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AN ELECTRON BEAM SPECTRUM MONITOR USING SYNCHROTRON LIGHT*

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Summary

This instrument shows the positions, widths, and shapes of momentum spectra of SLAC beams. It uses synchrotron light produced when the beam is deflected by a magnet. Some of the light is focused on the face of an image splitter consisting of acrylic light pipes. The light pipes illuminate twelve photomultiplier tubes. Pulses from the PM tubes are integrated, multiplexed, and displayed on an oscilloscope. The resolution of the instrument is usually better than 0.2%. It has some advantages over the secondary emitter foil spectrum monitors (SEM's) currently in use at SLAC. It need never be put out of service to avoid disturbing the beam. It is as sensitive as the most sensitive SLAC SEM. (Its performance has been optimized for high-current beams; it can easily be made much more sensitive.) It provides information on a pulse-to-pulse basis and, with better cables, could indicate electron beam pulse shapes.

Introduction

When a relativistic electron beam is deflected by a magnet it produces synchrotron light.[1,2,3] In many places at SLAC the light is bright enough to be observable by means of closed circuit television even at very low beam current levels, and has been used for monitoring beam profiles (Ref. 4, p. 660; Ref. 5). SLAC electron and positron beam momentum spectra are ordinarily observed by means of secondary emission monitors (Ref. 4, p. 669). In passing through the aluminum foils of these instruments, the beam produces secondary electrons and X-rays. Since this contamination is intolerable for certain experiments performed in end station "A", a spectrum monitor has been developed which uses synchrotron light.

The Light Source

The monitor is installed some 10 m downstream of the B13 bending magnet in the SLAC "A" line (Ref. 4, p. 586). It makes use of a previously existing vacuum pipe junction which has been modified to serve as a viewing port. The port constrains the light path so that the central ray originates ~0.5 m upstream from the center of the magnet. In this location, the electron beam is dispersed horizontally by about 3.3 cm for a 1% spread in beam momentum and a monoenergetic beam would produce a spot 4 mm wide or less. The apparent horizontal angular size of the arc of an electron orbit in B13, as viewed from the direction of the monitor, is limited by the horizontal angular distribution of the synchrotron light. The width of the light cone which is produced by a small local increment of magnetic deflection may be estimated using Schwinger's equation II.31,[1] by integrating over x and taking averages of the resulting $P(\psi,x,\omega)$ over intervals of 2π in the function F, where

$$F = (1-\beta^2+\psi^2)^{3/2}\ (\pi R/\lambda)(x+x^3/3) \quad ,$$

$\beta = v/c$, ψ is vertical angle, R is electron bending radius, λ is light wavelength, $x = (1-\beta^2+\psi^2)^{-1/2}\chi$, and χ is horizontal angle, measured from the tangent to the electron orbit. For visible light ($\lambda \simeq 0.4$ μm), produced in B13 ($R \simeq 57$ m), the averaged function $\langle P(\psi,\chi,\omega)\rangle$ is peaked at $\chi = 0$, and half the light power is confined within an angular interval $\pm\chi_0$, where

$$2\chi_0 \simeq (4/\pi)\ \Gamma(1/3)(3\lambda/\pi R)^{1/3} \simeq 6 \text{ mrad}$$

For $|\chi| >> \chi_0$ the intensity decreases as $1/\chi_0^2$ (Ref. 6). If one compares the full widths containing half the visible light power, the horizontal (χ) width of the "light cone" is thus ~5 times the vertical (ψ) width, which is $\sim(3\lambda/4\pi R)^{1/3} \sim 1.2$ mrad (Ref. 2, p. 9). In B13 an electron orbit remains within ±3 mrad of the line of sight to the monitor for ~.34 m of its path. The sagitta of this arc is ~0.3 mm, which corresponds to the distance between two electron orbits which differ in momentum by ~0.01%.

The Light Path

The light path (see Fig. 1) has been arranged to minimize the effects of radiation damage on the performance of the monitor. Some 9 meters downstream from the source, an aluminized copper mirror reflects the light down a 1.5 meter long vertical vacuum pipe from which the light emerges through a fused silica window. The light is then again reflected into a horizontal path by a first surface glass mirror.

