BEAM POSITION MONITOR BASED ON DIFFRACTION RADIATION[1]

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Abstract

We propose a Beam Position Monitor (BPM), based on the diffraction radiation (DR) of relativistic charged particles passing through a round hole or slit. Compared to the known methods, the proposed device has the advantage of a better resolution. It is shown, that the beam position can be measured with a precision < 1 μm. At the same time the monitor can be used for measuring Lorenz-factor $\gamma = E/mc^2$ of beam particles.

Introduction

New generation of linear colliders (LC) is supposed to be built in the forthcoming decade. Accelerated and stored particles at this machines will have a $\gamma >> 10^4$, while the beam transverse size will not exceed $r < 1 \mu m$. It refers to such devices as Final Focus of LCs. The precise measurement and continuous control of the beam position as well as the energy or γ-factor of beam particles become a serious problem. In case of cyclic accelerators the synchrotron radiation at the curved parts of beamline helps to solve this problem. However on LC the beam position monitoring requires development of non-traditional methods, because the conventional techniques are is either inapplicable, or are not able to provide the accuracy required. Methods based on the DR for measuring the center of gravity of the beam as well as the particles γ are suggested below.

Theoretical Considerations

It is well known that when the charged particle passes through the orifice or slit in the screen, there arises a so-called DR [1-3].The physical nature of this radiation is as follows. When the charge passes near the edge of an ideally conducting semi-infinite screen, on its surface there are induced currents that are a source of DR. The electric field emitted in the free space at distances exceeding the radiation formation zone has the form of cylindric waves that propagate from the slit edges .

If the particle passes through an x-opening slit at distance x_1 and x_2 to its edges (x_1+x_2), the number of quanta with wavelength λ is defined by [1]

$$\frac{d^2N}{d\lambda d\Omega} = \frac{1/137}{8\pi f^2\lambda^2}\left\{\frac{f^2+k_x^2}{f^2+k_y^2}\left[exp\frac{-4\pi x_1 f}{\lambda} + exp\frac{-4\pi x_2 f}{\lambda}\right] - \frac{(f^2-k_x^2)cos(2\pi x k_y/\lambda) - 2fk_y sin(2\pi x k_y)/\lambda}{2\pi^2(f^2+k_y^2)^2\gamma^2} exp\frac{-2\pi x f}{\lambda}\right\} \quad (1)$$

where $f^2 = kx^2 + 1/\gamma^2$, $k_x = sin\theta cos\varphi$, $k_y = sin\theta sin\varphi$, $d\Omega$, θ, and φ are solid, polar and azimuthal angles, respectively. DR is characterized by a narrow angular distribution. As it is seen from Fig. 1, almost the whole radiation practically concentrates

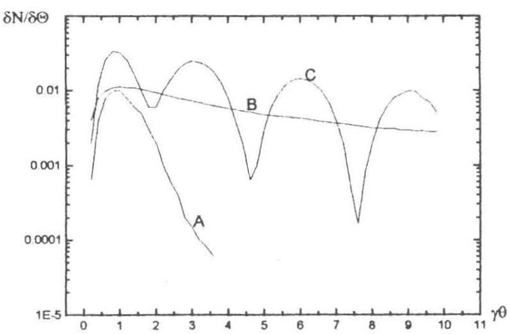

Fig.1. The angular distribution of DR at different azimuthal angles.
A - single screen $\varphi=0°$; B - single screen $\varphi=90°$; C -slit $\varphi=90°$.

within the angular range $0.5\gamma < \theta < 10\gamma$ (except for the azimuthal angles adjacent to $\varphi = \pi/2$).If the particle passes not very far from one of the edges, then at azimuthal angles near $\pi/2$ typical interference maxima and minima occur in the radiation (curve A). The azimuthal distribution has a maximum at $\pi/2$. Note that DR propagates both forward and backward, the angular distribution in both directions being identical. If x_1 or x_2 tend to infinity, the problem reduces to the radiation of the charge that passes near a single screen, and the interference term in (1) tends to zero. At $x=0$ the expression (1) defines the transition radiation of a relativistic particle at the vacuum - ideal-conductor boundary. As it follows from (1), the radiation is essential at

$$\gamma\lambda > x\,, \quad (2)$$

otherwise the radiation at wavelength λ will be suppressed. The number of photons is exponentially dependent both on with the distance between the particle and screen (Fig. 2) and on the γ.

