BEAM MONITORS BASED ON LIGHT OBSERVATION FOR THE BEAM SWITCHYARD OF THE STANFORD TWO-MILE LINEAR ACCELERATOR*

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Summary

This paper describes three monitors and the associated optical system used to observe the profile of the high-power electron beam in the switchyard of the two-mile linear accelerator. One device is based on the observation of synchrotron light emitted by the beam when deflected in the analyzing magnets. The second type uses the Cerenkov light produced in a gas cell which is inserted into the beam path when needed. The third type uses conventional zinc sulfide screens with a mechanism for replacing a screen which has become inactive, with a new screen. Reflective optics systems and closed circuit television are used to transmit the images of the beam spots to T.V. monitors in the control room.

Introduction

Before describing the beam profile monitors as individual devices, we would like to discuss some general aspects underlying the choice of these instruments and the factors that influenced their design.[1]

Previous experience has shown that a practical overall magnification from beam spot size to image size is between × 1 and × 2, and this is the range of magnification used in the switchyard. Two of the monitors described have to be inserted into the beam path during an observation, in both cases the thickness of material along the beam path has been made as small as possible and when retracted the devices leave the beam aperture free of obstruction. Although non-intercepting microwave beam position monitors[2] are used in the switchyard, position reference marks aligned to an accuracy of 1 mm are provided on the profile monitors as a back-up system.

The devices have been designed for a long lifetime in the beam and since the radiation levels in the switchyard will be very high, components have been chosen which are either resistant to damage by radiation or which can be replaced easily (and eventually by remote manipulators). Nitric acid corrosion may become a problem, particularly with aluminized mirrors, and alternative mirror coatings are being investigated.

Of the three devices described, the synchrotron light monitor is the only one that is non-intercepting and from this point of view it is highly desirable. Its application has been limited, for various reasons, to one station in each of the two beams in the switchyard.

The Cerenkov cell presents a relatively large amount of material to the beam (2×10^{-3} radiation lengths when helium is used). Due to beam blowup caused by multiple scattering the use of the cell in high-power beams is therefore limited by the amount of power deposited in downstream protection collimators.[2] The three-inch aperture of the cell is another limitation; however, its excellent performance and good resistance to radiation damage make it an ideal monitor for the conditions in the switchyard.

Zinc sulfide screens are used extensively in the switchyard, particularly at locations where the beam spot may be large. Apart from limited life, difficulty is sometimes encountered in relating image spot size to actual beam size, using these screens, particularly at high current densities.

The optical and T.V. system is basically the same for each of the three monitors. The light is reflected by a series of mirrors from its source in the lower half of the double tunnel structure of the switchyard to a radiation resistant telescope and television camera mounted in a shielded alcove in the upper part of the tunnel.

Synchrotron Light

Electromagnetic radiation is emitted tangentially to the path of an electron deflected in a magnetic field. For most of the magnets in the beam switchyard, the wavelength of this radiation covers the visible spectrum. This phenomenon has been used after the first bending magnet B-10 in the A-Beam of the switchyard as a non-intercepting means of visual observation of the beam spot.[3] The radiation covers a wide frequency spectrum which is dependent on the bending radius in the magnet and which shifts toward shorter wavelengths with the third power of the beam energy:

$$\lambda_c = 5.59\ R \cdot \left(\frac{1}{E}\right)^3$$

where λ_c = shortest wavelength radiated (Å),
E = electron energy (GeV), R = bending radius (m).

The bending magnet has a bending radius R = 57 meters, and the synchrotron radiation is therefore in the visible spectrum if the beam energy

$$E = \left(\frac{5.59 \cdot 57}{5000}\right)^{1/3} = 0.4 \text{ GeV or higher.}$$

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The photons are emitted in a forward cone with an angular distribution extending to 1.5 mr (half-angle)[3], the number of photons in the visible range emitted per second for each microamp of beam current being,

$$N = 2.4\ 10^{12}\ \frac{L}{R^{2/3}} \quad \text{photons/sec/}\mu\text{A}$$

where L = length of the path the electrons travel in the magnetic field. The optical system is arranged to accept light from the first twelve inches of the effective magnetic length of bending magnet B-10 (Figure 1).

