Coherent radiation of relativistic charged particles from dielectric target and applications for beam diagnostics

Veronika Bleko on behalf of the FLAP collaboration

Veksler and Baldin Laboratory of High Energy Physics, JINR, Russia

One of the major challenges faced when launching and operating particle accelerators is meeting the requirement of on-line beam position monitoring. A possible solution to this problem is the use of different types of polarization radiation: diffraction radiation, transition radiation, Cherenkov radiation (ChR) and Smith-Purcell radiation. The unique properties of radiation and the relatively simple realization of the occurrence conditions open up wide possibilities for the creation of new beam diagnostic method and sources of electromagnetic radiation in different spectral ranges. The purpose of the research is the theoretical and experimental study of the properties of radiation generated by the interaction of relativistic charged particles with the functional targets. This research is important both for deeper understanding of the nature of electromagnetic interactions and development of advanced diagnostic tools for accelerated beams of charged particles.

Fiber beam position monitor (BPM)

The principle of the proposed beam displacement determination is as follows. Cherenkov radiation is generated by the interaction of the Coulomb field of relativistic electron bunch with the fiber and propagates in the fiber material. In the case when fibers are located symmetrically relative to the electron beam, one can see a pronounced minimum that is caused by destructive interference. Accordingly, one can expect V-shaped dependences of radiation intensity on fibers displacement. If the beam would be displaced by a distance δ (along the X-axis), the electromagnetic field of the beam would also be shifted relative to the fibers, and the destructive interference would be perturbed. This would result in an offset of the previously observed minimum by a respective value.