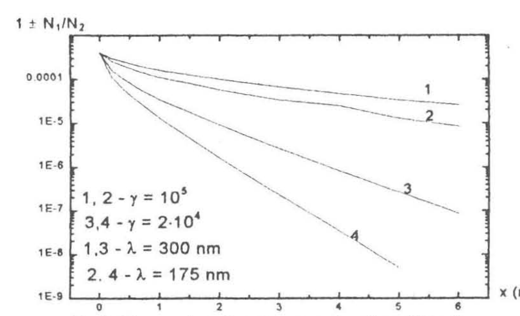

Fig. 2. The number of photons as a function of the slit opening for two different wavelengths.

[1] Work partially supported by the Grant 211-5291 YPI of the German Bundesministerium fur Forshung und Technology.

The Method of Beam Position Monitoring

As follows from (2), at the $\gamma>10^4$ one can provide reasonable distances between the particle and the screen edge $(x \sim 1\div10mm)$in the bandwidth $100nm<\lambda<1000nm$. This simplifies the task of DR detection, since in this range a large variety of detectors are available. At a given slit size the monitoring accuracy is the higher, the smaller the beam spot size, and its minimum value is limited by the wavelength registered.

Proceeding from the specific features of DR we suggest the following beam position monitor. It contains two screens - radiators made of metal plates or foils and located symmetrically to the beam. The screens can be moved with high precision perpendicular to the beam. (Such a device currently is used at SLC for wire scanning of the beam [4]). The inclined mirrors are placed at definite distance from the screen. Relative position of the screens, mirrors and the beam is specified so that to provide maximum light gathering and to minimize the background effect. The radiation reflected by the mirrors is extracted from the beampipe through the quartz window (or in case of VUV, a fused silica SUPRASIL II, HERAEUS CORNING 7940 window). Further, the radiation is directed through the polarization filter and monochromator to the photodetectors PD. Also the version to detect radiation with inclined screen in the backward semisphere is possible. In that case there is no need of mirrors.

The beam center-of-gravity position is determined from signals ratio on each of detectors. From simple considerations it follows that at small shifts ($\Delta x<<x$), in a small wavelength interval detecting radiation within $\Delta\lambda<<\lambda$ and in the given angular range the accuracy of coordinate determination is

$$(\Delta x)\geq(\gamma\lambda)^2/4\pi^2[(\gamma\theta\cos\theta)^2+1]ndN/d\Omega \qquad (3)$$

where n is the number of beam particles passing through the slit during the given time interval (the efficiency and other characteristics of PM being ignored). One can see that at a given γ, the accuracy of determination worsens with increasing slit opening or wavelength. Fig. 3 presents the signals ratio of two PMs as a function of beam shift for various wavelengths. Here curves 2 and 4 are plotted with regard to the DR spectral distribution and spectral sensitivity of phototubes.

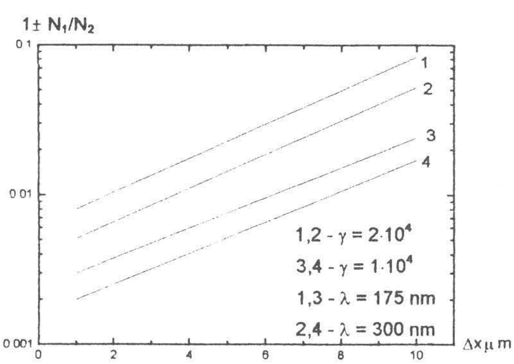

Fig. 3. The ratio of the signals from two PMs vs beam shift at different slit openings and wavelengths

Now we turn to some technical problems related to the measurement of the beam position using the DR monitors. We will suppose that the number of particles in the bunch is 10^{10}, the number of bunches is 10, the repetition rate is 120 Hz, the beam transverse dimensions are $\sigma_x*\sigma_y=0.6*1.0\mu m^2$. The use of two types of PD is possible: either Visible-Light Photon Counters (VLPC) which are cryogenic solid-state PD (wavelength range 350-800nm) featuring high quantum efficiency (at 530nm as high as 85%), high speed, high gain, low noise and low cost [5] or Hamamatsu R2059 photomultipliers (PM) featuring wavelength range 165-650nm, quantum efficiency 25% at 350nm.

