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DESIGN OF A WIRE IMAGING SYNCHROTRON RADIATION DETECTOR*

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Abstract

This paper documents the design of a detector invented to measure the positions of synchrotron radiation beams for the precision energy spectrometers of the Stanford Linear Collider (SLC).

The energy measurements involve the determination, on a pulse-by-pulse basis, of the separation of pairs of intense beams of synchrotron photons in the MeV energy range. The detector intercepts the beams with arrays of fine wires. The ejection of Compton recoil electrons results in charges being developed in the wires, thus enabling a determination of beam positions.

INTRODUCTION

The synchrotron radiation detectors documented here are part of the SLAC Linear Collider's precision energy spectrometers.[1,2] Precise energy determinations are essential to the SLC physics program; *e.g.*, for measurements of the mass of the Z^0. This introduction considers aspects of the energy spectrometers relevant to the design of our detectors.

Figure 1 is a schematic diagram of an SLC extraction-line spectrometer. Two dipole magnets, one upstream and one downstream of the spectrometer magnet, generate swathes of synchrotron radiation. The angle between these two synchrotron beams is inversely proportional to the SLC beam energy and proportional to the field strength of the spectrometer magnet. The angle is determined by measuring the separation between the pair of synchrotron beams at a known distance downstream from the magnetic center of the spectrometer magnet. The purpose of the Wire Imaging Synchrotron Radiation Detectors (WISRDs) is to monitor this separation—and hence the beam energy—on a pulse-to-pulse basis.

A WISRD is installed in both the electron and the positron energy spectrometers. Aside from mechanical details resulting from a 90° rotation about the beam direction, the positron spectrometer's WISRD is identical to the electron spectrometer's WISRD. For clarity of presentation, only the electron spectrometer is explicitly considered here. Basically, the WISRD functions as follows. The spectrum of the two intense beams of synchrotron radiation are characterized by a critical energy of approximately 3 MeV. A fine wire intercepting one of these beams will develop a positive charge due to the ejection of Compton recoil electrons. The intensity of synchrotron photons is sufficient to directly induce a charge that can be measured electronically. The WISRD provides a determination of the separation between the two synchrotron beams by intercepting both beams with arrays of fine wires and measuring the charge induced on each wire; see Fig. 2.

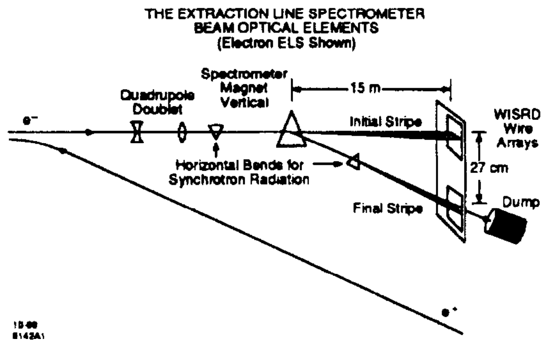

Fig. 1. Schematic diagram of the (electron) extraction-line spectrometer beam optics and synchrotron beams.

Photons in the MeV range are very penetrating. The spectrometer design provides two measures of the separation between the synchrotron beams. Just upstream of the WISRD is a phosphorescent screen monitor (PSM) that also provides a high-precision measurement of the stripe separation.[3] The slight loss in synchrotron beam intensity due to the presence of an upstream detector has practically no influence on the quality of data collected by the WISRD. This redundancy, provided by monitoring the synchrotron beams with two independent detector systems, is a key feature of the design of the SLC spectrometers.

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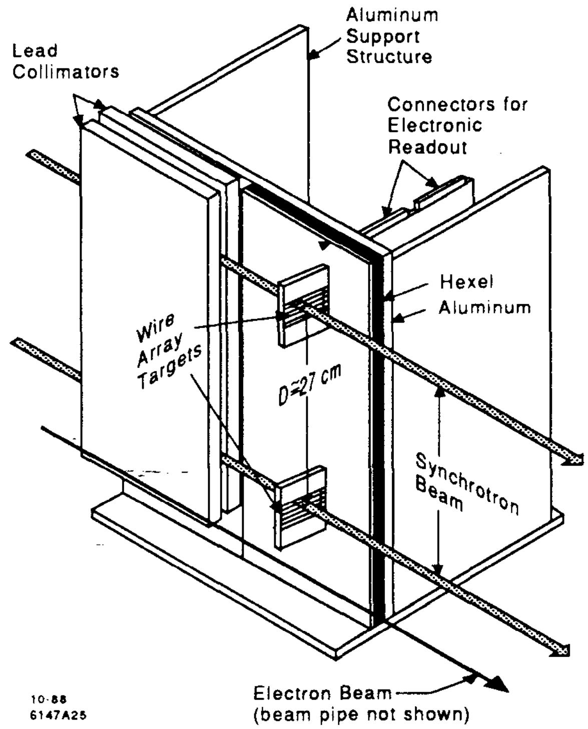

Fig. 2. A schematic view of a Wire Imaging Synchrotron Radiation Detector (WISRD), together with the SLC electron beam and the two beams of synchrotron radiation.

