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Coherent diffraction radiation as a source of radiation in far-infrared and terahertz range

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In the paper the results of measurements of the coherent diffraction radiation yield generated by femtosecond electron beam are presented. It is shown that the simulated and experimental data agreed quite well. The coherent diffraction radiation can be considered as a real candidate to develop a source of radiation in far-infrared and terahertz range.

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Various radiation sources based on accelerators (from THz up to gamma range) are widely used around the world. One of the promising source is the source based on generation of so called polarization radiation by charged particle beam which appears when electromagnetic (EM) field of a charged particle interacts with a medium (transition radiation, Cherenkov radiation, Smith–Purcell radiation, diffraction radiation and so on). Authors of papers [1, 2] proposed to use coherent transition radiation (TR) generated by short electron bunches with energy more than 20 MeV as source of far-infrared radiation. They used metallic foil as radiation source which crossed by electron beam. For diffraction radiation (DR) case charged particles move in vacuum in the vicinity of the target and origin of radiation is polarization of electronic shells of target atoms by EM field of initial particles. In the past, DR generated by the relativistic electron beam was widely used for beam diagnostics [3, 4]. In this paper we propose to consider DR as a possible radiation source and present the results of absolute measurements of the diffraction radiation yield in comparison with results of simulation.

The experiment was carried out at the SINAP linear accelerator facility, which is capable for providing electron bunches with pulse duration (FWHM) from 0.3 to 3 ps [5].

The main parameters of the experimental set-up shown on the Fig. 1 are the followings: 22.7 MeV electron beam, number of electrons per bunch is $0.44 \cdot 10^9$ (0.07 nC per bunch), number of bunches per train is about 8568, average train duration is about 3 μs, normalized emittance is equal to 10 mm-mrad, train repetition rate is 6.25 Hz, bunch repetition frequency (f) is 2856.2 MHz, average current per train (I_α) is about 200 mA.

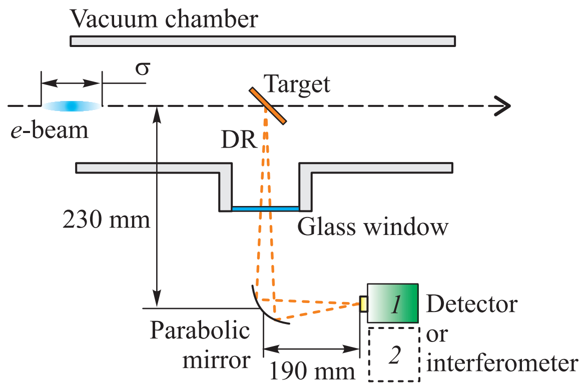

Fig. 1. The layout of experimental set up

In order to conduct measurements in the far-field zone detector was located on the parabolic mirror focal point. Also one may assert that the measurements from Michelson interferometer were in the far-field zone.

The DR target was consisted of a plate with sizes of 46×20 mm^2, made from the thin 2 μm aluminum foil covered on the 0.3 mm polyamide film. Larger plate side goes along the beam trajectory. The plate was fixed on the holder with a possibility to move it across the electron beam. During such a movement we measured coherent DR intensity for each position of plate.

The $LiTaO_3$ pyroelectric detector SPI-D-62 THZ (*Gentec-EO*) with the aperture diameter 2 mm and the sensitivity range 0.01–3 mm was used. The curve of detector sensitivity from specification is shown on the Fig. 2 which was used in simulation.

