A NONDESTRUCTIVE LINAC BEAM DENSITY PROFILE MONITOR*

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Introduction

Properties of the beam, emerging from proton linear accelerators, are normally measured with the aid of destructive diagnostic equipment such as slits and Faraday cups. The present paper describes a nondestructive beam density profile monitor which has been designed and built for use in the Argonne National Laboratory 50 MeV proton line.

The Detector

The beam profile monitor derives its signal from the ions produced in the residual gas by the proton beam. A system utilizing this principle is currently in operation in the main ring of the Zero Gradient Synchrotron,[1] where the available ion current is enhanced by the revolution frequency of the particles. Using the Sternheimer range energy relationship[2] for 50 MeV protons in air and assuming that 30 eV of energy is required to form an ion pair, one finds that a linac beam current of 20 mA will liberate enough ions to produce a current of approximately 35 nA per centimeter of length of proton beam in a gas pressure of 1×10^{-5} torr. Therefore, the design of an ion detector for use in the beam line of the linac must include relatively wideband, low current amplification. A schematic cross section of the detector is shown in Fig. 1. An electric field, transverse to the beam direction, exists in the region between the ground screen and the positively charged repeller electrode. Ions produced within the beam are accelerated through the ground screen and collected on the pickup electrode. A negatively charged secondary screen is used to return secondary electrons to the pickup electrode. The operation of the analyzer screen will be described later. The pickup electrode is segmented into twenty strips, each 2.5 mm wide by 2.5 cm long. Triangular electrodes are also included to independently measure the beam density center position.

Since the ion production rate at any point within the beam is proportional to the beam current density at that location, the ion current collected by each segment of the pickup electrode will be proportional to the instantaneous beam current in the corresponding 2.5 mm section of beam. A simultaneous sampling of the ion current being detected by each of the segments provides an instantaneous, one-dimensional, beam density profile.

The pickup electrode, secondary screen, and analyzer screen are supported by the lid of the vacuum enclosure. The separation between the repeller electrode and ground screen is 7.5 cm. The ground screen and its support form an electrostatic shield to eliminate pickup due to the 200 MHz bunched character of the proton beam.

All of the electrodes are fabricated from copper clad epoxy glass circuit boards. The configuration of the pickup electrode is etched using printed circuit techniques. Both the ground screen and the secondary screen are 97% transmission, mesh soldered to circuit board. Voltage and signal leads from the electrodes are fed through the vacuum interface to the electronic system described below.

Electronics

An analog signal is obtained from each ion collection strip on the detection electrode using current-to-voltage converters. The detected current from each strip is applied to the input of an inverting FET operational amplifier which has a high resistance feedback divider network. Cable drivers are then used to send the signals to the data station. The equivalent transconductance of the converter/driver is 20 nA/volt. The converter and driver are mounted on the electrode vacuum enclosure. It is desirable to locate these components as close as possible to the detector in order to minimize both noise pickup and capacitance on the amplifier inputs. They have been exposed to high radiation levels, due to nearby beam stops, during the several months of operation, without any noticeable deterioration.

Figure 2 is a block diagram illustrating the system used to acquire data from the detector. The analog signals are fed to a 1 MHz sequential multiplexer to obtain a scan of the electrode strips resulting in a beam profile. The multiplexer starts at channel one and sequentially

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samples each channel for 1 μsec upon receiving a timing pulse from the ZGS programmer.[3] A second pulse stops the multiplexer on channel ten. Since the multiplexer samples each channel for 1 μsec, the scanning of channels one through ten would give a 10 μsec spread in the analog sampled output. This time spread can be eliminated by inserting the appropriated time delay in each channel. Accordingly, time delays of 0, 1, 2, . . . , 9 μsec are placed in series with multiplexer channels 1, 2, 3, . . . , 10 respectively. The multiplexer output then corresponds to an instantaneous, 1 μsec sample of the beam profile.

An oscilloscope may be used with the multiplexer output to obtain a visual display of the beam profile and position either with a single scan at one particular time or a multi-trace display at several times during the linac pulse.

