A BEAM-PROFILE MONITOR
FOR THE BNL ACCELERATOR TEST FACILITY (ATF)

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Abstract

A beam-profile monitor has been designed to diagnose the 5-MeV high-brightness electron beam from the rf gun of the BNL Accelerator Test Facility (ATF). The monitor consists of a phosphor screen viewed by a CCD camera. The video images are digitized and stored by a framegrabber and analyzed by an IBM PC-AT to extract the emittance. Details of the hardware configuration are presented, along with the spatial resolution of the system measured as a function of phosphor-screen thickness. The strategies which will be used to measure the transverse and longitudinal emittances are briefly mentioned. The system should be capable of measuring a transverse geometric emittance of around 1 mm-mrad, as will be typical of the ATF beam.

Introduction

Several facilities are being developed for the purpose of exploring new charged-particle acceleration schemes and free-electron lasers. A common theme is the challenge of monitoring the low-emittance particle beams necessary to such studies. The Brookhaven ATF is being constructed to produce a 50- to 100-MeV electron beam with higher brightness than presently available. The first phase, nearing completion, is the production of a 5-MeV beam from a laser-stimulated photocathode in an rf gun. It will be necessary to characterize the beam produced by the gun and transported through the linac-injection line in order to verify that the expected beam quality has been achieved and to match the beam to the linac.

Initial studies will concentrate on the high-current beam which will consist of a nanocoulomb of charge in a pulse of 3-psec r.m.s. length. The expected transverse geometric emittance of about 1 mm-mrad necessitates a profile-monitor with good spatial resolution and, in some situations, sensitivity to individual electrons. Such a monitor has been developed and will be used to determine the transverse and longitudinal emittances.

Monitor Design

The monitor design is shown in Fig. 1. A phosphor screen is deposited on a thin (25 μm) aluminum-foil substrate. The screen is placed in the beam pipe perpendicular to the beam axis so that the beam impinges on the foil and exits through the phosphor layer. The 5-MeV electron beam excites the phosphor, producing an optical image of the beam spatial profile. This image is deflected out of the beam line by a mirror at a 45° angle to the beam axis. The image passes through a vacuum window and into the optics of a CCD camera (with an optional image intensifier). The RS-170 video signal is digitized and stored by a framegrabber card residing in a PC-AT computer, which will control the monitor system and analyze the beam profile images. The phosphor screen and mirror assembly will be withdrawn from the active beamline by an actuator during running conditions.

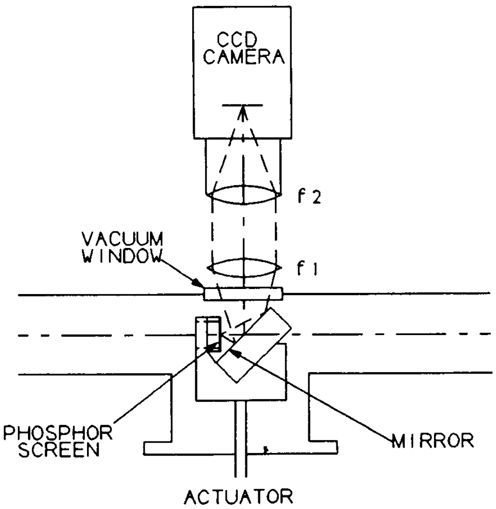

Fig. 1. The ATF beam-profile monitor

The phosphor,[1] Gd_2O_2S:Tb, was selected for its ability to form layers of uniform thickness and for its radiation hardness.[2] It is deposited on the foil substrate using the procedure recommended by GTE/Sylvania. The emission spectrum peaks sharply at 545 nm. It has high efficiency (one scintillation photon per 20 eV of deposited energy) and a decay time of a few milliseconds. The packing density is about 3 gm/cm^3 with grain sizes of 8–10 μm. The radiation length is 8.5 gm/cm^2. The phosphor was not found to be visibly damaged by the passage of 10^{17} minimum-ionizing electrons in a square centimeter. Only slight damage was found[2] after 2×10^{18} electrons/cm^2.