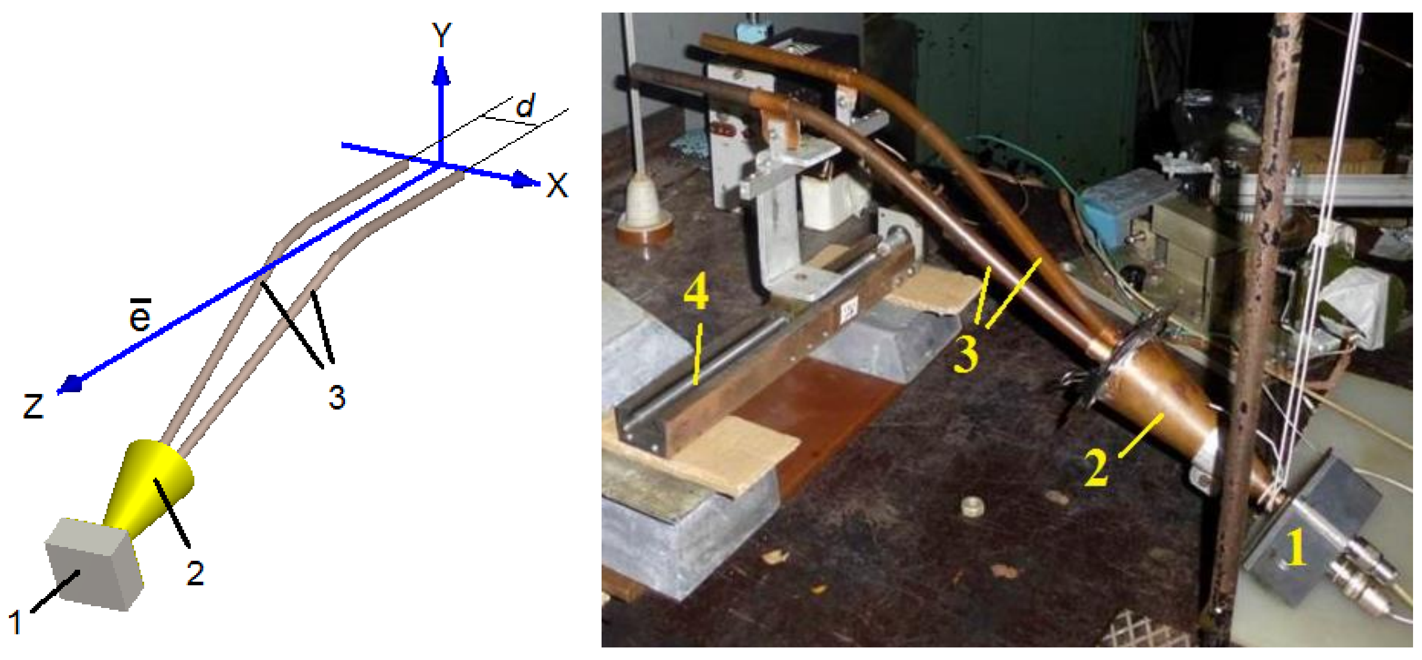

Figure 1. The scheme (a) and design (b) of the fiber BPM prototype: 1 – detector; 2 – mixing chamber; 3 – fibers; 4 – motorized linear stage

Extracted microtron beam parameters	
Electron energy	6 MeV
Average train current	25 mA
Beam size	≈ 5.5×5.5 mm
Bunch length	≈ 2.4 mm
Bunch population	≈ 5·10⁸
Beam divergence	0.08×0.08
Bunches per train	≈ 10⁴
RF wavelength	114 mm

For the extracted beam parameters the radiation with wavelength λ>8 mm is coherent, i.e. radiation intensity enhanced incoherent level more than 8 orders of magnitude.

The detector DP20M with sensitivity 0.3 V/mW in the wavelength range λ=3÷30 mm was used for the registration of radiation.

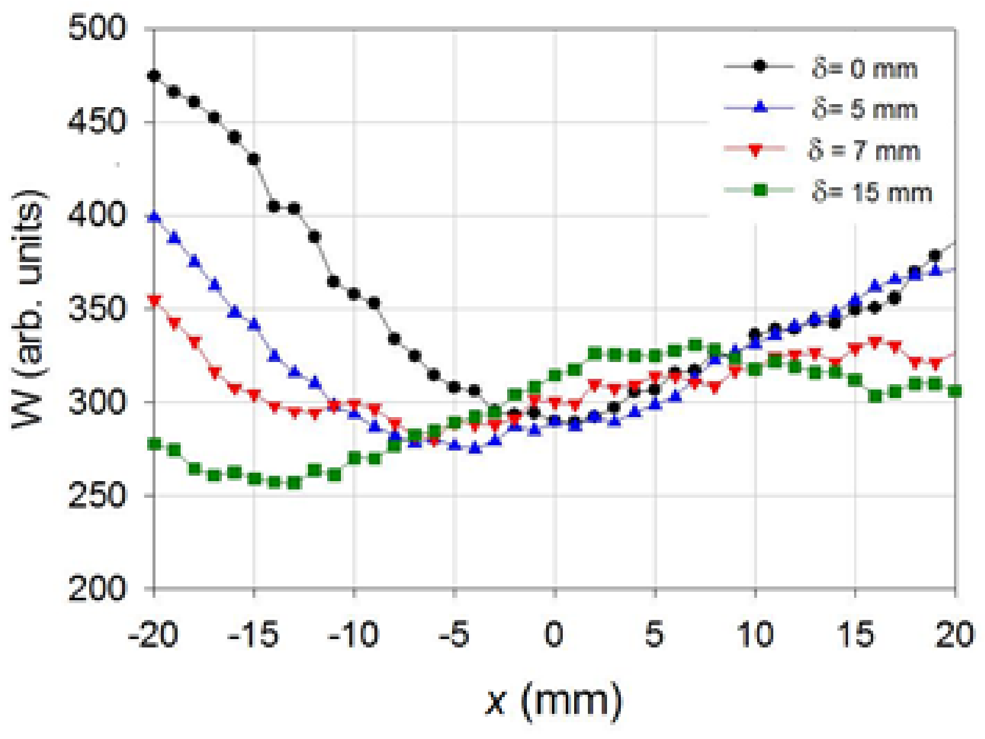

Figure 2. Dependence of radiation intensity on fiber displacement for different beam displacement parameter δ