For computer analysis of the linac beam profile, the ZGS monitor[3] with its high speed data acquisition station[4] was used to digitize and transfer the multiplexer output to the Control Computer. The data acquisition station consists of a high speed analog-to-digital converter and buffer storage memory. Two hundred eight-bit conversions are made during the linac beam pulse (one every microsecond) allowing twenty profile scans for analysis. The monitor then transfers the data to the computer and reactivates the data station. The results of the computer analysis can be plotted on the CRT display unit and/or printed out in tabular form on the line printer.

Operation

A beam profile detector has been installed in the proton line, 2 meters downstream from the high energy end of the linac, oriented so as to measure the vertical profile. Figure 3 is a typical vertical beam profile. These, and the data which follow, were taken with 5 mm detector strip widths obtained by connecting two individual strips to each channel. At standard operating vacuum pressures (about 1×10^{-5} torr) in the beam line, the total ion current to the strip electrodes is approximately 90 nA. This is in good agreement with the expected ion currents.

To provide a true representation of the beam profile, the ions must be transported to the pickup electrode without significant drift transverse to the electric field. Figure 4 shows the variation of the observed beam width versus the repeller high voltage. As expected, the observed width decreases with increasing repeller voltage and then becomes insensitive to repeller voltage at the higher values. The position resolution was determined using two slits to collimate the beam to a known size (smaller than a single 2.5 mm segment width) at the detector location. The detected beam width can be measured by moving one of the slits to position the beam successively at the edges of a single segment. The difference between the detected and calculated collimated beam widths is a measure of the position spread of the detected ions. Measured in this way, the position resolution, with a repeller voltage of 2,000 V, was found to be better than $\pm \frac{1}{3}$ mm.

The beam center location as determined by the position electrodes has been compared with the value calculated by the computer. The two measurements agree within 0.1 mm. In this type of position detector, the effective length is equal to the physical length of the electrodes because the ion motion transverse to the field is small.

The energy of detected ions depends on the electrostatic potential at the point of ionization. This energy dispersion can be used, in conjunction with the analyzer screen shown in Fig. 1, to provide information concerning the horizontal beam density profile. Using differences between the detected ion currents observed on each segment at various analyzer screen potentials, one can construct a two-dimensional, nondestructive beam density profile, i.e., a beam spot. Preliminary data have been taken with the beam monitor operating in this mode, but the accuracy of the measurements has not yet been determined. The primary advantage of this mode is that two-dimensional beam density information can be obtained from a single detector.

Results

Twenty beam profiles similar to that shown in Fig. 3 are digitized and stored in the computer, for each linac pulse. From these data, the computer calculates the following quantities: 1) the integral under each histogram which is proportional to the instantaneous linac beam current; 2) the 50% location of the beam density profile corresponding to the position of the center of charge of the beam; and 3) the difference between the 10% and 90% locations which is the width of 80% of the beam. Figure 5 is a plot of typical data from a single linac pulse, showing the relative beam current, position, and width versus time. In order to obtain a more rapid on-line look at the data, the format of Fig. 5 has been programmed for the digital display scope which is interfaced to the computer. This type of display is shown in Fig. 6. Data are displayed for two linac beam pulses. Data on the left half of the display are stored as reference conditions, while the plots on the right side are updated after each linac pulse. The updated plots can be transferred to the left side of the screen upon command of the operator. With this display, effects of varying linac parameters can be observed, on a pulse-to-pulse basis, by comparing the reference and updated plots. The data and time of day are indicated above the graphs. In Fig. 6, the reference data corresponds to arbitrary conditions during tune-up, and the response of the beam to the following conditions can be observed: Fig. 6a, the preaccelerator high voltage was reduced; Fig. 6b, the feedback loop of the Automatic Level Control[5] was opened; Fig. 6c, the ramp function in the Automatic Level Control program was removed. Such a display should prove useful to the machine operators. For example, in the reference conditions one observes very large width variations during the pulse. Such variations preclude the possibility of achieving good beam matching between the linac and the synchrotron. It should be pointed out that the large variations in the measured beam width shown in Fig. 6 do not normally occur.