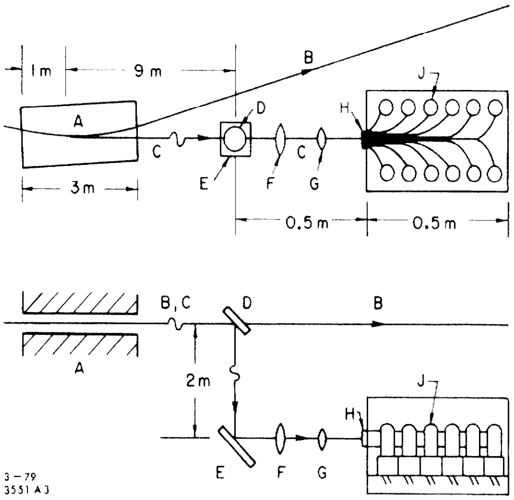

Fig. 1. Top and side views, not to scale. (A) bending magnet, (B) electron orbit, (C) light ray, (D) upper mirror, (E) lower mirror, (F) objective lens, (G) eyepiece or projection lens, (H) image splitter, (J) photomultiplier tube (typical).

An image of the light source is produced on the entrance face of the image splitter by a pair of positive lenses which are arranged in a manner similar to that used in making an image of the sun by eyepiece projection upon a screen with a small telescope or monocular. The 193 mm f/3.7 primary lens makes a real image in space which is refocused upon the face of the image splitter by a 12 mm eyepiece lens. The system accommodates a 3.6% beam momentum spectrum interval which is ~12 cm wide at the light source, and appears to be ~4 cm wide at the face of the image splitter. Only a portion of an electron orbit is well focused. As has been indicated above, electrons radiate reduced amounts of light in the direction of the monitor as

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they travel the parts of their orbits which are more than ~.17 m upstream or downstream from the point at which the orbit is tangent to the monitor's line of sight. Light originating .17 m from the focal plane in B13 is defocused into a ~.3 mm diameter circle at the image splitter face. The size of this circle is proportional to the diameter of the objective lens, and corresponds (full width) to $\Delta p/p \simeq .03\%$ in the electron momentum spectrum.

The image splitter consists of 12 strips of clear polished acrylic plastic, separated by aluminum foils, clamped together at one end, where they present their end surfaces at an image plane of the lens system. Each strip has been heated and bent into a gentle curve, and is clamped at its other end to the input window of a type 931A photomultiplier tube. Light is transmitted along the "light pipes" by total internal reflection. The strips are 2.5 cm wide and are made of 1/4, 1/8, 1/16, and 1/32 inch thick acrylic stock, so that the spectrum intervals are approximately 8,4,2,2,1,1,1,1,2,2,4, and 8 units wide, each unit representing $\Delta p/p = 0.1\%$. The intent is to match the display format of the previously existing secondary emission foil spectrum monitors (Ref. 4, p. 669).

The Electrical Circuits

It was anticipated that the synchrotron light would usually be very bright. The photomultiplier (PM) voltage dividers are consequently proportioned (see Fig. 2) to accommodate large anode currents and to remain nearly linear while delivering peak signals of a few volts to 50 ohm coaxial cables. The twelve voltage dividers are connected together at the number 5 dynodes and fed at this point from a nominally fixed 600 volt power supply. Each PM cathode is connected to a common adjustable high voltage supply through an individual gain adjusting rheostat. The relative gains of the different PM tubes are adjusted using a pulsed light source. The adjustable high voltage supply then serves as a common gain control to accommodate changing conditions.

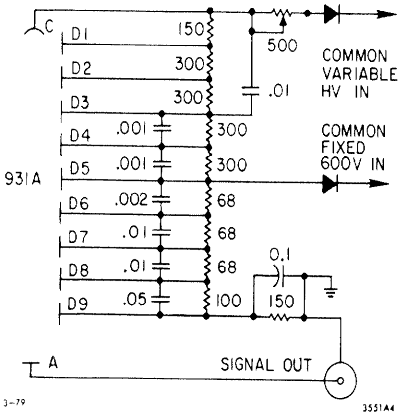

Fig. 2. Photomultiplier circuit proportioned for high peak current output. Values are in μF and kΩ.

