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High-Precision Absolute Measurement of CEBAF Beam Mean Energy

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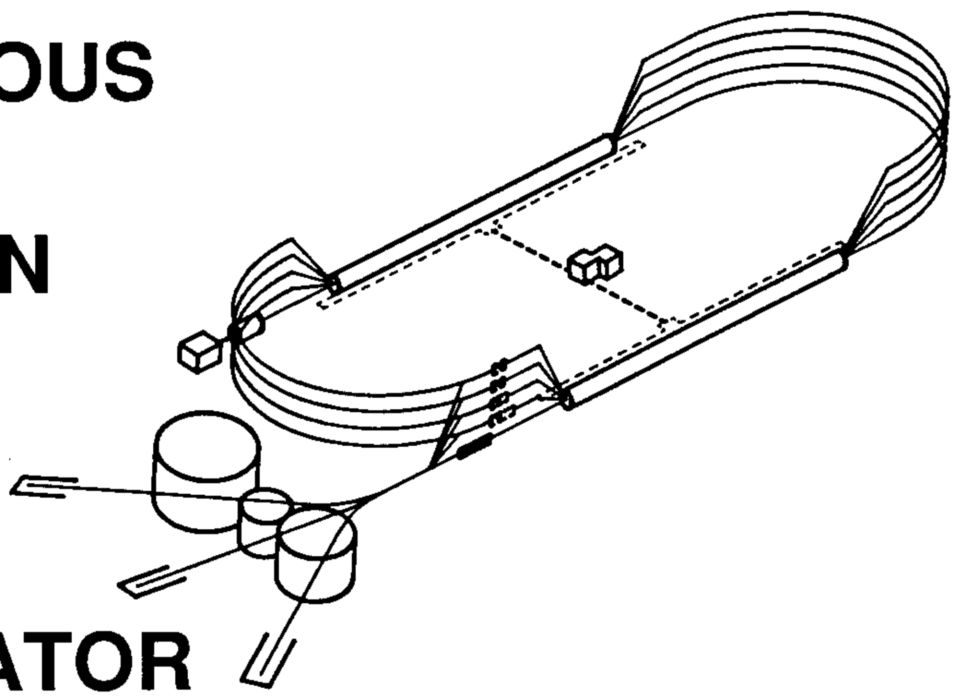

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High-Precision Absolute Measurement of CEBAF Beam Mean Energy*

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1. Introduction

The absolute measurement of the beam mean energy with an accuracy of one part in 10^4 or higher is an important demand of the CEBAF Hall A physics program [1]. This accuracy may reduce the uncertainty in the d(e,e'p)p cross section $\delta\sigma/\sigma$ to 1%. The need for such an accurately calibrated beam is not particular to CEBAF; at other electron facilities uncertainty in the incident energy has proven to be among the dominant sources of systematic error.

The following methods for solving the problem were considered at both CEBAF and the Yerevan Physics Institute during 1990 - 1991:

- Backscattering of a plane electromagnetic wave by the relativistic electron beam. Calculations show that the intensity of the backscattered radiation in a bandwidth of 10^{-4} near the maximum frequency is about 1 photon per second at 4 GeV and 0.3 mA [2].
- Magnetic spectrometers performing as three- and four-magnet chicanes [3,4,5] with appropriate detector systems. Such a system was used at SLAC for absolute measurement of the SLC beams energy, where a maximum accuracy of 5×10^{-4} was achieved. Calculations show that a similar accuracy can be achieved for the CEBAF beam in both proposed systems.
- Measurement of the vertical distribution of synchrotron radiation [6]. Calculations indicate that precision of about 2.5×10^{-5} is achievable for CEBAF.

2. The Resolution of Magnet Spectrometer Systems

The precision of determining the beam mean energy using magnetic spectrometers depends on the measurement accuracy of the field intensity B and the bending radius ρ. Since a high-precision direct measurement of ρ is impossible, this parameter has to be determined via other measurable values such as the beam deflection h or the bending angle θ.

The main problem is to design a scheme where the error of the measurements is minimal.

The beam energy E and the bending radius ρ in an extended nonuniform magnetic field are related by:

$$E = 300\left(\frac{\rho}{\delta s}\right)\int_{s_1}^{s_2} B ds, \tag{1}$$

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and can be adopted for the bending angle measurement. This formula, written in another form useful for a deflection measurement, is

$$E = \frac{300h}{\Delta s(1 - cos\theta_B)} \int_{s_1}^{s_2} Bds, \tag{2}$$

where Δs is the length of the trajectory in the magnetic field and θ_B is the bending angle.

Formulas (1) and (2) described the main functions of three and four magnet chicanes, and they are the basis for the calculation of tolerances. The scheme of these two types of spectrometers are presented in Figure 1, and their main parameters are given in Tables 1 and 2.

