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Measurement of Transverse Geometric Moments of the TRIUMF Beam with a Multistrip Monitor

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Abstract

A multistrip gap monitor has been built and tested in a TRIUMF beam line. Wall currents, induced by the beam, are carried along eight conducting strips arranged circumferentially around a non-conducting section of beam pipe. A gap in each strip is bridged by a resistor. The eight voltages may be analyzed by applying a circumferential Fourier transform (CFT) to give dipole (position) and quadrupole (aspect) moments of the beam. The device bandwidth (2 GHz) is sufficient to show variations in these moments along the beam bunch.

1 INTRODUCTION

Synchrotrons have employed wideband beam position monitors to measure the variation in beam position along the length of a bunch. Such variations may be caused by injection and capture processes or by beam instabilities. Oscillations in beam width can be produced by a mismatch between injected beam emittance and machine acceptance. Instabilities caused by wakefields can alter the transverse beam shape along a bunch. A wideband device measuring quadrupole or higher order moments will find many applications.

A wideband BPM, using wall currents carried on conducting strips fired on the inside of a ceramic beam pipe, has been described earlier[1]. This principle has been extended to yield the moments of the transverse distribution. Rather than take the signal from groups of strips in each quadrant of the pipe, the signal from each resistor is measured, and a CFT analysis of the distribution of these voltages yields the moments of the beam distribution. In the interests of economy, signals from 8 of 32 strips were used for the prototype and the sextupole moment was therefore the highest obtained; however, in principle, a finer division would yield higher moments[2]. This device will be of more interest to accelerators such as synchrotrons with a high instantaneous current than cyclotrons, which have a charge-per-bunch many orders of magnitude lower. The charge-per-bunch for the TRIUMF tests was much less than 10^7 ppb and significantly affected our signal-to-noise ratio.

Although the basic theory has been discussed in[2, 3], for convenience we will briefly mention it again. The direction of the electric field from a relativistic beam or an infinitely long uniform beam is orthogonal to the direction of motion. Consider an elemental line current ρ_i travelling down a conducting pipe at location (r_i, ϕ_i) with respect to the pipe axis. The wall current density, J, on a conducting cylinder of radius R at the point (R, θ) (see Fig.1) is given by, e.g., [4]:

$$J_{image}(r_i, \phi_i, R, \theta) = \frac{\rho_i}{2\pi R} \frac{R^2 - r_i^2}{(R^2 + r_i^2 - 2Rr_i \cos(\theta - \phi_i))} \quad (1)$$

Expanding in powers of r_i/R gives:

$$J_{image}(r_i, \phi_i, R, \theta) = \frac{\rho_i}{2\pi R} \left[1 + 2\sum_{n=1}^{\infty} (\frac{r_i}{R})^n \cos n(\theta - \phi_i) \right] . \quad (2)$$

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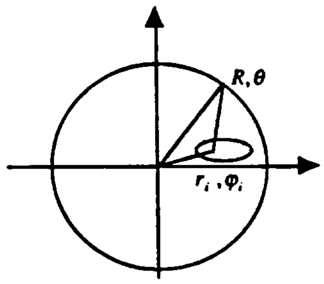

Fig.1: The wall distribution induced by a line current

The induced current density at one location on the wall will be the integral of the above expression over all the beam particles. The expression contains the moments about the centre of the pipe in the forms of $\sum_i \rho_i r_i^n \cos n\phi_i$ and $\sum_i \rho_i r_i^n \sin n\phi_i$. A co-ordinate translation can then be made to find the centroid moments[2]. These moments, when normalized to a unit integral of current, correspond to those used in beam instability theory. Each order of moment yields corresponding beam properties. The zero order moment gives the beam intensity and the first order (dipole) moments give the position. The second order (quadrupole) moments take the form: $\sum_i \rho_i r_i^2 \cos 2\phi_i$ and $\sum_i \rho_i r_i^2 \sin 2\phi_i$ and lead to the normalized beam transverse quadrupole moment, i.e. $(a^2 - b^2)/4$ and its orientation, where b is the half-short axis and a is the half-long axis[2].

Knowledge of the moments alone does not give the beam size since beams with the same $(a^2 - b^2)/4$ may have different aspect ratio and size. The size, however, and maybe the emittance, may be found using the moments together with a prior knowledge of the beamline optics[4].

Since the moments are the product of intensity and deviation from circularity, accurate measurements can be made for beams small in size that have a high intensity. Analysis by the method of moments will give, in principle, a beam position monitor that is linear and independent of bunch shape. The results of Monte Carlo simulations and bench tests have been reported earlier[2, 3].

2 CONSTRUCTION

Thirty-two copper strips were placed 11.25° apart along the outer surface of a Pyrex glass tube 15 cm long and 10 cm in diameter. The strips were placed outside the tube to avoid the requirement of feed-throughs and glass had then to be used rather than ceramic since the high dielectric constant would further attenuate an already weak signal. The ends of the glass pipe were ground flat to provide a vacuum seal to the stainless steel beam pipe; however, electrical continuity was provided to allow the wall currents to flow from the pipe through the copper strips. Four ferrite rings placed around the pipe increased the inductance and improved the low frequency response.

