BEAM CHARACTERIZATION WITH VIDEO IMAGING SYSTEMS AT THE ANL 50-MeV H^- BEAMLINE*

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Abstract

Video imaging systems consisting of scintillators and charge-coupled device (CCD) cameras and in-beam CCD detectors are being used to characterize beams at the Argonne National Laboratory (ANL) 50-MeV H^- beamline. The characterization technique consists of placing pinholes, slits, or wires in the beam and then viewing the resulting images or shadows on a downstream scintillator or CCD. The images are digitally recorded using a frame grabber. The images are stored in computer memory where they are analyzed to determine Twiss parameters and local beam divergence. Since many of these measurements involve low intensity beams and require good position resolution, studies have been performed on scintillators to obtain sensitivity and resolution data. Various scintillators, including Rarex, CsI, and CaF_2, have been evaluated. An in-beam CCD imager has also been tested.

Introduction

Video imaging systems consisting of 1) scintillators and CCD cameras and 2) in-beam CCD detectors are being used to characterize beams at the ANL 50-MeV H^- beamline [1]. Video systems have long been used to monitor the spatial profile of charged particle beams in beam transport systems. With the advent of inexpensive, high quality video imaging systems and the widespread availability of powerful online computer systems, it has become practical to extract additional beam characterization information from video images in near real time. The characterization technique involves placing a mask in the beam and viewing downstream the resulting image to determine the emittance, divergence, or beam aberrations.

The beams to be characterized at the ANL beamline are produced by a 50-MeV linac. Pulse widths up to several hundred μsec and repetition rates up to 30 Hz are being used. Beams with current densities as low as a few hundred nA/cm^2 and as high as an A/cm^2 and diameters as large as tens of cm are being imaged. The beam characterization techniques often require high sensitivity detectors with good position resolution. A scintillator-based CCD diagnostic has good sensitivity and position resolution and a large dynamic range. An in-beam CCD can detect single protons and has excellent position resolution, but the dynamic range is limited. The two systems that are currently being used are described in the following sections.

Scintillator Beam Diagnostic

A schematic of a typical scintillator based beam characterization system is shown in Figure 1. The system consists of a beam mask, a fluorescent screen, a camera, and a computer-based image acquisition and analysis system. The mask may be composed of pinholes, slits, or wires. A neutralizing foil and sweep magnet are placed between the mask and the scintillator to produce a neutral beam which is not affected by stray magnetic fields. For a 50-MeV H^- beam, the optimum thickness for maximum neutralization is about 5 $\mu g/cm^2$ for carbon foils. The image of the mask is viewed on the downstream scintillator.

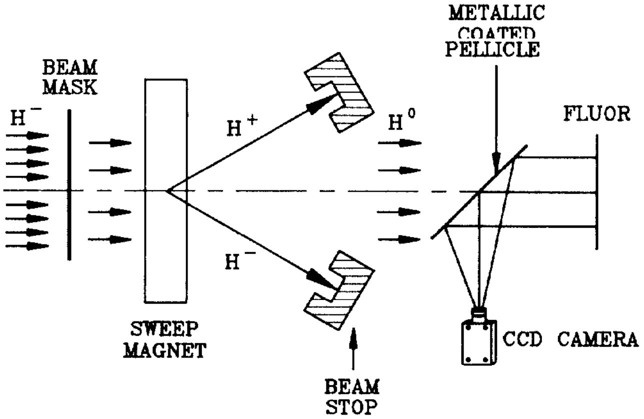

Figure 1: Schematic diagram of a beam diagnostic system based on a mask, scintillator, and CCD camera.

In order to optimize the video diagnostic system, it is necessary to use a fluorescent material which matches the optical characteristics of the camera. In the system used at ANL, CCD cameras are employed. The major performance benefits of a CCD imager relative to a vidicon are the essentially zero geometric distortion and reduced blooming. The standard CCD has very low quantum efficiency for wavelengths less than 400 nm, unless special coatings are used.

Samples of various fluorescent materials have been examined. The parameters of interest are the amplitude and spectral distribution of the emitted light, the fluorescence decay time, and the spatial resolution. The scintillator screens used in the ANL diagnostic system are fabricated using various preparations of $Gd_2O_2S(Tb)$. This material is among the brightest of the many materials tested. It is commercially available from MCI Optonics under the trade name Rarex BG. Rarex BG Regular is fabricated with a reflective backing to maximize light output. Rarex BG Fine uses half the thickness of fluorescent material and a light absorbing backing to optimize spatial resolution. The relative video amplitudes and spatial resolutions were recently measured for Rarex BG Fine, Rarex BG Regular and a 1-mm-thick sample of $CaF_2(Eu)$. The relative brightness, as observed with a Sony XC-77 camera are 0.32, 1.0, and 0.58, respectively. The spatial resolutions (FWHM) are 114, 392, and 120 μm, respectively.