Future Developments

The present system can be extended to many stations to provide fast, on-line measurements of parameters which were previously difficult to determine. For example, three beam width measurements, taken at three locations in a drift space, provide sufficient data to determine the instantaneous area and orientation of the phase space occupied by the beam, every 10 μsec throughout a single pulse. While such a system does not provide the accuracy and detail of phase space measurements made with slits, the fast time resolution should result in a useful diagnostic tool for studying the dependence of beam characteristics on various linac operating parameters and even transient phenomena.

Another obvious extension of the present system is the on-line computer control of matching the linac beam to the synchrotron. Data from profile monitors can be used as input to a beam transport program capable of calculating steering and quadrupole magnet currents necessary for proper matching. Digitally controlled power supplies on these magnets may be used to close the loop. For on-line control of dc transport magnets, only one sample per data channel per pulse is required. In this case, sample and hold amplifiers on each detector channel can be used to store the analog information temporarily, until it is digitized. Such a system significantly relaxes the switching and conversion rate requirements of the multiplexer and ADC, respectively.

Conclusion

The beam profile monitor has been found to be a useful diagnostic tool with good time response which can be used on-line at operating beam pipe pressures to make nondestructive measurements of linac beam parameters. Used in conjunction with a computer, the system can be expanded to accomplish a variety of beam monitoring, diagnostic, and control functions.

Acknowledgment

Without the close cooperation and assistance of the Central Computer Control Group, the computer analysis and display would not have been possible. In particular, the authors would like to thank G. Gunderson and M. Knott for the development and preparation of the necessary software and C. Swoboda for preparation and installation of the data acquisition station.

References

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(4) M. J. Knott, D. H. Nordby, and C. A. Swoboda, IEEE Trans. Nucl. Sci., NS-14, No. 3, 1057 (June, 1967).

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DISCUSSION

LAPOSTOLLE, CERN: Concerning the nondestructive beam profile device: when we heard of the Argonne work we started designing a device on the same principle to do the beam blow-up measurements discussed the other day. There are a few differences. Instead of ions, we use electrons. Instead of having several strips to measure the density of various points, we use a sweep and only one probe. However, we found the device extremely good. It is a very good principle to measure beam profile. This work in CERN has been reported to a symposium in Daresbury* a few months ago.

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*Nondistructive proton beam profile scanners (IBS) for the C.P.S. based on the ionization of residual gas in the beam vacuum chamber by C. D. Johnson and L. Thorndahl, presented at the Daresbury Symposium on Beam Intensity Measurement (23-25 April 68).

Also: CERN divisional report
MPS/Int CO 68-8

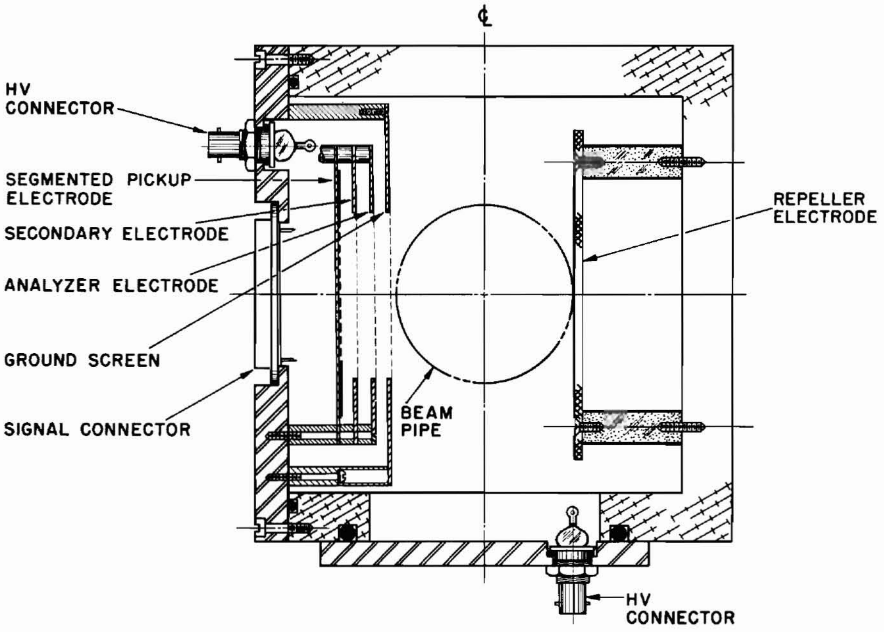


Figure No. 1. Schematic Assembly Drawing of Beam Profile Monitor.

