CTR intensity distribution in higher-order Laguerre-Gaussian modes. Subsequent propagation of CTR through an optical system can thus be described as a superposition of higher-order modes of a Gaussian beam. In this description an optical element with a certain aperture is acting like a high-pass filter cutting off the disperse intensity at low frequencies. Hence, the transmission function of an optical system can be calculated accordingly.

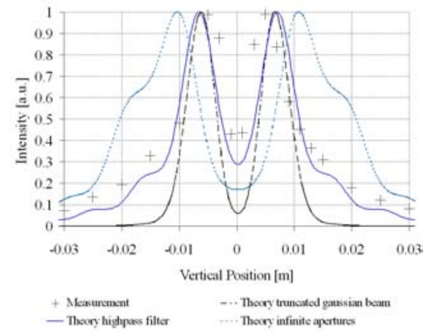

Figure 8: Calculated transmission through set-up B for the superposition of (only) 10 Laguerre-Gaussian modes (same electron distribution as assumed for fig. 6). Pointed line: Infinite apertures. Point-dashed line: Truncated due to mirror apertures. Full-line: The two parabolic mirrors treated as high-pass filters with $\nu_{cutoff} = 300$ GHz.

The peak field strength of CTR achievable at the SLS pre-injector LINAC was measured in order to estimate the CTR intensity distribution in the EO-crystal.

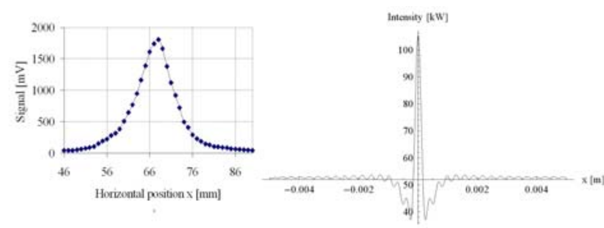

Figure 9: Left side: Horizontal scan of CTR in the focal plane of set-up B. The peak field strength exceeds 3 kV/cm. Right side: Simulated intensity pattern on the EO-crystal (acc. to eq. 1), assuming 3 optical elements with $\nu_{cutoff} = 300$ GHz and the same electron distribution as assumed for fig. 6 with 0.5 nC.

SUMMARY

A theoretical model for the CTR emission has been presented and confirmed by experimental data. Expansion of the CTR intensity distribution in higher-order modes of a Gaussian beam allows the determination of the transfer function of an optical system. CTR intensities were calculated based on the SLS pre-injector LINAC parameters, exceeding the peak electric field strengths of 1 kV/m, required for the proposed EO auto-correlation experiment.

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[2] V.L. Ginzburg, I. Frank, J. Phys. USSR 9, 353(1945).

[3] N.F. Shul'ga et al., Theory of Relativistic-Electron TR in a Thin Metal Target, Atoms, Spectra, Radiation Vol. 90,4 (2000).

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