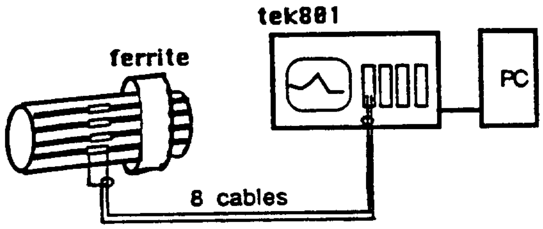

Fig.2: The multistrip monitor

3 THE EXPERIMENTAL ARRANGEMENT

The monitor was located in a section of the high-current beamline with a relatively low radiation field. Signals from the strips were taken by 28 m runs of 1/2 in heliax through concrete shielding blocks to racks of electronics. The monitor was not surveyed into place, so its axis may not correspond to the beamline centre; it was also installed with an 11° rotation between the centre of the uppermost strip and the beam line vertical axis.

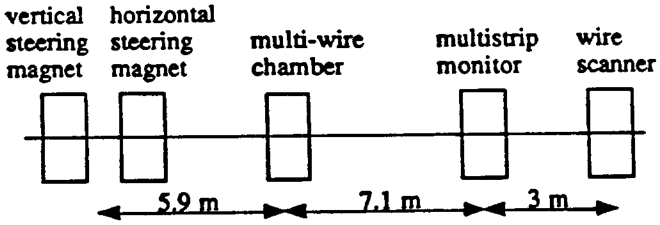

Fig.3: The experimental arrangement

No fast ADC or transient recorder was available, and sampling oscilloscopes were used. Their use assumes that beam conditions are stable during a measurement, on the order of 2.5 ms or for several seconds when averaged, which is a reasonably good assumption for a cyclotron. The response of each strip was measured using a TEK 11801 eight-channel sampling oscilloscope which can acquire the signals from all eight strips simultaneously. This has a bandwidth of 20 GHz, though the system bandwidth is 2 GHz, and data can be analyzed to give the beam distribution along a bunch.

The strip resistors and cables were calibrated in situ. 5 ns pulses similar to the beam were sent along a conductor at the monitor's centre. Although nominally identical, differences in construction led to a variation of 10% in sensitivity (pulse height) and 0.19 ns in time delay among the 8 channels.

The amount of 23 MHz cyclotron RF picked up by the strips varies and can be as much as 50% of the beam induced signal. Eight background measurements were taken with the beam off and subtracted from the data. To do this, the oscilloscope triggering was changed from the usual beam-derived signal to a signal obtained from the cyclotron RF in order to maintain the same phase relationship between background and signal with beam.

Two types of measurement were made. In the first, the beam was steered horizontally or vertically in small steps over a range several times the beam diameter. In the second, the beam was defocused by upstream quadrupoles into a tall, narrow beam or a short, wide one. The position, or size, at the monitor was interpolated among profile measurements made by two upstream and two downstream profile monitors. These multiwire ion chambers, or high-current scanning wire, measure the average profile projected in the longitudinal direction by the beam bunches. Measurements were made at a beamline vacuum of 15 mT. A four-fold change in pressure did not affect the signals observed.

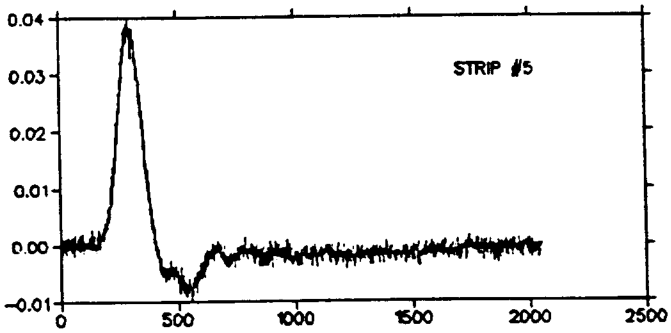

Fig.4: The wall current signal picked up by the multistrip monitor with RF background eliminated

4 RESULTS

4.1 *The Intensity Distribution or Zero Moment*

The zero moments, obtained from the CFT analysis, give the beam intensity at their locations along the bunch. The longitudinal distribution thus obtained agreed with that from our usual reference which detects scattered particles. The shape and resolution were similar to measurements made previously by a more conventional wall current monitor[5]. The longitudinal distribution shows a peak in intensity at both the leading and the trailing end of the bunch, with a reduced intensity in the middle of the bunch. Flags and slits may be inserted at the centre of the cyclotron to reduce the phase width of the beam accelerated. When this was done, it was observed that the trailing peak and a portion of the middle of the bunch were removed, shortening the bunch length; the same effect was seen by the scattering monitor.

4.2 *Position or Dipole Moment*

A comparison between the measured position averaged over the short bunches and that inferred from up and downstream monitors is given in fig. 5. Analysis of the long bunch (with the cyclotron phase acceptance unrestricted) at the two peaks and in the middle of the bunch show that the "position" varies along the bunch length. It would appear that the bunch is bent and travels crab-wise in both planes down the beam pipe. In the tables, ϕ_n is the phase angle of the nth order moment.

