An electron/positron energy monitor based on synchrotron radiation.

E. Syresin, Yu. Akimov, I.Meshkov, T. Mamedov,

Introduction

The magnetic spectrometer with an energy resolution of a few 10^{-4} is proposed for TESLA energy calibration experiment [1-2] (Fig.1). The energy spectrometer based on synchrotron radiation (SR) was used in SLAC for precision measurements of the SLC beam energy (Fig.2) [3-4]. The SLAC SR precision detectors (Fig.3-Fig.4) measured the synchrotron radiation beam positions of 30 µm at the electron beam energy of 50 GeV [3-4]. The phosphorescent screen monitors (Fig.3) detect the visible light produced at collision of 3 MeV SR photons with the monitor [4]. The second monitor (Fig. 4) is based on the Compton scattering [4].

The spectrometer set up for TESLA consists of two deflection magnets and one spectrometer magnet [1-2]. Below we consider the spectrometer parameters discussed in [5] (Table 1).

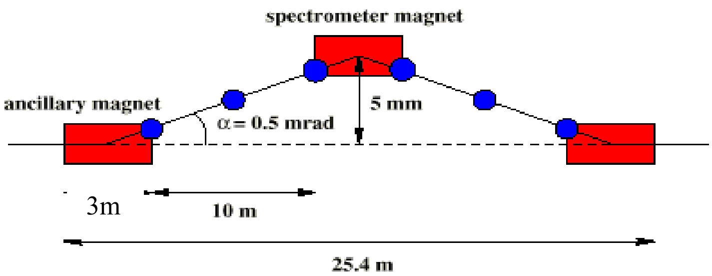

Fig.1. Scheme of magnetic spectrometer.

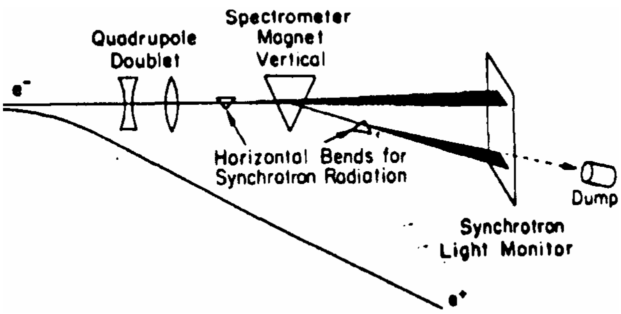

Fig. 2. Conceptual design of the extraction –line SLC spectrometers.

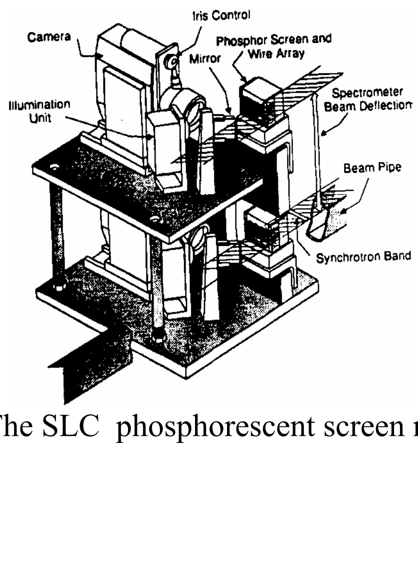

Fig. 3 The SLC phosphorescent screen monitor.

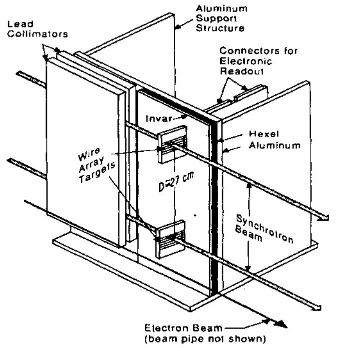

Fig. 4 SLC wire imaging synchrotron radiation detector

Table 1. Basic spectrometers magnet parameters

	SLC	LEP	CEBAF	TESLA (Proposal)
Energy ε (GeV)	42 – 50	40 – 100	0.5 – 7	45 – 400
Absolute accuracy of energy measurement Δε/ε	5×10^{-4}	1×10^{-4}	1×10^{-4}	1×10^{-4} – 1×10^{-5}
Bending angle (mrad)	18.286	3.75		1
Magnetic field range (T)	0.88 – 1.1	0.086 – 0.216	0.04 – 0.6	0.05 – 0.44
Magnetic field integral (T•m)	2.56 – 3.05	0.5 – 1.242	0.12 – 1.8	0.3 – 1.33
Magnetic measurement error of the field integral (relative)	7×10^{-5}	3×10^{-5}	1×10^{-5}	3×10^{-5}
Magnet iron length (m)	2.5	5.75	3	3

