ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-WEPMO03

SMITH-PURCELL AND TRANSITION RADIATION BASED CHARGED PARTICLE BEAM DIAGNOSTICS FOR THE FEMTOSECOND-RANGE

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Abstract

We will give an overview of the Smith-Purcell and Transition Radiation based longitudinal diagnostic methods employed at the ARES (Accelerator Research Experiment at SINBAD) linear accelerator to characterize femtosecond long electron bunches. The Smith-Purcell radiation mechanism has been studied for the case of metallic gratings, but not much experimental data has been published yet with respect to dielectric gratings as charged particle beam diagnostic devices. We expect a number of advantages in the detection of the radiation at the substrate side and the spectral properties of the radiation tailored by the geometric shape of the grating structures. Due to the advances in lithographic techniques dielectric gratings can be produced with optical wavelength periodicities and the shapes can be controlled with nanometre precision. For femtosecond bunch lengths the coherence of transition radiation starts to reach the near-infrared to optical regime. This opens up the possibility of characterizing the spectrum with readily available high sensitivity semi-conductor based detectors to draw conclusions on the form factor and measure bunch lengths.

INTRODUCTION

The length of a particle bunch is an important parameter for the accurate operation of accelerators and a crucial requirement in the development of novel acceleration techniques, such a Dielectric Laser Acceleration (DLA) and Plasma Wake Field Acceleration (PWFA). ARES (Accelerator Research Experiment at SINBAD) is a dedicated R&D linac for the production and subsequent diagnosis of single-digit femtosecond bunches and shorter, complete with a movable bunch compressor [1] and PolariX TDS [2] which is capable of single-digit femtosecond resolution through streaking the bunch at numerous angles. This diagnostic method is destructive to the bunch and there is much interest in the development of passive longitudinal bunch diagnostics.

Smith-Purcell Radiation (SPR) has been extensively studied from charged particle bunches passing metallic gratings [3–6], however the case of dielectric gratings has been neglected. A significant advantage of using dielectric gratings is the opportunity to observe the radiation on the substrate side, allowing for simpler geometries [7]. Dielectric gratings can be produced with nanometre precision and properties of the radiation's spectral power distribution can be tailored through careful consideration of the structure's geometry.

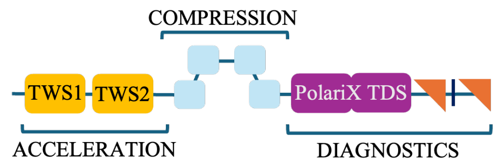

Figure 1: Schematic layout of ARES linac. The acceleration section consists of an electron gun (not pictured) and two Travelling Wave Structures (TWS) and is followed by a magnetic chicane. The diagnostics section has a PolariX TDS and two 45° silver mirrors, one in-vacuum and one in-air after a 50 µm Ti foil.

The radiation factors of SPR scale roughly inversely proportional to γ^2 [4], which means that, from ultra-relativistic beams, incoherent SPR is extremely challenging to detect. For the use of SPR in beam diagnostics, it is necessary that there is coherent enhancement of the radiation. This means that the bunch should already be shorter than the period of the gratings used. In order to obtain this information "online", Transition Radiation (TR) at optical frequencies can be used as an uncalibrated bunch compression monitor. For single-digit femtosecond bunch lengths, TR at optical frequencies is coherently enhanced and easily detectable.

The spectra of TR and the SPR contains information about the bunch form factor, which can be used to calculate the longitudinal current profile, $S(z)$,

$$F(\omega) = \left| \int_0^\infty dz S(z) \exp^{i(\omega/c)z} \right|^2 . \qquad (1)$$

In order to accurately calculate the longitudinal bunch shape, the relative phases of the spectrum are also required. A number of techniques have already been utilised for this purpose, including Kramers-Kronig pairs [8–10] and Frequency Resolved Optical Gating (FROG) [11, 12].

TRANSITION RADIATION DIAGNOSTICS

The TR produced by the beam incident upon the first 45° silver mirror in Fig. 1 has been used as a bunch compression monitor. The radiation was first imaged by a Basler camera outside of the vacuum chamber sensitive from 400 to 1000 nm. The camera was then replaced by an Ocean HDX spectrometer sensitive to wavelengths between 200 and 1100 nm. The responsivity of the spectrometer has not yet been considered in the following analysis.

Evident in Fig. 2 is the strong dependence of the TR signal on the phase of TWS2. Altering the phase of TWS2 will

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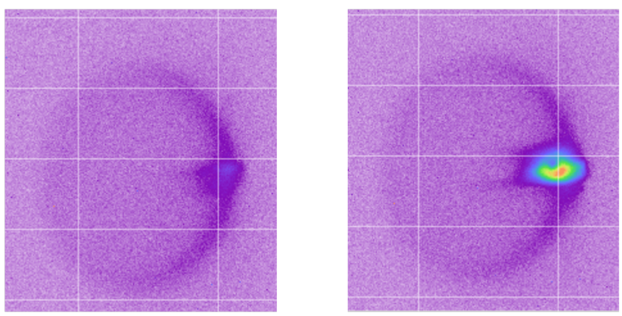
alter the energy chirp imparted on the bunches and change the degree of compression that is achieved at a certain longitudinal position after the magnetic chicane. The signal seen in Fig. 2a is the result of incoherent TR from a bunch that is longer than the wavelengths detected by the camera. In Fig. 2b, the signal has significantly higher intensity because the bunch, or a significant part of the bunch, has now been compressed below 1000 nm, so the wavelengths where coherent enhancement occurs were able to be detected by the camera. Figure 2b also has the CTR signature ring-shape due to the angular distribution of the mechanism. This already functions well as an uncalibrated compression monitor for live tuning of the bunch length, provided the bunch length is already compressed to around 1000 nm.