Table 1: position along the bunch

	x (cm)	y (cm)	ϕ_1 (°)
head	0.30	0.65	87.35
middle	0.20	0.57	92.68
tail	0.22	0.69	91.27

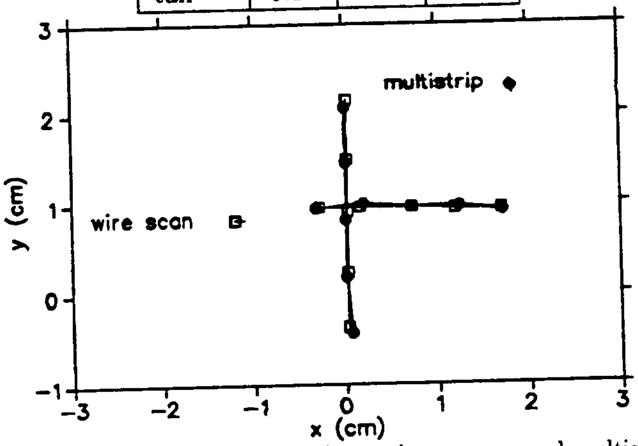

Fig.5: Position measurement from wire scanner and multistrip monitor from point of view of moments

4.3 *Aspect Ratio, and Quadrupole Moments*

Measured values of $(a^2 - b^2)/4$ and the orientation are given in table 2. Beam optics programs calculate an aspect ratio, a/b, of 2. If this is accepted then the semi-axes, a and b, of the ellipses fitted to the true shape can be obtained from the measured $(a^2 - b^2)/4$; the tail of the beam is larger than the head. These ellipses, representing the transverse cross section of the head, middle and tail of a beam bunch, are shown in fig.6. The profile measured by the downstream wire scanner was not Gaussian but showed a width consistent with the averaged multistrip data.

Table 2: Beam best-fit-ellipse size obtained from the measured moments, assuming a/b=2

	moment $\sum_i \rho_i r_i^2 \cos 2\phi_i / \sum_i \rho_i$	b (cm)	a (cm)	ϕ_2 (°)
head	1.31×10^{-2}	0.18	0.36	162.18
middle	1.38×10^{-2}	0.18	0.37	154.98
tail	3.32×10^{-2}	0.25	0.51	168.88

5 DISCUSSION

A dc beam is injected into the centre of the cyclotron where focusing forces depend strongly on the phase of the beam with respect to the accelerating RF. The beam, therefore, is matched to the cyclotron in only an average way and the degree of mismatch varies with longitudinal position[6]. It was expected, however, that the large number of turns made between injection and extraction, the fact that the beam is extracted over several turns and scattering from the stripping foil would blur this structure. The amount of variation in beam size and position measured along the bunch was unforseen. We are devising other experiments to further confirm and study our measured results.

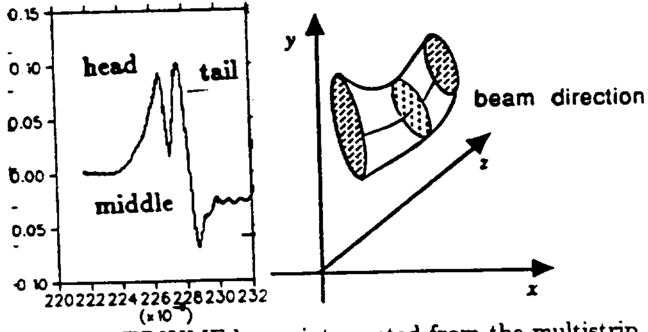

Fig.6: The TRIUMF beam interpreted from the multistrip monitor measurement

6 CONCLUSION

The method of multiple pickups and analysis by moments can be applied to other EM monitors whose electrodes are finely divided and distributed circumferentially. A wall current monitor, however, is easy to construct and has a wide bandwidth.

It has been pointed out by Miller[4] that for a Gaussian distribution the emittance can be inferred from several independent measurements of the moments of the beam distribution. An online measurement of beamline moments transformed into emittance could be very useful when tuning linear accelerators and transport lines. The motivation for developing this monitor, however, and its probable greatest use, is for observing the development of instabilities in high-intensity circular machines.

7 ACKNOWLEDGMENTS

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8 REFERENCES

[1] Y.Yin, W.R.Rawnsley, G.H.Mackenzie, D.Pearce, J.Worden, Proc. PAC, San Francisco, p.1133, 1991

[2] Y.Yin, Proc. PAC, Washington, D.C., p.2441, 1993

[3] Y.Yin, Proc. XVth Int. Conf. on High Energy Accelerators, Hamburg, p.260, 1992

[4] R.H.Miller, J.E.Clendenin, M.B.James, J.C.Sheppard, Proc. 12th Int. Conf. High Energy Accelerators, p.602, 1983

[5] Y.Yin, W.R.Rawnsley, G.H.Mackenzie, Beam Instrumentation Workshop, Sante Fe, 1993

[6] G.Dutto, C.Kost, G.H.Mackenzie, M.Craddock Proc. of 6th Int. Cyclotron Conf., AIP Proc. 6, p.340, 1972