Energy resolution in magnetic spectrometer

When electrons pass through the ancillary and spectrometer magnets they produce the synchrotron radiation (SR). The electron displacement in the dipole magnet corresponds to

$$\Delta = \frac{R\alpha^2}{2}, \alpha = \frac{\ell}{R},$$

where α is the electron deflection angle, R is curvature radius of electron orbit, *l* is the magnet length. The curvature radius of the electron orbit corresponds to $R \cong 5\,\text{km}$ at the magnetic field of B = 0,2 7 T and ε=400 GeV, $\gamma = 8 \cdot 10^5$ [5]:

$$R_{[cm]} = \frac{1{,}7 \cdot 10^3 \gamma}{\mathrm{B}(G)}.$$

The deflection angle α is equal to

$$\alpha \approx 0{,}6\,\text{mrad}$$

at the bending magnet length of $\ell = 3m$. The displacement in the bending magnet for these parameters corresponds to

$$\Delta \cong 0.9 \text{ mm}.$$

The total beam displacement is equal to

$$\Delta_{tot} \cong R\alpha^2 + L\alpha \cong 8 \text{ mm},$$

where $L \cong 10\,\text{m}$ is the distance between ancillary and spectrometer magnets.

The critical synchrotron radiation wave length and energy from bending magnets are given by

$$\lambda_{cr} = \frac{2\pi R}{\gamma^3} \cong 4 \cdot 10^{-4}\,\text{Å}, \quad \varepsilon_{cr[keV]} = \frac{2.2E^3[GeV]}{R[m]} \approx 0.65\,E^2(GeV) \cdot B(T) \approx \text{ 28 MeV}.$$

The hard synchrotron radiation vertical divergence angle is equal to

$$\theta_{SR} \cong \frac{1}{\gamma} \cong 1\mu rad .$$

The soft synchrotron radiation vertical angle distribution corresponds to

$$\theta_{sr} \approx 0.5 \cdot \left(\frac{\lambda}{R}\right)^{1/3} \approx 15 \text{ µrad}$$

at λ≈1.2 A (E=10 keV) and R=5 km.

The length of an electron trajectory in the spectrometer magnet from that the SR came to a detector corresponds to

$$L_{SR} \approx R/\gamma \approx 5 \text{ mm.}$$

The synchrotron radiation from other parts of the spectrometer magnet is collimated. The transverse size of this "shining" electron trajectory is

$$\Delta R \cong \frac{L_{SR}}{\gamma} \approx \frac{R}{\gamma^2} .$$

The variation of the electron energy $\Delta\varepsilon$ produces a variation of electron orbit curvature radius

$$\frac{\Delta R}{R} = \frac{\Delta\varepsilon}{\varepsilon} .$$

The transverse size of the "shining " electron trajectory gives a restriction on the energy resolution

$$\frac{\Delta\varepsilon}{\varepsilon} \approx \frac{1}{\gamma^2} .$$

An electron energy loses is of

$$\Delta\varepsilon_{SR[MeV]} = 1{,}2610^{-3} l_{mag[m]} \cdot \mathrm{B}^2_{[T]} \cdot \varepsilon^2_{[GeV]} \approx 44MeV ,$$

when electron passes through a bending magnet with $\mathrm{B} = 0{,}2\,7$ T at $\gamma = 8 \cdot 10^5$. A relation estimates the number of photons radiated by one electron

$$n_\gamma \cong \frac{\Delta\varepsilon_{SR}}{\varepsilon_{cr}} \cong 1.5 .$$

The SR energy loss in the bending magnet produces a reduction of the curvature radius

$$\frac{\Delta R}{R} = \frac{\Delta\varepsilon_{SR}}{\varepsilon} .$$

However together with a reduction of the electron energy of $\Delta\varepsilon_{SR}$ an electron energy spread is produced by SR. The fluctuation of average electron energy (the energy spread or "straggling") at SR radiation is equal to

$$\frac{\Delta\varepsilon}{\varepsilon} \cong \frac{n_\gamma^{1/2}\varepsilon_{cr}}{\varepsilon} \cong \frac{\sqrt{\Delta\varepsilon_{SR}\varepsilon_{cr}}}{\varepsilon} \cong 10^{-4} .$$

The application of the magnetic spectrometer for the electron energy measurements produces an additional electron energy spread of $\Delta\varepsilon/\varepsilon \approx 10^{-4}$ caused by a fluctuation of SR photon energy. These fluctuations give a restriction on the energy resolution in an SR detector.