It is known [3] that the bending angle θ_B can be measured with two synchrotron (SR) beams generated by two short kicker magnets which deflect the electron beam orthogonally to the main bending plane. The main benefit of the three magnet chicane method is that the distance between two SR beams may be measured by intercepting detectors.

The minimal bending angle will be determined from the ratio $\Delta\theta/\theta = A$, where A is the requested accuracy of the energy determination and $\Delta\theta$ is the achieved accuracy of the bending angle determination, which can be calculated as

$$\Delta\theta = \frac{1}{L}\sqrt{n_d(\delta x)^2 + n_k(\theta_v \cdot \delta\phi_k L)^2 + \Delta X^2 + (\delta \int Bds)^2} \tag{3}$$

In (3) $\delta \int Bds$ is the accuracy of the field integral measurement; δx, the resolution of the intersecting beam position monitors; θ_v the bending angle in the kickers; $\delta\phi$, the angle between magnetic lines of force in the kicker and the bending plane of the main magnet; L, the distance between the detector's plane and the point where SR is created; Δx, survey error; n_d, number of SR detectors; and n_k, number of kickers.

The four magnet chicane measures the deflection of the electron beam using transparent beam position monitors. The main limitation for this type of chicane is the error produced by the uncertainty in measurement of the beam entrance angle x'.

The uncertainty of the deflection measurement can be calculated by

$$\Delta h = \sqrt{2(\delta \int_{s_1}^{s_2} Bds)^2 + 3\Delta x^2 + (\rho\Delta x' sin\theta)^2} \tag{4}$$

It is known [8] that the field integral may be measured to an accuracy of 100 ppm. The accuracy of the SR beam centroid measurement by intersecting detectors is about 30 μm [9], and the minimal value of $\delta\phi$ is about 2 mrad [2]. The resolution of the transparent beam position monitors due to the signal to noise ratio is 10^{-4} m [10]. The errors are listed in Tables 3 and 4 at the end of this paper. The results confirm that the maximal accuracy of the spectrometers is several units of 10^{-4}.

3. Resolution of the Synchrotron Radiation Method

It is known that (see *e.g.* [11]) the vertical distribution of the synchrotron radiation for a given wavelength λ at one mA, a horizontal angle Θ of one mrad, a vertical angle ψ of one mrad, and a spectral bandwidth $k = \delta\lambda/\lambda$ is

$$N_k = 3.461 \cdot 10^6 k\gamma^2(\lambda c/\lambda)^2 F \tag{5}$$

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

$$F = F_{\|} + F_{\perp} = (1+x^2)^2\left[K^2_{2/3}(z) + \frac{x^2}{1+x^2}K^2_{1/3}(z)\right] \tag{6}$$

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 $z = (\lambda c/2\lambda)(1+x^3)^{3/2}$. This distribution is shown graphically in Figure 2.

The principle of this energy measurement [4] is as follows. When the following equation is satisfied

$$N_k(\gamma_0, \psi = 0) - \xi N_k(\gamma_0, \psi = \psi_0) = 0. \tag{7}$$

where

$$\xi = \frac{K^2_{2/3}(\lambda c/2\lambda)}{(1+x^2)^2[K^2_{2/3}(z) + \frac{x^2}{1+x^2}K^2_{1/3}(z)]}, \tag{8}$$

the beam energy is determined equal to γ_0. In [7] $N_k(\gamma, \psi = 0)$, $N_k(\gamma, \psi = \psi_0)$ 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 (7), then the difference $\Delta N_k(\Delta\gamma)$ (proportional to $\delta\gamma$) can be measured.

3.1 Definition of the Working Point ψ_0 and Accuracy of Its Measurement

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

$$|\Delta N_k| = A|F'\Delta x| + A|1/2F''\Delta x^2| + \dots \tag{9}$$

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:

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

The Bessel function derivatives are

$$\begin{aligned} K'_{1/3}(z) &= -K_{2/3} - (1/3z)K_{1/3}, \\ K'_{2/3}(z) &= -K_{1/3} - (2/3z)K_{2/3}. \end{aligned} \tag{11}$$

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 flux passing through two identical slits at vertical angles ψ_0 and $-\psi_0$ are added, then all the odd components in (9) vanish, and

$$\Delta N_k(\Delta\psi) = 2A[(\Delta x^2/2)F''(x) + (\Delta x^4/24)F''''(x)] \tag{12}$$

Furthermore, there is a point $x = x_0$ where $F''(x) = 0$, and this is the working point that corresponds to the bending point of $F(\psi\gamma)$. For $\lambda_c/\lambda = 1$ this point is $x = 0.801084$, and for $\gamma = 7828$ (4 Gev) the working point $\psi_0 = 1.02336 \cdot 10^{-4}$ rad. For this point the first element of the series (12) with non-vanishing value is $(F''''/24)\Delta x^4$. Calculating the derivatives of $F(x)$ for $x = 0.801084$ yields

$$F'(x) = -\,1.735, \quad F''(x) = 0, \quad F'''(x) = 14.26, \quad F''''(x) = 2.1$$

Taking

$$\frac{\Delta N_k(\Delta\psi)}{N_k} = F''''(x)\Delta x^4/24F(x) = 10^{-5}$$

for $\gamma = 7.828 \cdot 10^3$ and $F(x = 0.8) \simeq 0.5$, we obtain the tolerable value of $\Delta\psi = 0.945 \cdot 10^{-5}$ rad.

