Design of the Beam Profile Monitor System for the RHIC Injection Line*

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Abstract

A video profile monitor (VPM) system will be used in the AGS-to-RHIC (ATR) transfer line to acquire single bunches transferred at 30 Hz. An array of 12 video cameras will be connected to 4 frame grabbers through a wide-band mux. Fast VME image processing boards will analyze a 120x120 subset of the image, generated by a 4x4 convolution or an ROI computation and sent over the network during the AGS recycle time. Details of the design, results of lab tests and studies with ion and proton beams will be presented.

I. INTRODUCTION

The VPMs will monitor extracted beam shape and measure profiles with 2.5σ diameters varying from 4.4 to 18 mm. RHIC intensity will range from 10^9 Au^{+79} per bunch, to protons at 10^{11} per bunch. Three gold bunches or from 8 - 12 proton bunches will be accelerated each AGS cycle, then individually extracted at 30 Hz. The full AGS intensity of 6 x 10^{13} per cycle will be carried in the upstream portion of the line where 2 of the VPMs are located. VPMs, or "Flags" will be used because the beam widths are too small for multiwires and single scanning wires can't measure single bunches. By acquiring profiles at 4 locations on each transit the emittance of individual bunches can be measured if low mass screens are used to minimize scattering [1]. All 12 camera outputs are brought to a central frame grabber/image processing location over wideband analog fiber-optic links to preserve resolution.

II. FLAG DESIGN

The flag, mounted at 45°, is inserted to the center of the beam pipe using a 4" stroke pneumatic drive. To simplify alignment and lower cost, the drive and 4" viewing window are mounted on the same 8" conflat flange[2]. Two small windows on either side of the viewing port, angled at the flag, illuminate fiducials on the screen for calibration.

To see a single bunch per frame the phosphor must decay fully in less than 33.3 msec. The screen consists of a 0.002" thick coating of Gadolinium Oxy-sulfide doped with Terbium (Gd_2O_2S:Tb) on a 0.001" aluminum foil substrate with a potassium silicate binder. It fully decays in 2 msec and has good sensitivity. Tests at SLAC [3] indicated no damage at 0.8 x 10^{18} elec/cm^2 but flaking was observed at 2.5 x 10^{18} elec/cm^2. Similar mechanical failure has been seen at the BNL ATF facility [4]. D.Sagan of CESR [5] pointed out that barium acetate, a binder component used by SLAC (and ATF), is not recommended with a metallic substrate. A screen made without barium acetate appeared to be more durable and was tested in the Booster-to-AGS (BTA) line. Screens made in this way at ATF showed reduced flaking, but less adhesion than the BTA screen, possibly due to a different concentration of potassium silicate. Failure due to beam is not observed at ATF. Because of the lack of lifetime data, screens of 1 mm Al_2O_3:Cr will be used for 2 upstream units exposed to the full AGS intensity. These will not be used during an emittance measurement as they put too much mass into the beam and have long light decay time. The Gd_2O_2S:Tb flags should have several years lifetime for RHIC beam intensities. Fiducials consisting of 3 holes (0.015" diameter) in a line 1 mm apart, with 5 mm between lines, were made on the Gd_2O_2S:Tb flags using a numerically controlled laser. Similar patterns for the Al_2O_3 screens were scribed with a pencil.

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III. VIDEO CAMERAS

Standard TV cameras operate in "field" mode with odd and even lines acquired over alternate 16.67 msec periods, then interlaced to produce the full frame. The 2 msec beam flash would appear on alternate lines, halving the vertical resolution. The ATR cameras must allow "frame" acquisition, with all lines active for the full period. Other considerations include: resolution, sensitivity, signal-to-noise (S/N) ratio, linearity, pickup uniformity and radiation tolerance.

Vidicon tubes can withstand 10^7 Rad but suffer in uniformity, linearity and sensitivity compared to CCDs. CCDs have a low tolerance to radiation (10^2 to 10^3 Rad) but good uniformity, linearity and sensitivity. Charge Injection Device (CID) arrays can withstand 10^5 Rad but are 1 - 2 f-stops less sensitive and considerably more expensive. CCD cameras will be used in most locations, shielded behind 18" of heavy concrete or, in 5 locations, in 14" pipes inserted into the tunnel walls. In the worst radiation area near the AGS, a CID camera will be used.

A number of CCD cameras and a CID camera were tested using a TV resolution chart. Only relative comparisons were practical since the effect of the lens could not be decoupled from the camera resolution. The CCD camera selected was the Pulnix TM-7CN. The CID camera was the CIDTEK model CID-3710D, with RS-170 option. Both have frame acquisition and can be triggered to synchronize them with the beam, and have S/N ratios in excess of 50 dB to match the 8-bit resolution of the frame grabbers.

