DIAGNOSTICS OF ACCELERATOR BEAMS BY THE DEPENDENCE OF THE VAVILOV-CHERENKOV RADIATION INTENSITY ON THE REFRACTIVE INDEX OF THE RADIATOR "*n*"

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Abstract

The report presents the methods for finding of the particle velocity (energy) distribution of accelerator beams. Velocity distribution is deduced from the Volterra integral equation of the first kind with the right part, which is defined by the dependence of Cherenkov radiation (CHR) intensity on *n*, experimentally obtained for the given beam. Velocity distribution is the second derivative of CHR intensity. The problem of stability of the second derivative is solved by attracting a priori information. Using of optical dispersion of radiator is discussed. It enables to find velocity distribution even for the single bunch of particles. The method also enables to find velocity distribution for beams with a noticeable transverse velocity of the particles. The method is virtually non-destructive in many cases.

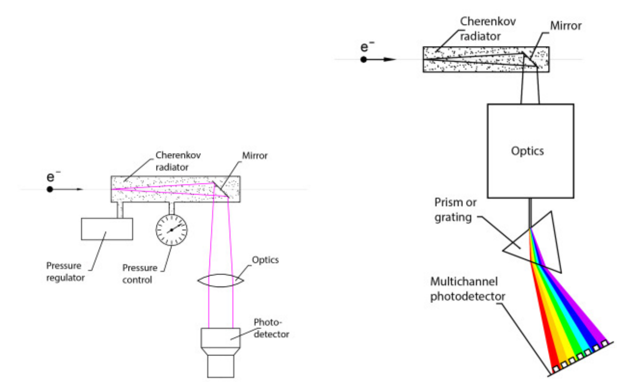
INTRODUCTION

The development of the non-intercepting methods for finding a velocity (energy) distribution of particles in accelerator beams is of great importance for irradiation process control in industry, medicine and science.

Existing methods of charged particle beam diagnostics have well-known disadvantages especially in the case of high energy beams. The non-traditional method of accelerator beam diagnostics based on the use of the CHR is considered below.

CHR angular distribution is used for a long time for determination of the velocity or the energy spectra of the charged particles [1]. However application of this method for the accelerator beams and especially for the electron beams of the high intensity industrial accelerators is limited by an essential transverse velocity component of the particles in the beam "smearing" the angular distribution of the radiation. Addition difficulty consists in superimposing of a transition radiation at radiator boundaries on the CHR angular distribution.

We consider two methods for finding a velocity (energy) particle distribution of beams based on the dependence of the CHR intensity and its spectral distribution on the phase velocity of the electromagnetic waves in the optical ranges (Fig. 1). The methods are practically non-intercepting and may be convenient for the energy and the energy spectrum measurements of beams including high intensity electron beams.



(a) (b)

Figure 1: Two methods for finding a velocity (energy) particle distribution with CHR. (a) The photons yield is registered by a photodetector depending on gas pressure. (b) The photons spectrum is recorded by the spectrum analyzer.

THEORETICAL BASES AND RESULTS

For the first time the possibility of determination of average electron velocity in the beam of the electron accelerator (the 4.5 MeV microtron) by the measurements of CHR intensity dependence on a radiator refraction index *n* in an optical range was demonstrated in [2, 3].

CO_2 was used as a radiator. The gases, which refraction index *n* varies with pressure *p* as $n(p) = 1 + kp$ at $kp<<1$, are natural choice of the CHR medium in this case. Once *p* passes the threshold of CHR for the maximum electron beam velocity in the detector ($1/\beta_{max} = 1+kp$) the CHR intensity *I* grows nonlinearly as more and more particles produce the CHR. Beginning from point where the minimal electron velocity β_{min} of beam particles becomes equal to the phase light velocity in the gas -radiator an intensity *I* of CHR in the detector is dependent on *kp* linearly. The intersection of the extrapolated CHR linear part with a background level corresponds to the average electron velocity in the beam [2, 3].

The same method was proposed in the work [4, 5] carried out 15 years later without reference to [2, 3]. No nonlinear part in *I(n)* dependence was noted.

In works of one of us (K.T.) [6] it was shown that nonlinear part of the intensity curve can be used for obtaining the velocity distribution and the energy distribution of the particles in the beam.

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If the same part of the CHR light is registered by the photodetector independently of the position and the direction of a particle (electron, nucleus etc.) passing through radiator (as in the spherical Cherenkov detector for example) then the velocity distribution of particles and the energy spectrum can be obtained for the arbitrary angular distribution of the particles. In the case under consideration (the accelerator monitoring), this condition can be easily fulfilled.

In further consideration, we will follow [6]. If $n = n(\lambda)$ (λ is wavelength) a number of the CHR photons $N_{ph}(n(\lambda))$ in a unit wavelength band reaching the photodetector can be written as:

$$N_{ph}(n(\lambda)) = g \int_{1/n}^{\beta_{max}} \left(1 - \frac{1}{n(\lambda)^2 \cdot \beta^2}\right) \cdot f(\beta) d\beta \cdot \lambda^{-2} \quad (1)$$

where $f(\beta)$ is a particle velocity distribution, $g = 2\pi\alpha N_e kL$, where α is the fine structure constant, N_e – the number of the electrons, L- the length of particle path in detector, k – the photon collection factor.