The SR detector is placed on a length of L_{S-d} from the magnetic spectrometer. The SR spot diameter in the detector is about

$$\delta \cong L_{S-d}\theta_{SR} \cong \frac{L_{S-d}}{\gamma} .$$

The spot size of 10 kev SR is equal to

$$d = L \cdot \theta_{sr} \approx 3 \text{ mm}$$

at L=200 m. The energy resolution is determined by the detector resolution. Two precision synchrotron radiation detectors were used in the Stanford linear collider (SLC) for electron/positron energy calibration experiments [3-4]. The space resolution in these detectors [3-4] is of $d \cong 30\mu m$.

The SR spectrum measurements

The information about SR spectrum from two different magnetic fields permits to calibrate the electron/positron energy when they pass through TESLA spectrometer. This method is used for electron energy calibration in the Novosibirsk BINP electron/positron storage rings [6]. The method is based on the SR spectrum measurements from two different magnetic fields of three-pole shifter with a large central pole field and a small edge pole field [7].

For TESLA spectrometer the SR detector (position 3, Fig. 5) measures the SR simultaneously from the ancillary magnet (position 1, Fig. 5) and spectrometer magnet (position 2, Fig. 5) which have different magnetic fields B_a and B_s

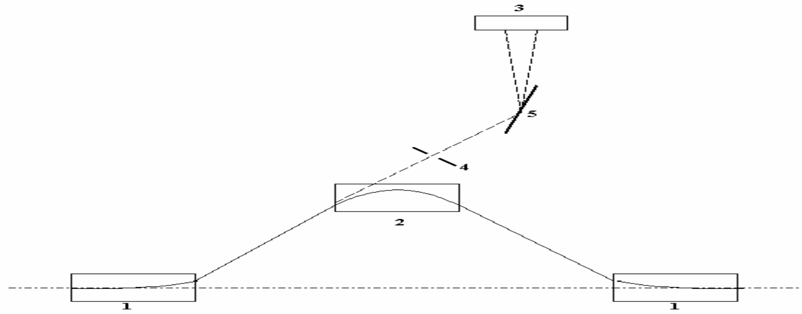

Fig.5 Scheme of SR spectrum measurements
1- ancillary magnet, 2- spectrometer magnet, 3- SR- detector, 4- vertical slit, 5- crystal monochromator.

The critical SR energies from ancillary and spectrometer magnet with different magnetic field B_a and B_s correspond to

$$\varepsilon_{cr_a}(keV) = 0{,}665 \cdot \mathrm{B}_a(T)\mathrm{E}^2\ (\mathrm{GeV}),$$

$$\varepsilon_{cr_s}(keV) = 0{,}665 \cdot \mathrm{B}_s(\mathrm{T})\mathrm{E}^2\ (\mathrm{GeV}).$$

where E is the electron energy. The ratio of SR fluxes from ancillary and spectrometer magnets is equal to

$$\frac{\mathrm{I}_s}{\mathrm{I}_a} = \frac{\mathrm{B}_s \cdot \psi_s \cdot S\left(\frac{\varepsilon}{\varepsilon_{cr_s}}\right)}{\mathrm{B}_a \cdot \psi_a \cdot S\left(\frac{\varepsilon}{\varepsilon_{cr_a}}\right)},$$

where ψ_a and ψ_s are horizontal angles at which is measured SR from ancillary and spectrometer magnets, S is normalized function for total SR power density

$$S = \begin{cases} \frac{27\sqrt{2}}{16\sqrt{3\pi}}\sqrt{\frac{\varepsilon}{\varepsilon_{cr}}} \cdot \exp\left(-\frac{\varepsilon}{\varepsilon_{cr}}\right) & \varepsilon >> \varepsilon_{cr} \\ \frac{4}{3}\left(\frac{\varepsilon}{\varepsilon_{cr}}\right)^{1/3} & \varepsilon << \varepsilon_{cr}. \end{cases}$$