3.2 Resolution of the Method and Its Limitation Caused by Quantum Fluctuations

The sensitivity of the method is expressed by

$$\Delta N_k(\Delta\gamma) = \Delta\gamma[N'_k(\gamma, \psi = 0) - \xi N'_k(\gamma, \psi = \psi_0)] \tag{13}$$

In (13) $N'_k(\gamma, \psi = 0)$ and $N'_k(\gamma, \psi = \psi_0)$ may be calculated from:

$$N_k(\gamma, \psi = 0) = \left[a^2\gamma^{-2}K^2_{2/3}\left(\frac{a\gamma^{-2}}{2}\right)\right] \times C \tag{14}$$

and

$$\begin{aligned} N_k(\gamma,\ \psi = \psi_0) = a^2\gamma^{-2}(1+\psi^2\gamma^2)^2 \Bigg\{ &[K^2_{2/3}(\frac{a\gamma^{-2}}{2}(1+\psi^2\gamma^2)^{3/2}) + \\ &+ \frac{\psi^2\gamma^2}{1+\psi^2\gamma^2} K^2_{1/3}(\frac{a\gamma^{-2}}{2}(1+\psi^2\gamma^2)^{3/2}) \Bigg\} \cdot C \end{aligned} \tag{15}$$

which can be written as

$$N_k(\gamma,\psi=\psi_0)=C\times\Big[\overbrace{a^2\gamma^{-2}K^2_{2/3}(z)}^{A_1}+\overbrace{2a^2\psi^2K^2_{2/3}(z)}^{A_2}+\overbrace{a^2\gamma^2\psi^4K_{2/3}(z)}^{A_3}+$$
$$+\overbrace{a^2\psi^2K^2_{1/3}(z)}^{B_1}+\overbrace{a^2\psi^4\gamma^2K^2_{1/3}(z)}^{B_2}\Big] \tag{16}$$

where

$z=\dfrac{a\gamma^{-2}}{2}(1+\psi^2\gamma^2)^{3/2}$ $C=3.461\times10^6\dfrac{\Delta\lambda}{\lambda}I$ in units of [mA, mradθ_{hor}, mradψ, sec^{-1}];

$a=\dfrac{7.12\cdot10^3}{B\lambda}$; λ is the synchrotron radiation wavelength in cm ; $\gamma=E_0/M_0C^2$ and

B is magnetic field strength.

The derivative of $N_k(\gamma,\psi=0)$ is

$$N_k(\gamma,\psi=0)=C\times\left\{2a^2\gamma^{-2}\Big[-K_{1/3}(z)-\frac{2}{3z}K_{2/3}(z)\Big](-a\gamma^{-3})-2a^2\gamma^{-3}K^2_{2/3}(z)\right\}, \tag{17}$$

and the derivatives of A_1', A_2', A_3', B_1', and B_2' are as follows:

$$A_1'=2a^2\gamma^{-2}K_{2/3}(z)\Big[-K_{1/3}(z)-\frac{2}{3z}K_{2/3}(z)\Big]\times$$
$$\times\overbrace{\Big[\frac{3}{2}\frac{a\psi^2}{\gamma}(1+\psi^2\gamma^2)^{1/2}-a\gamma^{-3}(1+\gamma^2\psi^2)^{3/2}\Big]}^{z'}-2a^2\gamma^{-3}K^2_{2/3}(z) \tag{18}$$

$$A_2'=4a^2\psi^2K_{2/3}(z)\Big[-K_{1/3}(z)-\frac{2}{3z}K_{2/3}(z)\Big](z') \tag{19}$$

$$A_3'=2a^2\psi^4\gamma K^2_{2/3}(z)+2a^2\gamma^2\psi^4K_{2/3}(z)\Big[-K_{1/3}(z)-\frac{2}{3z}K_{2/3}(z)\Big](z') \tag{20}$$

$$B_1'=2a^2\psi^2K_{1/3}(z)\Big[-K_{2/3}(z)-\frac{1}{3z}K_{1/3}(z)\Big](z') \tag{21}$$

$$B_2'=2a^2\psi^4\gamma\left\{K^2_{1/3}(z)+\gamma K_{1/3}(z)\Big[-K_{2/3}(z)-\frac{1}{3z}K_{1/3}(z)\Big](z')\right\} \tag{22}$$

Calculation of $\Delta Nk(\Delta\gamma)$ by (13) using (17 to 22) was performed for the following conditions:

$\lambda c/\lambda=1$; $\gamma_0=7828.0$; $B=10^4$ Gauss; $\lambda=1.16\mathring{A}$; $k=10^{-3}$; $I=0.3$ mA; $\Delta\theta_{hor}=10$ mrad; $\Delta\psi_{vert}=2.5\cdot10^{-2}$ mrad; $\psi_0=1.02\cdot10^{-4}$ rad. This gives the result

$$\Delta N_k(\Delta\gamma = 10^{-4}\gamma_0) = 4.412 \cdot 10^6 \text{ photons per sec}$$

The photon flux from the central slit is calculated using (14) and has the intensity $N_k = 2.3 \cdot 10^{10}$ photons/sec. The quantum fluctuation is accordingly

$$\Delta N_{fluct} = \sqrt{2N_k} = 2.14 \cdot 10^{-5} \text{ photons/sec}$$

which is more than 20 times smaller than $\Delta N_k(\Delta\gamma \cdot 10^{-4})$.

3.3 Tolerances Caused by Errors in Measuring λ_c and λ

The parameters λ_c and λ are the main variables in the formulae for determination of the absolute value of the beam energy. Errors in λ_c and λ are caused by errors in the measurements of the magnetic field strength B and the Bragg angle θ_B of the X-Ray monochromator.

Estimating the magnitude of these errors, we rewrite (8) in the simple form using only $F_{\|}$ as

$$\xi = \frac{K^2_{2/3}(y/2)}{b^2 K^2_{2/3}[(y/2)b^{3/2})]} \tag{23}$$

where $y = \lambda_c/\lambda$ and $b = 1 + (\gamma\psi)^2$.

The deviations of $\Delta B/B$ and $\Delta\theta/\theta$ produce errors in $y = \lambda_{c_0}/\lambda_0(\Delta y)$ which can be calculated using the relations

$$\lambda_c = \frac{7.12 \cdot 10^3}{\gamma^2 B}$$

and

$$\Delta\lambda = \lambda\Delta\theta ctg\theta_B$$

If $\Delta y \neq 0$, $\xi = \xi_0 + \Delta\xi$, where

$$\Delta\xi(\Delta y) = \xi'(y)\Delta y + \frac{1}{2}\xi''\Delta y^2 + \dots \tag{24}$$

This $\Delta\xi(\Delta y)$ produces errors in determining the absolute energy according to (8).

If the wave band $\Delta\lambda$ has a symmetric distribution around λ_0, the first component of (24) vanishes, and the error may be calculated by the second component

$$\Delta\xi = \frac{1}{2}\xi''\Delta y^2 \tag{25}$$

The errors in $\Delta B/B$ and $\Delta\theta/\theta$ shift the whole wavelength interval $\Delta\lambda$ with respect to λ_0, equivalent to introducing an asymmetric $\delta\lambda$ component. The intensity of this asymmetric part of the spectral distribution is $\delta\lambda/\Delta\lambda$ times lower than the entire intensity of the photon flux through the slit. Therefore the error produced by this parameter may be calculated from

$$\Delta F = \xi' \frac{\delta\lambda^2}{\Delta\lambda} \quad (26)$$

The expression for $\xi'(y)$ is

$$\xi'(y) = \frac{K_{2/3}(y/2)(-K_{1/3}(y/2) - \frac{4}{3y}K_{2/3}(y/2))}{b^2 K_{2/3}^2(z)} - \frac{K_{2/3}^2(y/2)b^{3/2}(-K_{1/3}(z) - \frac{2}{3z}K_{2/3}(z)}{b^2 K_{2/3}^3(z)} \quad (27)$$

where $z = (y/2)b^{3/2}$.

The following parameters have been chosen for numerical calculations:

$$\lambda_{c_0}/\lambda_0 = 1 = y; \quad \psi\gamma = 0.8; \quad b = 1.64; \quad K_{1/3}(0.5) = 0.989; \quad z = 1.05;$$
$$K_{1/3}(1.05) = 0.416; \quad K_{2/3}(0.5) = 1.206; \quad K_{2/3}(1.05) = 0.46; \quad y/2 = 0.5$$

With substitution of this into (27), one finds $\xi'(y) = 2.73$.

The value of $\xi''(y)$ was numerically calculated using (27), increasing the argument y by $\Delta y = 0.2$. The values of the parameters in the case of $y + \Delta y$ in (27) are:

$$z = 1.26; \quad K_{1/3}(0.6) = 0.8251; \quad K_1/3(1.260 = 0.308; \quad y/2 = 0.6;$$
$$K_{2/3}(0.6) = 0.983; \quad K_{2/3}(1.26) = 0.3406.$$

We find $\xi'(1.05) = 2.73$, $\xi'(1.26) = 3.28$, and accordingly, $\xi''(1.05) = 2.75$.