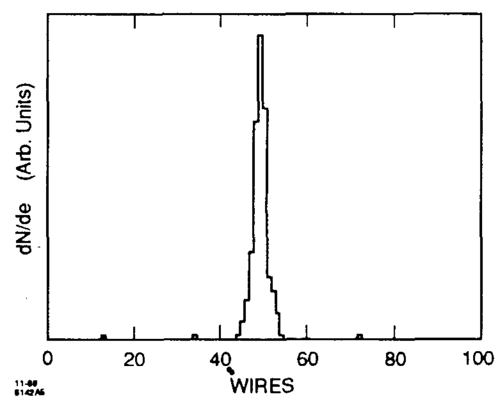

Fig. 3. Monte Carlo calculation of induced charge versus wire number. The above distribution corresponds to an ideal primary beam of zero emittance, width, and dispersion. The total charge for a primary beam of 10^{10} electrons or positrons is calculated to be 180 fC.

The Physical Basis of the Detector

The wire array targets are the heart of the detector shown in Fig. 2. The target arrays are composed of 75 μm-diam copper (5% beryllium) wires with center-to-center spacing of 100 μm. There are 96 wires per array. A separate channel of electronics is provided for each wire.[4] This section considers the physical mechanisms leading to signal generation on the wires and their implications for the design of the wire array targets as devices for providing precision measurements of synchrotron beam positions.

Figure 3 presents Monte Carlo predictions for the generated charge as a function of wire number for a wire array target exposed to a synchrotron beam. Such a calculation involves three major physical considerations which are sufficiently well known to allow quantitative predictions: properties of the beam of synchrotron photons, cross sections for the production of recoil electrons, and electron ranges in the wire material. The characteristic energy and intensity of the extraction-line spectrometers' synchrotron beams were unavailable in test beams.

The properties of the incident synchrotron photon beams have a decisive influence on the design of the wire array targets. Many of the beam properties follow directly from principles of electrodynamics.[5] Monte Carlo simulation of the synchrotron beams is straightforward for given assumptions regarding the intensity and beam optic properties of the primary $e^{\pm}$ beam.

The critical energy of the photon spectrum is approximately 3 MeV, which follows from a primary beam energy of about 45 GeV and a magnetic field strength of about 1.1 T. Synchrotron beams with such a high critical energy did not exist before the SLC. Because of this relatively high critical energy, Compton scattering dominates the generation of charges on the target wires.

Absorption of synchrotron photons due to the photoelectric effect is calculated to account for 20% of our signal. The photoelectric effect and Compton scattering contribute equally to the ejection of electrons from target wires by 250 keV synchrotron photons. However, due to its steep energy dependence, the importance of the photoelectric effect decreases rapidly with incident photon energy. The importance of the photoelectric effect for the detector is further reduced by electron range effects.

The diameter of the target wires corresponds approximately to the range of a 300 keV electron. Electron range is a rapidly increasing function of kinetic energy. The probability that a recoil electron stops before exiting a wire is essentially unity for 100 keV incident photons. Thus the physical mechanism of signal generation contains a "filter" that rejects photons with energies less than $\approx$ 200 keV. This is desirable because photons at the low end of the synchrotron spectrum are produced at greater emission angles with respect to the primary beam.

The recoil electrons produce δ-rays within the target wires. Some of these δ-rays will escape the wires. This effect is calculated to enhance the signal by 5%.

The wire spacing of 100 μm was chosen to permit the determination of a stripe centroid even in the presence of occasional dead channels. The synchrotron stripe profile shown in Fig. 3 is calculated for the case that the finite stripe width arises entirely from the finite production angles ($\approx 1/\gamma$) of synchrotron photons with respect to the momentum of the primary beam particles. For design tuning of the beam optics, one of the two synchrotron beams is close to this limiting case.

In general the stripe profile is a convolution of the profile in Fig. 3, with the spreads due to dispersion and spot size of the primary beam. The 100 μm-target wire spacing is optimal for our application; little would be gained from a closer spacing.