In a bandwidth 400÷450nm the number of photons detected by each VLPC amounts to $2\cdot10^{-4}$ per electron for $x_1=x_2=1mm$. At beam shift by 300nm, the signals ratio of two VLPCs change by $4\cdot10^{-2}$%. With account of the ADC accuracy as well as other errors, the accuracy of beam position measurement will not exceed 500-550nm.

Further reduction in error can be attained if we pass to the VUV bandwidth. In this case one should use R2059 PMs. Assuming that 60% of photons is lost in the windows, reflecting mirrors, etc., and the PM signal is stored for 1s, the error beam position measurement will not exceed 200-300nm.

Another advantage of the DR is the following. As far as the condition (2) is satisfied not only in the point of the screen edge nearest to the beam, but also in the more remote points, hence the radiation will occur practically throughout the screen. It is evident that the DR intensity will decrease with increasing distance between the emitting point and the particle trajectory, which is illustrated in Fig. 4. Here we present spatial distribution of emitted photons along the screen edge. This dependence can be used both for center-of-gravity determination and visualization of the beam. In this case as radiation detectors can serve position-sensitive detectors like CCD or optical fibers connected to the multi-anode PMs or photodiodes.

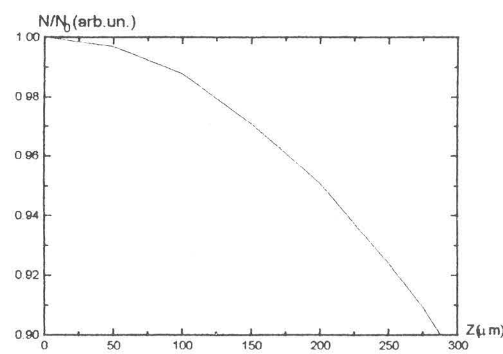

Fig.4. The radiation distribution along the screen edge.

Since DR is polarized, the use of polarization filters will allow one to suppress strongly the background of both scattered and synchrotron radiation..

As mentioned above, the relative shifts of the beam lead to a greater change in the signal. Nevertheless these changes are rather small, and one should take measures to provide the accuracy required. So, the gear system should provide positioning and stabilization of mirrors and screens with an accuracy better than $100nm$. The surface of mirrors and screen edges must be polished with the same accuracy. Fortunately, these requirements can be met by commercially available means (see, e.g., Ref. [4]). Stability of PDs, ADCs and other analog circuits must be better than 10^{-5}. Contributions of noises to the signal must not exceed the same level. To meet such rigid requirements, we may need to control the temperature of both the gear and electronic devices as well as to switch the PMs off in the intervals between the beam pulses.

Lorentz - Factor Measuring

As it follows from (1), the intensity of DR depends strongly on the Lorentz-factor of particles. This means that for the installation described above a change in the γ of the beam particles will be followed by a sharp equal change in signal values of both PMs, if the beam is in its central position. However it is evident, that the same result can be induced by a change in the beam intensity. To exclude the influence of the beam intensity, one can measure the radiation at two different wavelengths. For the sake of illustration Fig. 5 shows the

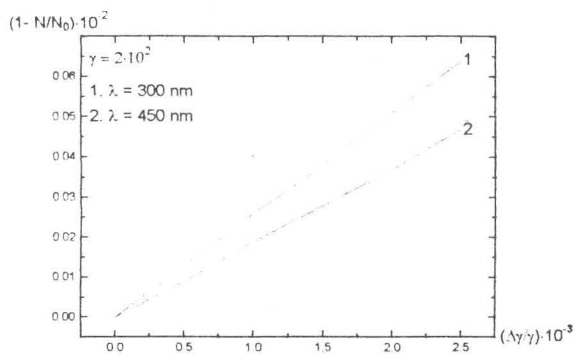

Fig. 5. The ratio of signals from two PM vs γ shift at two different λ.

dependence of a relative change in the number of photons on a relative change of γ at two different wavelengths.

The slopes of these dependencies strongly differ from each other. Therefore a change in γ will be followed by different relative changes of the emitted photon number while a change in beam intensity will produce equal changes of the number of photons at both wavelengths. The calculations show, that at $\gamma = 2*10^4$ the measurement precision will be $\Delta\gamma/\gamma<10^{-4}$.

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