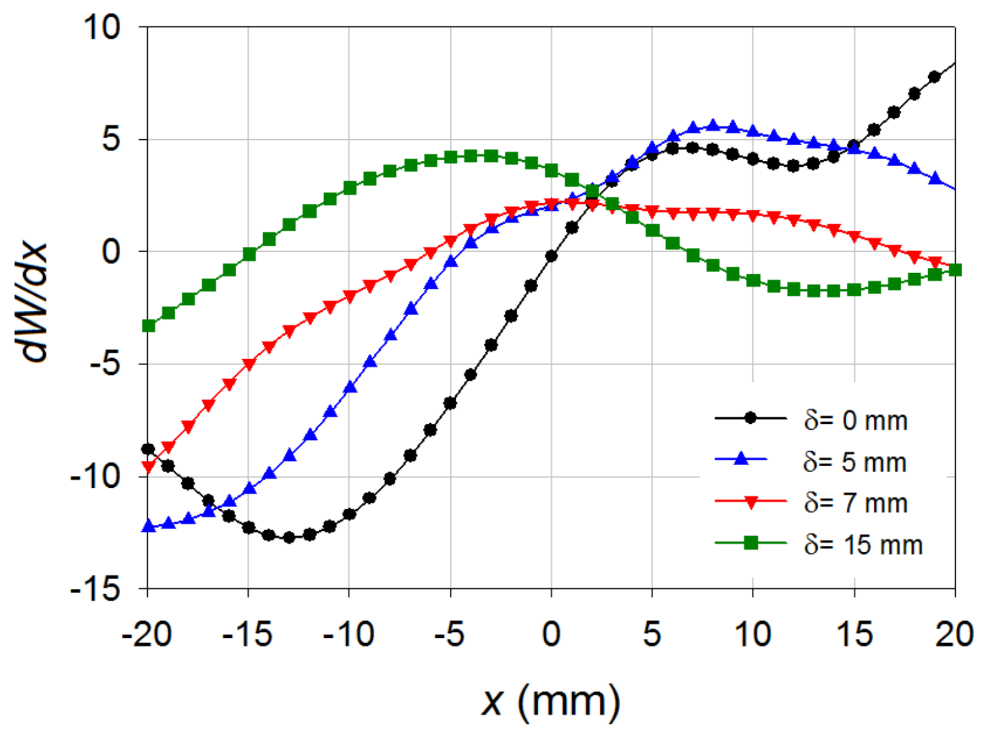

Figure 3. First derivatives of the radiation intensity corresponding to the fiber displacement

The obtained dependencies have an asymmetry. According to [1], the observed asymmetry can be explained by the difference between the bending degrees of fibers, which entails the difference between radiation intensity loss in the fibers. As a result, it affects the shape of the curves. Evidently, there is a positive correlation between the beam displacement and the position of radiation intensity minimum. It is shown that the Cherenkov radiation generated by the passage of a short electron bunch near the fiber surface can be used as a mechanism for beam diagnostic.

Monochromatic optical Cherenkov radiation of moderately relativistic ions in a dispersive medium (CVD-diamond)

