Experimental Verification of the Coherent Diffraction Radiation Measurement Method for Longitudinal Electron Beam Characteristics

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Introduction

This work presents a natural extension of prior theoretical investigations regarding the utilization of coherent diffraction radiation for assessing longitudinal characteristics of electron beams at Solaris. The study focuses on the measurement results obtained at the linac injector of the Solaris synchrotron and their analysis through a theoretical model. The findings are compared with previous estimates of the electron beam longitudinal profile. This contributes to the future diagnostics at the first Polish free electron laser (PolFEL) project, where it will be used for the optimization of particle accelerator performance.

COHERENT DIFFRACTION RADIATION

Electromagnetic radiation is emitted when a beam of charged particles accelerates or changes medium of propagation. If the emitted wavelength is comparable or greater than the bunch length, the radiation is said "coherent" because the contributions from the single particles within the beam interfere constructively and the bunch emits as a whole. In that case the emitted radiation power is proportional to the square of the bunch form-factor and increases with decreasing bunch length. For bunch lengths on the picosecond scale variations in the peak current can be easily monitored by GHz-THz detectors like Schottky diodes. Diffraction radiation is the radiation that a bunch of particles emits when crossing two regions of limited size with different index of refraction. This can be accomplished if the beam passes through a hollow disk of dense material. If the disk surface is metallic the radiation is emitted from localized layers of that surface, in such a way that the beam properties are imprinted into the emitted radiation at the transition plane and can be exploited for diagnostics. The spectral angular distribution of energy emitted backward in the form of diffraction radiation from a perfectly conducting round disk, with an internal and external radius equal to respectively a and b, can be described with the following formula:

$$\frac{d^2 I}{d\omega d\Omega} = |F(\omega)|^2 \times \frac{Q^2}{(4\pi^3\epsilon_0 c^5\beta^4\gamma^2)} \times \left| \int_a^b d\rho\rho K_1\left(\frac{\omega\rho}{\beta\gamma c}\right) J_1\left(\frac{\omega\rho}{c\sin\theta}\right) e^{\frac{j\omega^2\rho^2}{2c^2}} \right|^2 \qquad (1)$$

where Q denotes the bunch charge, ϵ_0 is vacuum permittivity, c is the velocity of light, β is the ratio of particle velocity and the velocity of light and γ is the Lorentz factor. The quantity $F(\omega)$ is called bunch form factor and strictly depends on the shape of the electron bunch. An example of spectral-angular distribution of emitted CDR energy is shown in Figure 1.

