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EXPERIMENTAL VERIFICATION OF THE COHERENT DIFRACTION RADIATION MEASUREMENT METHOD FOR LONGITUDINAL ELECTRON BEAM CHARACTERISTICS

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Abstract

This paper presents a natural extension of prior theoretical investigations regarding the utilization of coherent diffraction radiation for assessing longitudinal characteristics of electron beams. The study focuses on the measurement results obtained at the SOLARIS synchrotron and their analysis through a theoretical model. The findings are compared with previous estimates of the electron beam's longitudinal profile.

COHERENT DIFFRACTION RADIATION

Electromagnetic radiation is emitted when a beam of charged particles accelerates or changes medium of propagation (abruptly or continuously in terms of the local electromagnetic susceptibility) [1, 2]. If wavelength of the the emitted radiation is comparable or greater than the bunch length, the radiation is said to be "coherent" because the contributions from the distinct particles within the beam interfere constructively, and the bunch radiates as a whole. In the low frequency limit the emitted radiation power is proportional to the square of the bunch intensity, while for intermediate frequency ranges the power decreases with increasing bunch length. For bunch lengths of the picosecond scale, variations in the radiation intensity can be easily monitored by GHz-THz detectors like Schottky diodes [3, 4]. For shorter bunches, far-infrared diagnostics are needed, such as spectrometers [5].

Coherent radiation can be coupled out of the beamlines through suitable transparent windows, eventually transported in air into power detectors. For the diagnostic purposes of the PolFEL project [6], application of the Coherent Diffraction Radiation (CDR) was investigated at SOLARIS [7]. Diffraction radiation is a type of radiation that a bunch of particles emits while passing close to the boundary of two media with different indices of refraction, which allows for non-destructive bunch length measurements [8].

In the experimental setup at SOLARIS, the beam passes through a hollow alluminium disk. The radiation is emitted from localized layers of that surface, imprinting the beam properties into the emitted radiation at the transition plane and enabling diagnostics. The fact that the disk is hollow allows the beam not to be scattered, preserving the emittance even if the particles do not propagate inside it.

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 [9, 10]:

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

where Q denotes the bunch charge, ϵ_0 is the vacuum permittivity, c is the velocity of light, β is the ratio of particle velocity to the velocity of light, and γ is the Lorentz factor. The quantity $F(\omega)$ is called the *bunch form factor* and strictly depends on the shape of the electron bunch. The theoretical prediction of the spectral-angular distribution of CDR emitted with the experimental setup at SOLARIS is shown in Fig. 1.

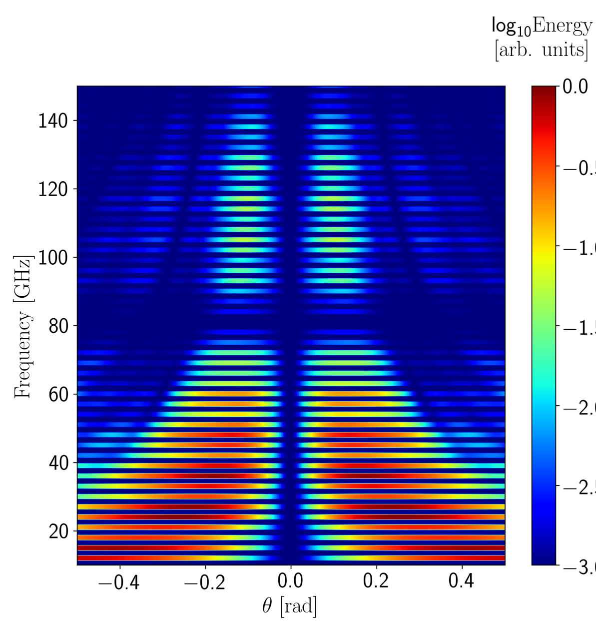

Figure 1: CDR spectral-angular distribution for the SOLARIS injector bunch repetition pattern and beam energy of 550 MeV.

BUNCH LENGTH MEASUREMENT

The diagnostic technique considered for PolFEL is based on the power balance of CDR radiation collected by Schottky

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diodes in different ranges of sub- THz radiation. Following 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 [11]:

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

where $I(t)$ is the normalized dimensionless beam current passing through the disk. Simply speaking, the form factor is 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 [3] and Coherent Cherenkov Diffraction Radiation [4].