The profile is viewed head-on since the beam enters the phosphor screen from the back. Multiple scattering of 5-MeV electrons in the foil introduces an r.m.s. transverse displacement of less than a micron, which can safely be ignored. The thickness of the phosphor layer will be determined by balancing the need for sufficient light output, which is proportional to phosphor thickness, with that of good resolution, which is degraded with increasing phosphor thickness. A typical thickness of 30 μm (10 mg/cm^2) will be assumed for this discussion.

The beam profile is imaged onto the CCD (or image-intensifier photocathode) by a pair of lenses. A video lens (f2 in Fig. 1) is mounted normally on the camera. A wide-aperture 35mm camera lens (f1 in Fig. 1) is mounted directly in front of the video lens so that the front optical elements of the two lenses are facing each other. Both lenses are focused at infinity. The back focal element of lens f1 is placed very near the optical vacuum window so that the screen is at the focal plane of the lens. This allows the optics to be as close as possible to the screen, maxi-

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mizing light collection. The image magnification is given by the ratio of the focal lengths of the two lenses, f2/f1. The lenses used at a particular diagnostic station will depend on the average beam parameters at that point.

The camera[3] is a SONY unit (using the CCD chip ICX018CL) which has been modified so that an image can be collected for a variable number of video frame cycles, controlled by an IBM PC. The video amplifier has also been redesigned to reduce readout noise to just under 1 ADC count out of a range of 255. The camera is found to have good linearity.

The image intensifier[4] will be used when the beam intensity is low, as will be the case at the longitudinal emittance monitor. It has a gain of 10,000–50,000, offering sensitivity to individual electrons, but with a resolution limited to about 50 μm FWHM.

The framegrabber[5] has two 512 × 512 × 8 bit video memories and uses a flash ADC to digitize a video frame. It plugs into the IBM PC.

We now give an estimate of light output. In a 30-μm layer of phosphor, a 5-MeV electron loses 17 keV, releasing an average of 850 photons. The 35mm camera lens (f1) which was used in the laboratory measurements and which will be used in some ATF profile-monitor configurations is a Nikkor f/1.4 35mm (focal length). This lens collects about 3% of the light emitted isotropically from the focal plane, and about 25% of the collected light is attenuated by reflection losses in the two lenses and optical window. (The apertures of the lenses are of similar sizes so that there is little vignetting of the collected light by the video lens.) This leaves about 18 photons incident on the CCD, which has a quantum efficiency of around 20% (the silicon has an efficiency of about 40%, and half the area of the CCD is obscured by the interline transfer-busses). The phosphor is spectrally well-matched to the peak response of the CCD. So about 4 charges are liberated in the CCD per beam electron. The framegrabber requires approximately 1000 charges in a pixel to register one ADC count, corresponding to 250 beam electrons.

A beam of 10^{10} electrons in an area of one square millimeter corresponds to about 2×10^6 electrons per pixel (assuming 1:1 magnification). This would be the equivalent of 8000 ADC counts in each pixel. Since the framegrabber has a range of 255 counts, the lens would have to be stopped down to f/8 to avoid saturation. The ATF monitor will include the ability to remotely change the f-stop of the 35mm lens.

If the beam is attenuated by a factor of 10^4, as will be the case in the longitudinal emittance measurement, the image intensifier will be needed. It has an S20-ER photocathode, which has a peak efficiency of 10%. The spectral matching factor between the phosphor and photocathode is 0.95. The total gain, including the photocathode response, is a maximum of 50,000. A photon which liberates a photoelectron results in up to 500,000 photons incident on the CCD, which detects 100,000 of them. The resulting 100 ADC counts are clearly detectable above the camera readout noise, so the intensified camera does have single-photon sensitivity. The 18 photons per beam electron incident on the photocathode yield about 4 photoelectrons or 400 ADC counts, so individual beam electrons can be detected. This has been confirmed by laboratory measurements as described below.

