A compact dielectric grating-based charged particle bunch length diagnostic device at ARES

B Stacey[1,2], R Assmann[1,3], W Hillert[2], W Kuropka[1] and T Vinatier[1]

[1] Deutsches Elektronen-Synchrotron DESY, Germany
[2] Department of Physics Universität Hamburg, Germany
[3] Laboratori Nazionali di Frascati, Italy

E-mail: blae.stacey@desy.de

Abstract. Dielectric gratings are already used in Dielectric Laser Acceleration due to their high damage thresholds at high acceleration gradients. When an electron bunch passes close to one of these gratings, it emits radiation, and the features of this radiation will be dependent upon the beam position relative to the grating, the bunch charge, and the bunch length. A compact high-resolution diagnostics device will be developed that consists of multiple gratings with different periods; these types of devices are required for the accurate operation of future compact accelerators which are currently undergoing development and testing. ARES linac at DESY is able to provide sub-fs electron bunches and has a range of high-resolution diagnostic devices installed, such as the PolariX Transverse Deflecting Structure, which will allow for performance verification of a new diagnostic. The electron bunches can be altered, allowing for the measurement and analysis of the emitted radiation for different bunch lengths and charges. This work will present the current progress in this area, including the presentation and discussion of simulations, and a discussion of the planned experiments at ARES.

1. Introduction

Due to advancements in the Dielectric Laser Acceleration (DLA) technique [1], and in grating-based deflection structures [2], there is interest in an entirely grating-based compact particle accelerator. In order for this to become a reality, there are requirements for suitable diagnostics devices that are capable of single-shot bunch length measurements and beam position monitoring. Manufacturing these diagnostics from similar dielectric gratings to DLA structures is highly favourable, since the production process is reasonably fast and inexpensive. These devices would also be very compact, with dimensions in the order of millimeters or centimeters depending on the operation parameters of the beam.

Bunch length diagnostic techniques generally involve either correlating the longitudinal coordinate to a transverse component of the beam through beam deflection or streaking [3], which is destructive to the bunch, or inducing the bunch to radiate and measuring the resulting spectrum, which leaves the bunch intact. As a charged particle bunch passes through an unpowered dielectric grating, it will decelerate and radiate at a wavelength equal to the period of the grating, through the radiation mechanism known as Smith-Purcell Radiation (SPR) [4]. Based on this mechanism, a bunch length diagnostic has been proposed [5]. When the bunch length is smaller than the grating period, the radiation will contain significant spectral content and increase in power; by varying the longitudinal periodicity of a grating and measuring the relative radiation output, a value for the length of the bunch can be obtained. This device could also function as a Beam Position Monitor (BPM), using a double-sided grating and comparing the photon yield on each side.

A similar concept used a dielectric grating as a high resolution BPM [6, 7], with a chirped period in the transverse direction, already shows potential for sub-nanometer resolution with sufficient photon yield.

2. WORKING PRINCIPLE

As a charged particle passes through dielectric material, it will emit Cherenkov radiation [8] if the particle's velocity is faster than the phase velocity of light in the material. When the particles pass close to a dielectric material, this is also true, due to the refractive index that the particle's electromagnetic field experiences. The refractive index varies periodically for a grating, giving rise to the SPR mechanism, which is described by the equation,

$$\frac{1}{\beta} - ncos(\theta) = \frac{m\lambda_e}{\lambda_g} \tag{1}$$

where λ_g is the period of the grating, n is the refractive index of the structure, θ is the emission angle of the photon from the direction of the particle's velocity, β is the velocity of the particle relative to the speed of light, m is the mode number, and λ_e is the wavelength of the emitted radiation [9]. The case of $m \neq 0$, $n \neq 1$ describes internal SPR of order m in a dielectric material with refractive index n.

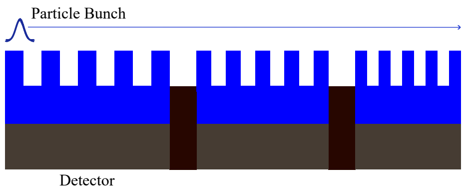

Figure 1. Proposed diagnostic device with grating period varied longitudinally.

A schematic of the proposed diagnostic device is shown in Fig. 1. It consists of multiple grating sections with different periods, separated by material that is opaque at the considered wavelengths to avoid the detection of radiation from one section by the detectors in neighbouring sections. The internal SPR, which passes through the dielectric material, can be detected behind the grating structure; if the bunch is smaller than the period of the grating, then the radiation will contain significant spectral content, and the radiated power will increase.

