PIC code KARAT simulation of different types of polarization radiation generated by relativistic electron beam

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Abstract. Different types of polarization radiation generated by a relativistic electron beam are simulated using fully electromagnetic particle-in-cell (PIC) code KARAT. The simulation results for diffraction radiation, transition radiation, Smith-Purcell radiation and Vavilov-Cherenkov radiation are in a good agreement with experimental data and analytical models. Modern PIC simulation is a good tool to check and predict experimental results.

1. Introduction

Modern scientific installations are very complex devices. Numerical simulation is a way of reducing the development time of installation and production costs. Simulation allows comprehensive analysis of the experimental conditions, investigate many parameters in a very wide range and choose their optimal values.

Particle-in-cell simulation enables you to visualize charged particles interactions with the targets, and also generation, propagation and interference of the radiation fields. The particle-in-cell method allows one to follow the dynamics of charged particles taking into account own fields of particles and external electromagnetic fields for any given geometry.

Using PIC simulations in problems devoted to polarization radiation generation allows to analyze the radiation fields formation in the near field, taking into account the form factor of the targets and spectral composition of the generated radiations.

In this paper the following problems of the polarization radiation generation by a relativistic electron beam will be considered:

- Smith-Purcell radiation. Generation of the resonant diffraction radiation from inclined gratings for bunch length measurements.
- Transition radiation. Coherent backward transition radiation from a bunched relativistic electron beam.
- Diffraction radiation. Generation of the diffraction radiation in two serial conductive targets.
- Vavilov-Cherenkov radiation. Coherent Vavilov-Cherenkov radiation from a bunched electron beam passing near a dielectric target.

All calculations were performed using a desktop PC. Duration of some calculations did not exceed several days.
2. Particle-in-cell code KARAT

KARAT is a fully electromagnetic code based on the particle-in-cell (PIC) method [1]. It is primarily aimed to the solution of non-stationary electrodynamic problems having complicated geometry and involving dynamics of relativistic electrons and non-relativistic ions. In particular, KARAT is well suited to the simulation of high-current electron devices such as vircators, free-electron lasers, gyrotrons, etc. It is also appropriate for the modeling of physical phenomena in laboratory and space plasmas.

There are three versions of the code: one, two and three spatial dimension problems. In all cases three electromagnetic field components and three momentum components are taken into account.

A finite difference scheme with overstepping on the rectangular shearing grid is used to solve Maxwell’s equations. The electric field is corrected with the help of Boris’ method [2]. The scheme’s unique feature is a special grid shear that provides fulfillment of the boundary conditions without any extrapolation.

In addition, the code has several features useful for modeling phenomena associated with charged particle beam devices. One may adjust the code for potential approximation of electromagnetic problems.

The boundaries consist of perfectly matched layers that absorbing outgoing waves from the interior of a computational region without reflecting them back into the interior.

The KARAT code has been compared to analytic solutions and applied successfully for many physical problems. The simulation results are in good agreement with experimental data.

3. PIC code KARAT simulations

3.1. Generation of the resonant diffraction radiation from inclined gratings for the bunch length measurement

In [3] the resonant diffraction radiation from an inclined grating and its application to measure the length of bunches of charged particles was analytically studied. It is well known that the Smith-Purcell radiation (SPR) obeys the dispersion relation, because of this SPR yield depends on the polar angle. Moreover, the coherence condition can occur under certain angles for the corresponding wavelength, which makes it possible to use this effect for the bunch length measurements.

![Contour map of $B_y$ component of the electromagnetic field.](image)

**Figure 1.** Contour map of $B_y$ component of the electromagnetic field.
The mechanism for bunch length diagnostics based on measuring the radiation intensity by two detectors versus grating inclination angle was experimentally investigated. Both detectors are placed in fixed positions on different sides relative to the beam trajectory.

It was demonstrated that a variation of the grating inclination angle leads to a wavelength shift of the emitted radiation at fixed observation point. The wavelength can easily be tuned by changing the grating orientation with respect to the beam axis.

Figure 1 represents a variant of the modeled geometry. For clarity, grating is 10 times zoomed. The electron beam is injected from the left boundary along the grating. The figure shows the $B_y$ component of the electromagnetic field. It is clearly seen the transition radiation field, which accompanies the electron beam. Transition radiation is generated when the beam injected into the calculation region.