By successively differentiating (1) with respect to ($1/n^2$) we obtain the solution in the form of the first and the second derivative of N:

$$f(\beta_\lambda) = \frac{\lambda^2}{2g}\{(\beta_\lambda)^2 \frac{d^2}{d\beta_\lambda^{\,2}} N_{ph,\lambda} - \frac{d}{d\beta_\lambda} N_{ph,\lambda}\} \quad (2)$$

where $\beta_\lambda = 1/n(\lambda)$ (Fig. 2).

The equation (1) is Volterra integral equation of the first kind with the right part having experimental errors. Its solution is ill - posed task. Finding derivatives from experimental data containing errors is ill - posed task too. There are several methods for solution of the problems. The stabilization is based on using a priory information about peculiarity of the solution. In this case, the main peculiarities are the next: number of CHR photons is greater or equal to zero, the first derivative is less or equal to zero, the second derivative is greater or equal to zero.

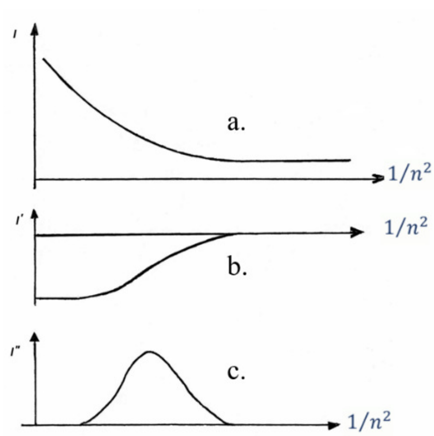

Figure 2: Dependence of CHR intensity on $1/n^2$ (a) and its first (b) and second (c) derivatives.

The equation (1) can be reduced to equation of convolution type [7]. Let us change variables:

$$\beta = y^{1/2}; \quad \Psi(y) = \frac{f(y^{1/2})}{2y^{3/2}}; \quad \frac{1}{n(\nu)} = z^{1/2} \quad (3)$$

Then

$$g \int_{z}^{z_{max}} \left(y - z(\nu)\right)\Psi(y)dy = N_{ph}(z(\nu)) \quad (4)$$

By successively differentiating (4) we obtain the solution as:

$$\Psi\left(z^{1/2}\right) = \frac{1}{g}\frac{d^2 N_{ph}(z)}{dz^2} \quad (5)$$

Of course, the equation (4) is also Volterra integral equation of the first kind with the right part having experimental errors.

The proposed method can be used not only for diagnostics of charged particle fluxes but also for diagnostics of powerful uncharged particles fluxes (neutrons, γ and bremsstrahlung radiation) with the help of the secondary charged particles.

To avoid the gas dissociation by the beam usage of the single atomic gases is preferable. For the narrow energy spectra typical for microtron beams, beams from the high brightness accelerators and for high energy beams the required change of the pressure will not large. The narrow band filter before the photodetector and measurement of gas refraction index with a build-up interferometer can decrease sufficiently the experimental errors. The instant gas expansion by high power beam pulses can be neglected if a pulse is very short ($\leq 10^{-8}$ s).

The yield of the CHR near the threshold for the most accelerators is more than sufficient for the reliable intensity registration with the photodetectors (photomultipliers). The energy loss fluctuations in the CHR detector should be taken into account in estimation of a device resolving power.

Consider now the second method based on the analyses of a spectral distribution of CHR photons (Fig. 1b). It is important that this method does not require sequential measurement of the yield of CHR photons with changing the gas pressure in the radiator. All measurements are performed at the single selected gas pressure. It also allows finding the velocity distribution of charged particles for non-repetitive "bursts" and, in principle, even for a single high power event.

Dependence of refraction index on the wavelength causes known trouble in Cherenkov counter methods. However, it becomes “friendly” phenomena in that variant of the method. The essence of method consists in following. CHR photons from the radiator is directed to a spectral

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device (grating, prism etc.) decomposing CHR into spectrum. CHR spectrum is registered with the line of photodetectors or with multichannel spectrum analyzer. Because of refraction index for any medium depends on a wavelength, the CHR threshold has such dependence also. Thus, the measurements at the different wavelengths are analogous to the measurements with variable gas pressure described above or to measurements with a large number of the threshold counters with different thresholds.

In the visible light range the refraction index decreases with the wavelength increase. Thus, the higher is the particle velocity, the longer the wavelength of CHR threshold. The number of the CHR photons having a wavelength λ in the unit wavelength range may be written as:

$$N_{ph,\lambda} = g \int_{\beta_\lambda}^{\beta_{mal}} f(\beta) \cdot (1 - \frac{\beta_\lambda^2}{\beta^2}) \cdot \lambda^{-2} \cdot d\beta \qquad (6)$$

(β_λ is the velocity threshold at the wavelength λ, g is as in (1)).