The incoherent part of the spectrum for each grating section can be estimated from a direct charge measurement, and this can be subtracted from the measured radiation at the detectors. From the remaining spectrum, the longitudinal current profile is given and the length of the bunch can be estimated from the bunch form factor and an assumed bunch shape. If the photon yield is sufficient, the bunch shape can be reconstructed by auto-correlating the signal from each grating and using the Frequency-Resolved Optical Gating (FROG) technique [10] to find the relative phases of each of the frequency components, giving the approximate spectral information.

The radiated power is expected to vary as a function of the bunch distance from the grating; by using a double-sided grating structure and rotating every other section in the transverse plane by 90°, this device should also be able to provide beam position data in both transverse planes, through the relative photon yield from either side of the structure.

Journal of Physics: Conference Series **2687** (2024) 072008 doi:10.1088/1742-6596/2687/7/072008

3. SIMULATION RESULTS

A double-sided fused silica ($\epsilon = 3.75$) grating of 5 periods has been modelled in the CST Wakefield solver [11]. A Gaussian-shaped particle beam excitation was simulated, propagating in the z direction, with constant charge of -1 pC and velocity $\beta = 1$. The model in Fig. 2 shows only the grating teeth, since the block dielectric behind them has a predictable impact on the SPR mechanism. From the tolerance studies carried out for a similar system in Ref. [12], it is evident that the manufacturing tolerances place more of a limit on the resolution than the simulation method.

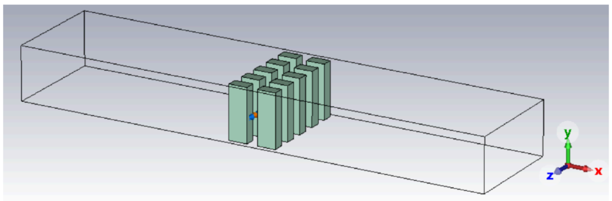

Figure 2. CST model of the grating with $\lambda_g = 2050$ nm.

The rms bunch length sigma of the particle beam excitation was varied to investigate the dependence of the radiation amplitude on the bunch length. Figure 3 shows the radiation amplitude perpendicular to the direction of particle propagation and the longitudinal current amplitude at a frequency component corresponding to a grating of $\lambda_g = 2050$ nm. Both the radiation and current amplitude scale with the length of the bunch, and this dependence highlights the potential for SPR to be used as a bunch length diagnostic tool.

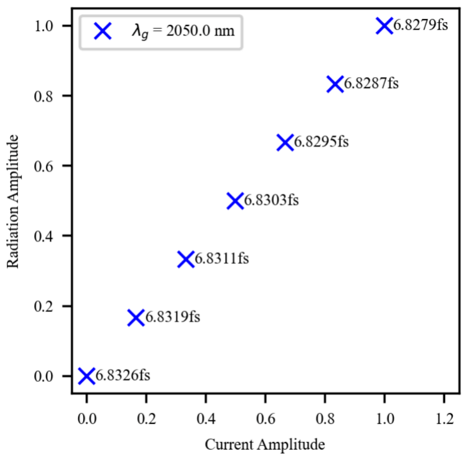

Figure 3. Plot of radiation amplitude and current amplitude vs. bunch length for a grating with $\lambda_g = 2050$ nm.

The radiation and current amplitudes are approximately proportional for a range of bunch lengths, which suggests that it may also be possible to determine an approximate bunch shape from the radiation spectrum, using the FROG technique mentioned previously, provided there is significant spectral content. For all data points shown in Fig. 3 the simulated particle bunch length is shorter than the period of the grating; all bunches contain significant spectral content at this frequency.

Simulations were also performed for a variety of grating periods using two different longitudinal bunch lengths of $\sigma = 870.6$ nm and $\sigma = 870.8$ nm, which correspond to temporal lengths of 6.834 fs FWHM and 6.836 fs FWHM respectively. This models the bunches passing gratings of different periods to provide a preliminary basis for a bunch length diagnostic device similar to Fig. 1.

