PRECISION SYNCHROTRON RADIATION DETECTORS*

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ABSTRACT

Precision detectors to measure synchrotron radiation beam positions have been designed and installed as part of beam energy spectrometers at the Stanford Linear Collider (SLC). The distance between pairs of synchrotron radiation beams is measured absolutely to better than 28 μm on a pulse-to-pulse basis. This contributes less than 5 MeV to the error in the measurement of SLC beam energies (approximately 50 GeV). A system of high-resolution video cameras viewing precisely-aligned fiducial wire arrays overlaying phosphorescent screens has achieved this accuracy. Also, detectors of synchrotron radiation using the charge developed by the ejection of Compton-recoil electrons from an array of fine wires are being developed.

1. INTRODUCTION

Detectors have been designed and installed to monitor positions of beams of synchrotron radiation. In our application we measure within 28 μm the absolute separation ($\approx$ 27 cm) between two beams of synchrotron radiation. A system of video cameras viewing phosphorescent targets has been designed for this purpose and is now in operation. These monitors, now in routine use, are the main topic of this paper. An independent system for making the same measurements is under development and will be described briefly at the end of this paper.

The synchrotron radiation detectors described here are part of energy spectrometers for the precision measurement of SLC beam energies.[1,2] Two dipole magnets, one upstream and one downstream of the spectrometer magnet, generate a pair of swaths of synchrotron radiation whose separation is inversely proportional to the SLC beam energy. The synchrotron beams are several hundred microns wide in the direction of separation and a centimeter or more long (depending on collimation); see Figs. 1 and 5. The critical frequency of the synchrotron radiation is $\hbar\omega_c \approx 3$ MeV, which implies that the beams interact with target materials dominantly via Compton scattering and the atomic photo-electric effect.

The phosphorescent screen monitors (PSM's) detect the visible light emitted from the phosphor materials when struck by synchrotron photons.[3] Each synchrotron beam is viewed by its own phosphorescent screen and video camera. An arrangement of fiducial wires overlaying the screens permits absolute position calibration.

An independent detector system is being developed to provide redundant measurements of the absolute separation of the synchrotron beams. They are based on intercepting the synchrotron beams with arrays of closely-spaced fine wires and detecting the amount of charge ejected from each wire by Compton scattering. When these detectors become operational in the near future, comparisons with measurements from the phosphorescent screen monitors will permit detailed studies of the performance of both detector systems.

2. DESCRIPTION OF THE PHOSPHORESCENT SCREEN MONITORS

The phosphorescent screen monitor shown in Fig. 1 consists of two identical target and video camera systems which monitor simultaneously a pair of synchrotron radiation beams. An Invar (iron-nickel alloy with low thermal expansion coefficient)

support structure holds both targets and fixes the distance between them. An independent support structure holds the video camera systems, mirrors, and illumination lights. The whole system is mounted on a base plate which is aligned to the beam line.
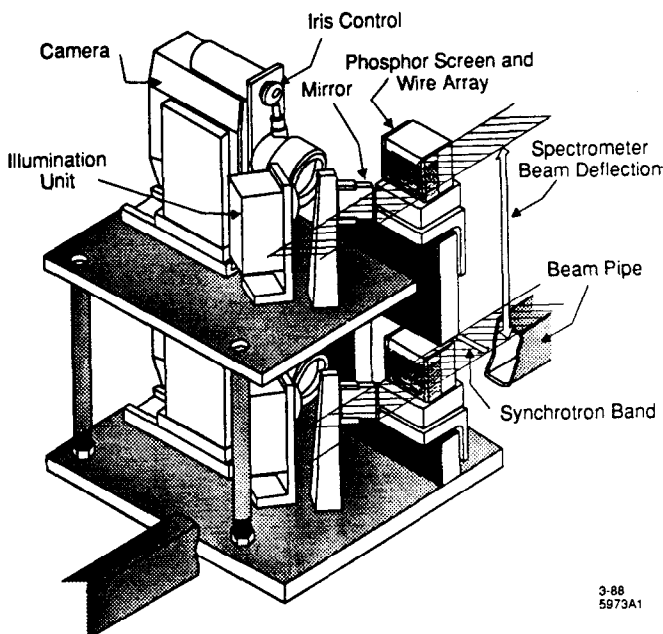

Fig. 1. An isometric view of the Phosphorescent Screen Monitor (PSM) together with the SLC beam pipe and the swaths of synchrotron radiation.

