NONDESTRUCTIVE BEAM PROFILE DETECTION SYSTEMS FOR THE ZERO GRADIENT SYNCHROTRON*

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ABSTRACT

Two nondestructive beam detection systems have been devised which allow continuous observation of beam position and profile throughout the accelerating and targeting cycle. For a signal, both systems rely upon the ionization of the residual gas at approximately 1 x 10^{-6} torr by the proton beam.

One system consists of a phosphorized glass screen and an electrode placed above and below the beam respectively parallel to the plane of the beam. The liberated electrons are accelerated to several kiloelectron volts before striking the phosphorized screen. Light emitted by the phosphor gives a visual measure of the proton beam width without destroying the beam. The phosphorized screen is observed with a television camera.

The second system uses a strip electrode in place of the phosphorized glass screen. In this case, the ions are collected on the strips with approximately one kilovolt. The ion current from each individual strip is amplified to yield a signal proportional to the amount of beam residing over the strip at any given time. The signals from the strips are multiplexed for an oscilloscope display. Movies of both displays show interesting and previously unobservable beam behavior which is being studied in detail.

I. Introduction

Beam width measurements in a synchrotron have always involved intercepting part of the beam in some fashion. Such methods are time consuming and limited in value since dynamic measurements are virtually impossible. Described in this paper are two nondestructive detection systems which yield continuous beam position and profile information throughout the accelerating and targeting cycle.

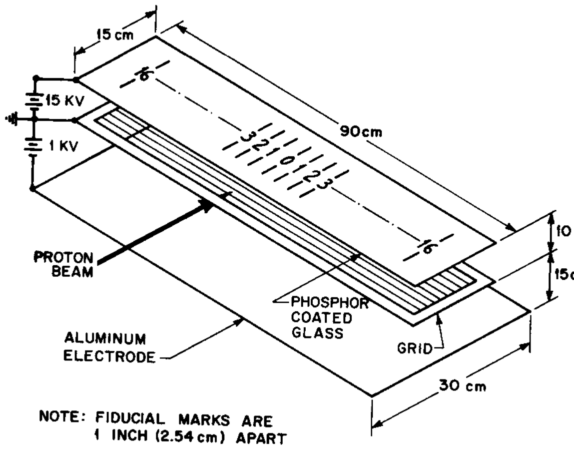
II. Principle of Operation

The vacuum chamber in the Zero Gradient Synchrotron (ZGS) is typically at a pressure of $1(10)^{-6}$ torr. At this pressure, approximately $3.2(10)^{16}$ gas molecules per cubic meter exist, a number of which are ionized by the proton beam. Using the Sternheimer range energy relationship[1] for 12 GeV protons in air and assuming that 30 eV of energy are required to form an ion pair, one finds that a circulating beam current of 300 mA, corresponding to approximately $1(10)^{12}$ protons in the ZGS, will liberate $1.9(10)^{13}$ ion pairs per sec (~ 3 μA) per meter length of proton beam in a gas pressure of $1(10)^{-6}$ torr. These liberated charged particles constitute a convenient signal; further, at a given proton beam energy, the number of liberated charged particles in a given volume is proportional to the amount of proton beam in that volume so that a signal bearing beam distribution information is available.

III. Phosphor Screen Detection System

A. Description

If the electrons liberated by the proton beam are accelerated by many kV to a phosphor screen, light is generated directly over the region occupied by the beam. The luminence is sufficient to be observed with a vidicon television system described later. Figure 1 illustrates the phosphor screen and associated electrodes. The phosphor screen has dimensions 15 cm azimuthally and 90 cm radially. It is spaced 10 cm above a parallel grid of the same dimensions which in turn is centered 15 cm above a parallel aluminum electrode of dimensions 30 cm by 90 cm. The proton beam passes between the grid and the electrode whose spacing is determined by the vertical aperture of the ZGS. The spacing between the grid and the phosphor screen is not important so long as it is sufficient to hold off the post accelerating voltage. In operation, the grid is grounded with the phosphor screen at +15 kV and the aluminum electrode at -1 kV. Such a scheme permits a large electron accelerating voltage resulting in high light output while maintaining a reasonably small electric field across the proton beam.