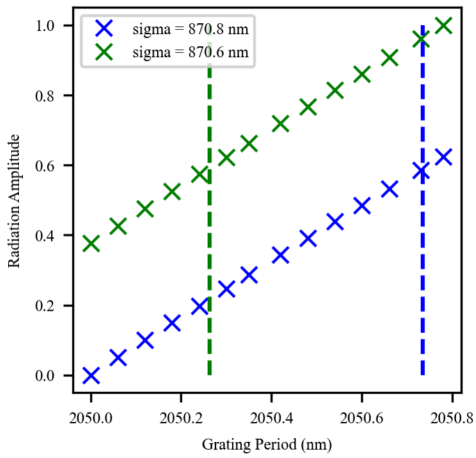

Figure 4. Amplitude of emitted radiation at the frequency component corresponding to the grating period vs. grating period. The dashed vertical lines indicate the length of the simulated bunch.

In Fig. 4, the radiation amplitude at the frequency component matching the grating period is shown against the grating period, showing the dependence. It can be seen from this result that the radiation amplitude increases above a threshold value, of around 0.6 in this normalisation, for bunch lengths shorter than the period of the grating, as was expected since in this case the emitted radiation becomes coherent. For a series of gratings with decreasing periodicity, the bunch length can be estimated from the period of the grating which shows radiated power above this predetermined background level when compared to gratings with shorter periods.

There are plans to conduct a preliminary experiment using the ARES linac at DESY, by passing bunched electrons through a fused silica grating with a period of 2050 nm that is already installed for the purpose of DLA experiments [12]. By inducing an angle between this grating and the electron beam, the effective period of the grating can be changed as a preliminary test of the feasibility of the SPR mechanism for use in such a diagnostics device. Since the length of this grating is around 1 mm, and each grating period is around 2 μm, changing the angle between the grating and the electron beam will have minimal impact on the symmetry of the structure beyond the effective period. A CCD-camera, InGaAs diode, or fiber coupled spectrometer will be used to detect the emitted radiation, depending on the intensity of the radiation and the resolution required. ARES is an S-band normal conducting linac [3, 13, 14] for accelerator research and development, that aims to provide sub-fs bunches in the near future. It is an excellent facility for testing this device since it has the ability to produce electron bunches of variable length on the scale of the grating period, and there will be an X-band TDS installed downstream of the experimental chamber to validate the diagnostic method proposed here.

4. CONCLUSION

From simulated results, it is shown here that there is a direct relation between the amplitude of the radiation emitted by a particle bunch at the frequency corresponding to the grating period and the particle bunch length. It is also shown that the radiation amplitude increases above a threshold value when the bunch length is shorter than the period of the grating. This is a promising result for the design and production of a dielectric grating-based bunch length diagnostic device that will be tested at ARES in the future.

Acknowledgments

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

References

[1] Peralta E A *et al* 2013 *Nature* **503** 91–94
[2] Plettner T, Byer R L, McGuinness C and Homelhoff P 2009 *Phys. Rev. ST Accel. Beams* **12** 101302
[3] Jaster-Merz S, Assmann R W, Brinkmann R, Burkart F and Vinatier T 2022 *Proc. 13th Int. Particle Accelerator Conf.* (Bangkok, Thailand) 279–281
[4] Smith S J and Purcell E M 1953 *Phys. Rev.* **92** 1069
[5] Kuropka W 2020 Ph.D. thesis, Phys. Dept., Universität Hamburg, Hamburg, Germany.
[6] Soong K and Byer R L 2012 *Opt. Lett.* **37** 975–7
[7] Soong K, Peralta E A, England R J, Wu Z, Colby E R, Makasyuk I, MacArthur J P, Ceballos A and Byer R L 2014 *Opt. Lett.* **39** 4747–50
[8] Cherenkov P A 1937 *Phys. Rev.* **52** 378–9
[9] Konakhovych D, Sniezek D, Warmusz O, Black D S, Zhao Z, England R J and Szczepkowicz 2021 arXiv:2105.07682
[10] Kane D J and Trebino R 1993 *Op. Lett.* **18** 823–5
[11] CST. http://www.cst.com/.
[12] Kuropka W, Assmann R, Dorda U, and Mayet F 2020 *J. Phys.: Conf. Ser.* **1596** 012018
[13] Burkart F, Assmann R W, Dinter H, Jaster-Merz S, Kuropka W, Mayet F, Stacey B and Vinatier T 2022 *Proc. Int. Linear Accelerator Conf.* (Liverpool, UK) 691–4
[14] Kuropka W, Assmann R W, Burkart F, Dinter H, Jaster-Merz S, Lemery F, Mayet F, Stacey B and Vinatier T 2022 *Proc. Int. Linear Accelerator Conf.* (Liverpool, UK) 695–8