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Beam Energy Absolute Measurement Using Visible Light of Synchrotron Radiation

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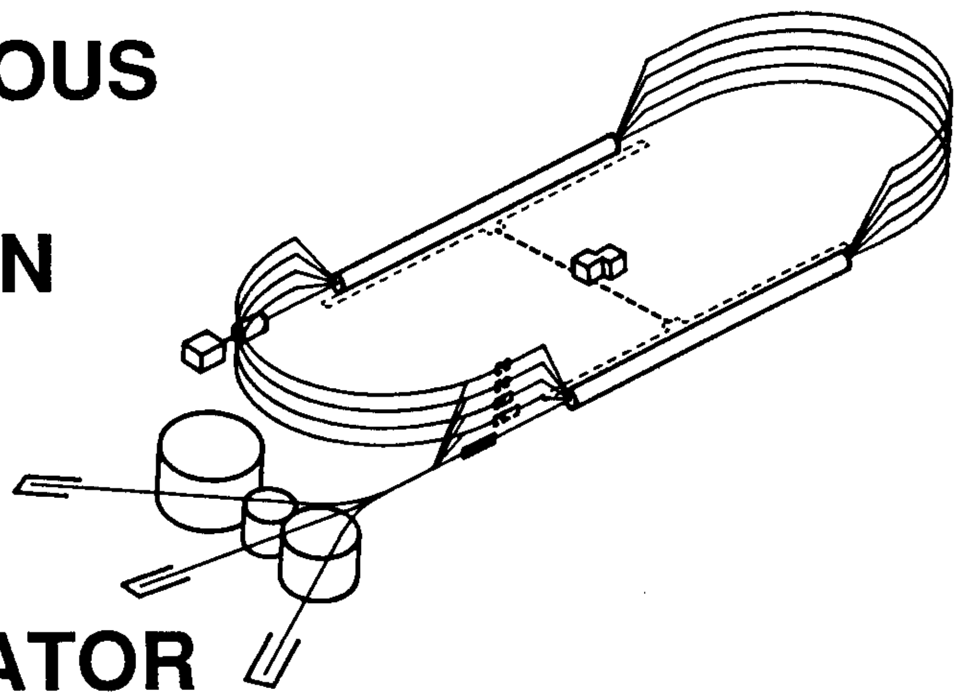

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Abstract

The results are presented from an investigation of high-precision absolute energy measurement using magnified angular distribution of visible light from synchrotron radiation.

The calculations affirm that resolution of about 1.0×10^{-4} is possible for all CEBAF beam energies when a cylindrical lens of focal length ~ 2.0 cm is used at a distance of 2.0 m from the point of the electron trajectory from where the radiation was collimated.

Introduction

During 1990–1992, intensive investigations were carried out to find the basic solution for precision absolute energy measurement for CEBAF. Two main measurement principles were discussed: a magnetic spectrometer method in a form of three [1] and four [2] magnet chicanes and a synchrotron radiation method [3,4] which uses the dependence of spectral and angular characteristics of this radiation on the absolute value of electron energy.

The first method has limited resolution of several times 10^{-4}. The best resolution of 5×10^{-4} using this method was achieved by SLC spectrometers [5].

The synchrotron radiation method in principle is more sensitive and can provide resolution one order of magnitude higher than spectrometers. But this technique has not been investigated experimentally, and there are many difficult tolerances connected with preparation and installation of the slits for the photon angular distribution measurement within angles of absolute value 10^{-4}. These tolerances arise because for the energy measurement x-ray radiation was proposed.

The main reason for using x-rays is that differential ionization chambers having resolution $I_1 - I_2/I_1 + I_2 \leq 10^{-5}$ [6] have been carefully investigated and widely used as research instruments for synchrotron radiation research in Yerevan Physics Institute.

The second reason was that the intensity of synchrotron radiation is proportional to $(\lambda_c/\lambda)^2$, and higher intensity permits achievement of better resolution.

In this paper we propose to use visible light from synchrotron radiation for precision energy measurement. This technique promises good resolution and is free of the main limitations under which the x-ray technique suffers.

The main advantage of visible light with respect to x-rays is that standard optical lenses can be used to enlarge the angles of radiation, and this part of the spectrum has comparably larger angular divergence. This permits using larger-width slits and having more space between them. For instance, magnification $M = 100$, which is easy to achieve by a cylindrical diverging lens having focal length about 2 cm, will permit the distance between the slits to be about 20 mm and the slit width to be 1.0 mm. Therefore the required absolute accuracy of the slit system can be achieved more easily.