Emittance Measurement

The methods of measuring the transverse and longitudinal emittances which will be implemented at the ATF have been described elsewhere.[6] A brief overview follows.

The ATF injection line is shown in Fig. 2. A photocathode in an rf cavity is driven by a NdYag laser. It produces 5-MeV electrons in nanocoulomb bunches of r.m.s. duration 3 psec. The defocusing rf force at the gun exit causes the electrons to exit with a large angular divergence, so it is necessary to focus the beam as soon as possible. This is done by the quadrupole triplet Q1-Q2-Q3. The 90° bend at dipole D1 results in momentum dispersion between the two dipoles, and dipole D2 reverses this dispersion before the beam is injected into the linac. A slit between D1 and D2 selects the beam momentum and momentum spread. The triplet Q6-Q7-Q8 focuses the beam as needed for diagnosis or injection into the linac.

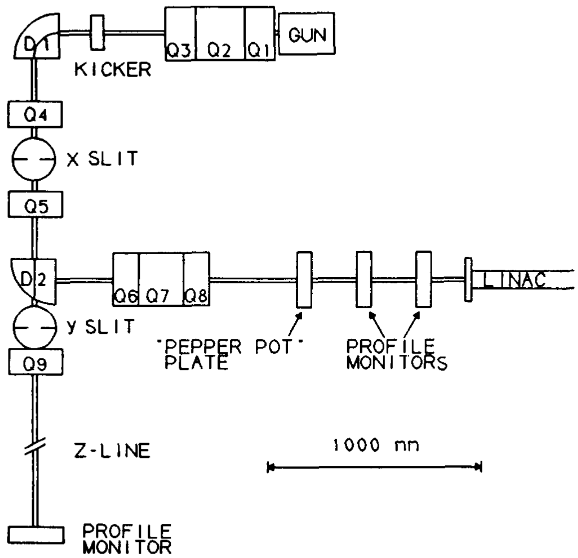

Fig. 2. The ATF injection line

The 5-MeV beam will be monitored at two stations placed between dipole D2 and the linac entrance. The transverse emittance will be measured in this region using one of two methods. The first is to take the beam's profile under several different transport conditions. The conditions are varied either by allowing the beam to drift different distances (requiring several monitors) or by changing the focus on one monitor by altering the strength of an upstream quadrupole magnet. The second method is the so-called 'pepper-pot' technique in which a selection screen, which collimates the beam into smaller individual beamlets, is placed upstream of a profile monitor. The transverse geometric emittance can be found from the resulting profile of a single beam pulse. The first method requires at least three beam profiles obtained during separate pulses.

If the second dipole magnet is turned off, the beam passes into the 'z-line,' in which the longitudinal emittance is measured. This is accomplished in a single pulse using a profile monitor in conjunction with an rf 'kicker' cavity, which gives the electrons a vertical deflection that is correlated with their time of arrival. Since the momentum spectrum is mapped onto the horizontal axis by the first dipole, the longitudinal phase space is converted into a transverse profile, from which the longitudinal emittance may be found directly.

Spatial Resolution

The 5-MeV beam from the ATF electron gun should have a transverse emittance of around 1 mm-mrad. This means beam sizes of several millimeters are common, ranging down to 100 μm at a waist. The relative precision with which the emittance can be measured is essentially determined by the ratio of the profile-monitor resolution to the size of the beam when brought to a waist at the monitor.[6] Thus high-resolution monitors are a requirement of low-emittance beam diagnostics.

The resolution of the ATF monitor has been investigated under conditions approaching the beamline environment. While each element of the monitor system affects the final image quality, the dominant factors are the thickness of the phosphor screen used to image the beam, as well as the inclusion of the image intensifier.