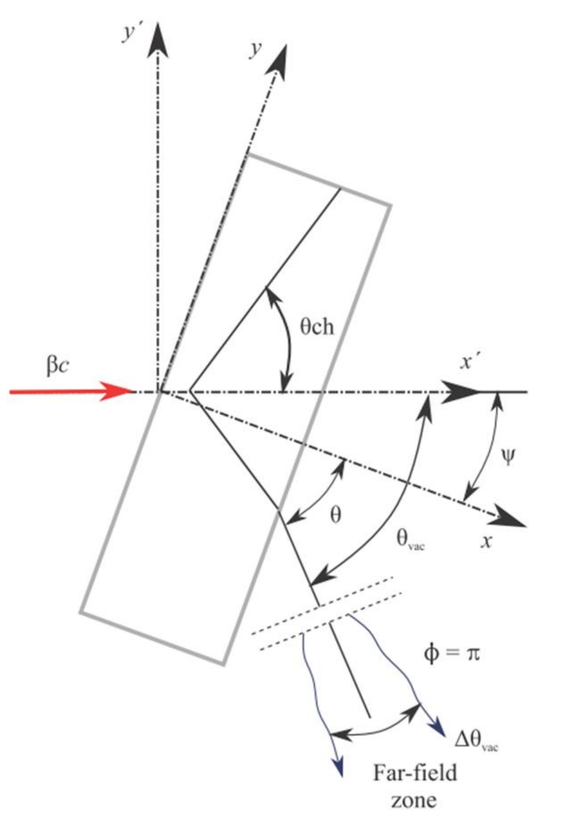

Figure 4. Geometry of ChR generation in a dielectric plate

The presented theoretical model based on a surface current approach [2,3] allows to predict angular and spectral properties of ChR.

$$\frac{d^2N}{d\lambda d\Omega} = 4\alpha \frac{\cos^2\theta}{\left(\left(1-\beta_y n_y\right)^2-{\beta_z}^2\cos^2\theta\right)^2}\left|\frac{\varepsilon-1}{\varepsilon}\right|^2 \mathrm{sinc}^2\left(\pi\frac{L}{\lambda}\frac{1-\beta_z Z-n_y\beta_y}{\beta_z}\right)\times$$
$$\times\frac{L^2}{\lambda^3}\left({\beta_y}^2{\beta_z}^2\sin^2\varphi\left(|Z|^2+\sin^2\theta\right)\left|\frac{\sqrt{\varepsilon}}{\cos\theta+Z}\right|^2+\right.$$
$$\left.+\left|\frac{\varepsilon}{\varepsilon\,\cos\theta+Z}\right|^2\left|\left({\beta_z}^2+n_y\beta_y+\beta_z Z-1\right)\sin\theta-\beta_y\beta_z\cos\varphi Z\right|^2\right)$$

α – the fine structure constant; sinc(x) – the cardinal sine function; $Z=\sqrt{\varepsilon-\sin^2\theta}$; $\beta_{y,z}$ – the particle velocity components; $n_{x,y,z}$ – the direction cosines.

CVD-diamond has frequency dispersion that described an empirical Sellmeier equation from Ref. [4]:

$$\varepsilon(\lambda)=n^2(\lambda)=1+\frac{4.658\lambda^2}{\lambda^2-112.5^2}$$

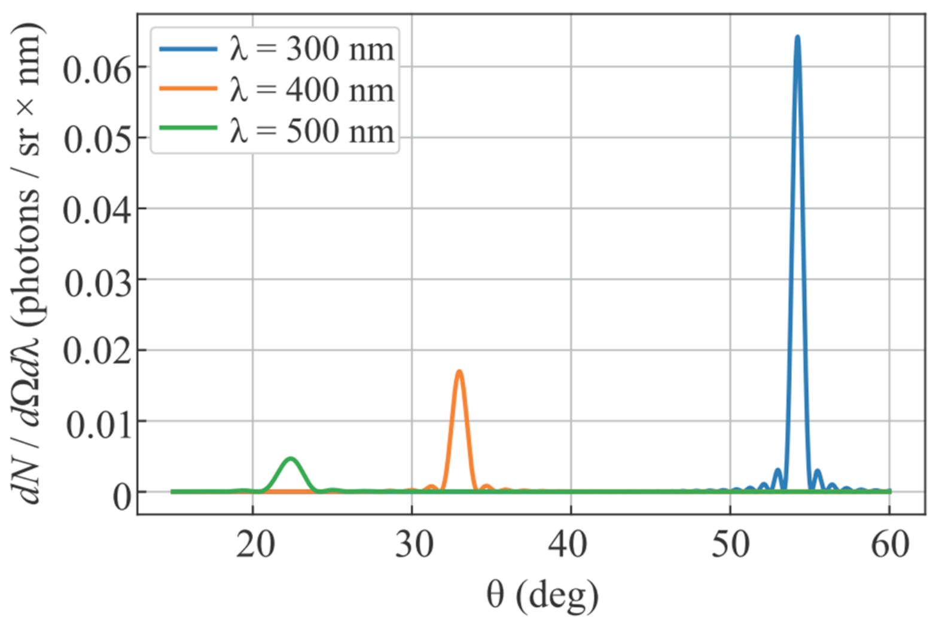

Figure 5. ChR intensity distribution as function of observation angle θ_{vac}

Modeling parameters	
Target material	CVD-diamond
Thickness of plate	100 µm
Ion velocity (units of c)	0.4166
Lorentz factor	1.1
Target tilt angle	$\psi = 0^{\circ}$

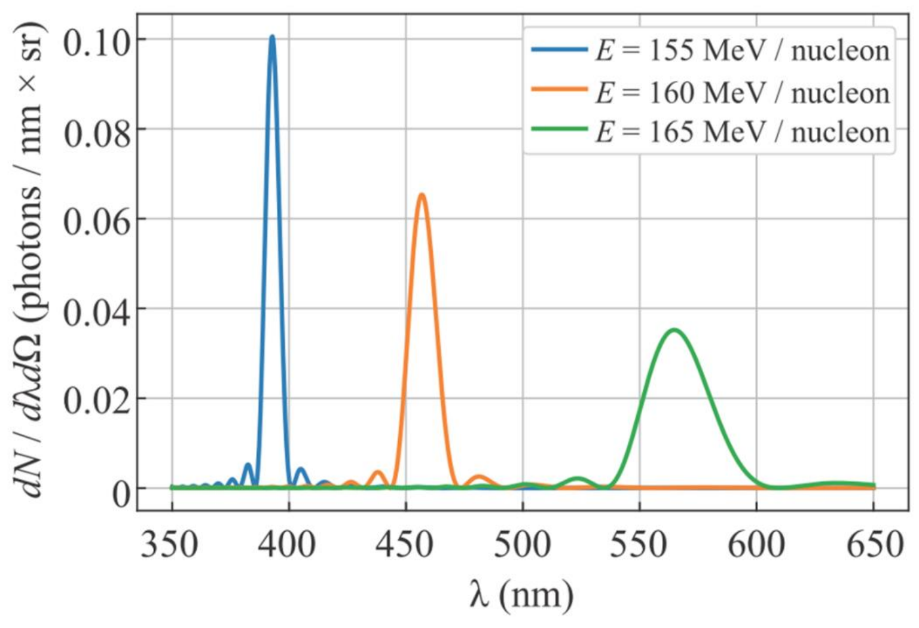

Figure 6. ChR spectral lines for different ion energies at fixed observation angle θ_{vac} =79° and target tilt angle $\psi = 17^{\circ}$