Each target consists of a phosphor screen and an array of fiducial wires. The 50 × 46 mm phosphor screens are custom made. The phosphor material, $Gd_2 : SO_2 : Tb$, emits visible green light when struck by synchrotron radiation. The phosphor is deposited on a thin (0.037 inch) aluminum substrate. The screens are easily replaced without disturbing the alignment of the fiducial wires.

The fiducial wires for absolute position calibration are the most critical part of the target assembly. Inconel wires of 100 μm diameter are strung a few hundred microns above the screen surface. The nominal center-to-center spacing between the wires is 500 μm. A bar code pattern is encoded in the fiducial wire array by selectively removing some of the wires. The two wire arrays were precisely aligned with respect to each other and then measured with a precision optical system. The position of each wire is recorded to an accuracy of 5 μm, yielding an overall accuracy of 8 μm on the absolute distance between the two wire frames.

Mirrors are used to enable placement of the cameras and lenses out of the path of the synchrotron radiation. The mirrors are made from an aluminum coating on a Zerodur substrate.

The camera system used is as follows: A high quality optical lens (Nikon 35 mm, F = 1.4) is used in conjunction with an RCA Ultricon video camera. Small projection lamps with light diffusers are used to illuminate the fiducial wire arrays during calibration. The cameras were aligned with respect to the wire arrays to an accuracy of 20 mrad. Much of the electronics of the video cameras are removed from the camera and relocated further from the beam line and shielded in order to minimize radiation damage effects.

The camera images are digitally recorded as follows. The fiducial wires and the synchrotron stripe which runs parallel to them are viewed by the video cameras. The video frame is then digitized and compressed into a one-dimensional array (perpendicular to the wire direction) before readout by using a DSP Technology 2030/4101 signal averager. Readout rates of up to the maximum SLC design repetition rate of 180 Hz have been achieved. The data is recorded on the data tapes of the Mark II detector presently installed at the SLC. Data is collected on a pulse-to-pulse basis and recorded for beam crossings producing Mark II triggers. Work is in progress to make data available to the SLC control room independently of the Mark II data acquisition system.

Synchrotron beams were first observed (with an SLC beam intensity of $2 \times 10^9 e^{\pm}$/pulse) on the phosphorescent screen monitors during February of 1988. Since then the monitors have been routinely collecting data. To date there have been no serious operational problems nor any evidence of degradation due to radiation damage of components.

3. PHOSPHORESCENT SCREEN PERFORMANCE

The phosphorescent screen monitors measure absolutely the separation between the pairs of synchrotron radiation beams with a systematic error of less than 28 μm. The contributions to this net systematic error are given in Table 1 and are discussed below.

Table 1. Systematic errors.

Source of Error	Size of Error
Fiducial wire positions	8 μm
Pixel image location calibration	14 μm
Uniformity of response	14 μm
Parallax error	9 μm
Centroid finding	16 μm
Total Error	28 μm

Careful attention has been given to the precise measurement of the fiducial wires. The individual wires and the spacing between the two arrays were measured on precision optical comparators to an absolute accuracy of better than 8 μm. Thermal effects are not expected to compromise the fiducial wire geometry at this level.

A calibration procedure determines the correspondence between camera pixels and the positions (relative to neighboring fiducial wires) viewed on the phosphorescent screens. Calibration data are collected with the target assemblies illuminated with diffuse light from a lamp. Fifty consecutive video frames are summed up for each of three different illumination settings. Figure 2 shows a sample digitized one-dimensional calibration image. The fiducial wires produce the valleys seen in the figure. Note the pattern of occasional missing fiducial wires that uniquely identify the portion of the target assembly being viewed. As each pixel is relatively close to an image of a fiducial wire, global optical distortions do not introduce significant calibration errors. An upper limit to the errors associated with this calibration of pixel positions is obtained by comparing the known wire spacings with the spacings in pixels of the wire images in the camera. Assuming no optical distortions and fitting the magnification, the agreement between actual and observed fiducial wire geometry implies a 10 μm error in determining pixel locations. Adding quadratically the calibration errors from both screens gives the second entry in Table 1.