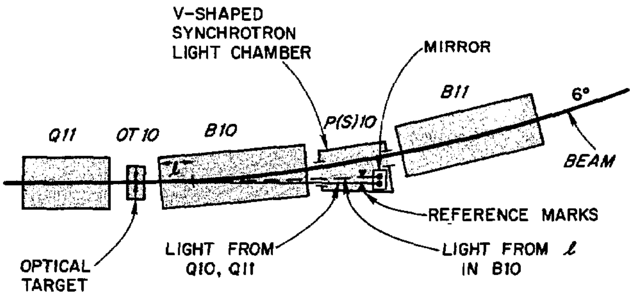

Figure 1.

The theoretical light production in this section is 4.9×10^{10} photon/sec/μA and all of the transmitted light will be collected by a 4" diameter mirror at a distance of 7 meters. The light is reflected by four front surface aluminized mirrors (reflectivity = 90%), and passes through one 3/8 inch quartz window (transmission 95%). Assuming a beam spot size in B-10 of 2 mm × 15 mm and a demagnification from the beam to the vidicon face plate of 1/30, we find a light level on the photo cathode of approximately 18.5×10^{11} photon/cm^2/sec/μA. The RCA 7735A vidicon tube, when adjusted for maximum sensitivity, operates with a faceplate illumination (highlight) of 0.1 foot candle = 4×10^{11} photon/cm^2 (according to the manufacturer's brochure). This corresponds to a beam current of 0.22 μA. For our purposes, a usable image can be obtained with lower light levels and we have observed experimentally that the beam is still visible at average currents of less than 0.01 μA.

The special V-shaped vacuum chamber located after B-10 contains a mirror which is adjustable manually via a three-point support from outside the vacuum box. Initial alignment of the mirror is accomplished by using the optical target OT-10 in front of B-10 and the reference marks (cross wires) fixed inside the V-shaped chamber (see Figure 1). The mirror consists of a 1/4" thick piece of polished high-purity fused silica, the front surface of which is aluminized. The shorter wavelength part of the synchrotron radiation as well as the visible light, representing a total of about 21 watts at maximum beam power is intercepted by the mirror and it was thought that there was some risk of damaging it. However, an electron beam with an average power of over 1 kW, has been directed at the mirror (accidentally) and damaged the downstream vacuum coupling of the device without affecting the mirror. A 12-inch quick disconnect vacuum flange enables the section containing the mirror and quartz viewing window to be replaced easily.

Cerenkov Light

Cerenkov light is emitted by charged particles moving through a medium with a speed greater than the phase velocity of light in that medium. In the profile monitors for the switchyard[4] the Cerenkov light is observed when the electrons pass through a gas at atmospheric pressure. The number of Cerenkov photons produced in a gas and their angle of emission are given by,

$$N_\varphi = 900\ (n\beta - 1)\ \text{ph/cm;}$$

$$\theta = \cos^{-1} \frac{1}{\beta n}$$

where n = refractive index, $\beta = \frac{v}{c}$

so that a light cone is developed in the gas with an opening angle $\alpha = 2\ \theta$. The beam image is observed by looking along one part of the cone. This introduces a distortion along one axis equal to $\ell \sin \theta$, where ℓ is the effective length of the gas cell. The construction of the Cerenkov profile monitor is shown schematically in Fig. 2. The gas in the cell flows through when the monitor is in the beam at a flow rate of 1 cc/sec. As a gas filling both argon and helium have been used at different times. Argon produces more light, but helium reduces the distortion as well as the beam scattering. A comparison between the two gases is made below:

Gas	n	N_φ/electron ℓ = 12 cm	θ(mr)	$\ell \sin \theta$ Error
Argon	1.000 281	3.	24	2.88 mm
Helium	1.000 036	0.39	8.5	1.02 mm

The gas cell is built in a tubular hammerhead configuration and has 0.003 inch thick, hard aluminum beam entrance and exit windows. The light cone is reflected vertically by a mirror placed in the beam at 45 degrees. The mirror consists of a 0.001 inch thick mechanically and chemically polished foil stretched over a ring, using a drumhead tightening principle. The gas cell swings about a pivot axis and is moved into the beam by the application of air pressure to a small cylinder.