For measurement of the photon fluxes, highly sensitive and almost 100% effective silicon photodiodes [7] can be used. These photodiodes have a shunt resistance of order of 10^{10} Ω and dark current about 0.1 fA, which is equivalent to about 800 photons per second, which is less than 10^{-7} of the SR beam intensity anticipated for the lowest electron energy.

The Principle of the Measurement

It is known that (see *e.g.* [8]) the vertical distribution of the synchrotron radiation for a given wavelength λ at 1 mA, a horizontal angle Θ of 1 mrad, a vertical angle ψ of 1 mrad, and a spectral bandwidth $k = \delta\lambda/\lambda$ is

$$N_k = 3.461 \cdot 10^6 k\gamma^2 (\lambda_c/\lambda)^2 F \tag{1}$$

where $\lambda_c = 4\pi\rho/3\gamma^3(\mathrm{cm})$ in CGS units, $\gamma = E/mc^2$, ρ is the bending radius in the magnets, and

$$F = F_{\parallel} + F_{\perp} = (1+x^2)^2 \left[K^2_{2/3}(z) + \frac{x^2}{1+x^2} K^2_{1/3}(z)\right] \tag{2}$$

Here, $x = \psi\gamma$, and ψ is the angle vertical to the bending plane. $K_{1/3}(z)$ and $K_{2/3}(z)$ are modified Bessel functions, and $z = (\lambda_c/2\lambda)(1+x^2)^{3/2}$. This distribution for $\lambda_c/\lambda = 1$ is shown graphically in Figure 1.

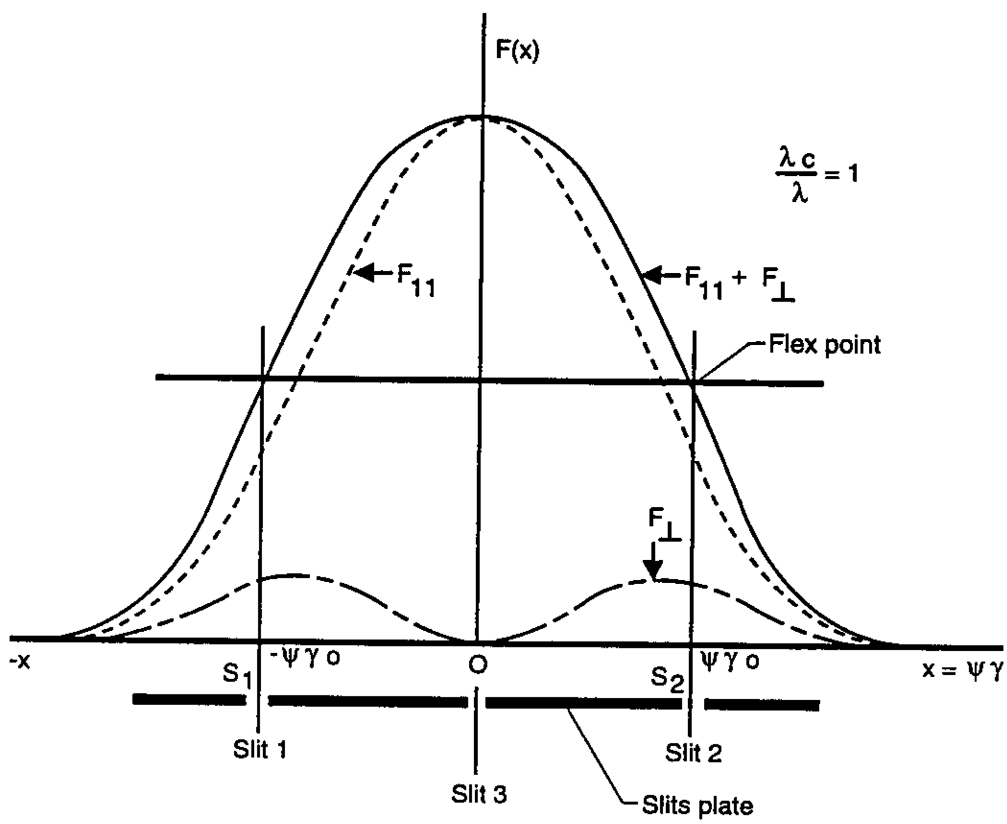


Figure 1. Distribution for $\lambda_c/\lambda = 1$.

The principle of this energy measurement, described in [3], is as follows. Let's have two equal-width h horizontal slits with ξ as the ratio of their lengths. The central line of the first is lying in the bending plane, and the second is parallel to and displaced from the bend plane so they collimate the photons radiated at the angles $\psi = 0$ and $\psi = \psi_0$.