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 [12, 13]. As result the corresponding form factor also differs from the smooth form factor of a single Gaussian bunch as presented in Fig. 2.

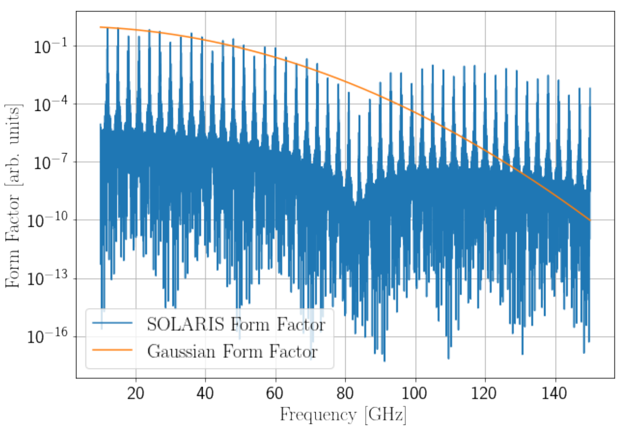

Figure 2: Form factors calculated for SOLARIS injector bunch train and a single Gaussian bunch. In both cases the FWHM bunch length is equal to 12 ps.

Although deriving the information on the bunch length from a narrow frequency band is not possible at SOLARIS, due to the oscillatory character of the form factor, the bunch length might be derived from the cumulative power within the broader frequency bands.

In the previous theoretical study [14] it was determined that the ratio of the powers within 26.5-40 GHz and 33-50 GHz bands allows to discriminate between bunch lengths in the range from 5 to almost 25 ps full width at half maximum (FWHM). Complementary, the power emitted within 50-75 GHz band, while comparing to 33-50 GHz band, can be used to refine an earlier measurement, but cannot serve as a standalone indicator, due to a local extremum it takes for bunch lengths of approximately 16 ps FWHM.

EXPERIMENTAL SETUP AND MEASUREMENTS

The measurement were taken in the end part of the SOLARIS linac, close to the beam dump section. After passing through 0.15 mm thick flange, the electrons move in the air and after 20 cm they reach the experimental setup.

The arrangement for measuring the length of the electron beam profile is visible in Fig. 3. It 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 focuses the radiation towards the apertures of three diodes sensitive to different frequency bands are employed as detectors, used alternately.

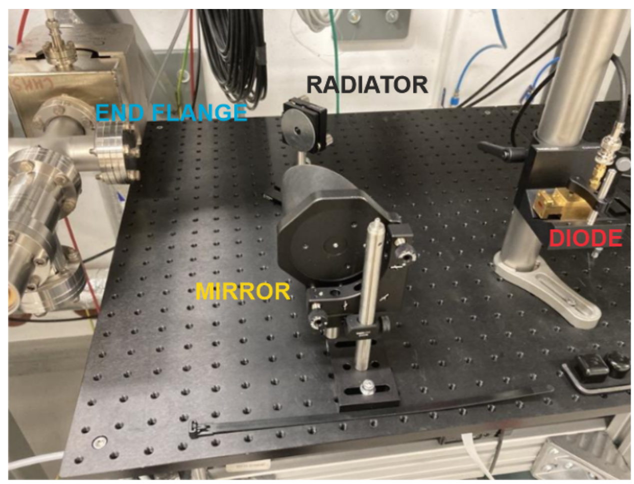

Figure 3: Experimental setup.

Schottky diodes produced by Mi-Wave [15] were used for the experiment, with the frequency band corresponding to the ones discussed in the previous section. An important factor to consider was not only the sensitivity of the diodes, but also their input aperture. 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.

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. In the future, this problem will be solved by 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.

As can be seen in the graph Fig. 4, the signal from the diode in the highest frequency band is at the noise level.

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This obviously lowers the accuracy of our measurement and is the most likely cause of the difference from the expected value. For this reason, the ratio of the signals from the diode in the middle and the lowest band was considered the most reliable.