Also in figure you can see the Smith-Purcell radiation. SPR is a spherical wave diverging from the grating. Registration of radiation carried out simultaneously by two detectors placed on both sides of the grating.

Parameters used in simulation: electron beam energy – 100 MeV, bunch length – 3 ps, number of electrons per bunch – $10^8$.

Simulation was done using a planar two-dimensional x-z version of the KARAT code.

![Figure 1](image1.png)

**Figure 1.** Bunched electron beam interacting with the period grating.

![Figure 2](image2.png)

**Figure 2.** Spectrum of CRDR for different grating inclination angles: (a) and (c) – theoretically calculated, (b) and (d) – simulated by KARAT code.

Comparison of the theoretical calculations and KARAT simulation is shown on figure 2. There is good agreement in position and intensity of spectral lines of the coherent resonant diffraction radiation (CRDR) depending on the inclination angle for both detectors.

The large width of spectral lines in the simulation is caused by a small distance between the grating and detectors.

![Graphs](image3.png)
3.2. Coherent backward transition radiation from a bunched relativistic electron beam

The calculations were performed for the beam parameters, target size and geometry similar to that used in [4]. Actually, the modeling geometry was the same as in the previous problem, but diffraction grating on the path of the electron beam was replaced by a conductive foil. The simulation results were compared with analytical data on the backward transition radiation at a wavelength of 15 mm and the experimental data for the range of 11–17 mm.

Parameters used in simulation: electron beam energy – 6.1 MeV, bunch length – 3 mm, number of electrons per bunch – 108.

Simulation was done using a planar two-dimensional x-z version of the KARAT code.

Registration of transition radiation was carried out using a point-detector array placed at equal distance from the intersection of electron beam and the target near the specular angle.

![Figure 3](image)

**Figure 3.** BTR orientation dependences obtained theoretically, experimentally and simulated by KARAT code.

The figure 3(a) shows a comparison of the orientation dependences of the backward transition radiation (BTR) obtained in the KARAT simulation and calculated theoretically. One can see a good agreement between the two peaks. The difference in the height of the peaks can be explained by a much broader spectrum of the radiation being registered in the simulation.

The figure 3(b) shows a comparison of the orientation dependences obtained in simulation and experiment using the "parabolic telescope" with detector DP21-M in the wavelength range 11–17 mm [4].

There is an acceptable agreement. One can see the asymmetry of the two peak characteristic of backward transition radiation. The differences may be interpreted by the difference in real and model electron bunch profile. Various distances from the target to the detector in the experiment and simulation can also affect the results of the measurements.

3.3. Generation of the diffraction radiation in two serial conductive targets

In [5] the generation of diffraction radiation in two serial conductive targets was experimentally investigated. It was found that the interaction of an electron beam with the first target has a significant effect on the interaction with the second target, and depends on the distance between the targets. With increase of the distance between targets the amplitude of the radiation angular distribution from the second target was also increased.

The dimensions of the model were up to 1000 × 1500 mm. Inside modeling region two conducting targets were placed at an angle of 45° to the electron beam trajectory. The beam and targets parameters were corresponded to the experimental conditions. Registration of the backward diffraction radiation...
(BDR) from the second target was carried out at the maximum possible distance from the front edge of the target to minimize the effect of pre-wave zone.

Parameters used in simulation: electron beam energy – 6.1 MeV, bunch length – 3 mm, number of electrons per bunch – $10^8$.

Simulation was done using a planar two-dimensional x-z version of the KARAT code.

Figure 4. Contour map of $B_y$ component of the electromagnetic field at a different stage of simulation.

The figure 4 shows a demonstration model. It is aimed to show the fields of transition and diffraction radiation generated by an electron beam. Low electrons energy of 1 MeV has been selected for the effective spatial separation of the beam field and radiation fields. Because of that radiation field is well ahead of the beam at distances less than the distance between the targets. This allows clearly see the process of forming a diffraction radiation fields.

The figures show the contour map of the $B_y$ component of the electromagnetic field allowing to analyze the simulated processes in the most convenient way. When the beam was injected into the computational region transition radiation was necessarily also generated, but it does not affect the final result.

