COHERENT RESONANT DIFFRACTION RADIATION FROM INCLINED GRATING AS A TOOL FOR BUNCH LENGTH DIAGNOSTICS[*]

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Abstract

The present report summarizes the status of an experiment devoted to the development of bunch length diagnostics based on coherent resonant diffraction radiation that will be carried out at the SwissFEL injector test facility at the Paul Scherrer Institute in Villigen (Switzerland).

INTRODUCTION

Nowadays there exist many different techniques devoted to the measurement of bunch lengths in the order of hundreds of femtoseconds at modern electron accelerators. One of these techniques widely in use is based on coherent radiation emission, i.e. emission at wavelengths in the order or smaller than the bunch length. In this case the radiation intensity depends quadratically on the number of particles per bunch. Thus, by measuring the radiation intensity as function of the wavelength it is possible to determine in principle both bunch length and bunch shape. Coherent radiation emission is a general physical process for bunches of charged particles that does not depend on the type of the emitted radiation. So far, coherent synchrotron radiation, transition radiation, diffraction radiation, and Cherenkov radiation are used as radiation mechanisms. These kinds of radiation have a polychromatic angular distribution, i.e. for the wavelength–dependent investigation of the emitted intensity an external spectrometer is required.

In this context coherent Smith–Purcell radiation (CSPR) is advantageous because of the dispersive radiation emission. Smith–Purcell radiation in generated when a charged particle passes close to the surface of a periodic structure, i.e. a diffraction grating. Due to the periodicity involved in the radiation generation, this kind of radiation obeys a characteristic dispersion relation which relates the observation wavelength λ and the radiation angle θ, the so called Smith–Purcell relation

$$\lambda = \frac{d}{|n|} \left(\beta^{-1} - \cos\theta \right), \tag{1}$$

with d the grating period, n the diffraction order, and β the charged particle velocity in units of speed of light. Smith–

Purcell radiation in view of particle beam diagnostics is discussed e.g. in Ref. [1].

A direct way to use CSPR for bunch length diagnostics would be to measure the angular distribution of the radiation, to estimate the spectrum of coherent radiation, and to extract finally the bunch size. Such diagnostic scheme was already investigated by G. Doucas et al. [2]. The authors used 11 detectors, mounted under different observation angles θ to select different wavelengths, and 3 interchangeable volume gratings with different periods. However, such experimental scheme implies the difficulty that the number of accessible observation wavelengths is limited by the number of detectors. Moreover, for a precise measurement all detectors have to be intensity–calibrated with respect to each other to a high level of accuracy. From theoretical point of view the application of a volume grating has some disadvantages because the angular distribution of the emitted radiation is not uniform with respect to the power, there exist some characteristic resonance structures which may drastically affect the achievable accuracy for bunch length diagnostics. These structures are known from optical grating theories as Wood–Rayleigh anomalies, an indication of their observation is reported in Ref. [3].

Unfortunately, up to now there is no exact theory describing the radiation from volume gratings in the case of finite grating sizes. There are several theories but they are not in complete agreement with the experimental data [4].

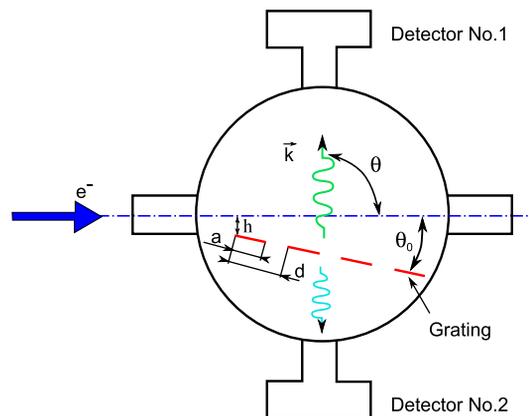Smith–Purcell radiation from an inclined grating with

Figure 1: Proposed scheme for CRDR based bunch length diagnostics.