The quality of modern camera-lens optics is such that the smallest feature that can be faithfully imaged by the CCD camera with a standard CCTV lens is determined by the size of the CCD pixels, 17×13 μm^2 in this case. This was verified by imaging a test pattern consisting of light and dark horizontal line pairs. When the magnification was such that the width of the image of a single line on the CCD was the same as that of a pixel, vertically adjacent pixels alternated between high and low digitized values.

The monitor design was tested by placing a screen, 45° mirror, and optics (f2/f1 = 50mm/35mm) in the same arrangement as will be used in the beam monitor. The 5-MeV beam was mimicked by a collimated β^- source, ^{90}Sr. This beta-decays in two steps yielding electron spectra with endpoint energies of 546 keV and 2.28 MeV. The electrons pass through the aluminum foil and phosphor, depositing an average of 1.6 and 1.3 MeV-cm^2/gm, respectively. Five-MeV electrons deposit 1.7 MeV-cm^2/gm. The β^- intensity was low enough that individual electron 'hits' were seen in each image collected over 2 video cycles (1/15 second). In this manner the image size of an individual electron passing through the monitor could be measured. This was chosen as an appropriate measure of the resolution of an electron-beam profile monitor.

Screen thicknesses ranging from 15 μm (5 mg/cm^2) to 90 μm were used to study the effect of phosphor thickness on resolution. The image of each electron consisted of a cluster of photons rather than a smooth source of finite extent. The size of each cluster was characterized by integrating the 2-dimensional image along the horizontal and vertical axes to obtain 1-dimensional profiles. The r.m.s. deviation from the mean (standard deviation) of each profile was calculated. The resulting widths were averaged and corrected for magnification and CCD pixel size to obtain the monitor resolution.

A primary cause of smearing in the light from a polycrystalline phosphor is 'blooming.' As light emitted within a phosphor layer propagates, it is scattered by crystals of the phosphor, which have a different index of refraction than the surrounding air. This gives a random-walk character to the path of a photon escaping the layer. Scattering and absorption also result in attenuation of light propagating through the phosphor. The attenuation length of green light in Gd_2O_2S was measured by passing a He-Ne laser beam with peak wavelength 543 nm through various thicknesses of the phosphor. The beam was attenuated as $\exp(-t/\lambda)$, where t is the phosphor thickness. The attenuation length λ was found to be 50 mg/cm^2 (150 μm).

The effect of multiple scattering on the lower-energy decay electrons is more severe than for the 5-MeV beam electrons. The Sr-decay electrons suffer an average r.m.s. deflection (in a plane) of 10 μm in the 30 μm screen, whereas this value is reduced to 1 μm for 5-MeV electrons. This contributes in quadrature to the resolution due to the screen. In addition, the image intensifier contributes a Gaussian width of about 20 μm to the image at the intensifier, primarily due to the phosphor which converts the amplified electron avalanche back into an optical signal. This figure must be divided by the magnification of the imaging optics to represent the effective width contribution at the monitor screen. This also adds in quadrature to the final resolution.

The total resolution of the system with a 30-μm screen was found to be 45 μm, corresponding to the standard deviation of an assumed Gaussian profile. The thinner screens show a progression of resolution widths which can be interpreted as a base resolution of 35 μm due to the detector optics, and a contribution in quadrature of t from a phosphor screen of thickness t. The increase in image size is less pronounced in thicker screens since an increasing amount of light emitted from deeper within the phosphor is scattered completely out the collection region.

The monitor system described above should prove adequate to the task of emittance measurement at the ATF. Both in terms of sensitivity and resolution, an electron beam with 1 mm-mrad transverse emittance brought to a waist of 100 μm should be well-characterized by this diagnostic.

Acknowledgments

We would like to thank Stan Ulc and Bill Groom for their work on the design and construction of the monitor system, and Brek Miller for his assistance in data collection and analysis. This work was supported in part by the U.S. Department of Energy under contract DE-AC02-76ER-03072.

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