Nonuniformities in the overall response of the phosphorescent screen system are estimated to contribute less than 14 μm to the measurement of the separation between the pairs of synchrotron beams. nonuniformities in response can arise from three sources: (i) variations in the screen light output as a function of position on the screen, (ii) gain or saturation effects in the video cameras, and (iii) shadowing due to the fiducial wires.
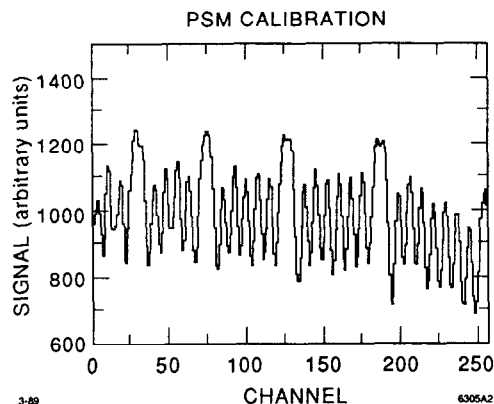

PSM CALIBRATION

Fig. 2. Phosphorescent screen monitor calibration data.

The uniformity in response of the phosphorescent material and video cameras as a function of position has been tested by viewing the same synchrotron stripe at two different locations on the screen. The two stripe positions determined from physically distinct areas of the phosphorescent screen are found to correlate very well, even when the synchrotron radiation beam is swept across the screen. From many measurements of this type it is clear that nonuniformities in the phosphorescent material or gain variations in the video cameras do not contribute a significant systematic error. In addition, remote control of the camera lens iris maintains the video camera within the linear region of its response for any beam intensity.

The fiducial wire array shadows 20% of the light emitted by the synchrotron stripes. A uniformly spaced array would not cause an apparent centroid shift for the typical beams of 750 μm to 1500 μm width (FWHM). However, the missing wire elements in the bar code pattern can cause an apparent centroid shift. A calculated average error of 14 μm on the determination of the distance between the two stripe centroids is assumed here due to this effect. In practice, corrections can be applied to fully eliminate this source of systematic error.

An additional source of systematic error arises from the parallax error due to the viewing angle of the video cameras. The cameras are aligned (to 20 mrad) to view the screens at normal incidence, the short depth of field requires this condition. Since the fiducial wires are a few hundred microns above the surface of the screens a slight viewing angle will skew the apparent position of the wires. This parallax error is estimated to contribute no more than 9 μm.

A Gaussian fit is used to determine the centroids of the synchrotron stripes. Good fits are obtained indicating that the stripe profiles are approximately Gaussian in shape. Code is available using other algorithms for centroid fitting, including weighted averaging and correlation techniques. These different centroid-finding algorithms give similar results. At an electron or positron beam intensity of 1×10^{10} particles per pulse a significant error of 16 μm arises from signal/noise considerations. Since this error is statistical in nature, this error is much reduced at higher beam intensities or when combined in a running average.

Combining the various systematic errors in quadrature, the net systematic error in the measured separation of the pairs of synchrotron stripes is estimated to be less than 28 μm.

Figure 3 shows raw data, including a peak from a beam of synchrotron radiation. During data collection, the illumination lamp is left on at its low setting in order to include the fiducial wire pattern in the recorded image. Calibration data is used to subtract signals not due to the synchrotron beam. The corrected data, such as those seen in Fig. 4, are fit to a Gaussian. In this way, the position and width of the synchrotron beams are measured.
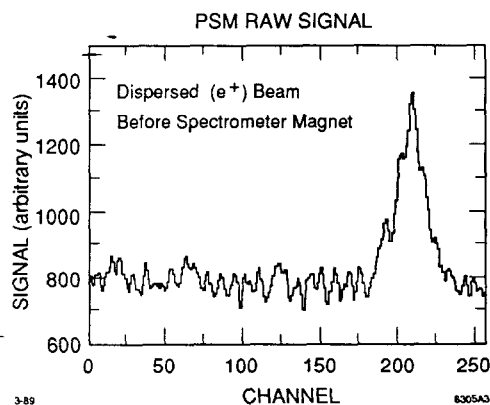
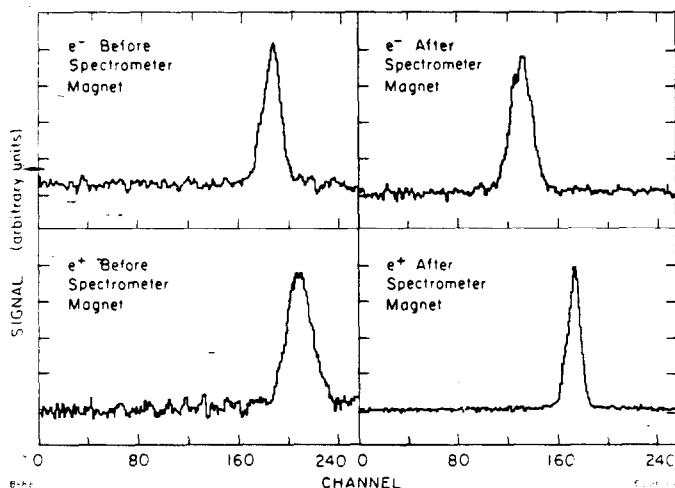Fig. 3. Raw beam profile from the phosphorescent screen monitor.