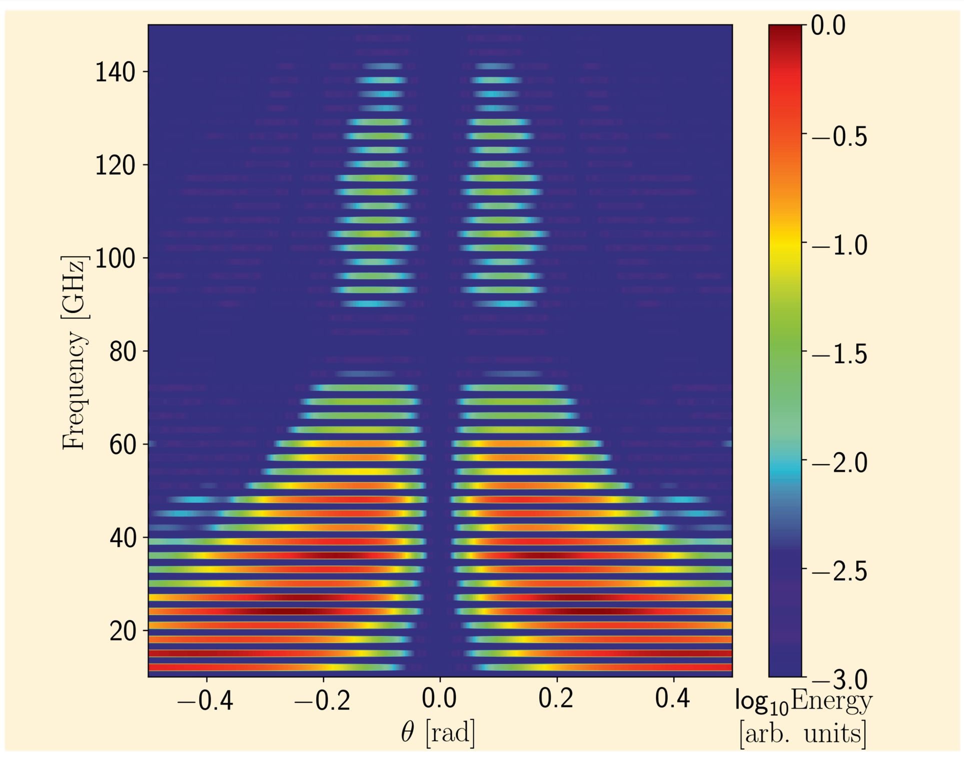

Figure 1: CDR spectral-angular distribution for the SOLARIS injector bunch repetition pattern and beam energy of 550 MeV.

BUNCH LENGTH MEASUREMENT

The diagnostic technique considered for PolFEL is based on the power balance of CDR radiation collected by Schottky diodes in different ranges of sub-THz radiation. As seen from Eq. (1) the emitted energy depends on the bunch length through the form factor $F(\omega)$. If the transverse size of the bunch is negligible, one has:

$$F(\omega) = \int_{-\infty}^{\infty} I(t)e^{j\omega t}\, dt \qquad (2)$$

where $I(t)$ is the normalized dimensionless beam current passing through the disk. Simply speaking, the form factor is squared modulus of the Fourier transform of the beam current. In certain cases, for example when the beam consists of a single Gaussian bunch, an exact analytical formula for the form factor can be given, parametrized by the RMS bunch length. This parameter can be then experimentally retrieved by calculating the ratio of CDR power at two distinct frequencies and comparing it to the theoretical predictions given by Eq. (1) The described technique is not limited to only one type of radiation, and has been previously demonstrated with measurements based on CDR and Coherent Cherenkov Diffraction Radiation. In the SOLARIS linac the beam is bunched, with the 3~GHz bunch repetition rate. The shape of a single bunch differs from the Gaussian and the bunch intensity is modulated proportionally to the 100~MHz sinewave . As result the corresponding form factor also differs from the smooth form factor of a single Gaussian bunch as presented in Figure 2. A larger aperture allows more radiation to enter the detector and thus for diodes with different apertures, it will change the power balance on the basis of which the longitudinal profile is estimated. The apertures of the diodes differed, therefore it was necessary to normalize the signals with respect to the surface area of the diode aperture. Bunch length to power ratio after this correction is presented below in Figure 3.

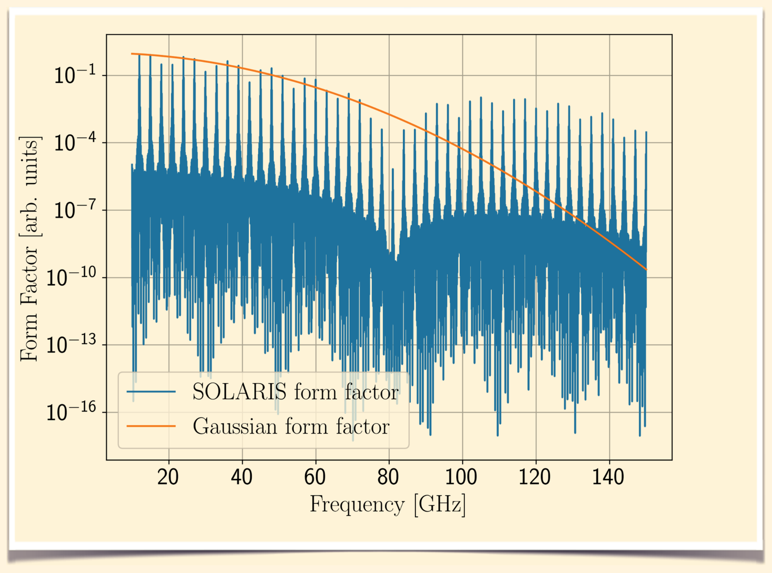

Figure 2: Form factors calculated for SOLARIS injector bunch train and a single Gaussian bunch.