NOTE: FIDUCIAL MARKS ARE
1 INCH (2.54 cm) APART

Fig. 1 Phosphor Screen and Electrode Configuration

The screen is made of 6.35 mm (1/4 in.) glass coated with P-31 phosphor. In addition to high luminance, this phosphor has a medium-short persistence (40 μsec decay to 10 percent of its original luminance) and a spectral emission which closely matches the spectral sensitivity of the vidicon tube. The phosphor is aluminized for the usual reasons; first, a conducting surface is provided; second, more light is emitted since back scattered light is reflected by the aluminum coating; and finally, the phosphor is protected from contamination.

The screen and the electrode are located in the upstream end of a straight section box between two magnet octants of the ZGS.

The television system is a General Electric[2] 4TE3A2 camera chain containing an RCA[3] 7735-A vidicon pickup tube with an f/0.95 lens. Although not necessarily optimum for this purpose, this system already existed at the required location. The phosphor screen is viewed by the camera through a window in the straight section box. The camera is mounted about 1.5 meters from the beam detection screen.

B. Observations

Figures 2 and 3 are photographs of the beam image on the phosphor screen as seen on the television monitor. The beam width illustrated

Fig. 2 Beam Width For Intensity of $1.2(10)^{12}$ Protons Per Pulse as Seen on the Television Monitor

Fig. 3 Beam Width For Intensity of $7(10)^{11}$ Protons Per Pulse as Seen on the Television Monitor

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in Figure 2 is for an intensity of $1.2(10)^{12}$ protons per pulse, while the width depicted in Figure 3 is for $0.7(10)^{12}$ protons per pulse. Both photographs were taken when a pressure of $2(10)^{-6}$ torr existed in the chamber. At this pressure, beam images for intensities as low as $5(10)^{10}$ protons per pulse are observable.

Figure 4 contains plots of the beam width versus the guide field for two separate machine cycles, one with an accelerated beam of $1.3(10)^{12}$ protons and the other with an accelerated beam of $0.7(10)^{12}$ protons. These data were obtained from movies taken of the phosphor screen. Normal damping of the beam width follows injection for both intensities; however, for the larger intensity, a distressing growth near 8 kG is illustrated. In general, this situation always occurs in the ZGS for accelerated beam exceeding $1(10)^{12}$ protons per pulse. Studies with this system reveal an abrupt threshold in intensity for the onset of this growth. Below the threshold, no growth tendency is evident; however, for intensities above the threshold, the growth is large, sometimes causing beam widths to exceed the aperture of the machine. The threshold level appears to be related to beam steering.

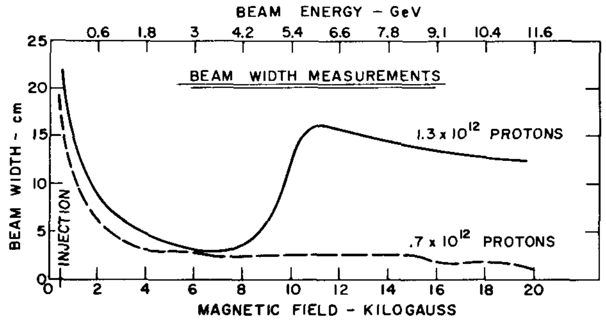
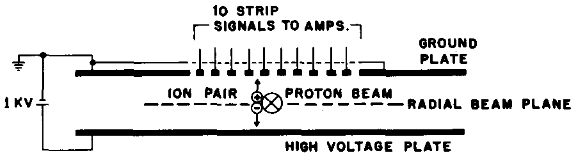


Fig. 4 Beam Width Versus Guide Field
For Two Different Intensities

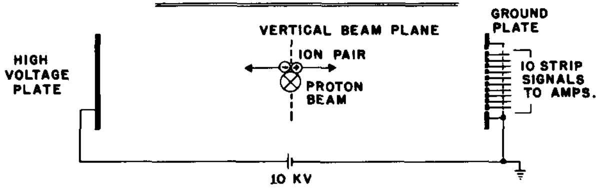
IV. Strip Electrode Detection System

A. Description

The radial and vertical detection schemes for the Position and Profile System (PAPS) are illustrated in Figure 5. Two plates are used in each case, one on each side of, and aligned parallel to, the plane of the beam being detected. By applying a high voltage, an electric field is generated between the plates. On the ground plates of both electrodes, ten insulated copper strips 10 inches long are mounted 0.1 inches apart with their lengths parallel to the movement of the beam. The strip width on the radial detection electrode is 1.5 inches and on the vertical detection electrode 0.5 inches. When the beam ionizes the residual gases, the electric field accelerates the ions (or electrons, depending upon the polarity of the voltage used) to the copper strips. Detection of these currents provides a measurement of beam location and distribution.