respect to the beam axis, which in the following will be named Resonant Diffraction Radiation (RDR), was calculated for the first time in Ref.[5]. Later on some of the authors proposed to use Coherent RDR (CRDR) for beam diagnostics [6]. The proposed scheme is shown in Fig. 1. The electron bunch travels with an impact parameter h close to the grating. In order to minimize the contribution of the Wood–Rayleigh-like anomalies a very thin strip–grating with vacuum gaps will be used. The radiation is measured with two detectors under observation angles $\theta = \pm\frac{\pi}{2}$. While the grating is parallel to the electron trajectory, both detectors measure radiation with wavelengths almost equal to grating period according to Eq. (1). However, if the grating is inclined, the radiation lines shift in opposite directions: one detector measures at longer wavelengths while the other at shorter ones. If the grating period is chosen to be close to the coherent threshold the line intensities changes drastically. Thus, measuring the dependency of the radiation intensity versus the inclination angle it is possible to estimate the bunch length.

The proposed scheme has the advantage that the number of accessible wavelengths is not limited by the number of detectors, therefore the number of data points available for a bunch shape reconstruction is much larger. In addition, only two detectors are required for which a relative intensity calibration is necessary. However, with the proposed experimental scheme it will not be possible to make a single–shot bunch shape reconstruction, but if the shape is known a priori a single–shot bunch length measurement seems to be realistic.

In this paper we calculate some features of the CRDR from inclined grating for the parameters of SwissFEL injector test facility and discuss some practical aspects.

THEORETICAL MODEL

The theoretical calculations are based on a generalized surface current method [7]. In this theoretical approach it is assumed that the grating is ideally conducting and infinitely thin. In addition it is assumed that both detectors are situated in far–field (wave) zone. The radiation field $\mathbf{E^R}(\mathbf{r_0}, \omega)$ can be expressed as follows (assuming that the grating is infinite in the direction transverse to plane of Fig. 1):

$$\mathbf{E^R}(\mathbf{r_0}, \omega) = -i\frac{e^{ikr_0}}{r_0}\mathbf{k}\times$$
$$\times \int_S dz\, [\mathbf{n}, \mathbf{E_0}(k_x, y = 0, z, \omega)]\, e^{-ik_z z} \qquad (2)$$

In the following a coordinate system associated with the grating is used, $\mathbf{k} = \frac{\omega}{c}\{ex, ey, ez\}$ is the wave-vector of the radiation, $\mathbf{n} = \{0, 1, 0\}$ the normal to the grating surface, $\mathbf{E_0}(k_x, y = 0, z, \omega)$ the Fourier component of the ini-

tial electron field. The latter can be written as

$$\mathbf{E_0}(k_x, y = 0, z, \omega) = -\frac{ie}{2\pi\beta c}$$
$$\exp\left[i\frac{\omega}{c}\left(\beta^{-1}\cos\theta_0 - \frac{\sin\theta_0}{\beta\gamma}\sqrt{1 + (\beta\gamma e_x)^2}\right)\right]$$
$$\frac{\exp\left[-h\frac{\omega}{c}\left(i\beta^{-1}\sin\theta_0 + \frac{\cos\theta_0}{\beta\gamma}\sqrt{1 + (\beta\gamma e_x)^2}\right)\right]}{\sqrt{1 + (\beta\gamma e_x)^2}}$$
$$\left\{\beta\gamma e_x, \gamma^{-1}\sin\theta_0 - \cos\theta_0\sqrt{1 + (\beta\gamma e_x)^2},\right.$$
$$\left.\gamma^{-1}\cos\theta_0 + \sin\theta_0\sqrt{1 + (\beta\gamma e_x)^2}\right\} \qquad (3)$$

The integration of Eq. (2) is performed over all grating strips. The following integral can be calculated analytically:

$$\mathbf{E^R}(\mathbf{r_0}, \omega) \propto \sum_{n=0}^{N-1}\int_{nd}^{nd+a} dz$$
$$\exp\left[\frac{\omega}{c}z\left(-ie_z + i\frac{\cos\theta_0}{\beta} - \frac{\sin\theta_0}{\beta\gamma}\sqrt{1 + (\beta\gamma e_x)^2}\right)\right] \qquad (4)$$

with d the grating period, N the number of periods, a the strip width, and $a = d/2$.