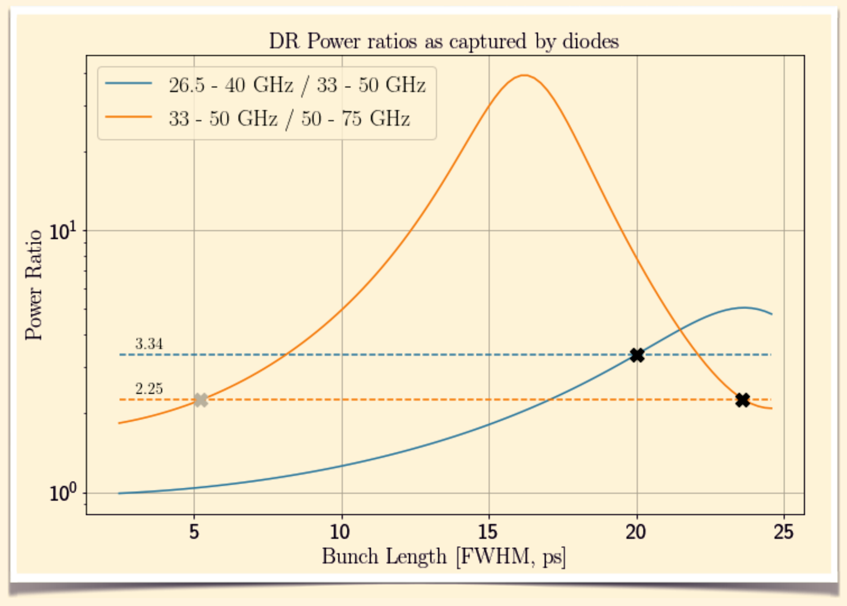

Figure 3: Bunch length to power ratio, corrected for diode aperture.

EXPERIMENTAL SETUP AND MEASUREMENTS

The characterized electron beam was at the end of the linac in beam dump section. After passing through 0.15 mm thick flange, the electrons move in the air and can be used for beam diagnostics 20 cm behind flange, before they end up in the lead beam dump.The arrangement for measuring the length of the electron beam profile visible at includes an aluminum radiator with a radius of 2.54 cm and a 5 mm radius hole at its center. Additionally, a golden-coated Ø3" 90° Off-axis parabolic mirror and three diodes from different bands are employed as detectors, used alternately.

The diodes were placed in the holder, in the same place. The big difficulty was the fact that it was impossible to adjust the diode position during the beam operation. the solution to this problem will be the installation of remotely controlled platforms on which the diodes will be placed, thanks to which it will also be possible to change the diodes during the measurement without having to pull them out as it is now.An important factor to consider is not only the sensitivity but also the input aperture of the diodes. FWHM of the longitudinal electron bunch profile at SOLARIS linac was estimated at 12 ps. As can be seen in the Figure 5, the signal from the diode in the highest band is at the noise level, for this reason, the ratio of the signals from the diode in the middle and the lowest band was used for the calculations. This obviously lowers the accuracy of our measurement and is the most likely cause of the difference from the expected value. From the first measurements using CDR radiation, the estimated FWHM of the longitudinal electron beam profile was about 20 ps.

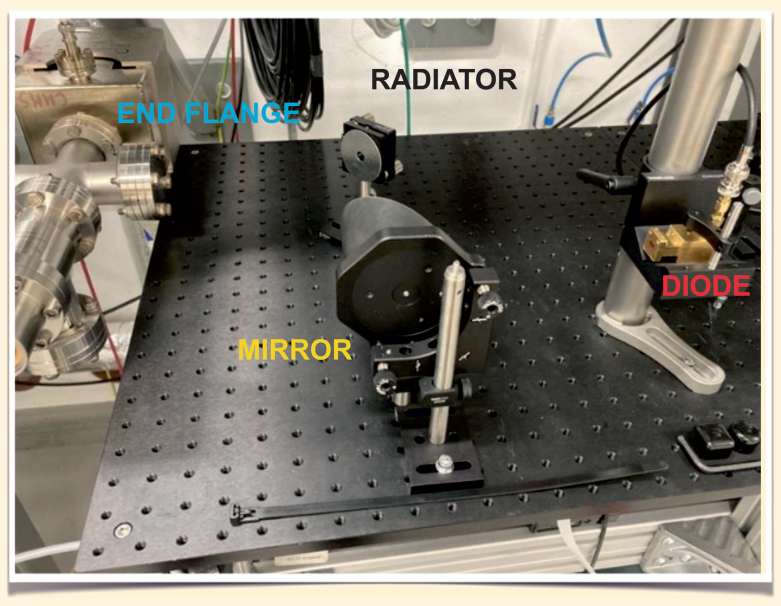

Figure 4: Experimental setup.