The vertical geometrical acceptance—and hence the number of wires—was chosen to be close to 1 cm. This acceptance accommodates reasonable variations in the steering of the primary beam. The synchrotron swath profiles are always considerably narrower than this.

The high intensity of the synchrotron beams makes it unnecessary to have any gain mechanism within the detector. This leads to a robust detector with a linear signal response. Primary beam intensities are typically 10^{10} particles per pulse, which is calculated to induce a total charge of 180 fC on a wire array target. With input capacitance from several meters of cable between the detector and the electronics, the ratio of signal-to-noise is of order 10^2 with appropriate electronics.

Given the center-to-center wire spacing of 100 μm, the 75 μm wire diameter maximizes the volume of target material without rendering the technical problem of maintaining electrical isolation between individual wires unmanageable. (A tilted wire-array-target geometry with a 100 μm spacing, as seen by the beam, but a larger physical wire spacing—would have permitted larger target wire diameters. For our application, this alternative was judged to be an undesirable complication.) The choice of target wire material also affects the signal amplitude. The number of Compton recoil electrons produced in a wire is proportional to the density of electrons within the wire material, *i.e.*, $\rho \cdot Z/A$. Copper was chosen as the target material because of its high density of electrons. The choice of copper over tungsten was based in large part on the solderability and more ductile nature of copper wire.

The specifications for the wire array targets followed quickly from a quantitative understanding of the mechanism of signal production. The remainder of the WISRD design is mainly a matter of providing the wire array targets with the necessary mechanical support and alignment, electrical connections, and electromagnetic shielding.

The Wire Array Target Assembly

The greatest technical challenge in the construction of the detectors was the mechanical design and fabrication of the wire array targets. The gaps between neighboring wires are only 25 μm. A great deal of care was directed to the problem of avoiding accidental electrical contacts between the wires both in the target region and in the fan-out for the electrical connections.

Figure 4 shows the wire target assembly built on a slab of machinable ceramic.[6] This material was chosen because it is a radiation-hard rigid machinable insulator of moderate cost. The synchrotron beam passes through the milled-out slot in the ceramic card before being intercepted by the wire array. Wires are glued in place at both ends of the target region by ceramic adhesive.[7] After the glue set, the target wires became mechanically part of the ceramic card.

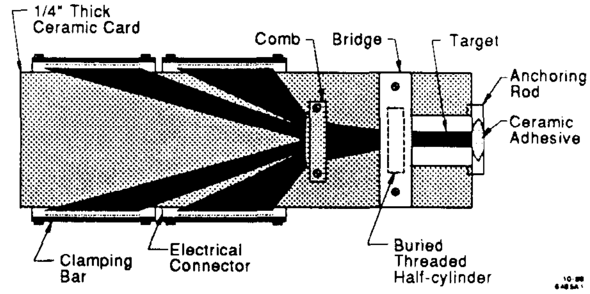

Fig. 4. Wire target array on its certamic card.

The proximity of the primary electron beam and the lower synchrotron beam (see Fig. 2) restricts the space available to the anchor outer end of the wire array target. This motivated gluing the target wires to a half-inch diameter MACOR[8] rod mounted at the end of the slot milled in the ceramic card. The silhouette of the rod was reduced by 25% by milling away its inside edge. This design satisfied the space constraints while providing enough mechanical strength to support the tension of the wires.

Essential to the success of the project was the successful threading at a pitch of 100 μm of half-inch MACOR rod. In addition to the anchoring rod previously discussed, the threaded MACOR rod was used to make a threaded half-cylinder that is imbedded in the bridge. It was these grooves in MACOR that aligned the target wires before gluing.

A custom winding jig was devised to string and hold the wires before the gluing step. Continuous lengths of wire were wrapped many times around the ceramic card. After the glue had dried on both ends of the target array, the wire was cut at the anchoring rod. An acid etch was applied to remove electrical contacts between the closely packed wire ends. The comb shown in Fig. 4 provides a secondary pivot point for the mechanical fan-out of the wires; this also was essential to avoid accidental electrical contacts. For mechanical and electrical protection, the wires were potted in silicone rubber on the fan-out side of the bridge.

Contractions of the glue during drying and imperfections in the MACOR rod threads lead to small deviations of the wires from their nominal positions. The final wire positions are known to better than 10 μm. Data analyses may utilize a data base of redundant measurements of the relative position of each wire within the target arrays.

The WISRD Support Structure

The structure seen in Fig. 2 satisfies the needs of the target arrays for support and alignment, electrical connections, and electromagnetic shielding. Also the support structure holds the defining collimators for the synchrotron beams.