IV. OPTICAL DESIGN

The camera will be located as far as practical from the beam to reduce radiation damage, requiring an optical relay to match the flag image to the camera pickup. While the SLAC design[6] using a segment of a parabolic mirror was very elegant, a planar mirror and a single 35 mm-camera lens will be used to simplify alignment. The field of view for each flag is about twice the 2.5σ beam diameter, the actual size depending on the closest lens focal length available. Most locations use a Celestron 500 mm f/5.6 reflector lens but the first flag requires a Celestron 1000 mm f/8 mirror lens. A 400 mm f/5.6 Sigma APO lens will be used at one location with a large beam width. At half of the locations the cameras will be rotated 90^o to better match the beam aspect ratio. Since the displays will be digitally regenerated, the correct beam orientation will be re-established by the computer.

Because the beam in the upstream portion of the ATR line will vary over about 3 decades a means of adjusting the light on the camera is required. A typical lens will only cover a range of about 32:1. Special lenses with graded neutral density center spots have a range of about 3 decades but these motor driven lenses are quite expensive. A simple mechanism was designed using small solenoids to insert up to 4 neutral density (ND) filters between the camera and lens. By choosing these to transmit 50, 25, 10 and 1% of the light, a range of 8000:1 can be covered with a simple digital interface.

The lens and camera and filters sit on an optical rail using commercial optical mounting hardware, allowing precise replacement in the tunnel. The optical rail is on a cradle which pivots in azimuth and elevation about the lens center. Translation along the beam line is also provided.

In most locations the vacuum tee housing the flag will be mounted with the viewing port facing down. This protects the window and mirror from dust and places the camera near the floor where it is more easily shielded. A front surface mirror mounted at 45^o on the tee stand base reflects the image normal to the beam line to the tunnel wall where the camera is located. It is adjustable in angle and height and translates in X and Y. Because of local conditions the first two flags require a second mirror.

The optical system will be aligned with a "leveling" laser [7] replacing the camera and lens, which can be precisely reinstalled. Using penta-prisms, which tolerate angular alignment errors, to deflect the beam 90^o, and a "hanging" mirror, which self-aligns vertically, the optics can be leveled and squared so the laser reflects back on itself off a mirror placed on the viewing port.

V. SYSTEM RESOLUTION

The overall resolution is limited by: Depth of Field, Camera (H and V) and lens resolution. Phosphor screen grain size, air waves and mechanical vibration, a factor in measuring beams of tens of micron size, are not significant for the ATR beam sizes which range from 4.4 to 17.8 mm diameter. Depth of field is a factor because the screen is tilted at 45^o with the top at a different distance from the lens than the bottom. This matters if the beam is well off center or large. In the latter case, however, finer resolution isn't required. Camera resolution is limited by the number of pixels in the array and the readout electronics bandwidth. The overall resolution was calculated using the manufacturer's data for the cameras and lenses and the parameters of the beam and optical path for each location.

Using an USAF resolution chart, both cameras were tested with the actual lens and distance from the flag. Using the Rayleigh criterion, the measured resolution was about two times worse than calculated. It is not clear what criterion the manufacturers used for their data. However, this is still sufficient as it represents only 4% of the 2.5 σ diameter in the worst case. The best resolution measured was 150 µm over a 3 m optical path. A longer focal length lens would improve this somewhat.

VI. SYSTEM ELECTRONICS

Figure 1 shows a block diagram of the system electronics. The controls to insert the flags and the ND filters is located in the closest of 4 equipment houses. The outputs from the cameras and the synchronizing triggers go to a central location in the 1000P house. Here 2 VME modules, configured as a 16x4 MUX [8], allow any 4 cameras to be multiplexed into the VME based acquisition and processing boards. The cable runs (100' to 1400') could degrade the signal bandwidth and severely limit the horizontal resolution. To prevent this, analog fiber-optic links which are flat to ± 0.5 dB from <1 Hz to over 10 MHz were used. [9]