(a) (b)

Figure 2: Screen images of TR with a 1.5° phase difference in TWS2. Both images were recorded with the same bunch charge incident on the silver mirror.

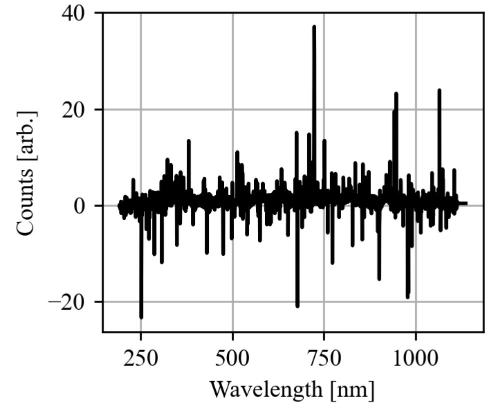
Figure 3 shows the spectrum detected with three different phase offsets in TWS2 for a bunch charge of 1.02 pC. There is no visible TR signal in Fig. 3a, likely indicating that the bunch length is longer than the wavelengths imaged by the camera. In Fig. 3b and Fig. 3c there are clearly visible spectra, with significantly higher intensity for a 31.5° phase offset in TWS2. The spectra indicate, in agreement with the images in Fig. 2, that coherent enhancement of the TR is extremely sensitive to the phase of TWS2. This also shows the qualitative difference in the bunch form factor, from Eq. (1), that can be calculated from the spectra to determine the bunch length.

Figure 4 shows the sum over the measured TR spectrum at different TWS2 phase offsets. The sum over the spectrum is largest for a TWS2 phase offset of 31.5° which is in agreement with what can be seen in the individual spectra in Fig. 3.

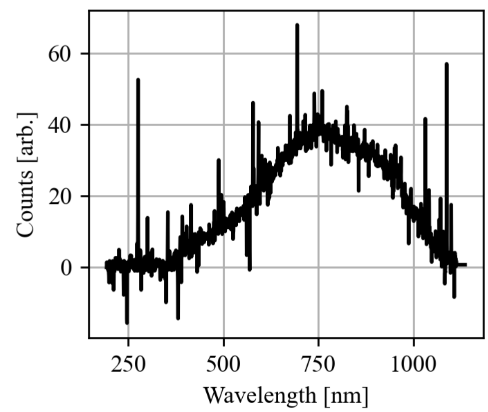
To calculate the bunch length, information over the whole spectrum is required, but this already shows the potential for ‘live’ bunch length feedback from optical TR. The in-air 45° silver mirror and the 50 µm exit window have also been investigated as potential TR targets, although no spectra has been captured of these yet.

SMITH-PURCELL DIAGNOSTICS

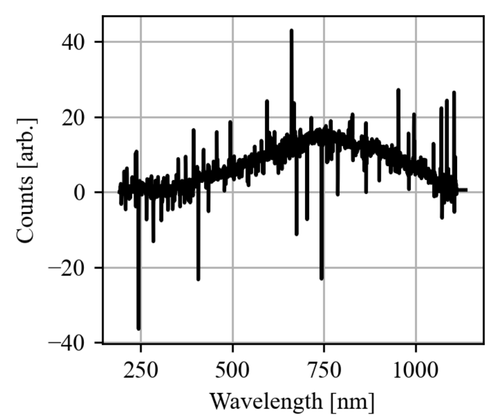
Metallic gratings with periods of 600, 1200, 1800, and 2400 lines/mm will be tested at ARES to verify the theory



(a) TR spectrum with 29.0° phase offset in TWS2.



(b) TR spectrum with 31.5° phase offset in TWS2.



(c) TR spectrum with 34.0° phase offset in TWS2.

Figure 3: Transition Radiation spectra for 29.0°, 31.5°, and 34.0° phase in TWS2.

and determine a suitable imaging system before tests with dielectric gratings are undertaken.

Figure 5 shows the proposed experimental geometry for the measurement campaign. The camera can be moved around the grating between 60° and 120° relative to beam direction. The grating can also be rotated about a central axis to change the effective period experienced by the bunch.

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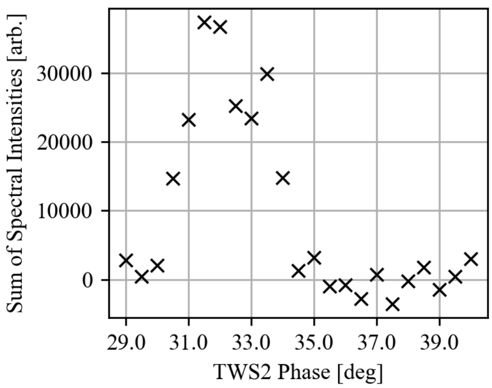

Figure 4: Screen images of TR with a 1.5° phase difference in TWS2.

Figure 5: In-air setup for the production and detection of SPR.

Another camera is mounted at the bottom of the translation stage to image the optical TR from the in-air 45° silver mirror to help verify that the beam is short. The setup will be moved as close to the exit window as possible to reduce scattering effects.

CONCLUSION

The viability of a bunch compression monitor utilising optical TR has been tested for bunches on the order of single-digit femtoseconds. Images or spectra of the TR can be used for ‘live’ feedback on the bunch length. The proposed measurements of SPR have been discussed and will be carried out by the end of 2025.

ACKNOWLEDGEMENTS

The authors acknowledge support from DESY (Hamburg, Germany), a member of the Helmholtz Association HGF.

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