At a small photon energy ($\varepsilon \approx$ 1-10 keV, $\varepsilon_{cr} \approx$ 30 MeV) of

$$\varepsilon/\varepsilon_{cr_s} << 1,\ \varepsilon/\varepsilon_{cr_s} << 1$$

the ratio of SR fluxes from ancillary and spectrometer magnets is equal to

$$\frac{I_s}{I_a} = \frac{B_s \cdot \psi_s \cdot \left(\frac{\varepsilon}{\varepsilon_{cr_s}}\right)^{1/3}}{B_a \cdot \psi_a \cdot \left(\frac{\varepsilon}{\varepsilon_{cr_a}}\right)^{1/3}} = \frac{\psi_s}{\psi_a} \cdot \left(\frac{B_s}{B_a}\right)^{2/3}.$$

The NMR magnetic field measurements with a relativistic accuracy of $\Delta B/B \approx 10^{-5}$ and SR flux measurements with accuracy of $\Delta I/I \approx 10^{-4}$ permits to get information about accuracy of horizontal angles

$$\frac{\Delta\psi_s}{\psi_s} \approx \frac{\Delta\psi_a}{\psi_a} \approx 10^{-4}.$$

The measurements of the ratio I_s/I_a at different magnetic fields $(B_s/B_a)^{2/3}$ bring information about ψ_s/ψ_a. One can reach conditions when $\psi_s/\psi_a=1$ at horizontal monitor scanning. The accurate measurements of horizontal angles let us to get information about deflection angle resolution

$$\frac{\Delta\alpha}{\alpha} \approx \frac{\Delta\psi}{\psi} \approx 10^{-4}.$$

SR detection on short distance from magnetic spectrometer

When SR spot diameter is comparable with SR detector channel size of $d \cong 30\mu m$ the SR signal is measured only by one detector channel. It corresponds to the distance between detector and spectrometer of

$$L_{S-d} = \gamma d \cong 25 \text{ m}.$$

The detector displacement from electron beam axis in an extraction line corresponds to

$$\Delta_{\det} \cong L_{s-d}\alpha \cong 10 \text{ mm}.$$

The SR spot size on the detector is about

$$\delta \cong L_{s-d}\theta_{SR} \approx 20\mu m,$$

$$\delta \approx d.$$

The detector energy resolution is determined by the width of the detector channel and the deflection angle in the magnetic spectrometer α

$$\frac{\Delta\varepsilon}{\varepsilon} \cong \frac{\Delta\alpha}{\alpha} \cong \frac{d}{L_{S-d}\alpha} \cong \frac{1}{\gamma\alpha} \cong 2\cdot 10^{-3}$$

at $\gamma \cong 8\cdot 10^5$ and $\alpha = 0{,}6 mrad$. The small deflection angle in the magnetic spectrometer gives a restriction on the energy resolution when the width of SR signal is comparable with a width of the detector channel.

The SR center gravity measurement

To increase the energy resolution by one order magnitude we increase the distance between detector and magnetic spectrometer up $L_{S-d} \cong 200$ m. The SR spot size is by one order magnitude larger than the size of the monitor channel

$$\delta \cong \frac{L_{S-d}}{\gamma} \cong 200\mu m,\quad d \cong 30\mu m.$$

The detector consists of 10 channels to measure the SR horizontal distribution. The number of photons counted by the SR detector is equal to

$$N_\gamma \cong \frac{\Delta\varepsilon_{SR}}{\varepsilon_{cr}} \frac{1}{\gamma\cdot\alpha} N_e \cong \frac{N_e}{\gamma\alpha} \cong 10^7 \text{ ph./bunch},$$

where $N_e = 10^{10}$ is the electron number per bunch and $\gamma \cong 10^6$. The hard synchrotron radiation at energy of $\varepsilon \approx \varepsilon_{cr} \approx 30$ MeV can not analyzed with high accuracy. The soft SR at energy of 1-10 keV is appreciable for electron energy calibration experiments. The number of photons at energy of $\varepsilon \approx 1$-10 keV corresponds to

$$N_\gamma \approx (N_e/\gamma\alpha)(\varepsilon/\varepsilon_{cr})^{1/3}(\Delta\varepsilon/\varepsilon) \approx 10^6.$$

