POSSIBILITIES OF DIFFRACTION RADIATION NON-DESTRUCTIVE DIAGNOSTICS FOR NON- AND MODERATELY RELATIVISTIC BEAMS*

D. A. Shkitov#, A. P. Potylitsyn, Tomsk Polytechnic University, Tomsk, Russia

Abstract

In this report the estimations of diffraction radiation yield from a slit target for European Spallation Source proton beam parameters is given. The possibilities of the non-destructive bunch length diagnostics using the diffraction radiation for non- and moderately relativistic beams of this accelerator are investigated.

INTRODUCTION

Diffraction radiation (DR) in mm wavelength region from relativistic electrons was first observed in 1995 [1]. Since then, the development of new approaches using the DR for charged particle beam diagnostics is continued. The DR is a radiation which occurs when charged particle moves near the media and only the electromagnetic field of particle interacts with the media. One significant advantage of DR diagnostics in contrast with transition radiation (TR) is its non-destructive character.

For instance, a rather well-known in scientific accelerator community the non-destructive diagnostic method of transversal bunch size determination is to use a slit target with optical diffraction radiation (ODR) [2]. Another examples are to use the radiation interference in order to determine such parameters as a bunch emittance based on system of two slit target [3] and a bunch length based on double DR target (where one plate is movable) [4].

However, all of these approaches were tested on the electron accelerators. For proton accelerators the studies of TR/DR application for diagnostics were conducted much less than for electron accelerators. There are a few articles which dedicated to the transverse beam shape measurements of relativistic proton beams using optical transition radiation (OTR) [5-7]. The possibilities of DR transverse size diagnostics for relativistic proton beams were discussed in [8] in optical wavelength range as well.

In this report we present the estimations and simulation results characterizing the DR applicability for non-destructive diagnostics of non- and moderately relativistic proton beams with the parameters of European Spallation Source (ESS) [9].

THEORY BACKGROUND

For the DR simulation we have used the generalized surface current method [10]. This method can be applied for the transition radiation and diffraction radiation calculations from different surfaces and for arbitrary particle energy. However, the only ideal conductivity of the target may be considered.

In our geometry a charged particle moves in the center between two semi-infinite plates through the slit. Using the formula obtained in Ref. [11], we may calculate the spectral-angular distributions in the single particle approximation from the slit target. In Fig. 1 the scheme of DR generation from this target is shown.

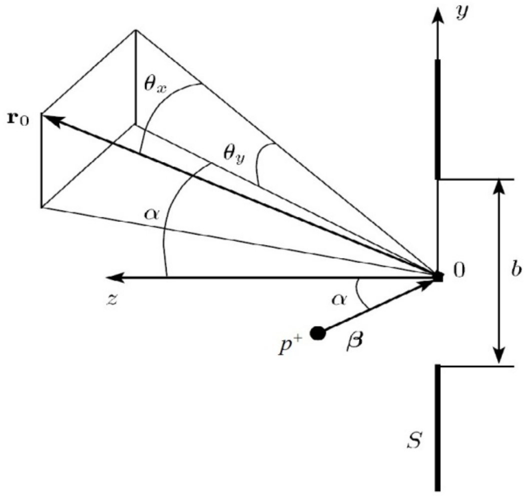

Figure 1: The scheme of DR generation by charged particle [11].

Here β is a particle velocity (in units of the light speed c), α is incidence angle, b is the slit width, S is an area of target surface, r_0 is a distance to observation point, θ_x and θ_y are the observation angles and γ is the Lorentz factor. Hereinafter in our calculations, we will assume that the angle $\alpha = 0°$.

DR YIELD ESTIMATIONS

The ESS is a multi-disciplinary research facility based on the world's most powerful neutron source [9]. The facility includes the most powerful linear proton accelerator ever built. The construction of the facility began in the summer of 2014. In Table 1 the main parameters of ESS proton beam are listed. In this facility the accelerator up to 90 MeV ($\gamma = 1.1$) of protons is normal and up to 2 GeV ($\gamma = 3.1$) is superconductive.