RADIAL DETECTION SCHEME



VERTICAL DETECTION SCHEME

Fig. 5 PAPS Strip Electrode Detection Schemes

The vertical electrode is illustrated in Figure 6. The plates must be 36 inches apart to accommodate the radial aperture of the ZGS. To obtain a uniform electric field and insure straight horizontal ion travel to the strips, gradient rods are used with resistor divider networks. To minimize fringing effects, the electrode extends 7 inches beyond each end of the strips. Since the plates of the radial electrode are only 6 inches apart, gradient rods are not used. To minimize electrostatic coupling with the beam, a transmission screen is used to shield the strips on both electrodes.

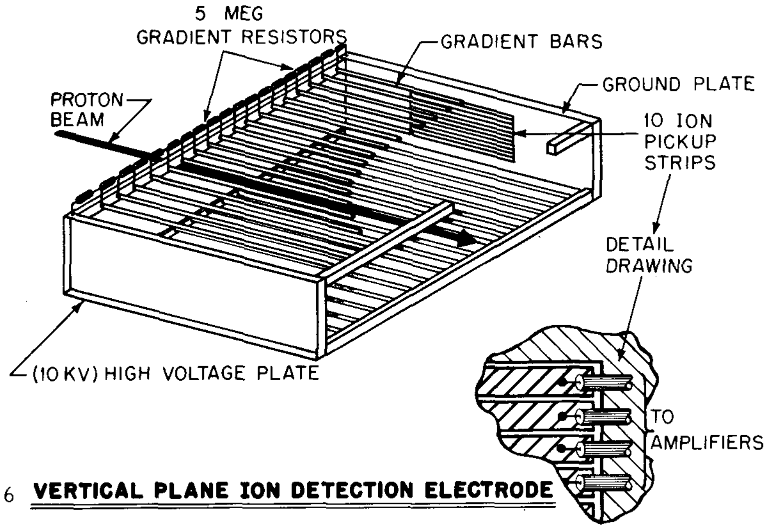


Fig. 6 **VERTICAL PLANE ION DETECTION ELECTRODE**

The strip electrode systems use ion rather than electron collection because it has been found that lower values of electrode high voltage are needed for beam detection. A minimum high voltage is still required to obtain accurate measurements when using ion collection. The minimum voltage for the radial detection electrode is 500 volts and for the vertical electrode 9 kilovolts. Values of voltage greater than the minimums do not change the detected beam profile. Flip targets have been used to confirm the accuracy of the systems.

The detected strip ion currents are converted to voltages and sent to the Main Control Room where they are multiplexed to a single multipurpose output, as shown in Figure 7. The overall system bandwidth is 30 kHz and the multiplexer sampling rate is 200 kHz. Radiation effects on the integrated circuit converters over several months have been minor. The multiplexer was designed for this specific application and has three modes of operation.

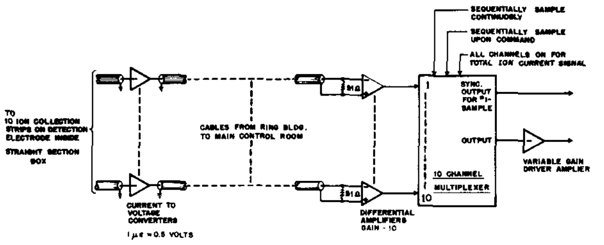


Fig. 7 PAPS Block Diagram

B Modes of Operation

In the first mode of operation, the multiplexer sums its inputs to give an output signal (Ion Sum) indicative of beam intensity.

Two useful displays are provided in the second mode of operation, where the multiplexer sequentially samples the ten strip signals continuously. The multiplexer provides a synchronizing signal every time the first strip is sampled. With this signal triggering an oscilloscope and the output of the multiplexer connected to the vertical input, a dynamic proton beam display is obtained suitable for high speed movies. Adjustment of the time base calibrates the oscilloscope display to the positions of the electrode strips.