When the intensities of the photon flux through these slits are equal,

$$N_k(\gamma_0, \psi = 0) - \xi N_k(\gamma_0, \psi = \psi_0) = 0, \tag{3}$$

where

$$\xi = \frac{K^2_{2/3}(\lambda c/2\lambda)}{(1+x^2)^2[K^2_{2/3}(z) + \frac{x^2}{1+x^2}K^2_{1/3}(z)]}, \tag{4}$$

and the beam energy is equal to γ_0.

In (3) $N_k(\gamma, \psi = 0)$, $N_k(\gamma, \psi = \psi_0)$ are the photon fluxes emitted at the vertical angles $\psi = 0$, $\psi = \psi_0$ respectively. If γ differs from γ_0 by $\delta\gamma$, where γ_0 satisfies equation (3), then the difference $\Delta N_k(\Delta\gamma)$ (proportional to $\delta\gamma$) can be measured and used for compensation of energy deviation.

Definition of the Working Point ψ_0

Deviation of the observation angles $\psi = 0$ and $\psi = \psi_0$ by the small value $\Delta\psi$ (or $\Delta x = \Delta\psi\gamma$) brings an additional flux difference $\Delta N_k(\Delta\psi)$

$$\Delta N_k = AF'\Delta x + \frac{A}{2}F''\Delta x^2 + \ldots \tag{5}$$

where A is the constant of proportionality. In order to estimate the maximum value of this possible error, ΔN_k at $\psi = \psi_0$ is used.

The derivatives of $F(x)$ are:

$$\begin{aligned} F'(x) &= 4x^3K^2_{2/3} - 6x(1+2x^2)zK_{1/3}K_{2/3}, \\ F''(x) &= 4x^2\frac{3+x^2}{1+x^2}K^2_{1/3} + 18x^2z^2\frac{1+2x^2}{1+x^2}(K^2_{1/3} + K^2_{2/3}) - \\ &\quad 6z\frac{10x^4+7x^2+1}{1+x^2}K_{1/3}K_{2/3}. \end{aligned} \tag{6}$$

The Bessel function derivatives are

$$\begin{aligned} K'_{1/3}(z) &= -K_{2/3} - (1/3z)K_{1/3}, \\ K'_{2/3}(z) &= -K_{1/3} - (2/3z)K_{2/3}. \end{aligned} \tag{7}$$

The expressions for $F'''(x)$ and $F''''(x)$ are very complicated and are not presented here. These derivatives are not small, and the only possible way to minimize their effect is to use the symmetry of the distribution of the SR flux relative to the orbital plane. If the photon fluxes passing through two identical slits S_1 and S_2 at vertical angles ψ_0 and $-\psi_0$ (see Figure 1) are added, then all the odd components in (5) vanish, and

$$\Delta N_k(\Delta\psi) = 2A[(\Delta x^2/2)F''(x) + (\Delta x^4/24)F''''(x)]. \tag{8}$$

Furthermore, there is a point $x = x_0$ where $F''(x) = 0$, and this is the working point that corresponds to the flex point of $F(\psi\gamma)$. Using the formula (6) one can find the value of x where $F'' = 0$ for chosen λ_c/λ.

The Calculations

The calculations were performed using (3) with (1) and (2) for all CEBAF energies in the range 0.5–4.0 GeV, beam current $I_e = 100$ μA, visible light wavelength $\lambda = 4747$ Å, bend angle $\Delta\theta = 10^{-2}$ rad, and angular width of the slits $\Delta\psi = h/L = 10^{-4}$ rad, where L is the distance between the point of source location and the slit plane along the tangent line.

The intensities of the magnetic field were taken equal to the fields in the arc bending magnets for the corresponding beam energy.

The results of the calculations are presented in Table 1. The photon flux difference $\Delta N_\gamma(\Delta E)$ corresponds to energy deviation $\Delta E = 10^{-4} E_0$.

According to these results beam energy can be measured absolutely with accuracy better than 10^{-4}, including the energy $E = 0.5$ GeV, so this method can be used for all experimental halls, as well as for superconductive linacs, for the stabilization of energy.