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The scintillator image is acquired by a Microvax II data acquisition system using commercial CCD cameras (Sony XC-39 and XC-77) and a frame grabber board (Imaging Technology FG-100Q). The system is based on the RS-170 video standard. The cameras use interline transfer CCDs with 485 rows. The XC-77 has 768 horizontal picture elements; the XC-39 has 384 elements. The cell size for the XC-77 is 11.0×13.4 μm; the size for the XC-39 is 23.0×13.4 μm. Both cameras allow external sync. The automatic gain control is turned off. The gamma is set to one so that the output voltage is proportional to the charge generated in the cell.

Since the beam pulse from the linac is synchronized to the AC line, a sync generator is needed to slave the camera to the line and trigger the frame grabber.

The frame grabber, which is on the Q bus of the computer, has two pages of 640×480 memory. The frame grabber digitizes the input video to eight bits. However, the video information for a pixel is stored in 12 bits so that false color and other enhancements are possible. The image is displayed on a standard RGB monitor.

The video diagnostic system is used to determine the beam characteristics from the mask image on a downstream scintillator. This requires that the optical system be calibrated to relate the image pixel positions to scintillator positions. Precision optical patterns are imaged and correction coefficients determined.

An interactive image acquisition and analysis program has been developed for the Microvax II using the Imaging Technology ITEX 100 library. This program allows the user to utilize typical image acquisition features such as image zoom, panning the image, 2-D to 1-D profile projections, and image enhancement filters. In addition, capabilities have been added which are specific to the acquisition and analysis of beam images. Among these are procedures to locate, window, and perform moment analysis on beamlet images. A FFT routine using a Cooley-Tukey algorithm, was developed to automatically identify images above the background noise. Interactive analysis procedures enable the user to enter data on the geometric arrangement of the mask-fluor system and calculate the beam parameters. This system was used with a pinhole plate to determine the Twiss parameters of a beam entering a telescope [2]. Figure 2 shows an example of a pinhole image that was used to determine the Twiss parameters.

Pinhole images have been obtained for beams with current densities of a few hundred nA/cm^2 for a pulse width of about 100 μsec. Spatial resolutions for the high resolution scintillators of close to 100 μm have been obtained. The scintillator-based CCD imager has a broad dynamic range. Beams with current densities as high as A/cm^2 have been imaged, but the scintillator degrades rather rapidly.

In-Beam CCD Detector

The possibility of using a CCD as a precision detector array for charged particles was first evaluated in 1981 [3]. Since that time, various groups have worked in this area [4]. One application that has received a considerable amount of attention is their use in vertex detectors for high energy physics research [5]. In general, these programs have used specially designed readout electronics and have used special noise reduction techniques, such as cooling, to reduce the noise. For our application, we wanted to determine if it were possible to use a simple, commercial CCD camera operating at a horizontal sweep frequency of 15750 Hz with 60 fields/sec and 2:1 interlace as a particle detector.

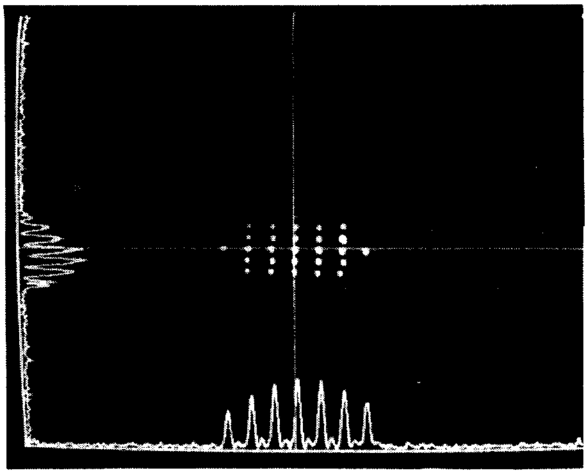

Figure 2: Image of a pinhole mask that is used to determine the Twiss parameters.

We chose a Sony XC-39 camera. Figure 3 shows the basic structure of the CCD. This particular camera uses interline transfer. The photosensors are placed next to vertical shift registers. This keeps the size of the array small. The sensitive area is 8.8 mm wide and 6.6 mm high. The charge from each of the photosensors is transferred to its companion vertical register at the same time. The vertical shift registers are then shifted one row at a time to the horizontal shift register which communicates to the outside world through an output amplifier on the chip. The photosensors are able to collect charge during this time. During normal operation as a camera, almost all the charge is collected in the potential wells located below the photosensors. For the typical CCD, this region extends about 10 μm below the surface and is called the depletion depth. Below the depletion depth is a region of undepleted epitaxial silicon that is also about 10 μm thick. About half of the charge created in this region