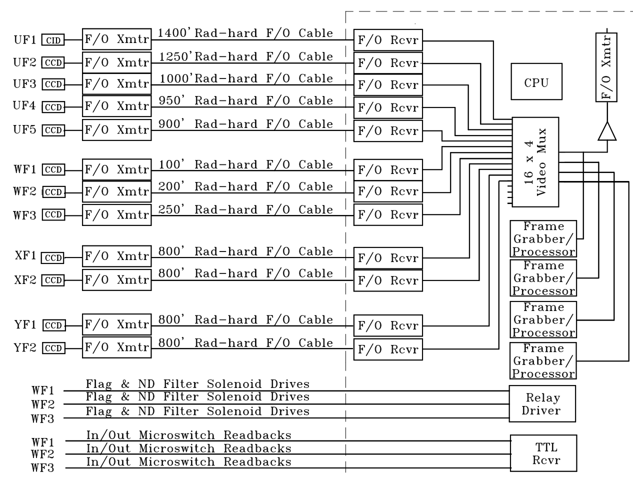

Figure 1. Video profile monitor system electronics

The acquisition and processing of the video is done using 4 Imaging Technology Inc. IMA-VME-4.0 boards with 4 AMVS-HS Acquisition modules, 2 CMCLU-HS Convolver-Arithmetic modules, and 2 CMHF-H Histogram/Feature Extractor modules. The system runs under VxWorks. It is able to store 48 512x512 frames, plus frames for background subtraction, and computational results. A reduced data mode allows operation on a 128x128 data subset derived from a 4x4 convolution or a region-of-interest (ROI) set by either the operator or dynamically from the data. The frames will be stored at 30 Hz and processed in the 2 sec AGS recycle period. Computations include: Pixel-by-pixel base frame subtraction, Centroid, H and V projections, and Sum of all pixels. After the data is analyzed the reduced frame and the computational results will be moved to conventional VME memory for off-line network transfer to a work station for display or analysis. Alternatively the full frame data can be sent to VME memory for detailed beam studies or testing the acquisition system.

VII. TESTS WITH BEAM

Early in the design a Gd_2O_2S:Tb screen was tested in the BTA line with Au^{+33} and proton beams. A Sony XC-57 CCD camera with a 385 mm Tele-Athenon lens was used with a 2-mirror optical relay. The optical rail was not used, but the flange with the flag drive and window was similar to the present design. Data was acquired with a Spiricon LBA-100A Laser Beam Analyzer[10] which contains a frame grabber and processor with firmware to generate a 2D or 3D false color display with projection, centroid and computations as well as background subtraction and guassian fits to the data. It can be controlled from the front panel or a IEEE-488 interface. The data can be processed at up to 15 Hz on a 120x120 sub-set or full frame at a reduced rate. While the LBA-100A showed great capability as a stand alone unit and performed well in the beam tests, it did not match the control system requirements and could not be used for the final design.

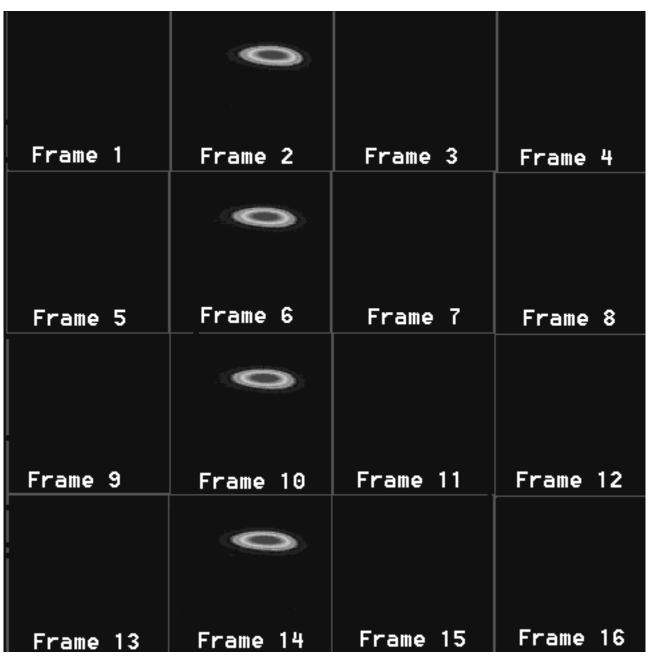

Figure 2. **Data from BTA tests. The 30 Hz framing captures the 7.5 Hz beam with no afterglow.**

Tests were run over a range of intensities of about 25:1 by adjusting the number of turns in the Booster. At the low end, injected bunch length was varied for a single turn. The data showed that the response was extremely linear over the intensity range for normal RHIC injection and studies intensities. Higher intensity could not be used due to lack of lens aperture adjustment. The lifetime of the Gd_2O_2S:Tb screen couldn't be established since the camera failed from radiation damage. Thermo-Luminescent Detectors (TLDs) on the camera were removed when the image first began to look "grainy" and read as 130 Rad. Total failure probably occurred within a dose many times this but it was not possible to retrieve the TLDs until long after the camera died. No damage was apparent upon visual inspection of the phosphor screen.

Using the LBA-100A with all computations off, frames were successfully acquired at 30 Hz. Figure 2 clearly shows no residual phosphor glow in the 3 frames between the 7.5 Hz Booster pulses, confirming the light decay rate would be suitable for single bunch measurements in the ATR.

VIII. STATUS

All optical and video components are on hand. A prototype cradle for the optical rail was built and tested and production has begun. The vacuum tees are installed as will be the flag flanges when the phosphor screens are done. The frame grabbers/image processing boards are being tested. The low level code to control the acquisition and perform the analysis is being developed. Full installation will be completed for the first extracted beam tests in the fall of 1995.

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