A counterweight (see Figure 3) moves the cell out of the beam when the air pressure is released. Except for a beam position reference cross the input window is blackened using a graphite spray (Aquadag, ammonium hydroxide and water)[5]. The cross can be illuminated with a lamp mounted outside the viewing window. Table 1 compares the characteristics of the Cerenkov profile monitor to those of zinc sulfide screens. Due to directional properties of the Cerenkov light considerable care is required when aligning the optical system, however, our experience has shown that once the system is correctly aligned the operation of the monitor is very satisfactory.

Zinc Sulfide Screens

Zinc sulfide screens are easy to make and have good sensitivity, however, they have the disadvantage of losing luminescense after exposure to an integrated beam current of about 10 μA hr/cm^2. The replacement of such screens is a difficult task in the switchyard because of the severely limited access. For this reason, an automatic device has been developed that will replace the screens after they have become inactive. Several possible mechanisms have been considered, among which are a large disc with its axis of rotation tilted 45 degrees with respect to the beam, and the film roll principle. The mechanism adopted for the switchyard is a carousel with 48 independent screens, shown in Figure 4. The 48 screen arms hang on balls in the slotted rim of a 10-inch wheel. The screen frames can be raised into the beam by the blade lift mechanism. The u-shape of the screen ensures that the beam is intercepted only by the .002 inch thick, zinc-sulfide-coated aluminum foil. The index drive mechanism rotates the wheel 7.5 degrees so that a new screen comes into the lift position. The carousel can be removed from its housing when all the screens have been used. The individual screen frames can then be lifted out of the slotted rim for replacement. The image of the beam spot on the screen and position reference marks are observed through a fused silica vacuum window at the top of the light pipe and a front surface mirror, at the lower end of the light pipe. The adjustable mirror on top of the light pipe and the two drive motors shown in Figure 5,protrude into a slot in the 2-foot thick concrete shielding floor. In this way they are shielded from radiation and easily accessible. Figure 5 shows various other details designed to make remote replacement possible: A fast disconnect plug, two plug-in type drive motors, assembly guide rods, a 12-inch fast disconnect vacuum flange, and lift eyes. Two types of the multiscreen profile monitors described above have been built, the carousel being identical in each case. One is for a 6-inch beam pipe (4-inch wide screen) and the other is for a 12-inch beam pipe (8-inch wide screen). The only difference in the two types being in the angle at which the screen is presented to the beam (see Table 1). The screens are sprayed at a temperature of about 80°, using a suspension of 10 micron P-4 phosphor in glycerin, sodium silicate and water[5].

TABLE 1.

	CERENKOV CELL	ZnS SCREEN
Sensitivity	(He)10^{-9} amp/cm^2	
	(Ar) 3×10^{-10} amp/cm^2	10^{-9} amp/cm^2
Spot Definition	1 millimeter	1 millimeter
Max. Aperture	3-in. diameter	8 in. wide 2 in. high
Material in Beam	2 Al. windows 0.003"; 1 Al. mirror 0.001" 20 cms gas	0.002" Al. foil at 65° or 90° to beam
	0.001" graphite (Aquadag) on one window	0.001" and 0.004" thick zinc sulfide, Sylvania (P-402)
Rad. Length in Beam	6×10^{-3} rad. ℓ (Ar) 2×10^{-3} rad. ℓ (He)	1.3 to 3.5×10^{-3} rad. ℓ
Mechanical	Moved into beam by air pressure, out by gravity.	Selected and operated by electric motors
Expected Life	Mirror 1.5×10^4 μA hr/cm^2	10 μA hr/cm^2 per screen