Tolerance Limits of the Bandwidth $\Delta\lambda/\lambda$.

Let the tolerable error in ξ due to $\Delta y = \Delta\lambda/\lambda$ be $\Delta\xi = 10^{-5}$. Using (25) one finds

$$\Delta\xi(\Delta y) = \frac{1}{2}\xi''\Delta y^2 = 10^{-5},$$
$$\Delta y = \Delta\lambda/\lambda = 2.7 \cdot 10^{-3}$$

Tolerance Limits for $\Delta B/B_0$.

The tolerable errors for the magnetic field strength measurement are

$$y + \Delta y = \frac{\lambda_{c_0}}{\lambda_0}(1 + \frac{\delta\lambda_c}{\lambda_{c0}}) \text{ and } \Delta y = \frac{\delta\lambda_c}{\lambda_{c_0}} = -\frac{\delta B}{B_0}.$$

Let the wavelength interval $\Delta\lambda/\lambda = 10^{-3} = \Delta y$, and the tolerable error in ξ due to $\delta B/B$ be $\Delta\xi = 10^{-5}$. Then

$$\Delta\xi(\delta y) = \xi' \frac{\delta y^2}{\Delta y} = 10^{-5} \text{ and } \delta y = \Delta B/B_0 = 0.6 \cdot 10^{-4}.$$

Tolerance Limit for $\Delta\theta$.

The tolerable errors for the Bragg angle θ_B can be calculated using the well-known relation $\delta\lambda/\lambda = \delta\theta \text{ctg}\theta_B$. It is evident that

$$\delta y = -y(\delta\lambda/\lambda)$$

Let the tolerable value of $\Delta\xi(y) = 10^{-5}$. Using (24) and (27) yields

$$\Delta\xi(\delta y) = \xi'(y)\frac{(\delta\theta ctg\theta_B)^2}{\Delta y} = 10^{-5}$$

Let $\theta_B \simeq 0.2$rad, $\quad \Delta y = \Delta\lambda/\lambda = 10^{-3}$. This yields an error $\delta\theta = 2.72 \cdot 10^{-5}$ rad .

Tolerance limit from the emittance of the Electron Beam.

Due to the angular (y') and spatial (y) distributions of electrons the photons at the slit fill an angle $\delta\psi = y' + y/L$. L is the distance between the central point of the arc, where the radiation is created, and the plane of the slits. The distribution of photons emitted by electrons having coordinates y, y' is shifted by $\delta x = \delta\psi\gamma$. Since the distribution is symmetrical with respect to the orbit plane for observation angles ψ_0 and $-\psi_0$ the shifts are accordingly δx and $-\delta x$. Using the same considerations which were discussed in paragraph 3.1 the tolerable value of the angular distribution of the electrons in the bunch may be calculated from

$$\delta F(x) = \frac{F''''(x)}{24}\delta x^4 \tag{28}$$

where $F''''(x) = 2.1$. For $\delta F(x) = 10^{-5}$, which corresponds to $\delta x = 10^{-1}$, one finds $\delta\psi = 1.25 \cdot 10^{-5} rad$.

All the tolerances are presented in Table 5 at the end of the paper.

4. Technical Performance of SR Method

4.1 The Slit System

The distance between the midpoint of the dipole and the slit plane is 5.0 m, and the slit is 50 mm long. The 3σ radius of the vertical emittance is about 2×10^{-9} mrad ($2 \cdot 10^{-5}$rad $\times\ 1 \cdot 10^{-4}$m). Accordingly, the height of the slit will be 400μm. The two slits that collect the photons emitted at angles $\psi_0 = \pm 1.02 \times 10^{-4}$ rad are separated by 1.04 mm, measured center-to-center. The central slit ($\psi = 0$) with the same length of 50 mm is shifted 50 mm parallel to the horizontal axis with respect to the double slits ($\pm\psi_0$). This arrangement of the slits has many advantages for the counting system, particularly for the ionization chambers that measure the photon flux differences and for precise mutual alignment. The accuracy of better than 10^{-5} for the slit alignment under SR beam is possible because the error of 10^{-5} of ψ_0 in the observation angle create an photon flux difference about 5×10^5 photons per second which is higher than the quantum fluctuations level. The slit system will be worked out with the absolute accuracy of 0.1 μm. The accuracy of 10^{-5} will be achieved by constructing 10 times bigger slit plate and installing it at the angle of 0.1 rad with respect to the SR beam axis.This angle will be measured by the accuracy 0.1 angular seconds which produces the error in distance between the slits of 0.01μm.

The slits are made of tungsten plates with a thickness of about 1.0 mm. The absorption coefficient of tungsten is about 4×10^3cm^{-1} for $\lambda \sim 1\mathring{A}$.