Table 1: Simulation Parameters

Name	Value
Proton energy, E_e	up to 90 MeV "warm" up to 2000 MeV "cold"
Bunch length, σ_z (r.m.s.)	~1 – 4 mm
Bunch size, σ_t (r.m.s.)	~0.5 – 4.5 mm
Bunch population, N_e	$\sim 1.83 \cdot 10^8$
Bunches in macro-pulse, N_b	$\sim 6.13 \cdot 10^6$
Repetition rate, f	14 Hz
Macro-pulse duration	2.86 ms

---

* Work was partially supported by the RFBR grant No 15-52-50028.

shkitovda@tpu.ru

As we see the amplification of DR spectral-angular intensity due to the coherent effect will be about 10^8 times larger than incoherent radiation from the same beam. Note that in ESS case the coherent radiation appears when observed radiation wavelength $\lambda > 5 - 20$ mm and the impact parameter should be $\geq 4\sigma_t$ (~2 – 18 mm). An exact value of these quantities depends on the bunch length and size.

For the brief estimations we may use the total energy formula [12] of backward DR (BDR) from slit target for single non-relativistic and relativistic particle with charge "e" $W = \frac{3}{4}\left(\frac{e^2}{\hbar c}\right)\beta^2\hbar\omega_c$, where $\omega_c = \frac{\gamma c}{2h}$ is the characteristic frequency of radiation, h is the impact parameter. We assume that a slit width $b = 2h$ ($\alpha = 0°$). These estimations are presented in Table 2 for $\gamma = 1.1$, for higher γ the values of radiation energy will be more.

Table 2: Total Radiation Energy Estimations

h, mm	5	10
b, mm	10	20
ω_c, GHz	33	16
$WN_e^2N_b$ (one macro-pulse)	~4 mJ	~2 mJ
$WN_e^2N_b$ (per second)	~60 mJ	~30 mJ

One of the commercially available detector is MD902 [13] with working frequency range 10 MHz – 40 GHz (wavelength > 7.5 mm) and input signal dynamic range from -40 to +20 dBm (0.1 μW to 100 mW). Assuming uniform distribution of BDR throughout the solid angle of half space, we may estimate the average energy passing through the detector aperture per one second as $WN_e^2N_b \cdot f \cdot \frac{\Delta\Omega}{2\pi} \approx 10$ μW, where $\Delta\Omega = S/r_0^2$, $S = 50\times20$ mm^2 is the detector aperture and $r_0 = 1$ m and b was equal to 10 mm (see Table 1 and 2). We see that 10 μW is reliable value.

We have to note that these estimations were done based on the formula for single particle. For the bunch of particles we need to take into account the longitudinal form factor (see Fig. 2) because of its influence to the radiation spectrum. Even if we will detect 1% from obtained energy (see Table 2) it is enough for the modern detector.

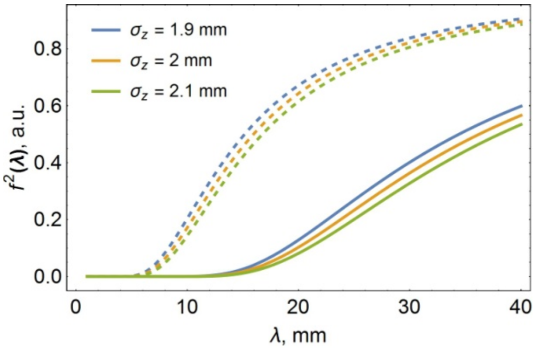

Figure 2: Gaussian longitudinal bunch form factor calculated for different bunch lengths σ_z and energies $\gamma = 3.1$ (dashed lines above) and $\gamma = 1.1$ (solid ones below).

The approach how to detect the TR (or DR) in mm wavelength range is presented in Ref. [14].

SIMULATION RESULTS AND DISCUSSION

Further the results of angular and spectral distribution calculations are described. In this section all simulations were conducted with taking into account the form factor (Fig. 2). The reading direction from top to bottom (↓) of legends and curves in all graphs is matched. Figure 3 shows the DR spectral-angular distributions for two cases of proton energies.