Fig. 4. Corrected data for both screens of both electron and positron spectrometers.

Fig. 5. An isometric view of the wire imaging synchrotron radiation detector.

4. WIRE IMAGING SYNCHROTRON RADIATION DETECTORS

A second novel detector of the intense synchrotron radiation beams generated in the SLC energy spectrometer is being developed. The penetrating beams of photons pass through the PSM's and into this new detector. The charge distribution remaining on a fine-wire array as a result of Compton emission forms an image of the synchrotron radiation beam profile. These detectors, Wire Imaging Synchrotron Radiation Detectors (WISRD's), shown schematically in Fig. 5, are presently installed in both of the SLC energy spectrometers. Each synchrotron beam is intercepted by an array of 96 75-μ-diameter copper wires with 100 μ center-to-center spacing. The wires are perpendicular to both the beam direction and the direction of separation between the stripes. Compton scattering of synchrotron photons results in the ejection of Compton recoil electrons from the wires. Electronics is nearing completion to measure and record the residual positive charge left on each wire.[4]

A swath of synchrotron radiation is calculated to eject from a wire array a total charge of typically $200 fC$. This was computed assuming swaths were generated by SLC beam pulses containing 10^{10} beam particles which are collimated to a width of 1 cm. The total charge is distributed over a small fraction of the wires in each array. Measurements with analog sums over many wires have confirmed this prediction within a factor of two.
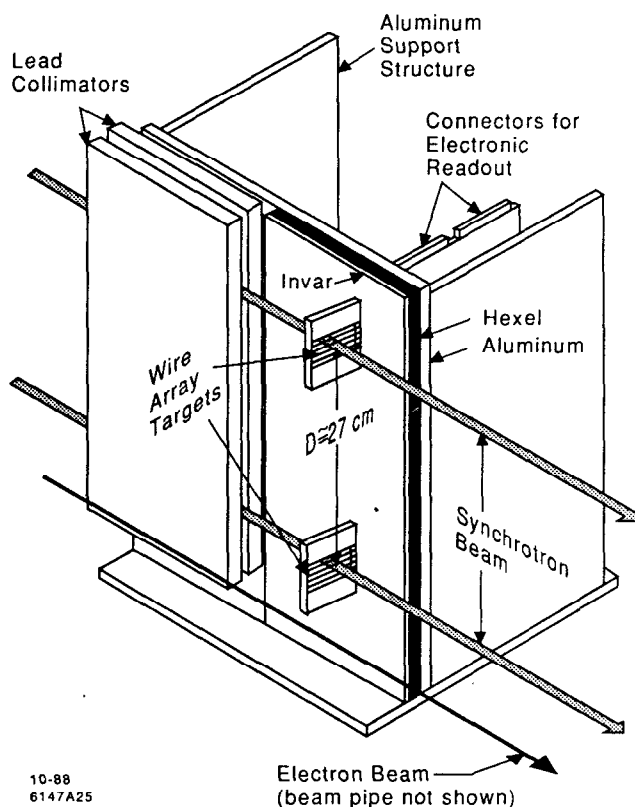
5. CONCLUSIONS

Phosphorescent screen monitors are now providing precise measurements of positions of synchrotron radiation beams. Separations of pairs of synchrotron stripes are measured absolutely within 28 μm. Wire imaging synchrotron radiation detectors are expected to provide redundant measurements in the near future. These detectors are part of the SLC energy spectrometers.

REFERENCES

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