The other display in this mode of operation is used to obtain a time display of the beam position and profile for the entire machine cycle. A 20 kHz sawtooth voltage is generated in synchronism with the multiplexer and connected to the vertical input of an oscilloscope. A series of adjacent vertical lines results since the horizontal time base is slow compared to the sawtooth frequency. Each vertical line can be visualized as being divided into equal segments with each segment representing a strip on the electrode. The vertical lines are then intensity modulated by connecting the multiplexer output to the Z axis of the oscilloscope so that the intensity of a given vertical line segment corresponds to the associated strip ion current. Vertical gain adjustment is used to calibrate the oscilloscope display to the positions of the electrode strips. Figure 8 is a photograph of the resulting display. The horizontal lines are the result of transients which occur when the multiplexer switches channels. Work is continuing on improving the resolution of this display.

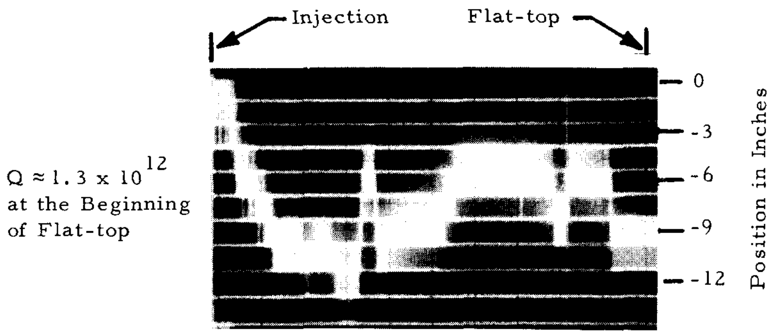


Fig. 8 Time Display of Beam Profile and Position in a ZGS Short Straight Section Box

The third is a triggered mode of operation where the multiplexer sequentially samples upon command providing measurements at chosen values of B field. The command signals are obtained from the ZGS Programmer System.

C. Observations

The Ion Sum signal and the slow Q intensity signal are shown in Figure 9. It has been found that at a pressure of $7.5(10)^{-6}$ torr, at 12.5 GeV, with a beam intensity of $1.5(10)^{12}$ protons the Ion Sum signal measures 24 μA of ion current. From previously published data,[1] it is found that for a fixed volume of gas at a given pressure the number of ion pairs increase approximately 25% as the energy of the incident beam of fixed intensity changes from 2.0 to 12.5 GeV. The Ion Sum signal in Figure 9 shows this increase. It also illustrates the usefulness of the signal in detecting unbunched beam. Slow Q shows a 90% reduction in beam during the improper flat-top slow spill targeting, while the Ion Sum shows a 60% reduction. At invert, which is the end of flat-top when the B field starts to fall, the 30% difference, which is the unbunched beam, is lost out of the machine. The remaining beam was used for a bumped spill on the falling field.

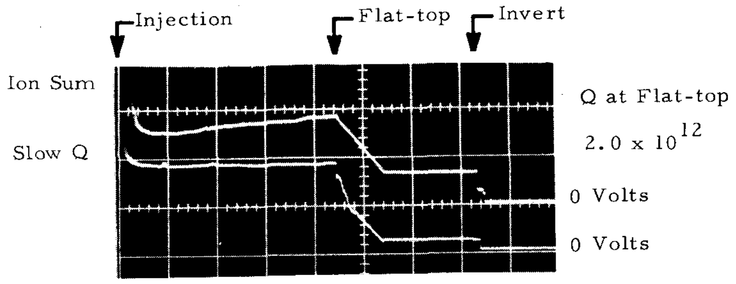


Fig. 9 Ion Sum and Slow Q Intensity Signals

Motion pictures have allowed detailed analysis of beam behavior throughout the acceleration and targeting cycles. Initial studies of this film indicate that the beam is approximately 0.25 inches above the vertical median plane for the first kilogauss after injection, and slowly moves to the median plane during the second kilogauss.

Using the triggered mode of operation, Figures 10 and 11 were obtained. In Figure 10 the device was triggered at 700 G and again at 2000 G during the same machine cycle to illustrate the vertical shift mentioned in the previous paragraph.

