CODE FOR SIMULATION OF DIFFRACTION RADIATION FROM FLAT FINITE SURFACES

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Abstract

In this report a description of developed diffraction radiation simulation code is presented. This code is suitable for calculating the diffraction radiation characteristics (angular and spectra distributions) from flat finite surfaces (compound targets) for charge particles with different energies and for wavelength range from optics to mm. The code can be used for transition radiation simulation too.

INTRODUCTION

Nowadays practically all investigations and developments in physics content the simulation as one of the big part of research. The simulation allows predict many characteristics of objects in the physical investigations and saves a time as well. The accelerator physics is not an exception.

The large and important part of this science area is diagnostics. Practically all accelerators must be constructed with special diagnostic tools. One of the phenomena which apply in order to control the accelerator is the diffraction radiation (DR) which already has a long history [1]. The application history of DR for the beam diagnostics counts a little bit more than 20 years [2]. At the moment DR has several fields of application such as transversal sizes [3], bunch length [4], and emittance [5] diagnostics. And until now a new idea how to use DR in diagnostics is proposed [6].

This radiation occurs when charged particles move close to a target [7]. There are several DR calculation methods which were developed in the past. But all of them are analytical [8] and contain series assumptions, for example, infinite target size, far field zone approximation [9] and so on. We know only one theory with analytical solution in near field zone but for transition radiation (TR) case [10].

However, until now there are no special codes for DR simulation from different types of targets. All researchers have to develop their own numerical codes to calculate DR characteristics for their cases (target size, geometry of task, detector location, optical system presence and other) or have to use the analytical formulas. This is the general way how the most researchers do.

It is need to be noted that there are codes which can be used to calculate DR properties: *CST* [11] and *KARAT* [12]. *CST* is a well-known commercial 3D electromagnetic (EM) code. *KARAT* is 3D EM code based on particle-in-cell (PIC) solver which belongs to the state institute. With all advantages of these codes, they require large experience from the users in order to start simulation the DR characteristics (as practically all big computational program).

Mentioned that code *ZEMAX* [13] can also be applied for working with DR. But this code was developed for optics and, based on our knowledge, require to preliminary calculate the DR field which should be input into *ZEMAX* [14]. It may be only additional tool in diagnostics approach development based on DR.

In this report we present the code for DR characteristic calculations from metal targets with finite dimensions and finite distance to detector. Our code is written on *Wolfram Language* (WL) [15]. It represents a set of files which contain the internal and custom functions. These functions allow to calculate the EM fields of DR from arbitrary finite flat surfaces. Despite the fact that *Wolfram Mathematica* (WM) is also commercial product, on our knowledge almost all academic institutions have and use it.

Our mathematical model is the integration equations and is based on the exact solution of Maxwell's equations. That's why this code is implemented, in other world, on the semi analytical approach in comparison with fully numerical *CST* [16] and *KARAT* [17]. Moreover, mentioned that it is need significantly less time to obtain the results to use our code.

CODE AND TARGETS DESCRIPTION

Developed code is just two main files (**.m* format) written on WL. First file contains the custom functions which calculate all three EM component and intensity of DR. Second file contains the custom functions which allow to create the geometry of the targets. These two files should be launched after starting WM session and before the simulation. The files structure is divided into 2 parts: the function description and functions themselves.

The schematic view of the process simulated in the code depicts on Fig. 1, where θ_0 is the target rotation angle and η is the observation angle. Charge particle EM field interacts with the target surface and after this the radiation is produced which is registered by the detector.

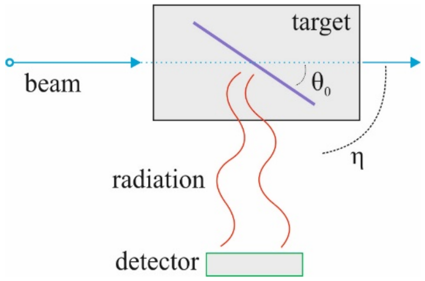

Figure 1: A schematic view of charge particle interaction with a target and radiation registration by a detector.

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The calculation approach in this code is based on the generalized surface current method (GSCM) [18]. Above method is suitable for the targets with the ideal conductivity (metal target case) and applicable for diffraction and transition radiation, for charged particles with arbitrary energies and incidence angles to the surfaces, for wavelengths from optics to mm range. The mathematical model of radiation intensity based on GSCM is presented by the formulas as follow:

$$\frac{d^2W_e}{d\omega d\Omega} = cL^2 |E_R^D(r_D,\lambda)|^2$$

$$E_R^D(r_D,\lambda) = \frac{1}{2\pi}\iint \left[[n(r_T), E_e^T(r_T,\lambda)], \nabla G(r_T,r_D,\lambda)\right] dS_T$$