The signals are brought through coaxial cables to a multiplexer, which integrates, holds, and scans the twelve signals at intervals of 100 μs following each electron beam pulse. The scanned signal is displayed on an oscilloscope. The coaxial cables are ~150 m long, and degrade the response of the transmitted pulses, so that the pulse risetime is ~0.3 μs. This has no harmful effect on the multiplexed display, but limits the usefulness of the signals for the examination of electron beam fine structure.

Alignment

Most of the visible synchrotron light produced in the magnet is confined within a vertical (ψ) angular range which is about twice the full width mentioned above, or ~2.4 mrad (Ref. 2, p. 9). At a distance of 11 m, the light illuminates a horizontal strip ~2.6 cm high. It is necessary to center the 5.2 cm diameter objective lens of the monitor upon this strip and to align the axis of the lens system and beam splitter assembly along the line of sight determined by a tangent to the central beam orbit and the mirror system. To do this, an observer watches the primary lens by sighting through the bore of the bending magnet B13 with binoculars while his partner shifts the direction of the vertical pipe and the position of the lower mirror until it appears that the area of the primary lens is bisected by the proper horizontal plane. Then an optical target, illuminated by a 600 watt projection lamp, is placed in the synchrotron light source position in the magnet gap. The orientation of the lower mirror and the beam splitter and lens assembly are then manipulated, and the focus is adjusted to form an image of the target at the image splitter input plane. A remotely controlled motor drive is provided for a final small angular adjustment of the lower mirror to center the spectrum in the multiplexed display under electron beam operating conditions.

Radiation Damage

The monitor was first operated with the beam splitter optical axis vertical, and with a single mirror deflecting the light downward. In this configuration, in spite of a 20 cm thick Pb shield just upstream, the window and lenses became opaque from radiation damage after a few days of accelerator operation at high beam current levels. The radiation seems to come from both the upstream and downstream directions. In the present arrangement, with all the transparent optical parts near the floor, stacks of lead bricks shield the components from radiation coming from several directions. It now appears that the monitor, which was refurbished last summer, will survive the radiation well enough to be useful until next summer's shutdown.

Sensitivity

With new lenses and a new window, it was found that the monitor would be useful with a beam current as low as 5 μA peak at 1.6 μs pulse length. The limit on "sensitivity" was not noise, but was the width of the trace on the oscilloscope, operated at 10 mV/cm. The usefulness of the display was comparable with that of the SPEAR injection beam line secondary emitter foil spectrum monitor operated at the same peak current at 1 pps rate. The SPEAR monitor is the most sensitive foil monitor at SLAC. It would be easy to increase the sensitivity of the synchrotron light monitor by a large factor, if necessary, for example, by replacing the present 9 dynode PM tubes with 14 dynode ones.

Resolution

The resolution of the instrument is mainly governed by the monoenergetic horizontal spot size of the electron beam as it passes through B13. The spot size is limited in width by the acceptance of the accelerator to 4 mm, but can be smaller. This corresponds to 0.13% $\Delta p/p$, which is comparable to the minimum observed spectrum width (Ref. 4, p. 86). Spectra observed with the monitor have upon occasion been confined entirely to 3 of the 0.1% slices making up the oscilloscope display.

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References

1. J. Schwinger, Phys. Rev. 75, 1912 (1949).
2. R. A. Mack, "Spectral and Angular Distributions of Synchrotron Radiation, Cambridge Electron Accelerator report CEAL-1027 (1966).
3. K. R. Lea, Physics Letters 43C, 338 (1978). (This paper has a recent bibliography.)
4. R. Neal, editor, The Stanford Two-Mile Accelerator, New York, W. A. Benjamin, Inc., 1968.
5. A. P. Sabersky, IEEE Trans. Nucl. Sci. NS-20, No. 3, 638 (1973).
6. D. Reagan, unpublished notes.