4.2 The Counting System

The counting system consists of two air-filled ionization chambers (IC). They are 50 cm long and have entrance window of 50mm in width. The construction of the chambers will provide a leakage current of less than 10^{-14} A, the IC current anticipated for a photon flux intensity of $2 \times 10^{10} s^{-1}$ is 10^{-6}A.

5. High Precision Energy Measurement for CEBAF

The investigations presented indicate that the measurement of the vertical SR distribution would allow determination of the CEBAF beam mean energy with an accuracy of 10^{-4} or better.

Clearly, the creation of synchrotron radiation requires a high precision magnetic field. For this purpose, a special short magnet will be inserted in the beam transport system as close as possible to the target area. The best place for this magnet is at the location of the penultimate dipole. For compensation of the distortion of the electron beam path caused by the inserted magnet, an optical system like the three magnet chicane is required. Such optics may be created using neighboring ordinary magnets to give an additional bending angle (see Figure 3). This additional angle $\delta\theta$ may be achieved by increasing the current in the magnet conductors. The tolerable increase of the current is about 20%, which yields $\delta\theta = 0.2$rad.

The high precision magnet length is about 50 cm long. The new straight section has a length of more than 2 m, which allows installation of two 0.2 m long kicker magnets with 2 mrad vertical deflection. If the distance between the point of SR generation and detectors is about 7 m and the distance between intersecting beam position monitors is measured with the accuracy $3 \times 10^{-5}m$ the preliminary beam energy determination will be performed with an accuracy of three units of 10^{-4}. Accuracy of up to $2.5 \cdot 10^{-5}$ can be achieved using SR light generated in the high precision magnet.

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7. Tables

Table 1. Main parameters of 3-magnet chicane

Parameter	Size
Bending angle	10^{-1} rad
Magnet length	1.0 meter
SR path length	3.0 meters
Vertical bend angle	10^{-2} rad
Number of spectrometer magnets	1
Number of kicker magnets	4
Number of position detectors	4
Total length of chicane	6 meters

Table 2. Main parameters of 4-magnet chicane

Parameter	Size
Bending angle	$16^\circ \times 4$
Dispersion	1.73 meters
Bending radius	11.1 meters
Number of magnets	4
Length of magnets	3.0 meters
Length of long straight section	3.0 meters
Length of short straight section	2.0 meters
Beam position monitor	
- resolution	10^{-4} meter
- number	4
Beam entrance angle resolution	10^{-5} rad
Total length of chicane	20 meters

Table 3. Systematic error for 3-magnet chicane

Source of error	size of error	contribution to energy error
Magnetic measurement	10^{-4}	$1. \times 10^{-4}$
Detector position	$2. \cdot 10^{-5}$	$2. \times 10^{-4}$
Kicker rotation	$4. \cdot 10^{-5}$	$4. \times 10^{-4}$
Survey error	10^{-5}	$1. \times 10^{-4}$

Total $\Delta E = 4.69 \times 10^{-4} E_0$

Table 4. Systematic error for 4-magnet chicane

Source of error	size of error	contribution to energy error
Magnetic measurement	$2. \times 10^{-4}$	$2. \times 10^{-4}$
BPM Measurement	1.73×10^{-4}	$1. \times 10^{-4}$
Beam entrance angle	1.6×10^{-4}	2.06×10^{-4}
Survey error	5.2×10^{-5}	0.3×10^{-4}

Total $\Delta E = 2.29.4 \times 10^{-4} E_0$

Table 5. Tolerances for absolute energy measurement at 4 GeV

The source of error	Symbol	Tolerance	Error $\Delta E/E_0$
angle between orbit plane and the slit system symmetry plane	$\Delta\psi$	$0.945 \cdot 10^{-5} rad$	10^{-5}
the number of photons in			
quantum fluctuations	ΔN_k	$2.140 \cdot 10^{5} ps^{-1}$	$0.5 \cdot 10^{-5}$
the arc in bending	$\Delta\theta -$	0.148 rad	10^{-5}
wavelength	$\Delta\lambda/\lambda$	$2.700 \cdot 10^{-3}$	10^{-5}
accuracy of measurement of field intensity	$\Delta B/B$	$0.600 \cdot 10^{-4}$	10^{-5}
accuracy of measurement of the monochromator angles	$\delta\theta$	$2.720 \cdot 10^{-5}$	10^{-5}
emittance parameters	$\delta\psi = y' + (y/L)$	$1.250 \cdot 10^{-5} rad$ at $L = 5 \cdot 10^{3}$ mm	10^{-5}