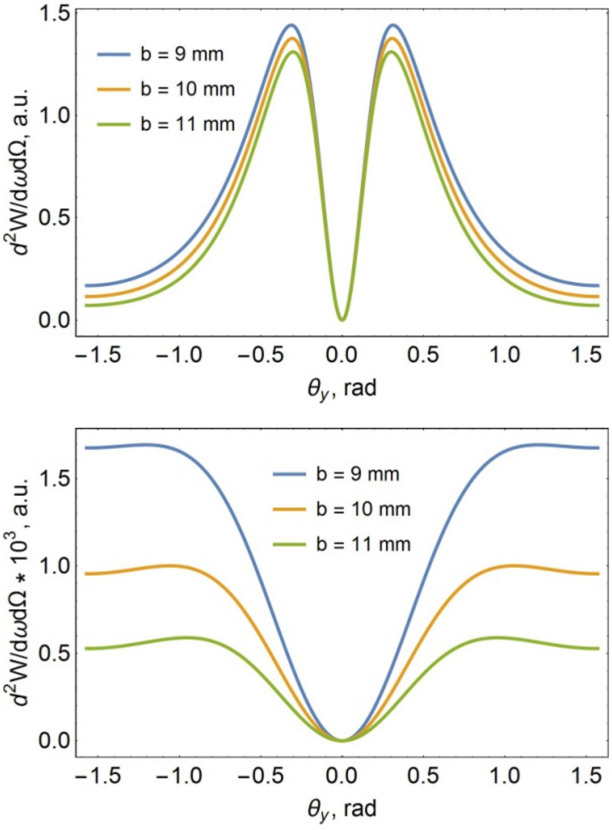

Figure 3: Cross-section of the spectral-angular of DR distributions for two energies $\gamma = 3.1$ (top picture) and $\gamma = 1.1$ (bottom one) with different slit widths. Simulation parameters are $\sigma_z = 2$ mm, $\theta_x = 0$, $\lambda = 25$ mm.

One may clear see these two distributions are significantly different in shape. The quantity $1/\gamma$ for both of the cases is equal to 0.32 rad / 18.5˚ ($\gamma = 3.1$) and 0.91 rad / 52.1˚ ($\gamma = 1.1$). It means that the directions of radiation maxima are different for them. This fact should be appreciated in the measurements. Note that in the presented data the relative changes of spectral-angular distributions by reason of the slit width variation are greater for lower energies. These changes depend on the chosen wavelength.

Figure 4 presents the DR spectral distributions for two cases of proton energies as in Fig. 3. These spectral calculations were done in the maxima of above DR distributions. As we observe from these pictures, the DR spectrum is changed with the bunch length. For this reason, after measuring the spectrum we may reconstruct the lengths of bunches in the certain points of accelerator.