For our application, it is important that the distance between the pair of target arrays in Fig. 2 be known and stable to one part in ten-thousand (25 μm). Stability is achieved by making the two target arrays part of one rigid mechanical structure. The wires are glued to the ceramic cards which in turn are glued into an invar plate. The target separation is fixed even when subjected to reasonable temperature variations. Careful and redundant measurements in the shop before installation permit us to know the target separation within the desired accuracy. The invar plate is attached to a larger aluminum support structure to provide additional strength to the invar plate. A layer of aluminum hexcel is laminated between the invar plate and the aluminum support structure with the various layers attached with metallic adhesive. This arrangement allows the aluminum structure to keep the invar flat. Note that linear thermal expansions of the aluminum do not stress the invar plate.

The aluminum support structure serves a number of other purposes, including the following. The lead collimators, shown schematically in Fig. 2, define the 1 cm width of the synchrotron beams reaching the wire array targets. Three large threaded rods (not shown) connect the aluminum support structure to the mounts in the machine tunnel. A number of tooling-ball holes in the support structure permit surveyors to measure the alignment of the WISRD.[9]

The WISRD is designed to be radiation hard. The detector operates in a high-radiation environment. The materials used to construct the WISRD, such as metals and ceramics, are radiation hard. The ceramic adhesive, used to glue the wires in place and to fasten the ceramic cards in the invar plate, is very fine alumina powder set with water; *i.e.*, high-technology dried mud. This ceramic adhesive can be trusted to be radiation hard. The weakest link in radiation hardness is the plastic cable connectors shown in Fig. 4. To minimize our dependence on the mechanical strength of this plastic, the connectors are clamped in place with aluminum bars.

Electronic issues have a decisive influence on the mechanical design of the detectors. The SLC machine tunnel is an electromagnetically noisy environment. The high radiation levels at the WISRD force the associated front-end electronics to be placed several meters from the detector. This increases the potential for pickup and grounding problems and increases the equivalent noise charge.

To minimize electromagnetic pickup, the WISRD is provided with an RF shield which is distinct from signal ground. The signal conductors are completely surrounded by the signal ground which in turn is enclosed by the RF shield. Electrical contact is avoided between the RF shield and local grounds such as the beam pipe. This topology of conductors is continued in the cabling to the front-end electronics. Realizing this shielding and grounding philosophy was a major issue in the mechanical design of the WISRD.

The "onion" topology of signal, signal ground, and RF shield is realized as follows. All structures shown in Fig. 2 that are not part of the ceramic card assemblies (see Fig. 4) are part of a common signal ground. At the connectors on the ceramic cards, the target wires electrically continue as inner conductors of coaxial cables whose outer conductors are extensions of signal ground. The entire assembly shown in Fig. 2 is completely surrounded by an aluminum sheet metal box which is the RF shield. It comprises two pieces that are electrically joined with the aid of metal mesh squeezed between iridited aluminum surfaces. This RF box is electrically connected to another RF box containing the electronics by shielding foil surrounding each of eight bundles of coaxial cables.

The signal conductors are completely surrounded by the signal ground to eliminate any direct capacitive coupling between the RF shield and the signal conductors. Not shown in Fig. 2 are metal shells that enclose the ceramic cards with signal ground. Sheet metal shells screwed onto the aluminum support structure surround the fan-out section. Metal cups screwed tightly, with an indium seal, onto the invar plate assure that the wires in the target area are completely surrounded by signal ground.

The metal cups protecting the wire arrays also permit control of the atmosphere surrounding the target. Both nitrogen and a rough vacuum have been used with success. A dry atmosphere is preferred to avoid corrosion of the wires and to avoid a drop in the AC resistivity due to humidity in the ceramic adhesive used to anchor the wires.

Conclusions and Discussion

Novel wire imaging synchrotron radiation detectors have been successfully designed and operated. The SLC energy spectrometers make use of two such devices. Preliminary data demonstrate that the detectors function as anticipated.[10] The WISRDs have an important role to play in precision energy measurements for the SLC.

Acknowledgments

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[5] See, for example, J. D. Jackson, *Classical Electrodynamics.*

[6] Cotronics 914, machinable glass ceramic.

[7] Cotronics 989, ceramic adhesive.

[8] CORNING GLASS^{tm}.

[9] SLC Energy Spectrometer Note Nos. 55 and 56, unpublished.

[10] MARK II/SLC Note Nos. 242 and 243, unpublished.