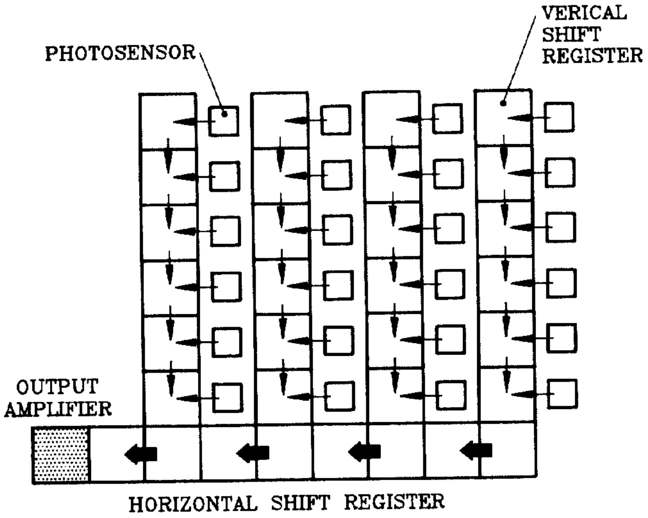

Figure 3: CCD structure for an interline CCD.

diffuses into the depletion region where it is collected. The electrons and holes that form below the top 20 μm in the substrate, which is typically a few hundred μm thick, quickly recombine. Thus, the effective sensitive region of the CCD for charged particles passing through it is about 15 μm thick.

The CCD detector has been used at our facility to image H^-, H^0, and H^+ particles. A 50-MeV H^- is like a 50-MeV proton and two 27-keV electrons. The range of a 27-keV electron in silicon is about 5 μm. Some of this energy loss will be in the depleted region, since the dead layer is probably no more than a few μm thick. Thus, it is reasonable to assume that for an electron about 20 keV is lost in the depleted region. The energy loss for a 50-MeV proton is 2.3 keV/μm, which is about ten times the energy loss of a minimum ionizing particle. The energy loss of the proton in the CCD is thus about 30 keV. Most of the experiments that we conducted used H^0 particles, so that the total energy loss would be about 50 keV in the sensitive region. Since 3.3 ev are required to form an electron-hole pair in silicon, each H^0 will create about 15,000 e^-. Since the noise level for this type of camera is typically about 1000 e^-, individual protons are easily detected.

Because the CCD is basically a charge storage device, the individual cells can hold only a certain amount of charge before saturation. The typical well depth for CCDs with the size pixel of the XC-39 is a few hundred thousand electrons. Thus, a pixel will saturate if struck by a dozen or so H^0 particles. The dynamic range is thus rather limited. Even with this limitation, the high sensitivity and excellent position resolution, make this the detector of choice for certain special applications.

One of the experiments conducted on the beamline involved imaging a narrow long slit to determine the divergence of the beam. A Sony XC-39 camera, including the electronics, was placed in vacuum. The only modification to the camera was to break the cover glass on the CCD and to move the electronics outside the beam. Figure 4 shows the image of a slit that is 25 μm high and 3 mm wide. Some of the bright spots in the wings are probably individual protons. The traces along the axes are the intensities for a single row or column. Some of the brighter pixels have intensity values that are near saturation. We have also imaged pinholes as small as 10 μm diameter with the detector.

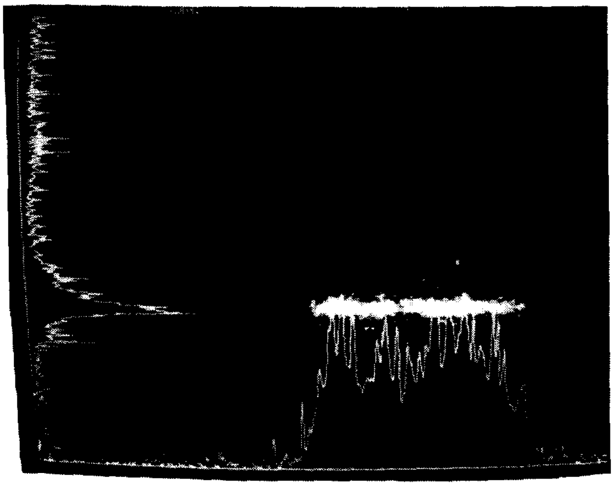

Figure 4: Image of a 25-μm high and 3-mm wide slit collected with an in-beam CCD detector.

Conclusion

Modern video imaging systems allow beam characterization studies to be carried out in near real time. At the ANL 50-MeV H^- beamline, scintillators and CCD cameras are used to determine the Twiss parameters. An in-beam CCD has been used to measure beam divergence. This detector can register individual protons and has excellent resolution. However, these detectors are rather small in size and have a limited dynamic range.

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