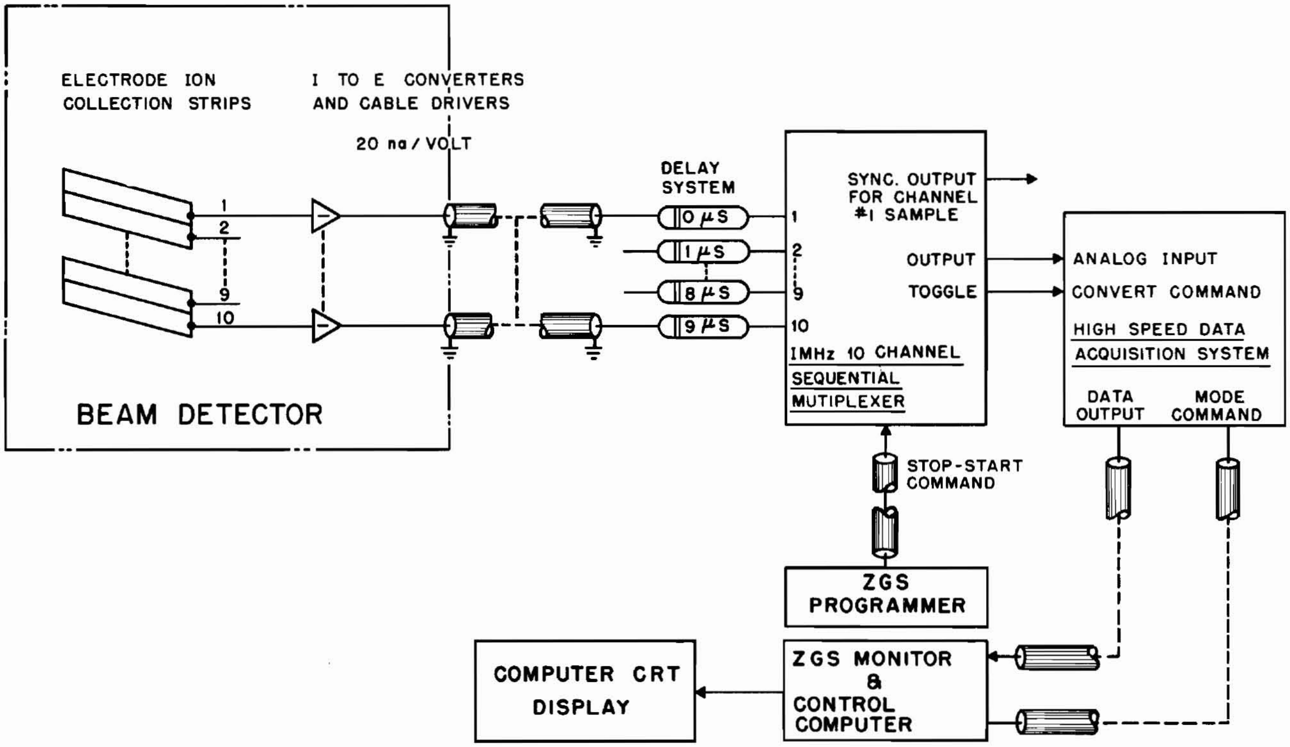


Figure No. 2. Block Diagram of Beam Profile Electronics System.