The integration of Eq. (2), taking into account Eqs. (3)-(4), results in the radiation field of interest. The spectral-angular density of RDR both incoherent and coherent emission is given by:

$$\frac{d^2 W}{\hbar d\omega d\Omega} = \frac{cr_0^2}{\hbar}\left|\mathbf{E^R}(\mathbf{r_0}, \omega)\right|^2 N_e\left(1 + (N_e - 1)|f_z|^2\right) \qquad (5)$$

with N_e the bunch population and f_z the longitudinal bunch form–factor. For a Gaussian bunch the latter one can be written as

$$|f_z|^2 = \exp\left[-\frac{4\pi^2\sigma_z^2}{\beta^2\lambda^2}\right] . \qquad (6)$$

THEORETICAL CALCULATIONS

The calculations were carried out for the following parameter set: electron energy $E_e = 165\,\text{MeV}$, bunch length $\sigma_z = (70...250)\,\mu\text{m}$, grating period $d = 700\,\mu\text{m}$, and impact parameter $h = 20\,\text{mm}$.

Fig. 2 demonstrates the shift of a monochromatic emission line as seen by both detectors for fully coherent radiation $\sigma_z = 0$. From there it is also obvious that a bunch traveling parallel to the grating surface ($\theta_0 = 0$) both detectors
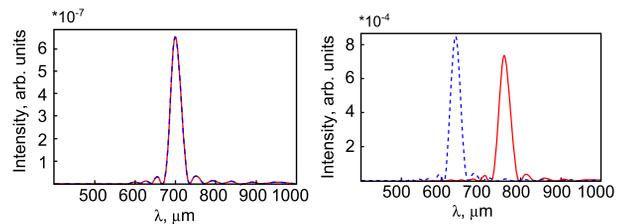

Figure 2: Monochromatic emission line shift as seen by both detectors. Blue dashed line – lower detector ($\theta = -90°$), red solid line – upper detector ($\theta = 90°$), left figure – $\theta_0 = 0$, right figure – $\theta_0 = 5°$.
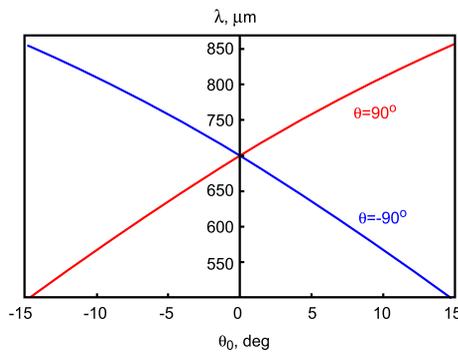
Figure 3: The dependence of the line shift for both detectors versus inclination angle θ_0, blue dashed line − lower detector ($\theta = -90°$), red solid line − upper detector ($\theta = 90°$).

measures radiation with the wavelength almost equal to the grating period $\lambda \simeq 700\,\mu m$ according to Eq.(1). If the grating is inclined the lines are shifted in opposite directions. A further aspect to note is the increase of the radiation intensity from the inclined grating. This fact is very promising for beam diagnostics because the intensity of conventional CSPR is low.

Fig. 3 shows the dependence of the line shift for both detectors versus inclination angle θ_0.