$$E_e^T(r_T,\lambda) = \frac{2e}{\beta^2 c\gamma\lambda} \cdot e^{i\frac{k}{\beta}z_T} \cdot \left\{ \begin{pmatrix} \frac{x_T}{\rho} K_1\left(\frac{k}{\beta\gamma}\rho\right) \\ \frac{y_T}{\rho} K_1\left(\frac{k}{\beta\gamma}\rho\right) \\ -\frac{i}{\gamma} K_0\left(\frac{k}{\beta\gamma}\rho\right) \end{pmatrix} \right\}$$

$$\rho = \sqrt{\mathrm{x}_T^2 + \mathrm{y}_T^2}$$

$$\nabla G(r_T,r_D,\lambda) = \frac{r_D - r_T}{|r_D - r_T|^2} \cdot e^{ik|r_D - r_T|} \cdot \left(\frac{1}{|r_D - r_T|} - ik\right)$$

$$n(r_T) = A(\psi) \times \{0,0,1\}$$

$$r_D = B(\varphi) \times \{x_D, y_D, L\}$$

Where $r_T = \{x_T, y_T, z_T\}$ and $r_D = \{x_D, y_D, z_D\}$ are the coordinate on the target and the detector surface respectively, λ is the radiation wavelength, γ is Lorentz factor, $k = 2\pi/\lambda$ is the wave number, $|r_D - r_T|$ is the distance between the points on the detector and the target, $A(\psi)$ is the rotation matrix for the normal vector $n(r_T)$ at ψ angle for each different flat surfaces in the target, $B(\varphi)$ is the rotation matrix for the detector (observation point), L is the distance from zero point of coordinate system to the detector, S_T is the surface area, E_e^T is the electron coulomb field, E_R^D is the radiation field, e is an elementary charge, β is the particle velocity in term of light speed, c is the light speed, K_1 and K_0 are the modified Bessel functions and operator "×" is the matrix multiplication.

Following to these expressions note that the particle moves along Z axis. The normal vector should be set differently depending on the given flat surface in the compound target. Assumptions and limitations which are incorporated in the current code version are listed in Table 1. Note that some limitations of GSCM are connected with classical electrodynamics approaches as well.

Table 1: Assumptions and Limitations

Detector sizes	Point-like
Material permittivity	∞
Geometry of targets	Only flat surfaces
Beam	Single particle
Re-reflection	Not available
Detector sensitivity	Equal to 1
Radiation coherence	Incoherent
Optical system	Not available

At present moment in the code 5 types of target geometries were created. These geometries are shown on Fig. 2. All target geometries were built by the intrinsic WL function – *Polygon* (integration over this function access only on WM version 10 or higher). This WL function creates the surfaces S_T on which the integration is carried out.

The TR target is also added into our code (see picture (a) on Fig. 2). The targets of DR from single plate [19] and plate with a slit [20] (see pictures (b) and (c) on Fig. 2 respectively) were developed for two modifications. First ones are as shown on above mentioned pictures – plate edge and slit edge along Z axis. Second ones are when plate edge and slit edge goes along Y axis (not represented here). Picture (d) on Fig. 2 shows Smith-Purcell grating [21]. If we rotate this grating on some angle along Y axis, we obtain the target which generates the grating transition radiation [22]. Picture (e) on Fig. 2 shows almost the same target but in the case of grating diffraction radiation (GDR) [23]. All targets can be rotated on the arbitrary angle along Y axis and shifted along all axes. Rotation along X and Z axes may be added if it will be necessary.

There are some other DR target, for example, disphase target [24] which is analog of DR slit target but with different tilt angle of two plates relative to the particle trajectory and the target [25] which consists of two plates located in some distance along Z axis. And there is the target with variable geometry which is also analog of DR slit target where one plate moves along particle trajectories [26]. These geometries may also be added into the code. There are some other exotic DR targets but they do not consider here. Note that our code based on GSCM can calculate radiation from the periodic flat target as well. That's why we have created the geometries with periodic structure.

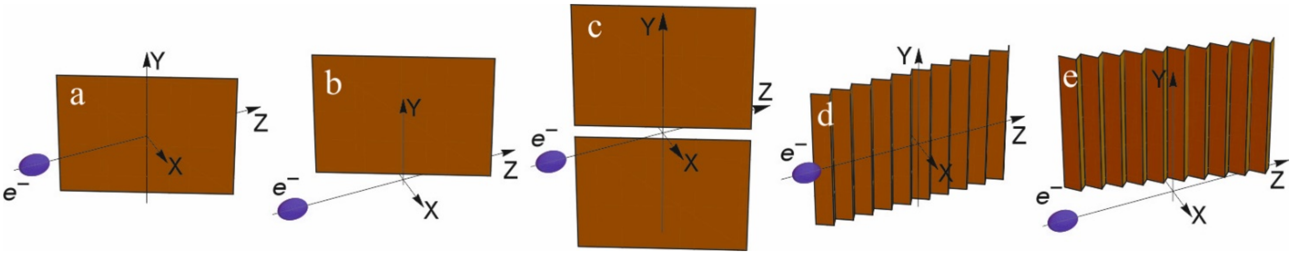

Figure 2: Set of different targets created for the developed code which correspond the following types of radiation: transition radiation (a), diffraction radiation (b, c), Smith-Purcell radiation (d), grating diffraction radiation (e). Note that all these radiation types are a kind of polarization radiation.