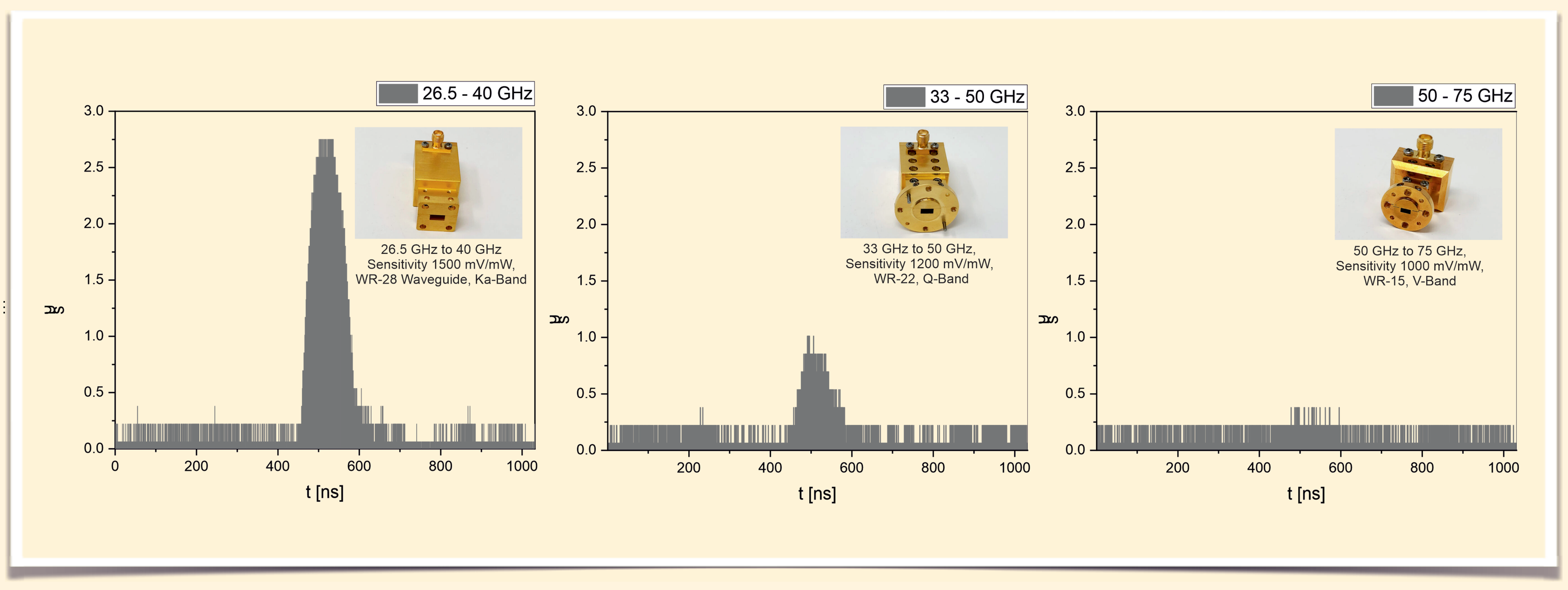

Figure 5: Signals measured by diodes with different bands.

Conclusion

In this contribution, progress has been made at SOLARIS towards an experimental test of the CDR-based characterization of the electron beam's longitudinal profile for PolFEL project. Additionally, tools for processing the measured data and calculating the bunch length have been developed and updated. Schottky diodes were acquired and placed in the setup, enabling the first measurements and calculations. The results obtained after the analysis do not align with the expectations. The possible cause is a weak signal, which, in the case of a diode in the highest frequency range, made it impossible to extract the signal from the noise level.It is anticipated that by improving the signal strength from the diode in the highest band, the estimated bunch length will decrease and become closer to the one from the previous estimate. In order to increase the signal strength, the system will be re-adjusted using motorized platforms, which could be done online with the present beam. Currently, adjusting the setup with the beam is not feasible. If that proves insufficient, additional horn antennas will be installed on diodes.The tested system has shown potential, indicating that it can be used as a low-cost alternative to more complex systems like transverse deflecting cavities (TDC) and streak cameras for monitoring the longitudinal beam profile. After appropriate calibration using the methods mentioned above, such a system based on the CDR could monitor the degree of bunch compression after magnetic chicane.

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