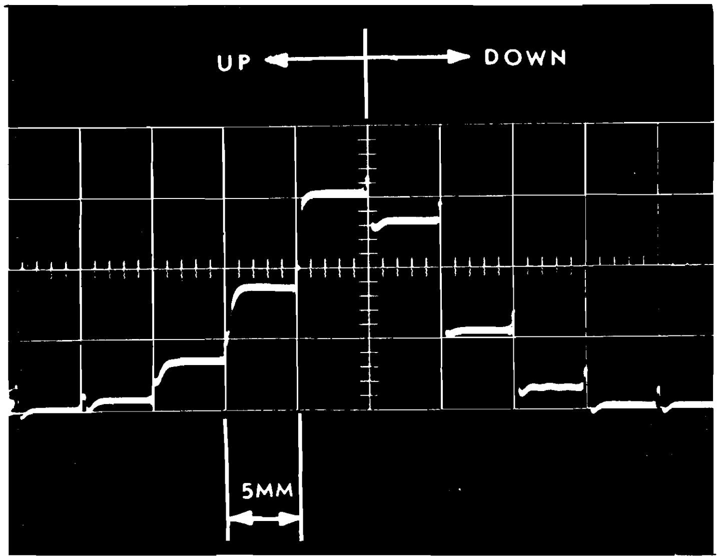


Figure No. 3. Multiplexer Output Showing a Typical Vertical Beam Profile (0.5 V/cm, 1 μsec/cm).

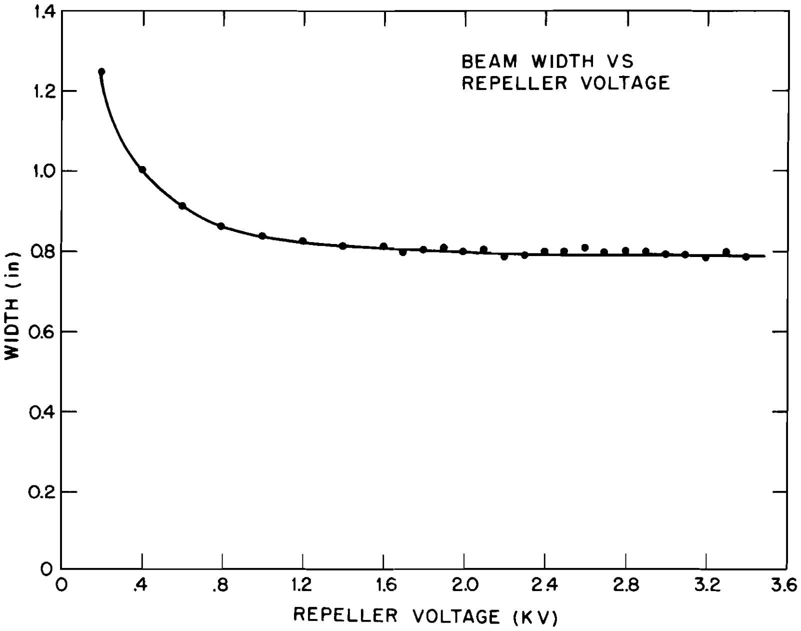


Figure No. 4. Plot of Detected 10% to 90% Beam Width vs Repeller High Voltage.