Table 1
The Results of the Calculations

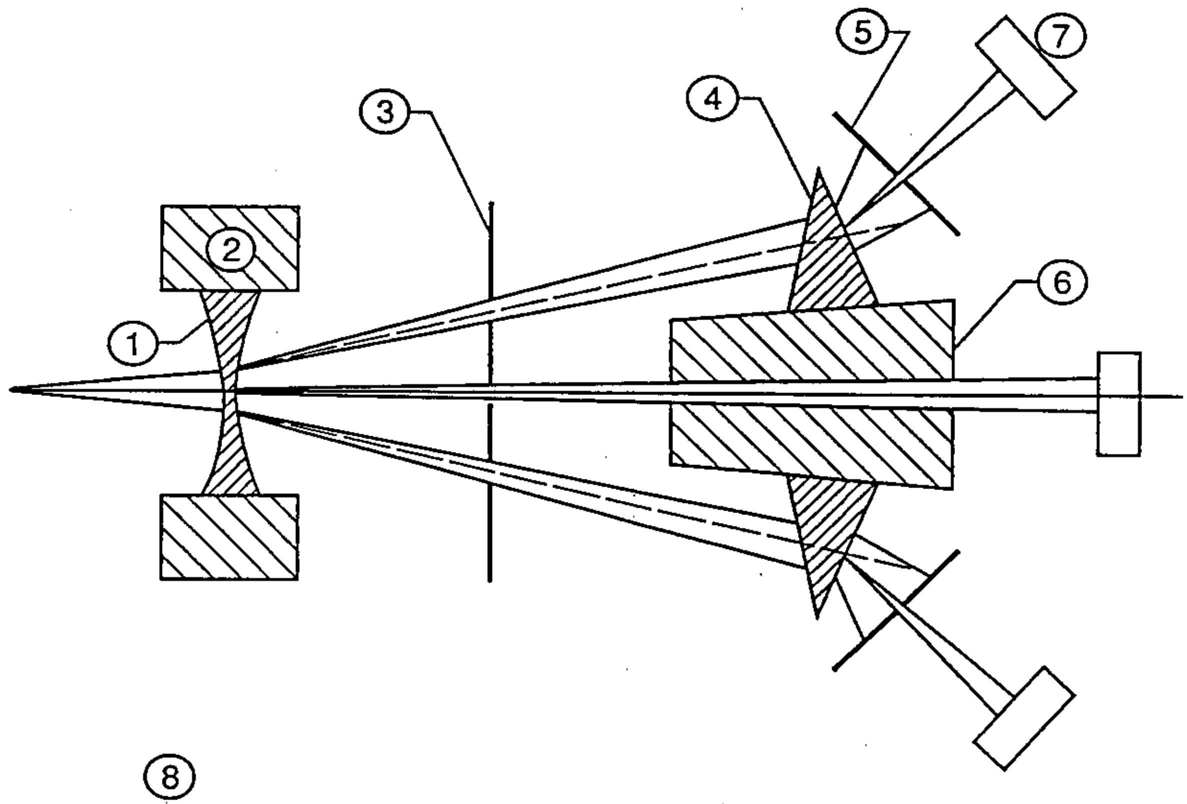
E (GeV)	N_γ $(\mathrm{ph} \cdot \mathrm{s}^{-1})$	$\Delta N_\gamma(\Delta E)$ $\Delta E = 10^{-4} E_0$ $(\mathrm{ph} \cdot \mathrm{s}^{-1})$	ΔN_{fl} $(\mathrm{ph} \cdot \mathrm{s}^{-1})$	$\frac{\Delta N_\gamma(\Delta E)}{\Delta N_{fl}}$ $\frac{\text{signal}}{\text{noise}}$	B (Gauss)	λ_c (Å)
0.5	2.085×10^9	5.76×10^4	4.72×10^4	1.22	1.5×10^3	474.7
0.85	1.858×10^9	2.54×10^5	4.3×10^4	5.9	2.9×10^3	88.76
1.74	2.695×10^9	3.385×10^5	5.19×10^4	6.52	4.362×10^3	14.8
2.0	2.704×10^9	2.173×10^5	5.2×10^4	4.18	5.816×10^3	7.85
2.5	3.46×10^9	3.65×10^5	5.88×10^4	6.21	3.636×10^3	8.1
3.0	6.873×10^9	1.665×10^6	8.2×10^4	20.3	3.49×10^3	6.0
4.0	5.28×10^9	4.05×10^6	7.2×10^4	56.25	4.65×10^3	2.49

Experimental Installation

The scheme of the energy measurement monitor is shown in Figure 2. The entire installation consists of the following parts:

- bending magnet,
- special vacuum chamber having appendix for SR light extraction,
- precision magnetometer for continuous field measurement,
- optical diverging lens,
- light monochromators,
- plate with horizontal slits having a remote control system of precision vertical and horizontal positioning,

- photodiodes,
- high-sensitivity electrometers and associated standard electronics and computing elements.