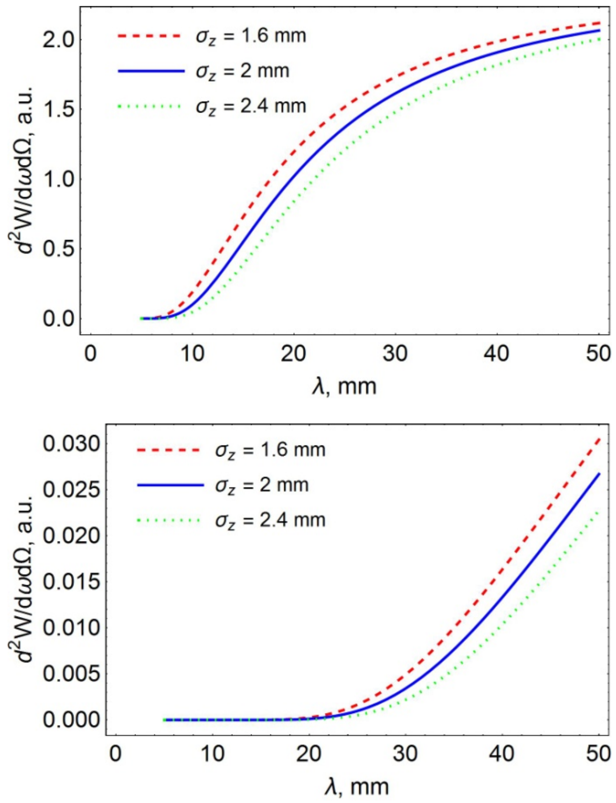

Figure 4: Spectral distributions in the peaks for two energies $\gamma = 3.1$ (top picture) and $\gamma = 1.1$ (bottom one) with different bunch longitudinal sizes σ_z (r.m.s.). Simulation parameters are $b = 10$ mm, $\theta_x = 0$, $\theta_y = 1/\gamma$.

CONCLUSION

We may conclude the following:

- We propose to consider the DR technique for non-destructive diagnostics of non-relativistic and moderately relativistic ESS proton beams.
- The DR yield from ESS proton beam can achieve the level of 10 μW ($\gamma = 1.1$) and more (in average) which can be detected without problem.
- Technique based on DR may be considered as a diagnostic tool for determination of the bunch length in proton accelerators using coherent radiation measurements. For this purpose we may suppose to use the approach applied in [4] (double DR target) or with the help of interferometer (e.g. Michelson, Martin-Puplett).
- In future studies to analyze the DR properties from non-relativistic beam in more detail is essential. We need to take into account the influence of such beam parameters as transversal size, target tilt angle, beam divergence and so on.

REFERENCES

[1] Y. Shibata et al., “Observation of coherent diffraction radiation from bunched electrons passing through a circular aperture in the millimeter- and submillimeter-wavelength regions”, Phys. Rev. E, vol. 52, p. 6787, 1995.

[2] P. Karataev *et al.*, “Beam-Size Measurement with Optical Diffraction Radiation at KEK Accelerator Test Facility”, *Phys. Rev. Lett.*, vol. 93, p. 244802, 2004.

[3] A. Cianchi *et al.*, “Nonintercepting electron beam size monitor using optical diffraction radiation interference”, *Phys. Rev. ST Accel. Beams*, vol. 14, p. 102803, 2011.

[4] D. A. Shkitov *et al.*, “Non-invasive bunch length diagnostics based on interferometry from double diffraction radiation target“, in *Proc. IPAC’13*, Shanghai, China, May 2013, paper MOPME067, p. 583.

[5] S. D. Borovkov *et al.*, “On studying a possibility to use optical transition radiation for proton beam diagnostics”, *NIM A*, vol. 294, pp. 101-107, 1990.

[6] V. E. Scarpine *et al.*, “OTR imaging of intense 120 GeV protons in the NuMI beamline at FNAL”, in *Proc. PAC’07*, Albuquerque, USA, 2007, paper THOAC02, p. 2639.

[7] V. E. Scarpine, “Transverse beam shape measurements of intense proton beams using optical transition radiation”, *Physics Procedia*, vol. 37, pp. 2123-2128, 2012.

[8] T. Sen *et al.*, “Prospects of diagnostics with optical diffraction radiation in hadron colliders”, in *Proc. PAC’07*, Albuquerque, USA, 2007, paper TUPAS032, p. 1721.

[9] ESS Technical Design Report, `https://europeanspallationsource.se`.

[10] D. V. Karlovets, A P. Potylitsyn, “Generalized surface current method in the macroscopic theory of diffraction radiation”, *Phys. Lett. A*, vol. 373, pp. 1988-1996, 2009.

[11] D. V. Karlovets, A. P. Potylitsyn, “On the theory of diffraction radiation”, JETP, vol. 107, p. 755, 2008.

[12] A. P. Potylitsyn, M. I. Ryazanov, M. N. Strikhanov, A. A. Tishcenko, Diffraction Radiation from Relativistic Particles, Berlin, Springer, 2010.

[13] `http://www.micran.com/sites/micran_eng/data/UserFile/pdf/mmic/MD902.pdf`.

[14] B. N. Kalinin *et al.*, “Measurement of the angular characteristics of transition radiation in near and far zones”, *JETP Letters*, vol. 84, pp. 110-114, 2006.