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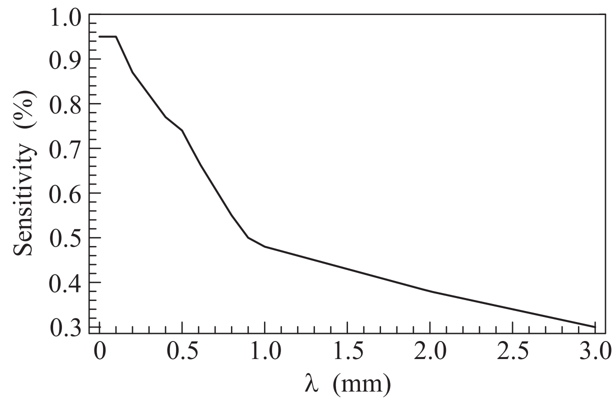

Fig. 2. The curve of THz detector sensitivity

On the Fig. 3 one can see the glass transmission of the chamber output window measured in mm and

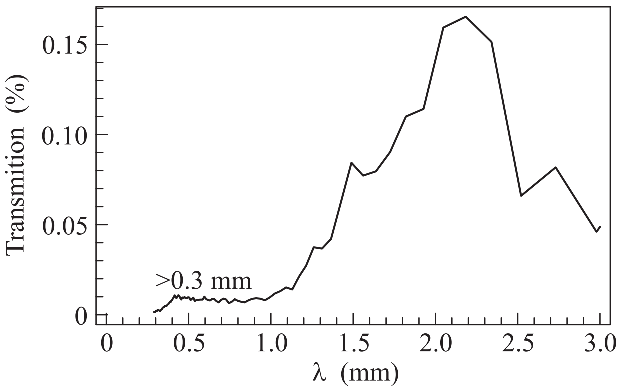

Fig. 3. The measured glass transmission for output window of vacuum chamber

THz range. Glass thickness is equal to 4 mm, diameter 40 mm, distance from beam trajectory to window 185 mm, material of window is toughened glass.

On the Fig. 4 the dependence of DR intensity on the impact parameter of the plate is presented (location *1* on Fig. 1). The meaning of "X" axis was recalculated from operating values taking into account that the peak maximum is approximately zero (position when the plate touches the beam). The positive values of "X" refer to TR generation (a beam crosses the target) but negative ones describe DR generation. It should be noted that the transverse bunch size is approximately equal to 200 μm and the step of the measured dependence is 32 μm.

For analyzing the experimental data, a simple and intuitively clear model was developed with several reasonable assumptions. This model is based on the pseudo-photon diffraction approach [6] without far-field approximation. For correct consideration of the experimental set up in the simulations we took into account the followings conditions: a finite size target (one rectan-

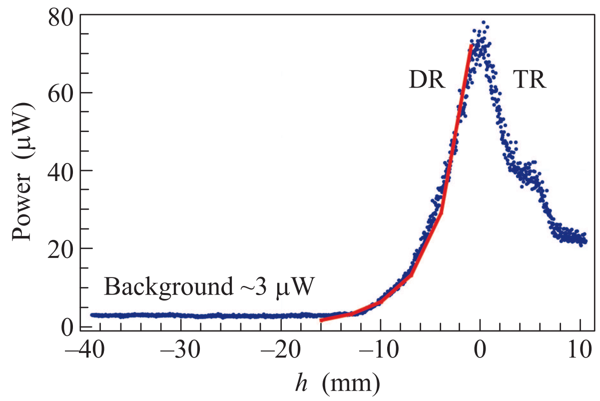

Fig. 4. (Color online) The experimental dependence (blue dots) and simulated dependence (red curve) of DR intensity on the impact parameters of target

gular flat plate), the finite distance between the target and detector, the detector spectral sensitivity and the influence of the output vacuum window (glass transmission) onto observed DR spectrum were taken into account. In order to verify our model we have compared the spectral distributions of coherent DR calculated using the developed model and analytical expressions based on the polarization current model [7] for the far-field case with a perfectly conducting semi-infinite target (see Fig. 5). As one can see both approaches give

