ILC BEAM ENERGY MEASUREMENT BASED ON SYNCHROTRON RADIATION FROM A MAGNETIC SPECTROMETER

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Abstract

A magnetic spectrometer with a relative energy resolution of $5 \cdot 10^{-5}$ was proposed for ILC beam energy calibration. A complementary method of beam energy measurement based on registration of synchrotron radiation (SR) from the dipole magnets of the energy spectrometer is proposed. Measuring both horizontal edge positions of the SR fan at a distance of 50-70 m downstream of spectrometer allows to determine the beam energy with high accuracy. The main principals of the SR beam energy measurement, first numerical simulations by means of GEANT and physical limitations of the detector coordinate determination are described. Two versions of novel detectors for low-energy (<20keV) photon registration are proposed. They are characterized by a high counting rate and a linear resolution of 2-3 μm.

INTRODUCTION

A magnetic spectrometer with an energy resolution of $\Delta E/E = 5 \cdot 10^{-5}$ was proposed for ILC beam energy calibration [1]. The measurement is based on precise determination of beam positions with a resolution of 100 nm and the spectrometer B-field integral with a relative accuracy of $2 \cdot 10^{-5}$. The electrons/positrons which pass through the spectrometer magnets produce synchrotron radiation. Complementary, the beam energy is proposed to be measurable with an uncertainty of $\Delta E/E \cong 5 \cdot 10^{-5}$ by monitoring synchrotron radiation photons within the energy range of 1–20 keV and a high-spatial resolution detector allowing coordinate measurements with 2-3 μm precision.

An energy spectrometers based on SR was used at SLAC for precision measurements of the SLC beam energy [2-3]. The SLAC SR spatial detectors measured the beam position with an accuracy of 30 μm and the 45 GeV beam energy was determined with a resolution better than 250 ppm [2-3].

SYNCHROTRON RADIATION FROM THE ENERGY SPECTROMETER

The ILC spectrometer proposed in [1] consists of two ancillary magnets and one spectrometer magnet (see Fig.

1). The spectrometer magnetic rigidity corresponds to 0.84 T·m and the nominal beam energy is 250 GeV. The length of spectrometer magnet is 3 m, the distance between the ancillary and spectrometer magnets is 10 m and the length of the ancillary magnet 1.5 m.

We assume that the SR detector is placed 50 m downstream of the spectrometer magnet. The horizontal spot size and the positions of both edges of the SR fan are defined by the deflection angles in the magnets, the beam energy and the geometry of the set-up. The deflection angle in the bending plane $\theta/2 = eBl/2\gamma mc$ depends on the magnetic rigidity Bl and the beam energy. It results to $\theta \approx 1$ mrad for a beam energy of 250 GeV and a magnetic rigidity of 0.84 T·m respectively a magnetic field strength of 0.28 T.
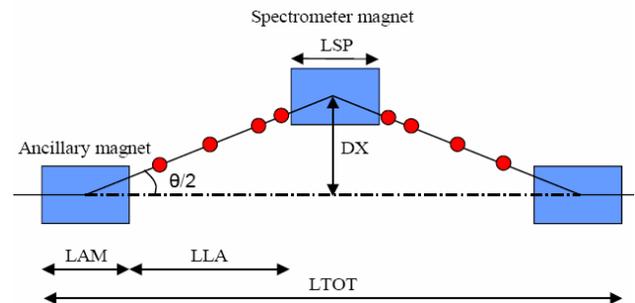

Figure 1: Scheme of magnetic spectrometer proposed for ILC beam energy measurements [1].

The position of the left horizontal SR spot edge $x_R = L_1\theta/2 \approx 3.1$ cm is defined by the distance between the first ancillary magnet and the detector, $L_1 = 61.5$ m, and the deflection angle. The position of the right horizontal edge $x_L = L_2\theta/2 \approx 2.4$ cm is proportional to the distance between the center of the spectrometer magnet and the detector, $L_2 = 48.5$ m. Hence, the horizontal spot size corresponds to $x = x_L + x_R \approx 5.5$ cm. The SR fan horizontal size is inversely proportional to the electron energy $x \propto \gamma^{-1}$. This variation constitutes the basic concept of monitoring the beam energy.

The vertical SR spot size depends on the photon energy. For photons with an energy close to the critical energy of $\varepsilon_{cr} \approx 11.4$ MeV, E=250 GeV and B=0.28 T the divergence angle is equal to $\theta_{SR} \approx \gamma^{-1} \approx 2$ μrad, while the divergence angle for soft 20 keV photons equals to $\theta_{sr} \approx 12$ μrad . The

vertical spot size for such γ-quanta corresponds to y≈$L_1\theta_{sr}$ ≈0.6 mm.

The 1/γ-variation of the horizontal SR fan edge position permits to measure the beam energy with a resolution of $\Delta E/E \approx [(\Delta x/x)^2+(\Delta Bl/Bl)^2+(\Delta L/L)^2]^{1/2} \approx 5\cdot10^{-5}$ for a detector resolution of $\Delta x \approx 2$ μm (or a relative detector uncertainty of $\Delta x/x \approx 5\cdot10^{-5}$), a relative accuracy of the magnetic rigidity of $\Delta Bl/Bl \approx 2\cdot10^{-5}$ and an error for the distance to the detector of $\Delta L/L \approx 5\cdot10^{-6}$. The last two requirements seem to be feasible, while the most critical quantity is $\Delta x/x$.