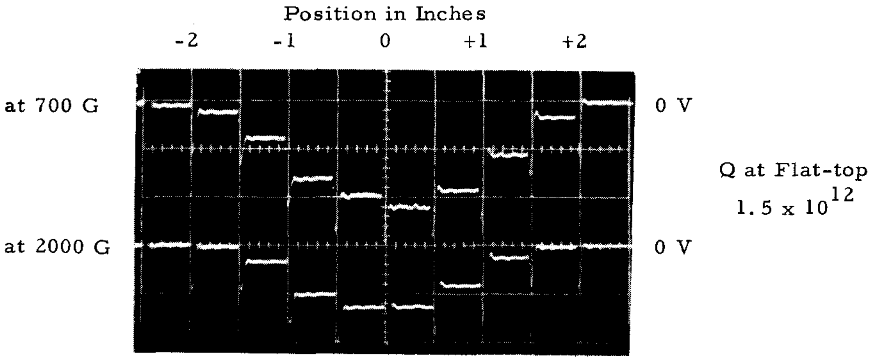


Fig. 10 Beam Vertical Position and Profile in a ZGS Long Straight Section Box

Likewise in Figure 11 the triggers were at 2.3 kG and at 10 kG to illustrate the radial growth which was indicated in Figure 4.

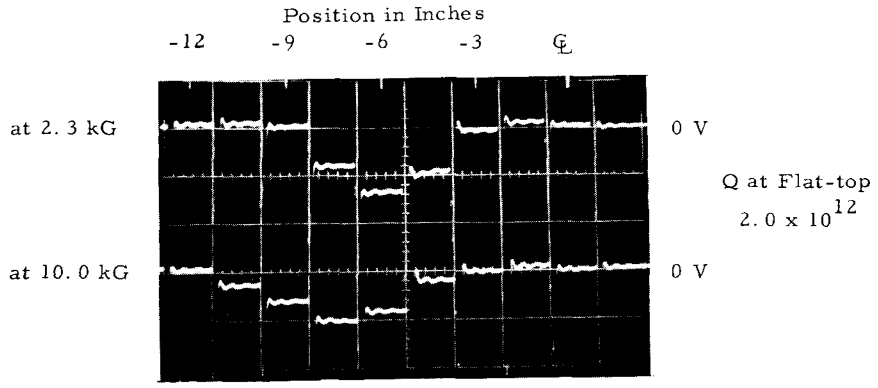


Fig. 11 Beam Radial Position and Profile in a ZGS Short Straight Section Box

Initial studies of injection show that the beam can be observed at this time using ion collection. To further these studies, system bandwidths are being increased to 200 kHz and multiplexer sampling rates are being changed to 1 MHz. Delay lines are required on the multiplexer inputs to achieve a simultaneously sampled output signal.

A similar system with a bandwidth of 200 kHz utilizing an electrode composed of two 1 inch long strips, is presently being tested at the high energy end of our linac. The two detected signals are simultaneously displayed on a dual beam oscilloscope. The position of the linac beam has been detected and preliminary studies indicate that the profile can be obtained. For a linac current of 16 mA at 50 MeV and a chamber pressure of 5×10^{-5} torr, the total ion current measured was 115 nA.

V. Conclusions

These systems are providing nondestructive measurement of beam profile and position in two planes. Previously unobservable beam behavior of significant importance is now studied in detail. The systems are being expanded to study the linear accelerator and external proton line.

VI. Acknowledgements

We should like to thank J. H. Martin for his thoughts as well as R. Daniels and L. Klaisner for their observations and assistance. In addition, A. Cook, D. Fearnley, and M. Missig were most helpful in getting the systems working.

References

1. Sternheimer, R. M., Phys. Rev. 115 (1959) 137.
2. General Electric, Industrial Electrons Division, Electronic Park Syracuse, New York.
3. Radio Corporation of America, Electron Tube Division, Harrison, New Jersey.

DISCUSSION (condensed and reworded)

K.H. Reich (CERN): What is the lifetime of the screen?

Daniels: We have not had any fail yet. We have replaced several of them because we changed the calibration marks. This means they have been in the machine for weeks.

Auld (British Columbia): What range of vacuum can you work at, at any given intensity, to keep the picture on the screen reasonably understandable?

Daniels: I do not know that we have checked this. The only thing I can say is that the lowest intensity we can see is about 5×10^{10}.

K. Kuiper (CERN): Is transverse smearing by the impact ionization negligible?

Daniels: Yes. This is indicated by the saturation effect above a minimum voltage.