The fluctuation of the SR intensity I_{SR} in each detector channel is equal to

$$\frac{\Delta I_{SR}}{I_{SR}} \approx \frac{1}{N_\gamma^{1/2}} \cong 10^{-3}.$$

An electron energy variation of $\Delta\varepsilon$ produces a center gravity displacement for SR horizontal coordinate distribution. The 30 channel SR detector can measure the SR center gravity signal with an accuracy of

$$\delta x \cong \frac{4\sigma}{N^{1/2}_\gamma} \approx 4\cdot\frac{L_{S-d}}{\gamma N_\gamma^{1/2}} \cong 3\mu m,$$

where $L_{S-d}/\gamma \approx 200\mu m$, $N_\gamma \approx 10^6$ ph/bunch at energy of 1-10 keV. A small variation of the electron energy (spectrometer magnetic field) produces a small variation of the deflection angle in the magnetic spectrometer and finally a displacement of the SR signal center gravity (Fig. 6). The SR center gravity measurement with an accuracy of 3 μm permits one to get an energy resolution of

$$\frac{\delta\varepsilon}{\varepsilon} \approx \frac{\Delta\alpha}{\alpha} \approx \frac{\delta x}{L_{S-d}\cdot\alpha} \cong 3\cdot 10^{-5}.$$

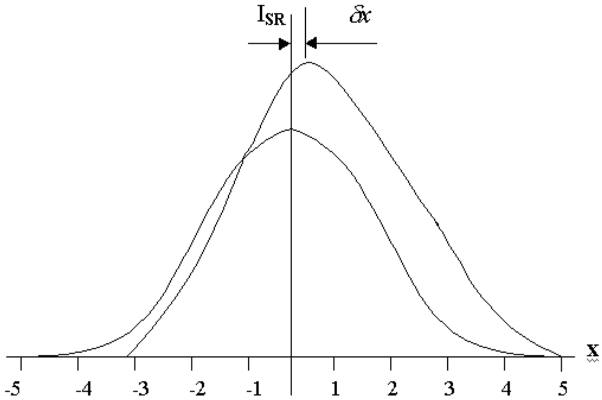

Fig. 6 SR horizontal distribution in 10 channel detector

So high-energy resolution in the SR detector is restricted by a stability of the spectrometer magnetic field and an electron energy fluctuation in the magnetic spectrometer. There is an opportunity to obtain an electron energy resolution of

$$\frac{\delta\varepsilon}{\varepsilon} \approx 3\cdot 10^{-5}$$

for a spectrometer magnetic field stability of

$$\frac{\Delta B}{B} \approx 3\cdot 10^{-5}.$$

The fluctuations of the average electron energy caused by the SR radiation in the magnetic spectrometer restrict the energy resolution of

$$\frac{\Delta\varepsilon}{\varepsilon} \cong \frac{n_\gamma^{1/2}\varepsilon_{cr}}{\varepsilon} \cong \frac{\sqrt{\Delta\varepsilon_{SR}\varepsilon_{cr}}}{\varepsilon} \cong 10^{-4}.$$

Detector

A semiconductor strip detector with a strip width of 10 μm and distance between strips of 10 μm can be used for detection of 10 keV synchrotron radiation produced in the spectrometer magnets. The number of strip channels corresponds to 30. The strip thickness is of 10 mm. The detector square root space resolution is about 3 μm. The total number of 10 keV detected photons is of 10^6. The normal SR flux distribution is registered by 20 strips with a maximum photon intensity per strip of 10^5. The absorption photon energy is measured for each strip and it is written in a dynamic memory FIFO type. Finally the three dimensions spectrum is measured as a function of the number of strips, the photon absorption energy in the strip and the time interval between bunches.

The center gravity of absorption energy distribution for all strips is fined for each electron bunch (for each time interval of 300 ns). The absorption photon energy for each strip corresponds to $\mathrm{E}_{str} = \mathrm{N}_\gamma \mathrm{E}_\gamma \cong 10^9 eV$. The energy required for production of one electron – hall pair in detector semiconductor is $\mathrm{E}_e \cong 3{,}6\ eV$. The number of electrons produced in the central strips is estimated as $\mathrm{N}_e \cong \mathrm{N}_\gamma \mathrm{E}_\gamma / \mathrm{E}_e \cong 3 \cdot 10^8$. This number of electrons produces a 1 V signal on photomultiplier output for 50 Ohm cable. The noise input for this signal is small. It means the semiconductor strip detector does not restrict the center gravity resolution. The resolution is determinate only by the photon statistic and detector electronics. The amplitude analysis of the events for each bunch is realized, as example, in the CERN CMS project at a time interval of 125 ns [8].

Conclusion

The application of SR detector permits one to reach energy resolution of $\Delta\varepsilon/\varepsilon \approx 10^{-4}$ for an 30 channels detector with 10 μm space resolution per channel.

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