ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-TUP28

COHERENT DIFFRACTION RADIATION FOR LONGITUDINAL ELECTRON BEAM CHARACTERISTICS

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Abstract

For the need of diagnostics of the longitudinal electron beam characteristics at the first Polish free electron laser (PolFEL) project, a Coherent Diffraction Radiation (CDR) system is being developed and tested. It will allow for non-destructive bunch length measurement based on the power balance of CDR radiation collected by Schottky diodes in different ranges of (sub-)THz radiation. The first tests and measurements will be performed at the end of the SOLARIS synchrotron injector linac, where the beam has been already characterized and aligned. In this paper the theoretical background of the measurement, calculations and first experimental achievements will be presented.

COHERENT DIFFRACTION RADIATION

Electromagnetic radiation is emitted when a beam of charged particles accelerates or changes medium of propagation (abruptly or continously in terms of the local electromagnetic susceptibility) [1, 2]. 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 [3, 4]. For shorter bunches far-infrared diagnostics are needed, for example spectrometers [5]. If the goal is to infer a relative information of the bunch compression, then a source of coherent radiation coupled to a power-detector can provide this information, since for a detected frequency which is high-enough the amount of detected power scales with the shortness of the emitting bunch. 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], Coherent Diffraction Radiation (CDR) will be exploited, which allows for non-destructive bunch length measurements. Diffraction radiation is the radiation that a bunch of particles emits when crossing two regions of limited size with different index of refraction [7]. 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 fact that the disk is hollow allows for the beam not to be scattered and the emittance be preserved (the field lines polarize the radiator 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 [8, 9]:

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

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 Fig. 1.

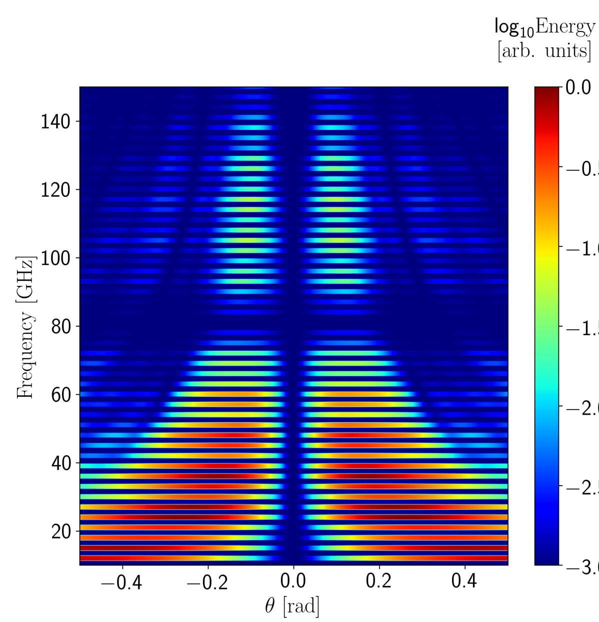

Figure 1: CDR spectral-angular distribution for the SOLARIS injector bunch repetition pattern and beam energy of 550 MeV. The radiator diameter has been set to 5 cm with 1 cm diameter hole for non-destructive diagnostics.

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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

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

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]. First tests for PolFEL [10] will be conducted at SOLARIS [11], on a diagnostic station at the end of the injector linac, just before the beam dump, placed for this and other experimental purposes . 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.

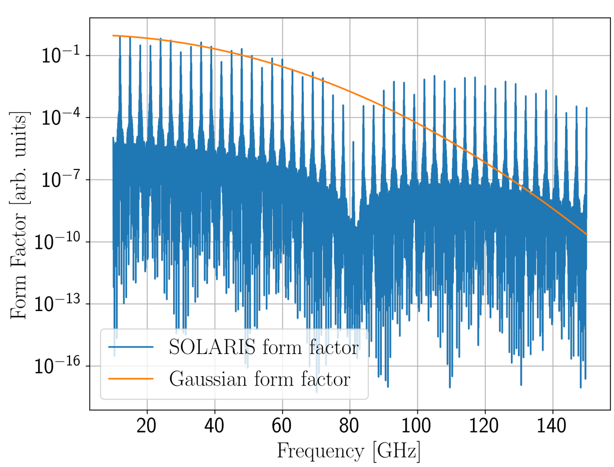

Figure 2: Form factors calculated for SOLARIS injector bunch train and a single Gaussian bunch. In both cases the RMS bunch length is equal to 5 ps.

