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26

DISCLAIMER

NON-INTERCEPTING MONITOR OF BEAM CURRENT AND POSITION*

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Summary

A compact monitor has been developed which measures beam current and beam position without intercepting or appreciably affecting the particle beam being measured. It is a broad band device which prevents the development of beam disturbing resonant modes. Although developed specifically for use on a short-pulse electron induction accelerator, it might be applied to other accelerator beams of pulsed or rf-bunched nature. The monitor consists of a resistive band inserted in the beam pipe wall with connections for reading the voltage across the band at each vertical and horizontal axis intercept. For pulsed or rf beams, return current equal in magnitude to the beam current flows on the beam pipe inside wall and through the resistive band. If the beam is centered, equal voltage appears on all four monitor connections. If the beam is off-center, the return currents are unsymmetrical and unequal voltages appear at the monitor connections. Beam current is proportional to the sum of all monitor voltages, while beam position is approximately proportional to the difference in voltage at opposing monitors. Tests and operating experience confirm its operation.

Principle of Operation

Following is a somewhat simplified analysis which illustrates the principles. Consider a beam pulse of charged particles moving through a beam pipe (Fig. 1). For relativistic beams ($\gamma > 2$) this is analogous to a pulse traveling along a coaxial transmission line. The beam current induces currents of opposite polarity in the wall. These wall currents have approximately the same pulse shape and magnitude as the beam current. The current distribution on the wall, however, is dependent on the position and shape of the beam pulse. For an off-center line current the wall current distribution is $J_z = \frac{I}{2\pi a} \frac{(r^2-a^2)}{(a^2+r^2-2ar\cos\theta)}$ where r is the displacement from center, a is the pipes radius, and θ is the angle from some reference plane to the plane between the beam and the center. The smoothing of the current wave shape at the front and rear of the pulse is dependent on geometric factors and beam velocity, giving a rise time of the order of $\frac{a}{\gamma c}$, which is typically less than 1 ns. The wall current magnitude remains equal to the beam current magnitude at least until the magnetic field of the beam starts to penetrate through the wall, typically 10^{-5} to 10^{-3} sec, after which time the magnitude will change if an alternate current return path exists outside the beam pipe. So, for a wide range of pulse durations the wall current closely duplicates the beam current.

Next, consider the case where a short length of the wall is replaced by a section with a circumferentially uniform resistance R_s. If the beam is centered, the resulting uniform wall current produces a circumferentially uniform voltage drop $e = iR_s$. If the beam is off center (Fig. 3), the wall current density is highest where the beam is closest and for small offsets r, the voltage drop can be expressed approximately as

$$e \approx iR_s[1+2\frac{r}{a}\cos(\theta-\phi)] \qquad (1)$$

If voltage sensors are placed at the axis intercepts and noting that $\Delta x = r\cos\theta$ and $\Delta y = r\sin\theta$, we get

$$e_{x1} + e_{x2} + e_{y1} + e_{y2} = 4\ iR_s \qquad (2)$$

$$e_{x1} - e_{x2} \approx 4iR_s\frac{\Delta x}{a} \qquad (3)$$

$$e_{y1} - e_{y2} \approx 4iR_s\frac{\Delta y}{a} \qquad (4)$$

These equations indicate that all are proportional to the beam current, that the sum signal is independent of beam position, and that the two difference signals are proportional to beam position in the x and y directions respectively. How good are the approximations? The sum of currents at four monitoring points and θ = 0 gives

$$\Sigma J_z = \frac{I}{2\pi} \quad \frac{2a+r}{a^2-r^2} + \frac{2a^2-ra-2r^2}{a(a^2+r^2)}$$

which is within 5% of $\frac{I}{2\pi}\ \frac{4}{a}$ to $r = \frac{a}{2}$. The difference in the currents between two diagonal points is $J_z = \frac{I}{2\pi}\ \frac{3r}{a^2-r^2} + \frac{r}{a^2+r^2}$ which is within 5% of the approximation $\Delta J_z = \frac{I}{2\pi}\ \frac{4r}{a}$ to about $r = \frac{a}{4}$. In both cases the approximations improve as the beam is steered toward the center.