Using known formula by Cauchy $n(\lambda) = a + b\lambda^{-2}$, where a and b are the constants for given gas we obtain the threshold wavelength for given β_λ:

$$\lambda^{-2} = (\beta_\lambda^{-1} - a)/b \qquad (7)$$

Substituting (7) into (6), converting this one, performing the differentiation with respect to β_λ, transforming, performing the differentiation with respect to β_λ, converting again, we obtain:

$$f(\beta_\lambda) = \frac{\beta_\lambda^2}{2g} \frac{d}{d\beta_\lambda} (\frac{1}{\beta_\lambda} \cdot \frac{d}{d\beta_\lambda} (\frac{b}{\beta_\lambda^{-1} - a} \cdot N_{ph,\lambda})) \qquad (8)$$

The equation (6) can be reduced as above (the equation (3)) to the equation of the convolution type also (the designations are the same):

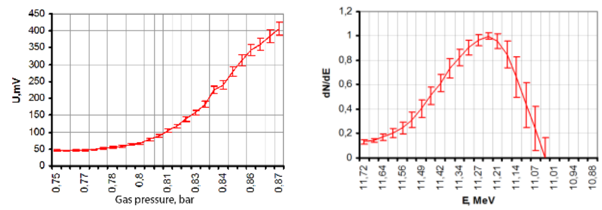
$$\int_{z}^{z_{max}} (y - z(\lambda)) \Psi(y) dy = \frac{\lambda^2}{g} N_{ph,\lambda}(z(\nu)) \qquad (9)$$

Its solution can be found by successive differentiating as described above.

Thus, to get a beam velocity distribution it is necessary to measure the number of photons in different wavelength ranges and to get their first and second derivatives with respect to the wavelength. The number of photons is known with error and this procedure is ill -posed task, so appropriate methods to obtain stable solution must be applied.

The proposed method is convenient for the accelerator beam monitoring especially in the case of the narrow energy spectra. As an example, at the bean energy 30 MeV and the energy spread 0.5 MeV the spectral interval in the case of xenon is from 400 nm to 600 nm. As already noted it seems likely that the method will permit to measure the energy and the energy distribution at the single and non-repeating powerful pulse fluxes of the charged and non-charged particles. If the photodetectors (or special optical shutter built-in between CHR detector and the photodetectors) are high – speed then it is possible to measure the energy and the energy distribution within the pulse (the bunch).

At Fig. 3 we illustrate energy spectrum measurements for race-track microtron [9] done by first method.



(a) (b)

Figure 3: Energy spectrum measurements for race-track microtron by first method: (a) is photodetector signal dependence on gas pressure; (b) is reconstructed energy spectrum.

REFERENCES

[1] Zrelov V.P. Vavilov - Cherenkov radiation and its applications at high energy physics. V. I, V. II. M. Atomizdat. 1968.

[2] Bhiday M.R., Jennings R.E., Kalmus P.I.P. Measurement of electron beam energy using a gas Cerenkov detector. Proc. Phys. Soc., 72, 973 - 980, 1958.

[3] Jennings R.E., Kalmus P.I.P. A gas Cerenkov detector for the accurate determination of electron beam energy. Nucl. Instr. Meth., 6, 209 – 212. 1960.

[4] De Almeida C.E., Almond P.R. Energy calibration of high energy electrons using a gas Cerenkov detector and a comparison with different methods. Phys. Med. Biol., 19, N. 4, 476 – 483. 1974.

[5] De Almeida C.E., Almond P.R. In Proc. Amer. Assoc. Phys. in Med. A. Cerenkov detector for the energy calibration of electron beams from 9-22 MeV. Phys. Med. Biol., 17, N. 6, 870. 1972.

[6] Trukhanov K.A. Measurement of particle energy by the dependence intensity of Vavilov - Cherenkov radiation on the phase velocity. In Proc. of seminar “Cherenkov detectors and their applications in science and technique” (1984). M. Nauka. 380 –383. 1990.

[7] Trukhanov K.A., Shvedunov V.I. Measurements of accelerator beam spectrum through dependence of Cherenkov radiation intensity on phase velocity of electromagnetic waves in optical and microwave ranges // Rad. Phys. and Chem. 2006. V. 75. N. 8. P. 899-902.

[8] Trukhanov K.A., Larkin A.I., Shvedunov V.I. Measuring the distribution of particles according to their velocity in accelerator beams on the basis of Cherenkov radiation in the optical and microwave range. Bulletin of the Russian Academy of Sciences: Physics: 2010, Vol. 74, № 11, pp. 1600-1603.

[9] V.I. Shvedunov, R.A. Barday, D.A. Frolov, et al, Racetrack Microtron with High Brightness Beams, Nucl. Instrum. Meth. A531 (2004) 346-366

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