Optics and T.V. System

A 735 scan line I.T.T. closed circuit television system is used, its optimum resolution of 520 lines both horizontal and vertical being below that of the optical system. There are a total of 8 cameras in the switchyard, the video signals and the controls for the instruments being multiplexed into 2 display channels. The vidicon tube selected for the television cameras is the RCA 7735A, which is available with a standard, or at a much higher price, with a non-browning faceplate. Radiation levels in the switchyard are still low and the standard tubes will be used until faceplate browning rather than photo-cathode degradation limits tube life. The photo cathode of this tube has a fairly sharp spectral sensitivity curve with a peak at 5500Å, the other optical components in the system being chosen where possible to match this wavelength. The light is focused on the vidicon tube with a reflector telescope using spherical front surface aluminized mirrors (Liberty Mirror No. 756). The advantages of the telescope are that the mirrors are less expensive, are better resistant to radiation than non-browning lenses and, using the Newtonian arrangement with the camera perpendicular to the telescope, the camera can easily be shielded from radiation. Light from the monitors passes in each case through a radiation-resistant vacuum window (Corning pure fused silica, code 7940) and is directed into the telescope by a remotely adjustable front surface mirror. This mirror can be rotated through small angles about two axes by electric motors driving cams, the cams being contoured to give two speeds. The front surface aluminized mirrors are unaffected by radiation but are very sensitive to nitric acid corrosion. Other metallic coatings such as gold, titanium,and chromium are resistant to nitric acid corrosion, but have a low reflectivity. The reflectivity of a front surface chromium on glass mirror was increased to about 90% at 5500Å by the application of several 1/4"thick layers of magnesium fluoride and titanium dioxide. This mirror was found to be unaffected by nitric acid and no significant changes in reflectivity could be found after exposure to a radiation dose of 10^{10} ergs/gm. Due to the uncertainty in estimating the nitric acid vapor concentration in the switchyard, it was felt that the expense of these mirrors could not be justified. However, a fully dielectric commercial mirror (Liberty Mirror No. 90-500) has been purchased and installed on one of the Cerenkov cells for further evaluation.

The telescopes are designed to give an overall magnification on the 17-inch T.V. monitor between one and two times the actual beam size. The spherical mirrors vary in focal length between 10 and 20 inches for the different monitors in the switchyard. The telescopes are constructed in such a way that they will accept any 4-1/4 inch-diameter mirror in this range. Coarse focusing is provided by means of a thumbscrew on each telescope; fine focusing is provided by remote control of the position of the vidicon tube inside the T.V. camera.

In the case of the zinc sulfide screen changers, where viewing angles introduce different distortions along the two axes, an elliptical disc is mounted just out of the beam path in such a way that it corresponds to a circular beam spot and can be seen on the T.V. monitor when there is no screen in the beam. By adjusting the T.V. monitor so that this disc appears circular, the distortion of the system can be corrected.

Acknowledgements

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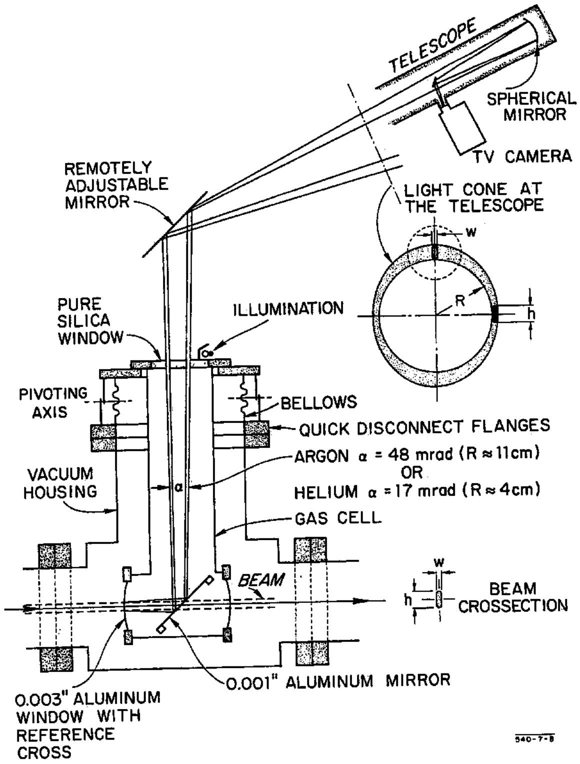