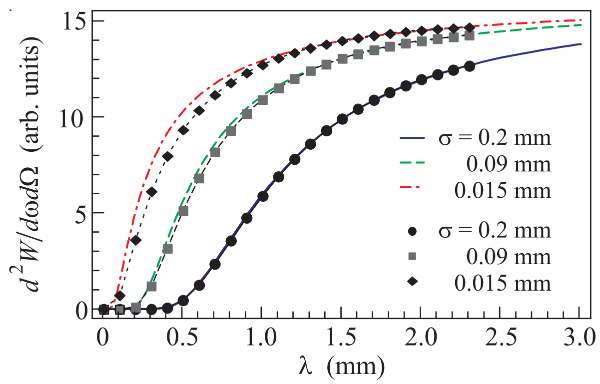

Fig. 5. Comparison of spectra obtained from the developed model (dots) and analytical model (curves) for different bunch length

the same results, so we can use our model to simulate DR characteristics with taking into account the above-mentioned experimental parameters.

For our experimental scheme, the simulation parameters are listed below: Lorentz factor is about 40, target size is $46 \times 20\,\mathrm{mm}^2$, target-to-detector distance (L) is 230 mm, wavelength minimum ($\lambda_{\min}$) is 0.33 mm, wavelength maximum ($\lambda_{\max}$) is 3 mm, detector solid angle ($\Delta\Omega$) is 0.04 sr, impact parameters are from 1 to 16 mm and bunch length (σ) is 0.2 mm (667 fs). The simulated dependence of DR intensity on the impact parameters of target divided by factor 1.5 shown on Fig. 4 (red curve) has a good agreement with a comparison to the experimental dependence.

On the Fig. 6 the calculated spectrum and the measured one from a Michelson interferogram (location *2* on Fig. 1) the impact parameter $h = 1$ mm. The reconstruction of the spectrum was performed using the approach [8].

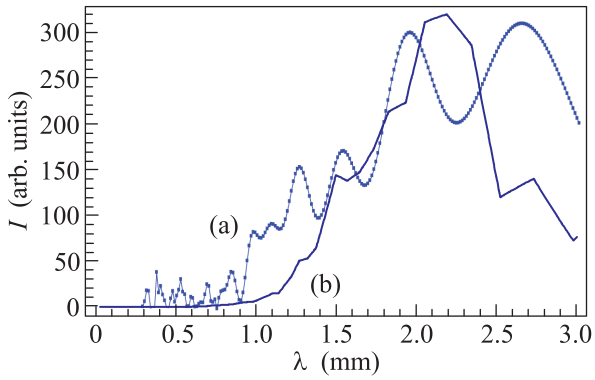

Fig. 6. The obtained spectrum from Michelson interferometer (a) and simulated spectrum (b) comparison for the impact parameter $h = 1$ mm

It may be noted the shapes of both spectra are close to each other. The difference between them can be explained by the aggregated effect of the additional equipment in the Michelson interferometer such as parabolic mirror, splitter and reflectors placed in the air [9].

Eliminating the glass properties and detector sensitivity for the impact parameter $h = 1$ mm we have estimated the radiation power $P = 4.9$ mW, while energy radiated into fixed solid angle from each bunch is $W_{\mathrm{CDR}} \approx 91.5$ nJ. As one may see from Fig. 4 the radiation power attenuated by the exit window and registered by our detector is about 70 μW (equivalent energy per bunch is about 1.3 nJ). This value of energy has a good agreement in comparison with energy for one bunch from paper [2], if the difference in the bunch population will be taken into account. In presented measurement the bunch population was 200 times less.

Hereby first, the absolute scale measurements of the sub-picosecond electron bunch lengths were carried out from ordinary DR target and the simulation of absolute DR yield for SINAP facility was also presented. Second, the developed simulation model has a good agreement with the experimental data with taking into account the near-field zone effect and the target finite size as well as detector and chamber output glass window properties such as spectral sensitivity and window transmission respectively. In contrast with source based on coherent transition radiation [1, 2] the scheme proposed by us can be used for such accelerators as FEL because the DR target disturbs beam characteristics insignificantly. Finally, as a result one may conclude that the coherent diffraction radiation from a few MeV energy electron beam may be considered as an effective radiation source in THz range if the length of short electron bunch is less than 100 femtoseconds.

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