During the line shift the radiation intensity is changed according to the bunch form–factor. In order to estimate the bunch length the ratio R of both detector signals versus the inclination angle θ_0 is measured, thus avoiding the need for absolute detector calibrations. This ratio strongly depends on bunch lengths as demonstrated in Fig. 4.
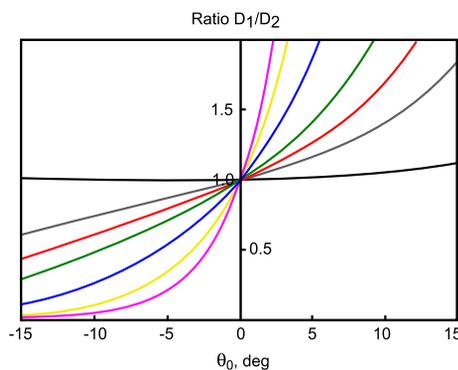

Figure 4: The ratio of detector signals $R = D_1/D_2$ versus inclination angle θ_0 for different bunch lengths σ_z. Black line − $\sigma_z = 0$, gray line − $\sigma_z = 70\,\mu m$, red line − $\sigma_z = 90\,\mu m$, green line − $\sigma_z = 110\,\mu m$, blue line − $\sigma_z = 150\,\mu m$, yellow line − $\sigma_z = 200\,\mu m$, pink line − $\sigma_z = 250\,\mu m$.

PRACTICAL ASPECTS

The experiment is planned to be carried out at SwissFEL injector test facility at the Paul Scherrer Institute in Vil-
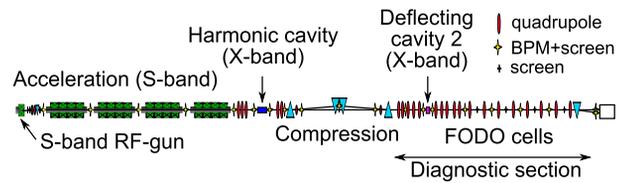

Figure 5: The scheme of SwissFEL injector test facility.

ligen (Switzerland). The accelerator scheme is shown in Fig. 5. The vacuum chamber will be installed in FODO section close to a deflecting cavity, thus render it possible to make a direct cross–check with the CRDR measurements. The electron energy may vary from $E_e = 130, 170, 200, 230\,\text{MeV}$, the bunch length from $\sigma_z = 50\,\text{fs}$ up to $\sigma_z = 1\,\text{ps}$, and the bunch charge from $10\,\text{pC}$ up to $200\,\text{pC}$. The shortest bunch length will be possible for the lowest bunch charge. The experiment will start with bunch lengths $\sigma_z \simeq 300\,\text{fs}$ ($\sigma_z \simeq 90\,\mu m$) and a grating period of $d = 700\,\mu m$. It is planned to use $100\,\mu m$ thick gratings made out of silicon wafers, covered by some metal for a better conductivity. At the beginning only one detector will be used, and the grating has the option to be rotated by $180°$ in order to obtain both detector dependencies.

It is planned to install the equipment in July 2011 and to start the experiment in October 2011.

CONCLUSION

A monitor concept based on CRDR from an inclined grating is presented which could be an interesting tool for bunch length diagnostics. The radiation properties are well suited for the application as an easy and compact bunch length monitor with the advantage not to rely on absolute intensities. Therefore, in the nearest future a proof-of-principle experiment is planned in order to verify the radiation properties and to investigate the sensitivity limits of such a kind of monitor.

REFERENCES

[1] G. Kube et al., Proc. DIPAC 2003, Mainz, Germany (2003), p. 40.

[2] G. Doucas et al., Phys. Rev. Spec. Top. - Accel. Beams **9**, 092801 (2006).

[3] G. Kube et al., Phys. Rev. E **65**, 056501 (2002).

[4] D.V. Karlovets and A.P. Potylitsyn, Phys. Rev. Spec. Top. - Accel. Beams **9**, 080701 (2006).

[5] A. P. Potylitsyn, P. V. Karataev, and G. A. Naumenko, Phys. Rev. E **61**(6), 7039-7045 (2000).

[6] A.P. Potylitsyn, D.V. Karlovets, and G. Kube, Nucl. Instrum. Methods Phys. Res., Sect. B **266**, 3781-3788 (2008).

[7] D.V. Karlovets and A.P. Potylitsyn, Phys. Lett. A **373**, 1988-1996 (2009).