An electron/positron energy monitor based on synchrotron radiation.

I.Meshkov, T. Mamedov, E. Syresin

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).

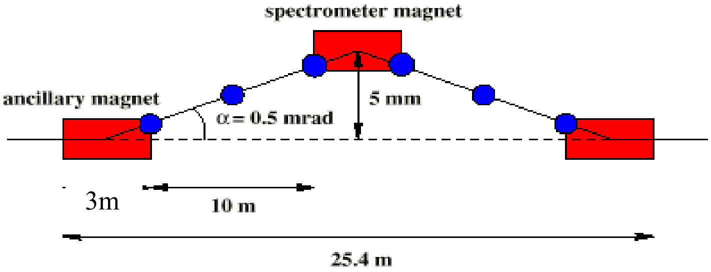

Fig.1. Scheme of magnetic spectrometer.

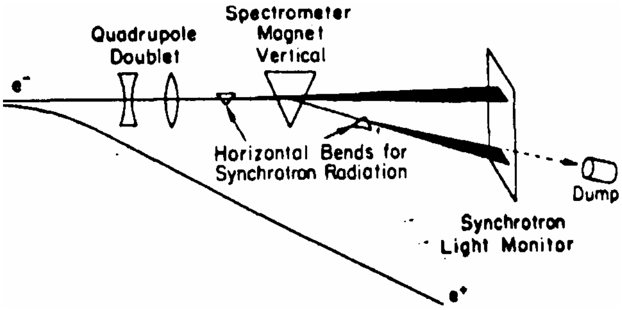

Fig. 2. Conceptual design of the extraction –line SLC spectrometers.

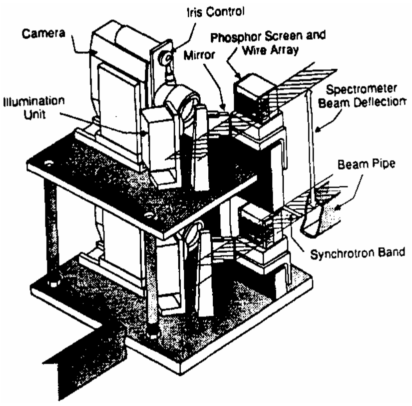

Fig. 3 The SLC phosphorescent screen monitor.

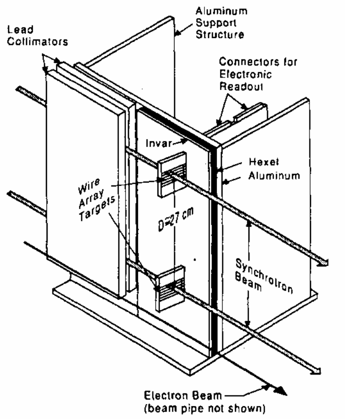

Fig. 4 SLC wire imaging synchrotron radiation detector

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 $L \cong 10$ m is the distance between ancillary and spectrometer magnets.

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

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

The synchrotron radiation divergence angle is equal to

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

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

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

when electron passes through a bending magnet with $\mathrm{B} = 0{,}27$ 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 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 $d \cong 30\mu m$.

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

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

$$\delta \approx \text{d}.$$

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 $\alpha = 0{,}6mrad$. 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 center gravity measurement of SR signal.

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

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

where $\text{N}_e = 10^{10}$ is the electron number per bunch and $\gamma \cong 10^6$. The fluctuation of the SR intensity I_{SR} in each detector channel is equal to

$$\frac{\Delta\text{I}_{SR}}{\text{I}_{SR}} \approx \frac{1}{\text{N}_\gamma^{1/2}} \cong 10^{-3}.$$

An electron energy variation of $\Delta\varepsilon$ produces a center gravity displacement for SR horizontal coordinate distribution. The 10 channel SR detector can measure the SR center gravity signal with an accuracy of

$$\delta x \cong \frac{4\sigma}{N^{1/2}{}_\gamma} \approx 4\cdot\frac{L_{S-d}}{\gamma\text{N}_\gamma^{1/2}} \cong 0.5\mu m,$$

where $L_{S-d}/\gamma \approx 200\mu m$, $\text{N}_\gamma \approx 10^7$. 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. 5). The SR center gravity measurement with an accuracy of 0.5 μm permits one to get an energy resolution of

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

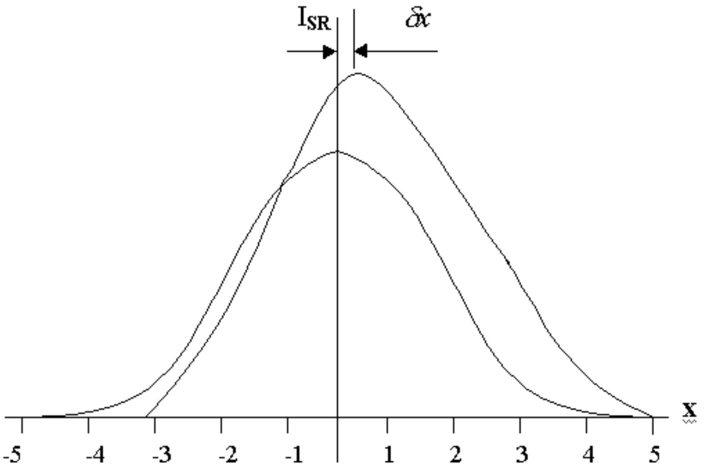

Fig. 5 SR horizontal distribution in 10 channel detector

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

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

Conclusion

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

References:

1. TESLA Technical Design Report, DESY TESLA-01-23, 2001.
2. Dehning B. - Status of the LEP2 Spectrometer Project. In Proceedings of EPAC 2000, Vienna, Austria, 2000.
3. J. Kent, M. King, C. Von Zanthier et al Precision measurements of the SLC beam energy, PAC, Chicago, 1989.
4. M. Levi, F. Rouse, Precision Synchrotron radiation detectors, PAC, Chicago, 1989.
5. N.A.Morozov, H.J.Schreiber Magnetic field calculations for the technical proposal of the TESLA spectrometer magnet, Preprint JINR, 2003.