1. Defocusing lens
2. Lens holder
3. Slit plate
4. Monochromator
5. Monochromator's slit
6. Monochromator's holder
7. Photodiodes
8. Installation platform

Figure 2. Energy measurement scheme.

For experimental investigations of the method and its immediate utilization for the stabilization of the energy of the north linac, the facility will use the radiation created in the spreader bending magnet AI1S04 in the second elevation of the 400 MeV energy beam. The magnet is installed with its yoke inside the bend trajectory so there are no problems connected with extracting synchrotron radiation. A sketch of the modified beam pipe is shown in Figure 3. The beam pipe will be made of copper or aluminum so that the field intensity inside the pipe is equal to that measured by the probe in the gap outside the vacuum chamber.

The energy measurement for experimental halls will use a bending magnet of the beam transport system.

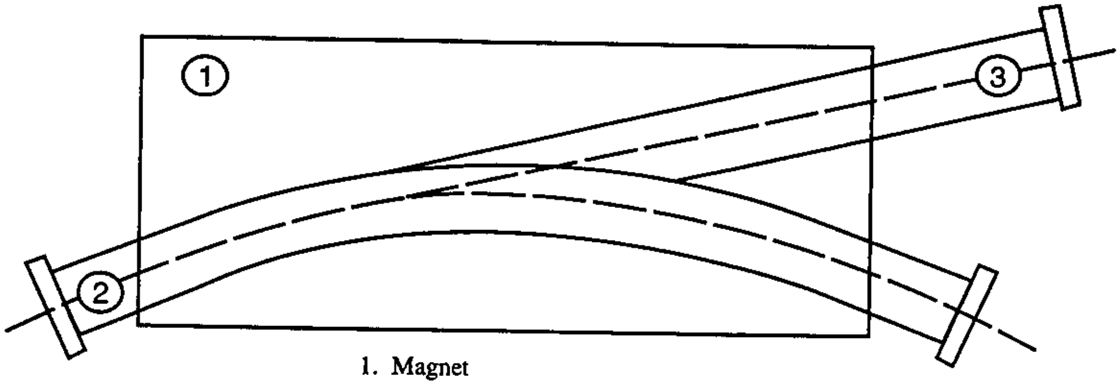


Figure 3. Sketch of modified beam pipe.

A cylindrical diverging lens having magnification about 100 and a working aperture not less than $x = 20.0$ mm and $y = 4.0$ mm will be installed after the glass window. For the lens magnification equal to 100, the distance between the slits along the vertical axis will be 10 mm and the slit plate will be installed after the lens at a distance of about 100 mm. The slits will be 100 μm wide and 20 mm long. The gap area of the slits can be made equal by changing the slit length.

The equality of the photon fluxes can be measured by photodiodes joined in a differential scheme as shown in Figure 4. With S1226 – 8BQ tip photodiodes and an OPA128LM operational amplifier, a sensitivity of 0.1 fA was achieved [7].

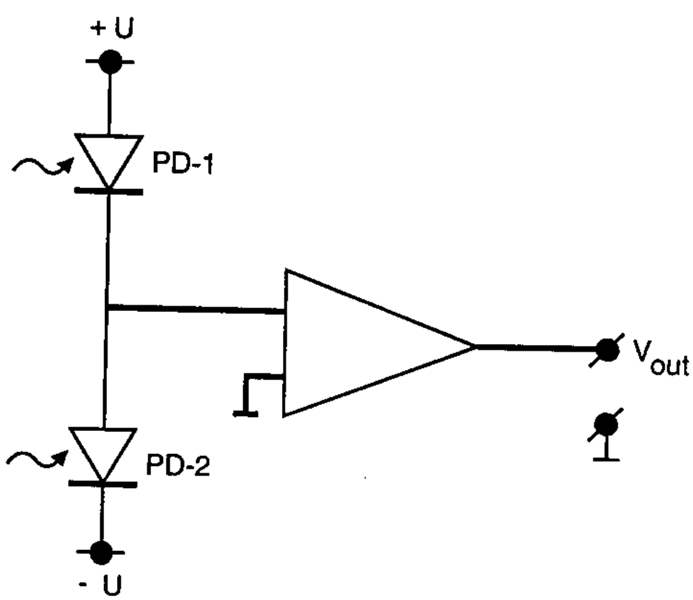


Figure 4. Scheme for measuring equality of photon fluxes.

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