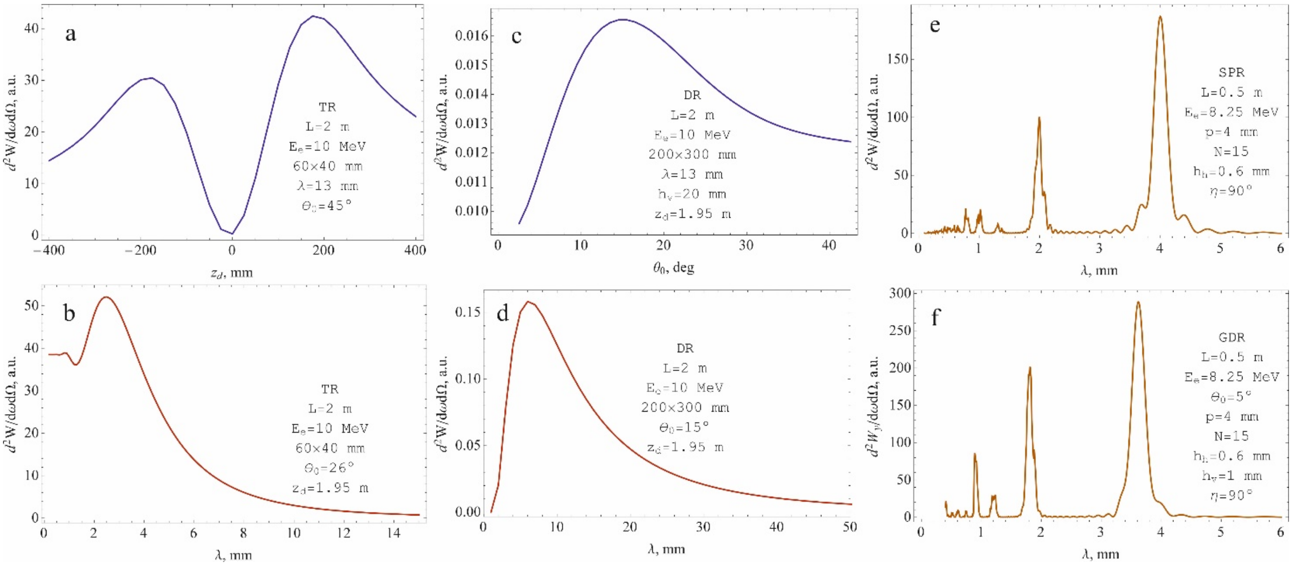

Figure 3: The simulation result examples of different radiation types: TR angular distribution (a), DR orientation distribution from one plate (c), TR spectrum (b), DR spectrum from one plate (d), Smith-Purcell radiation (e) and grating diffraction radiation (f) spectra (h_H and h_V are the impact parameters, N is the number of periods, p is the grating period).

SIMULATION RESULTS

We have not described the results in details because, in our opinion, it is important to do only for particular task. In this part we have presented some results which can be computed based on developed code. These results are shown on Fig. 3.

Figure 3 on pictures (a) and (b) presents the TR angular distribution with peak asymmetry as expected and continuous TR spectrum with cut-off of long waves due to the target finite size respectively. Figure 3 on pictures (c) and (d) presents DR orientation dependence with common single peak which is wide due to off central axis detector position z_D and DR spectrum with cut-off of long and short waves respectively. Figure 3 on pictures (e) and (f) presents Smith-Purcell radiation spectrum with a set of diffraction order which corresponds to the dispersion relation and GDR spectrum with a set of diffraction order as well but shifted due to grating rotation angle θ_0 respectively. All simulation parameters are located on the picture legends.

CONCLUSION

Developed code based on the generalized surface current method and written on Wolfram Language can simulate different DR (TR) characteristics from metal target with flat surfaces in single particle approximation for wide range of particle's energy and for radiation from optics (in fact UV) to mm wavelength with taking into account the real target sizes and distance to the detector.

Code can be used to calculate DR (or TR) characteristics for improvement existed and development new beam diagnostics tools and, in principle, radiation sources development.

The current version of the code may be sent by email to the researchers who are interested on request.

FUTURE CODE UPGRATE

Here we would like to express the possible directions of code development. Ones of them are rather easy to add by slightly change formulas in the model. We may take into account:

- Detector sensitivity;
- Particle shifting in X and Y projections;
- Coherence effect of radiation [27];

Another one requires additional test of the code and it modification:

- Target curvature, for example, spherical [28], cylindrical [29] or parabolic;

Another ones require additional multiple integration which commonly very time consuming:

- Detector aperture;
- Transversal bunch sizes;
- Lens or parabolic mirrors.

The analytical expressions based on exact formulas may be included into the code as well in order to have a possibility to compare the analytical and simulation results.

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