One of the sources for SR spot size spreading is related to the electron energy spread within a bunch. The electron energy spread, expected to be of $\Delta E/E \approx 10^{-3}$, leads to a spreading of the SR horizontal spot size of $x^E_{edge}=L_1\theta/2\cdot\Delta E/E \approx 25$ μm in the detector.

The fringe fields of the magnets produce additional SR and increase the horizontal fan size. Although the integrated fringe field for each magnet only constitutes a very small fraction of the total B-field integral, its impact on the SR yield close to the edges is non-negligible and has to be accounted for in detailed studies.

Another source of edge position dilution is related to the photon angular spread. It is expected to be of the order of $\Delta x^{SR} \approx L_1\theta_{sr} \approx 600$ μm.

Interactions of hard SR photons with the vacuum pipe material are an important source for additional γ-quanta with low energy and increase the SR fan horizontal size. Avoiding such interactions is an essential constraint for the design of the set-up.

As a result, the sensitive horizontal width of the detector area has to be in the range of 3 mm for registration of soft SR quanta. This area has furthermore to accommodate possible jitters of the beam position, angle and charge as well as to provide a sufficient large x-range for SR endpoint fitting procedures.

In summary, two SR detectors with a sensitive region of about $x_{det} \approx 3$ mm and high-spatial resolution are required to measure the horizontal edge positions of the fan which covers a range of some 5 cm.

EXPERIMENTAL CONDITIONS

The approximate number of γ-quanta produced in the SR fan will be $N_0 \approx 2\cdot10^{11}$ for a bunch intensity of the $2\cdot10^{10}$, an electron energy of 250 GeV and the dipole fields as specified in [1]. The number of photons with energies of $\Delta\epsilon \approx 1$–20 keV entering an active detector area of $x_{det} = 1$ mm is estimated as $N_\gamma \approx N_0(\Delta\epsilon/\epsilon_{cr})^{1/3}\cdot x_{det}/x \approx 5\cdot10^8$, where ϵ_{cr} is the critical photon energy and x is the horizontal SR spot size. From the comparison of N_γ with N_0 it follows that the background SR component is much greater than the number of useful soft γ-quanta. Therefore, a highly selective reflecting mirror should be used to separate the interesting γ-quanta with energies below 20 keV

For mirrors with a large atomic number Z the critical angle below which total external reflection occurs is φ_{max}

$(rad) \approx 0.08/E_\gamma (keV)$. For angles below the critical one reflectivity is close to unity. For our case, rhodium (Rh) is an ideal reflecting material. The reflecting mirrors may be placed downstream of the spectrometer at a distance of e.g. 10 m from the detector. Hard γ-quanta will pass through the reflector and only quanta with energies less than 20 keV will be deflected from the main SR stream toward x-values larger than ±3 cm. Application of such mirrors permits to solve several problems: selection of soft radiation photons with energies between 1–20 keV from hard γ-quanta, strong suppression of radiation doses within the detectors, and provision of high conversion efficiency of the photons to photoelectrons in the detector material.

GEANT SIMULATION OF SYNCHRO-TRON RADIATION

Synchrotron radiation light produced in the energy spectrometer magnets is simulated by means of GEANT [4]. GEANT simulation includes effects related to the energy spread of the electrons within a bunch, the bunch size, the magnetic fringe fields, and possible SR interactions within the thin steel vacuum chamber wall.
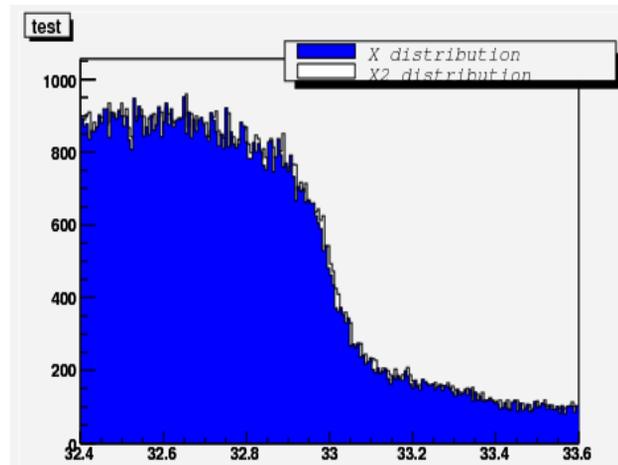

Figure 2: SR counting rate versus horizontal coordinate at electron energies of 250 GeV and 250.05 GeV (blue histogram) close to left SR fan horizontal edge.