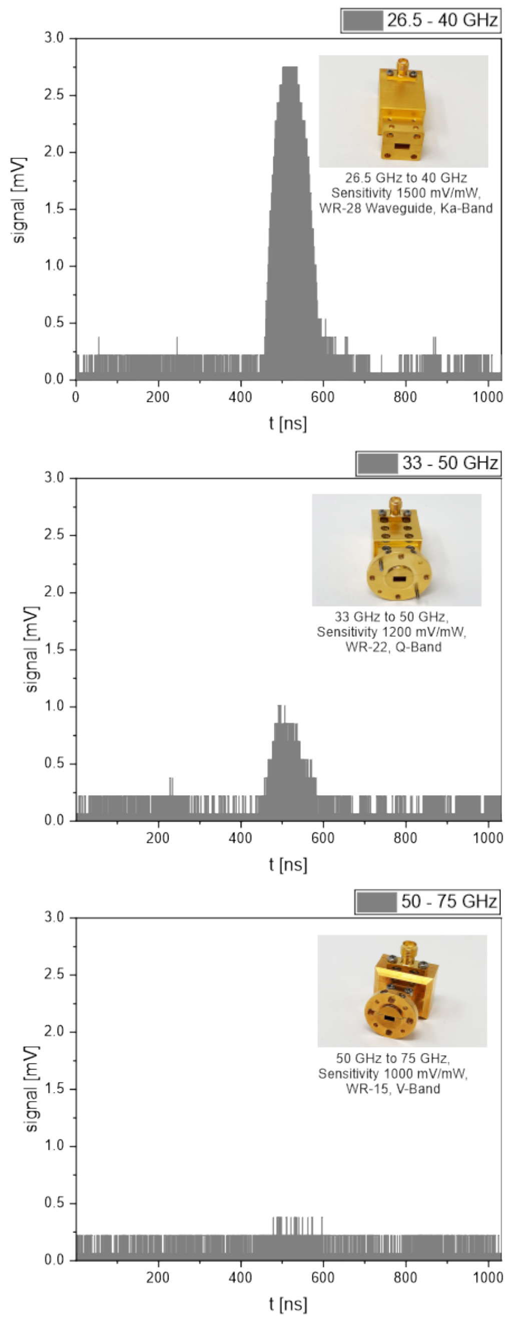

Figure 4: Signals measured by diodes with different bands.

Calculating the ratio of the measured powers, we can compare them with theoretical curves which describe the change in ratio as a function of the bunch length, as presented in Fig. 5. Results from both measurements estimate the FWHM of the longitudinal electron beam profile to be around 20 - 25 ps. In the work [12], the FWHM of the longitudinal electron bunch profile at SOLARIS linac was estimated at 12 ps.

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 from the experiment do not align with the theoretical expectations. The possible cause is a weak signal, which, in the case of a diode in the highest frequency range, made it almost impossible to extract the signal from the noise level.

It is anticipated that by improving the signal strength from the diode in the highest and medium 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.

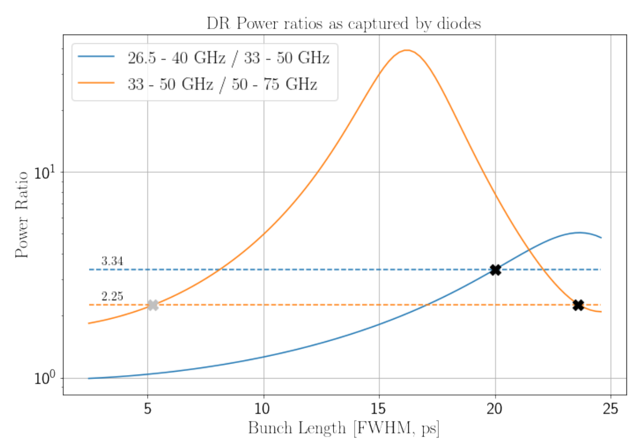

Figure 5: Solid lines: theoretically predicted ratio of CDR power within different bands as a function of the bunch length. Dashed lines: experimentally measured CDR ratios. Black crosses indicate the crossing points and therefore the estimated bunch lengths. Grey cross indicate a crossing point rejected based on the low-medium band ratio.

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