The total error $\Delta E = 2.5 \cdot 10^{-5} E$

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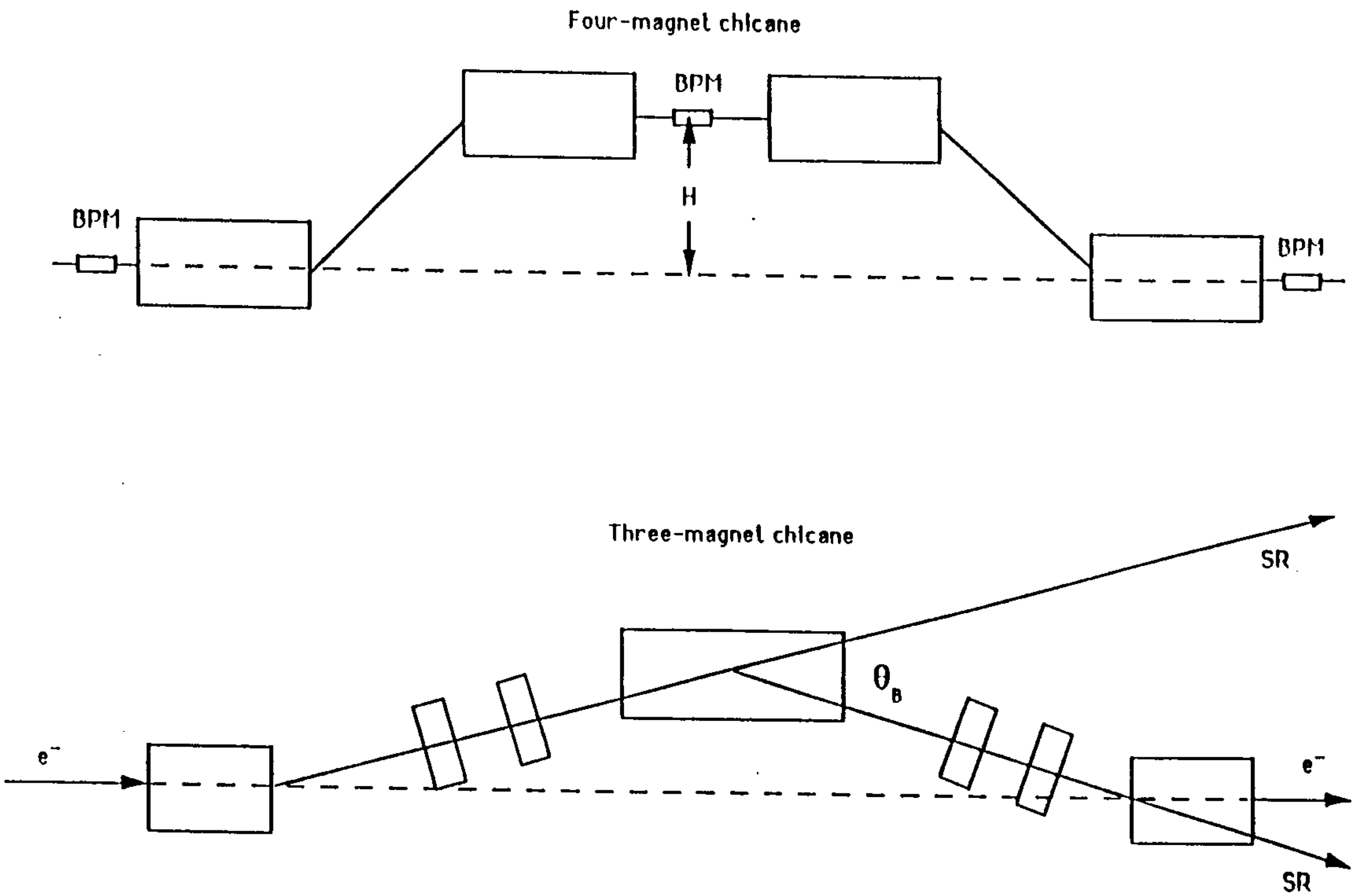