A beam energy variation of 50 MeV from the nominal energy of 250 GeV (corresponding to a relative energy uncertainty of $\Delta E/E \approx 2\cdot10^{-4}$) produces the displacement of the right edge position of 5 μm, while the shift of the left edge position is 7-8 μm (Fig.2), so the total width shrinks by 12μm. If we assume that the simulated resolution will be conserved for a beam energy variation of 10 MeV, the sensitivity of the method will be 2.5μm/10MeV. Such sensitivity permits to reach a beam energy resolution of $\Delta E/E \approx 5\cdot10^{-5}$ provided the endpoints of the SR fan can be determined with 2 μm precision.

If the detectors are positioned within Roman Pots separated by a thin foil from the beam vacuum, photon interactions do not alter the sharpness of the SR fan edges

strongly. The edges become somewhat less sharp, but they are still good recognizable and shifts of edge positions were not observed.

NOVAL DETECTORS WITH SUB-MICRON SPATIAL RESOLUTION

Properties of the SR light arising from the passage of electrons through the ILC magnetic spectrometer demand that possible detectors should have a position resolution of 2-3 μm for two detectors with a sensitive area of some 3mm in horizontal direction. The detectors can be an assembly of many individual channels or layers 2 μm thick interleaved with dielectric of 0.03 μm.

Technology for production of such multilayer coatings is well developed and the structure needed is perfect from the point of view of crystallography. Methods of electron-beam sputtering and laser-induced evaporation were widely used with layer thickness precisely checked by a reflectometer. The active material of the detector should be a semiconducting medium. The choice of the material with the required conductivity should be subject to the following condition: the relaxation time of the volume charge in the material should not be smaller than 30% of the peaking time of the charge-sensitive amplifier, which in turn should not be smaller than about 10 ns and larger than the ILC bunch-to-bunch spacing time of about 300 ns. Out of all abundant materials, *Si* is the best choice meeting the above condition [5].

The number of γ-quanta with energies below 20 keV entering 1mm active detector area was estimated as $N_\gamma \approx 5 \cdot 10^8$, see above. If we assume that a photoelectron spends about 10 eV for an ionization event in Si, and 30% of the total photon energy is transformed to photoelectrons, we expect on average 150 electrons. Eventually, about $7 \cdot 10^{10}$ photoelectrons are produced within 1 mm active detector area, so that each 2 μm detector layer contains about $1.5 \cdot 10^8$ secondary electrons. With an amplifier conversion factor of 50 mV/pC these electrons produce output signal amplitude of 1.4 V. With the (realistic) assumption that the photon energy distribution in each layer is close to a constant, any charge measurement of the photoelectrons in each layer provides correctly the position distribution of the soft photons registered.

The structure of the proposed detector is schematically shown in Fig.3. Its sensitive region of 2 mm contains about 1000 Si layers, each 2μm thick. The layers are separated by dielectric SiO with a 0.03 μm thickness.

To read out the information, each layer of the assembly is surrounded with a gold contact 5 μm wide and 0.9 μm thick connected to the charge-sensitive amplifier. For charge collection, each layer is connected to the plus terminal of the external power supply. The detecting and read-out electronics may be arranged in a simple and compact scheme as used e.g. for the readout of he cathode strips of the muon-chambers at the ATLAS facility [6].

Together with Si detector a plane-parallel avalanche detector with gas amplification of 10–50 and a linear

resolution of 2-3 μm is discussed also. Schematically, the avalanche detector is a flat capacitor filled with xenon at a pressure of 100 atm. The anode plane of the detector comprises Ni layers of 1μm separated from each other by 2 μm SiO dielectric. To eliminate edge effects, the sensitive elements are placed inside a plastic frame of 10×10 mm² covered by Al. The 10 mm by 10 mm entrance window of the detector is made of 1mm beryllium foil. High voltage is applied to the beryllium cathode foil.

The distance between the anode and the cathode of the detector may less than 1mm at a pressure of 100 atm. For gas amplification of about 10 the transverse dimension of the avalanche will be within the 1 μm mean free path of the photoelectrons.

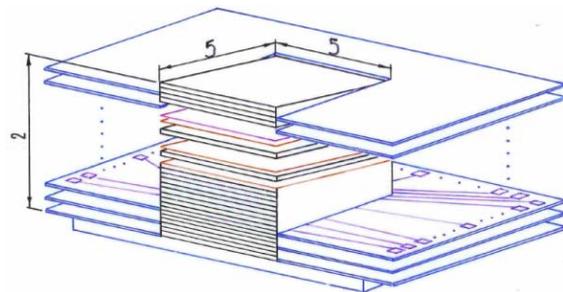Figure 3: Semiconductor SR detector scheme with sub-μm spatial resolution.

CONCLUSION

Precise position measurements of both horizontal edges of the SR fan permits to monitor the ILC beam energy with a precision of better than $\Delta E/E \cong 10^{-4}$.

Sensitivity estimates of the method from GEANT simulations result to 12μm/50MeV for beam energies of 250 GeV. If this sensitivity is scaled to SR fan endpoint measurements with 2 μm accuracy, beam energy measurements with a resolutions of $\Delta E/E \approx 5 \cdot 10^{-5}$ seem to be achievable.

Novel high-position resolution detectors for low energy gamma registration within large radiation background are proposed. Detector production however seems rather challenging and may be carried out by methods developed in microelectronic industry.

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