It is clearly seen that both targets are the sources of the forward (FDR) and backward (BDR) diffraction radiation. They are of the different direction of the $B_y$ component of the electromagnetic field. Moreover at the second target there is an interference of the FDR from the first target and BDR from the second target in the radiation registration direction (straight down). In the case of relativistic energy, such as 6 MeV, the interference will be more significant.

With increasing distance between the targets negative contribution of the FDR from the first target was reduced and the amplitude of the radiation from the second target was increased.

The figure 5 shows the dependences of the radiation intensity on the observation angle for different distances between targets simulated by KARAT code (a) and measured experimentally (b).

There is good agreement between the amplitude of the BDR angular distribution depending on the distance between the targets and the position of the maxima of distributions. The simulation showed
that under experimental conditions there is the interference of the diffraction radiation from the first and second target which has a significant effect on the resulting angular distribution.

**Figure 5.** Dependences of the radiation intensity on the observation angle for different distance between targets simulated by KARAT code (a) and measured experimentally (b).

The discrepancy between the position of the maxima of distribution and the specular angle (90 degrees) caused by the difference in the phenomena of electromagnetic diffraction and diffraction radiation generated by an electron beam.

Simulation gives results similar to the experimental one and following the dynamics of radiation generation. In addition, simulation enables to visualize the sources of radiation fields and estimate their relative influence.

### 3.4. Vavilov-Cherenkov radiation

**Coherent Vavilov-Cherenkov radiation from a bunched electron beam passing near a target**

In [6] the method of non-invasive bunch length diagnostic based on an analysis of the spectra of coherent Vavilov-Cherenkov THz range was considered. The paraffin and teflon prisms were used as the Cherenkov targets. The electron beam was injected along the large face of the prism. Figure 6 shows the experimental setup. Simulation was carried out in accordance with the experiment.

**Figure 6.** Experimental setup.

Measurements of the angular characteristics were carried out at the maximum distance to reduce the effect of the pre-wave zone. Modeling was performed for prisms with dielectric permittivity $\varepsilon = 1.988$ ($\alpha = 45^\circ$) and $\varepsilon = 2.22$ ($\alpha = 40^\circ$).

Parameters used in simulation: electron beam energy – 6.1 MeV, bunch length – 3 mm, number of electrons per bunch – $10^8$. 
Simulation was done using a planar two-dimensional x-z version of the KARAT code. The figure 7 shows a demonstration model. It was aimed to show the formation of the Vavilov-Cherenkov radiation (VCR) in the dielectric prism. One can clearly see the front of VCR, and also re-reflection radiation inside the prism.

![Contour map of $B_y$ component of the electromagnetic field at a different stage of simulation.](image)

**Figure 7.** Contour map of $B_y$ component of the electromagnetic field at a different stage of simulation.

The radiation output from the prism had minimal losses because the angle of prism was chosen to be equal to the Cherenkov radiation propagation angle.

There is a good agreement in the position of the maxima of the angular distributions on both figures 8 and 9. In addition, the distributions obtained in the KARAT simulation agree very well with the experimental data.

KARAT simulation shows VCR generation in a prism, a reflection of the generated field from the internal faces of prism and the contribution of reflected pulses in the total signal. The simulation takes into account a wide spectral range of radiation and the form-factor of the electron beam, which may influence the form of the angular distribution of the VCR. These effects may be particularly important in the case of materials with frequency dispersion.
Figure 8. The angular distributions of coherent VCR for paraffin target with $\varepsilon = 2.22$ ($\alpha = 40^\circ$).

Figure 9. The angular distributions of coherent VCR for teflon target with $\varepsilon = 1.988$ ($\alpha = 45^\circ$).

4. Conclusion

The agreement of the KARAT simulation code results for the Smith-Purcell radiation, transition radiation, diffraction radiation and Vavilov-Cherenkov radiation with theoretical and experimental data was shown.

Particle-in-cell simulation allows analyzing the interaction of the electron beam with a targets and generation of various types of the radiation as well as optimizing experimental setup parameters.

Modern PIC simulation is a good tool for cross-check and prediction of the experimental results. In some cases, numerical simulation can partially or completely replace the real experiment, or assist in setting up the installation and detecting apparatus.

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