Figure 2. Schematic of Cerenkov Cell

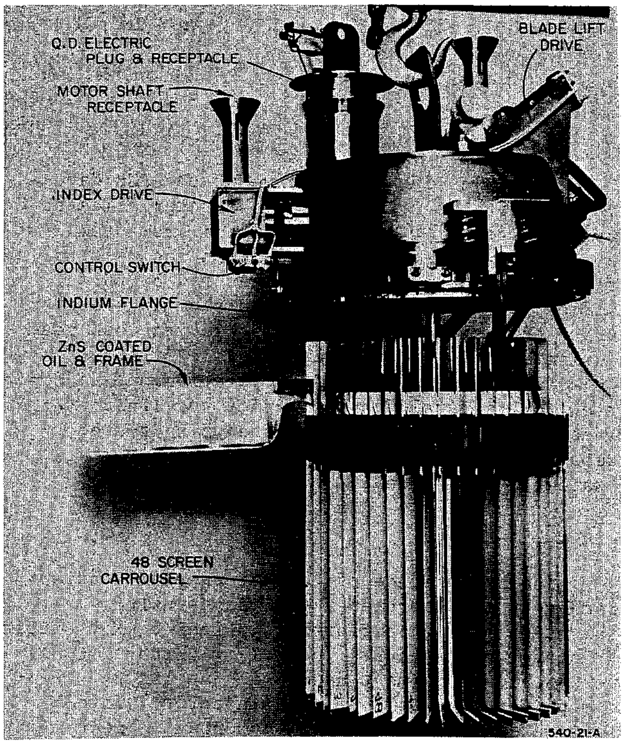

Figure 4. 48 Screen Carousel

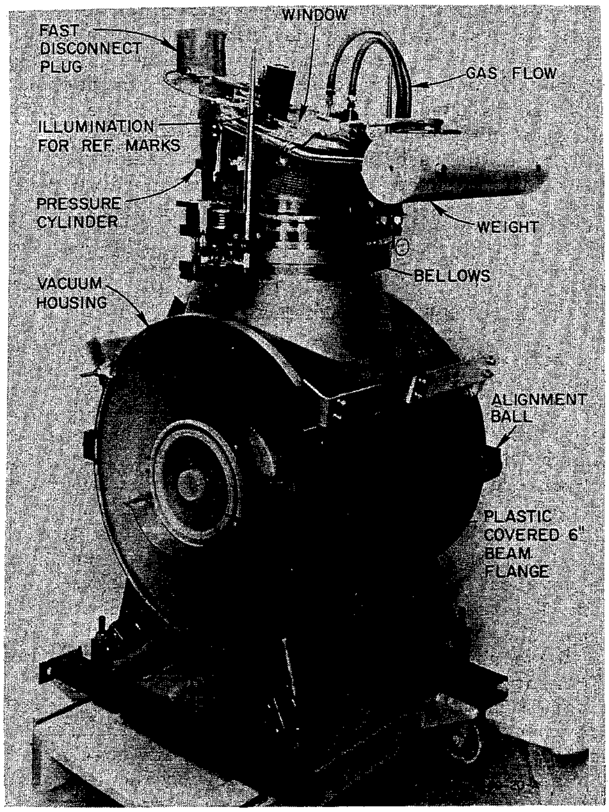

Figure 3. Cerenkov Cell

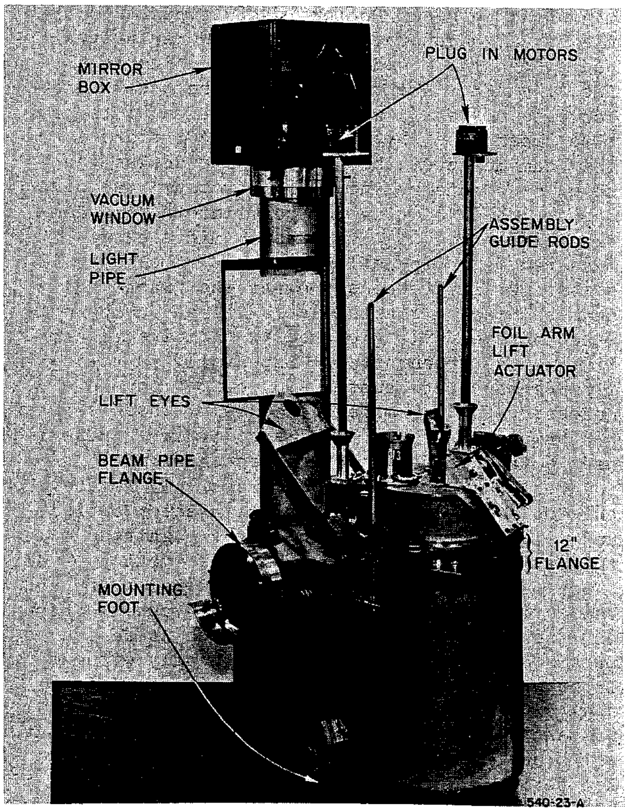

Figure 5. ZnS Screen Profile Monitor