Although deriving the information on the bunch length from a narrow frequency band is not possible, 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 Fig. 3 the ratios of the CDR power expected in SOLARIS within three frequency bands is plotted as a function of the RMS bunch length. The bands correspond to the bands of commercially available Shcottky diodes offered by Eravant [14]. As can be seen, combination of 50-75 GHz diode with any of two other diodes can provide a sensitive measure of the bunch length, but only for bunches shorter than approximately 6.5 ps. The longer bunches can be however measured using the less sensitive 26.5-40 GHz / 33-50 GHz ratio.

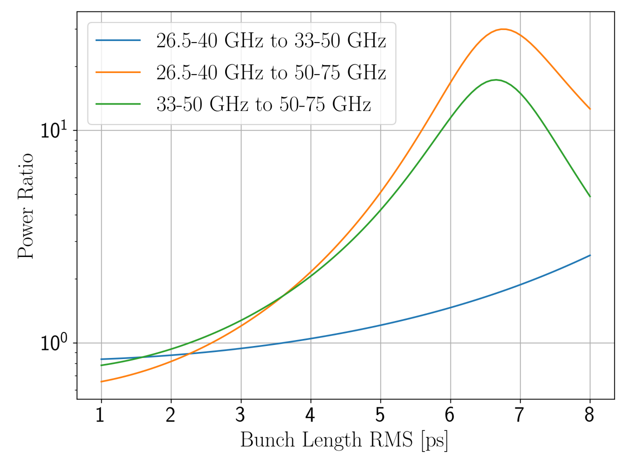

Figure 3: Ratios of CDR power emitted in distinct frequency band, as a function of RMS bunch length.

EXPERIMENTAL SETUP

The first step taken when preparing the setup for measuring the longitudinal electron beam profile using CDR radiation was to place the YAG screen about 20 cm behind 0.15 mm thick flange at the end of the linac in beam dump section. A series of tests was carried out on how the electron profile can be modifed by linac magnets settings, but ultimately it was left with the original machine setup, because the linac had to remain operational so as not to interfere with the operation of the synchrotron. Afterwards the YAG screen was replaced with a CDR radiator in the form of metal coated mirror at an angle of 45° to the incident electron beam. The reason for using a metallic mirror as a radiator instead of a hollow disc was to induce transition radiation, which facilitated the alignment process. In order to focus radiation on the detector, a golden coated parabolic mirror was placed in the setup. The fact that the emitted transition radiation contains part of the visible spectrum, and reflects off the Ø3" 90° Off-axis parabolic mirror in the same way like CDR radiation, makes it possible to use optical CCD camera as radiation focus detector. In this way the location for the Schottky diodes was determined. Placing the latters there and measuring the CDR signal will be the next action to take. In parallel and for more general purposes, a remote controlled lens was mounted on the diagnostic camera for prototyping and testing. The system has been built with a

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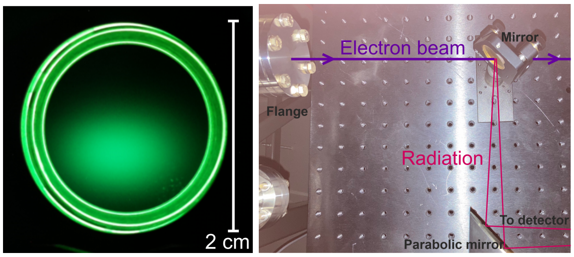

Figure 4: Transverse electron beam profile measured with YAG screen at radiator position and top view of longitudinal profile measurement set-up at SOLARIS.

widely available and low cost Canon EF lens that is also compatible with a general purpose Canon still cameras. The electronic control system was made using a STM32 microprocessor and an Ethernet controller chip. These controllers may be mounted on the other diagnostics cameras in the linac or even at the Pinhole diagnostic beamline in the SOLARIS ring. At the diagnostic station before the beam dump we have for now mounted a Raspberry Pi camera with a in-house modified hardware that has the ability to be triggered from the timing system. Thanks to this it is possible to take a synchronized beam image just when the radiator is hit and light is emitted, as in Fig. 4.

CONCLUSION

In this contribution the first steps made at SOLARIS towards an experimental test of the CDR-based electron bunch length measurement for PolFEL have been presented. As a parallel development, an imaging system with automatic focusing and trigger has been successfully commissioned during the setup construction. Additionally, tools for processing the measured data and calculating the bunch length have been developed. The Schottky diodes purchase process is currently underway. After placing them in the setup, first results will be obtained, analyzed and compared to the expected values in order to verify the correctness of measurements and calculations. If all tests pass, analogous setups will be implemented for the PolFEL project.

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