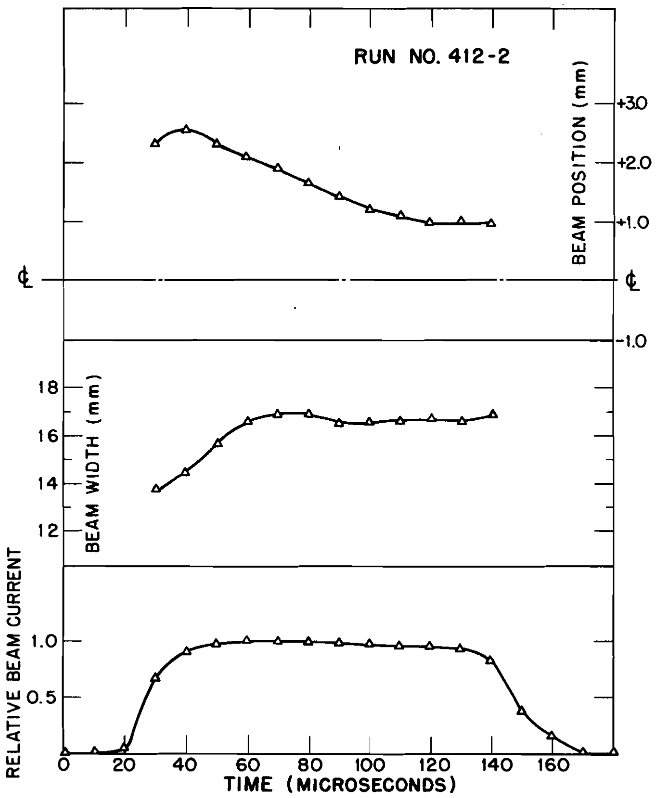
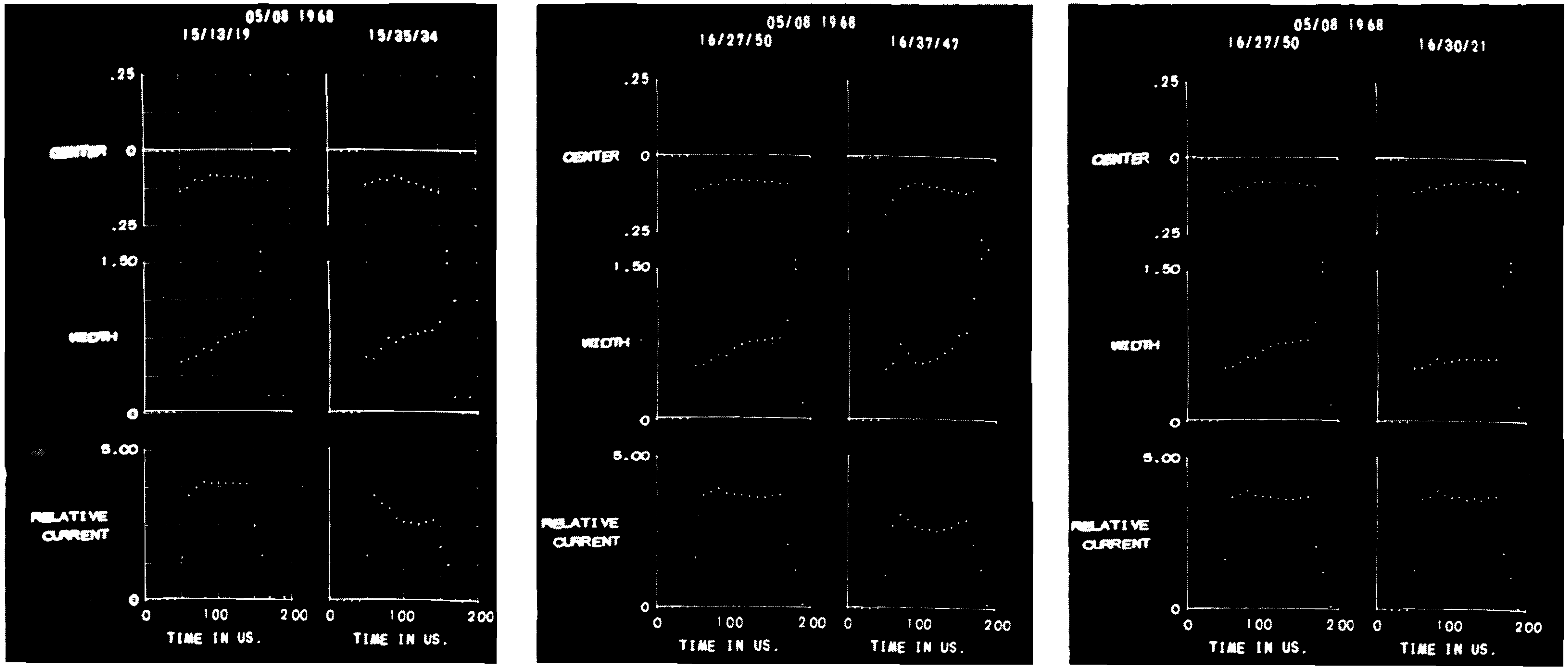


Figure No. 5. Plot of Computer Generated Beam Width, Position, and Relative Current.



a

b

c

Figure No. 6. Computer Displays of Beam Width, Position, and Relative Current. Beam width and position are given in inches.