Figure 1. The Proposed Schemes of Spectrometrical Chicanes

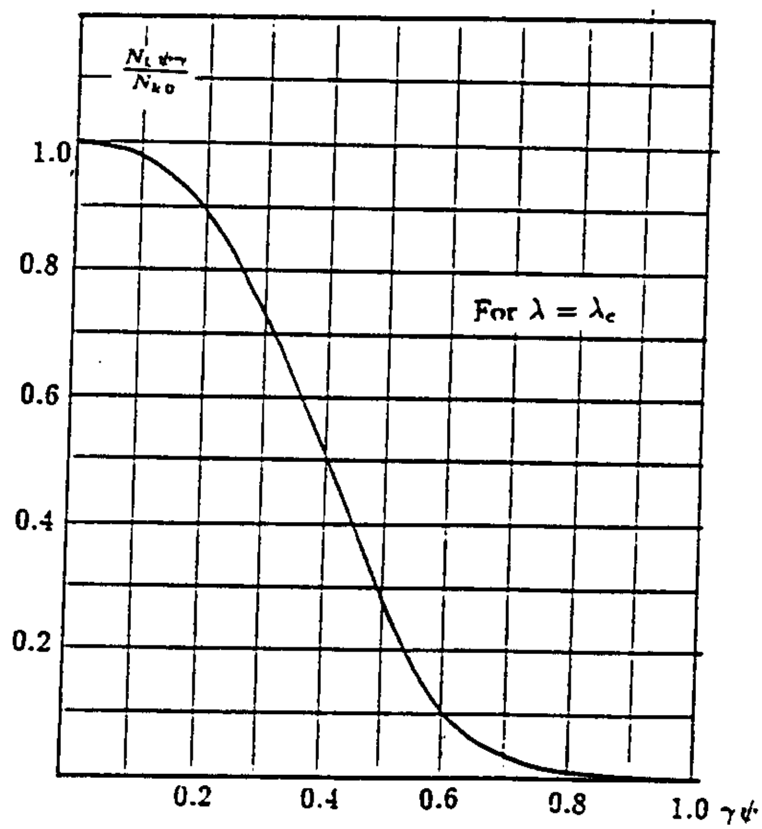

Figure 2. Vertical Distribution of Synchrotron Radiation

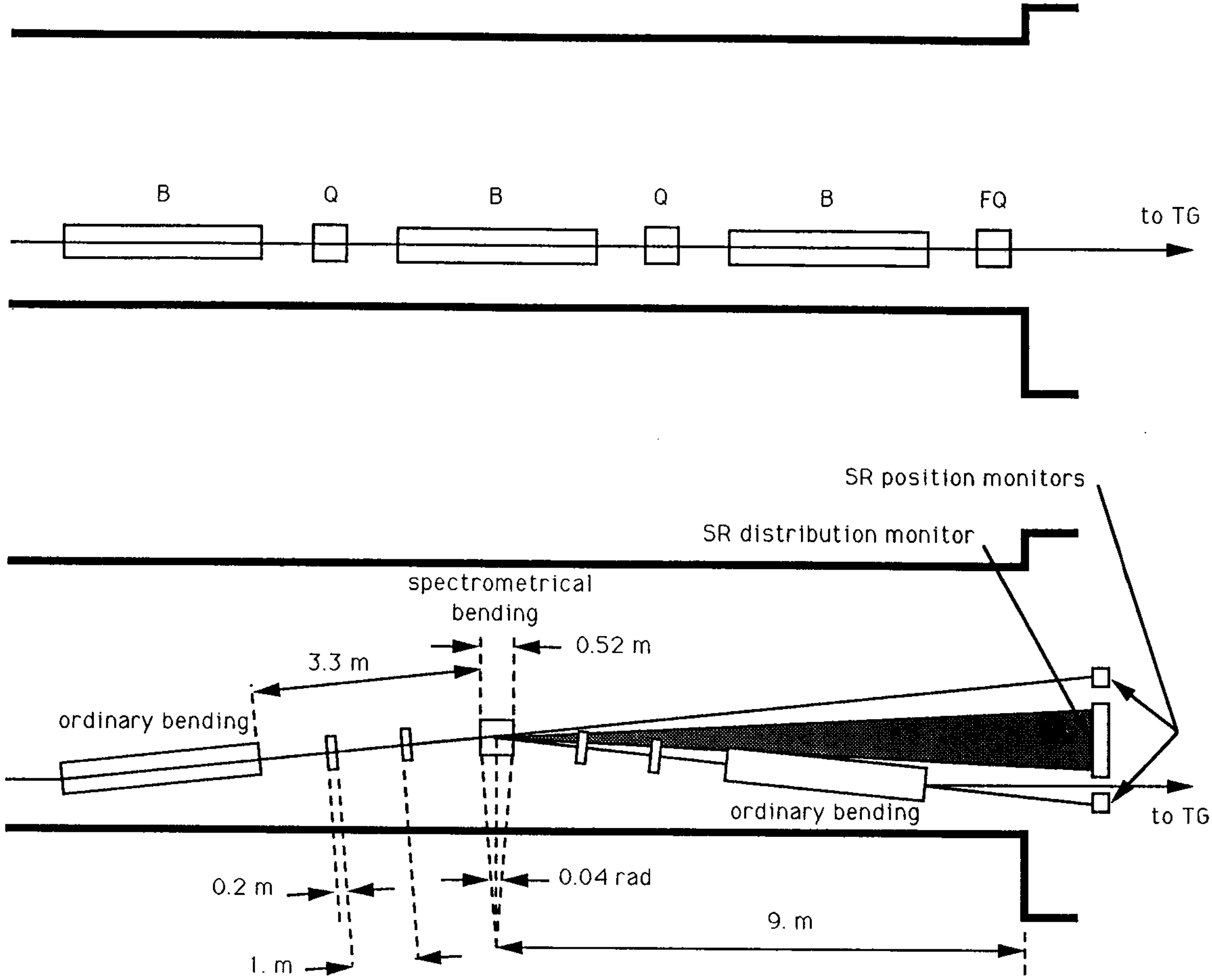

Figure 3. Energy Measurement Facility for CEBAF