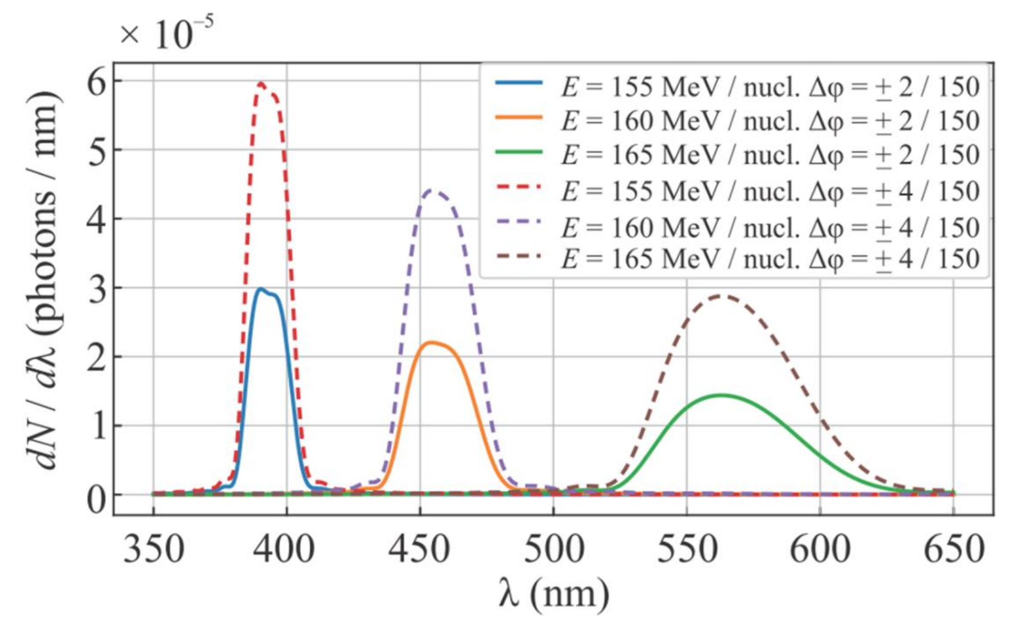

Figure 7. ChR spectral lines when detected by a spectrometer with a finite aperture $\Delta\theta_{ap}$=0.76 ° $\Delta\varphi_{ap}$=0.76 ° (solid lines); $\Delta\varphi_{ap}$=1.52 ° (dashed lines)

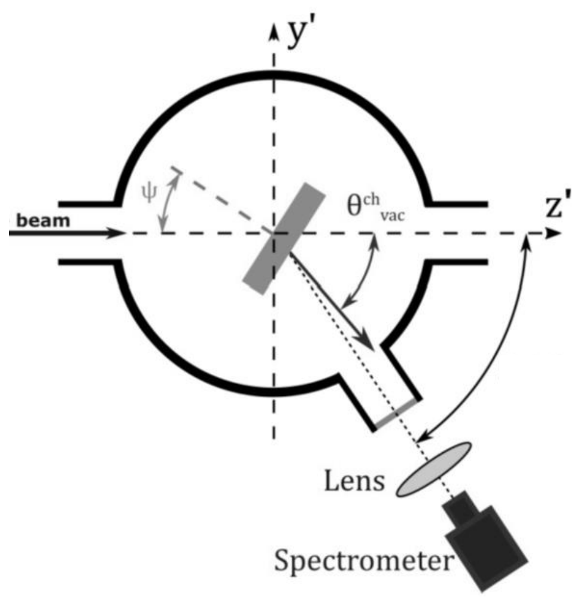

Figure 8. Scheme of the experimental setup

Due to the frequency dispersion inside the target, outgoing Cherenkov photons propagate afterwards divergently in vacuum. This allows to "expand" the Cherenkov cone and, accordingly, to measure monochromatic ChR lines at fixed observation angles θ_{vac}.

A CVD-diamond plate is placed on a goniometric stage in the center of the experimental chamber which allows a precise target alignment with respect to the beam axis.

Conclusion and future plans

As part of the FLAP collaboration on the basis of the MARUSYA facility in the SPD test zone of the NICA accelerator complex, it is planned to conduct joint experiments with Tomsk Polytechnic University to observe the monochromatization effect of optical Cherenkov radiation generated by an accelerated ion beam in a radiator target with frequency dispersion. The results obtained in the course of these studies will allow to evaluate the possibility and efficiency of using this effect as a tool for ion beam diagnostics (measurement of ion energy dispersion). Test measurements have been carried out.

The scheme of the experiment has been assembled. We are waiting for the beam time to be provided.

References

[1] G.A. Naumenko et al., *Coherent radiation of relativistic electrons in dielectric fibers in the millimeter wavelength range*, 2015 *JETP Lett.* **100** P776.

[2] Karlovets, D.V., Potylitsyn, A.P. *Diffraction radiation from a finite-conductivity screen*, 2009 *Jetp Lett.* **90** P326.

[3] Karlovets, D.V. *On the theory of polarization radiation in media with sharp boundaries*, 2011 *J. Exp. Theor. Phys.* **113** P27.

[4] G. Turri et al., *Index of refraction from the near-ultraviolet to the near-infrared from a single crystal microwave-assisted CVD diamond*, 2017 *Opt. Mater. Express* **7**(3) P855.