What might be the limitations of the device? First, the initially non-uniform current (and voltage) distribution of Eq. (1) decays to a uniform azimuthal distribution at a rate dependent on the inductance L_d of the "difference current" circuit, which produces magnetic field of character shown by the dashed lines in Fig. 3, and on the portion of the resistance R_s coupled by this circuit. The exact time dependence for the decay of the transverse voltages has not been worked out yet, but it is clear that the transverse inductance L_d is small, of the order of $2 \times 10^{-9} \times \ln\frac{a^2}{a^2-r^2}$ Hy per cm, and that the decay is not simply exponential. For a 0.1 Ω R_s, the decay is shown in Fig. 6, and is sufficiently slow to be used with our < 45 ns beams. If the L_d/R_s ratio is not high, the difference current might have a waveshape as shown in Fig. 2C. Second, if there is an external ground return circuit (dashed line in Fig. 1), the current through the resistors R_s will gradually shift to it at a rate dependent on the inductance L_e of the enclosed volume and the resistance of the loop circuit (primarily R_s) - with a high L_e/R_s ratio being desirable. Ferrite or other ferromagnetic material might be used to increase the foregoing inductances and forestall current decay (Ref. μ in Fig. 1).

Selected Configuration

Fifteen beam monitors have been fabricated and installed in the ERA 4-MeV Injector[1] which produces a pulsed electron beam of ~ 1,000 A for 45 ns at a rate of 1 Hz. A beam chopper is used to shorten the pulse

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length to either 5 ns or 20 ns at the output of the accelerator. The selected configuration is shown in Figures 4 and 5.

The monitor was designed to fit on the 11.75-inch diameter metal flanges of the accelerator beam pipe. This arrangement occupies a minimum of beam pipe length and permits beam monitoring at any beam pipe joint by addition of an insulating sheet between flanges. The waveform distortion due to the resistors being at the outside diameter, instead of inside diameter, is small (< 1 ns). The shunt resistance R_s consists of 100 one-watt carbon resistors in parallel, each having a resistance of 10Ω for a total resistance $R_s = 0.1\ \Omega$. This value was chosen because it would give a large enough signal to be used with a Tektronix 519 scope. This gives a voltage level of 100 V for 1000 A beam current. The inductance of the 100 parallel resistors is of the order of 10^{-10} H which produces only ~ 100 V for a current rise of 1000 A per nanosecond. For our pulse lengths signal decay as described at the end of the preceding section is not a problem. The resistors are soldered to two split copper rings which are easily clamped to the beam pipe flanges.

Two coaxial connections are made to the resistor assembly at each 90° station (8 total). A 50 Ω back-terminating resistor is used at each connection. Four coaxial lines, one from each quadrant, are fed together to give the "sum" signal proportional to beam current. Two coaxial lines at 180° intervals are combined, with inversion of one, to give the Δx or Δy "difference" signals proportional to beam position.

Calibration

The beam monitor was bench calibrated using a short length of coaxial line. The outer conductor was of 11.75" diameter to simulate the beam pipe. A radially movable inner conductor of 1/2" diameter was used to simulate the electron beam. A pulse generator supplied pulses of 1 ns rise. Figure 6 shows waveforms of the "sum" and "difference" signals for 2 cm displacement steps. It was found that the difference signal was closely proportional to the center conductor radial position, with the linearity evident from the evenness of the oscilloscope traces. The amplitudes of the sum and difference signals were approximately equal for $r = a$, thus a convenient calibration is $\frac{r}{a} = \frac{\Delta I}{\Sigma I}$.

Performance on Accelerator

The beam monitors have been used successfully on the ERA 4-MeV Injector to measure both current and position. Typical waveforms are shown in Figure 7. Values of current agree well with independent measurements by toroidal transformer and Faraday cup techniques. Beam position data agrees qualitatively with beam movement on scintillation screens and with beam steering characteristics. The primary function of the position monitors is to help in centering the beam in the beam pipe. This is the region where the approximations made about a linear output versus position are most accurate.

Future Possibilities

In our present configuration (Ref. Section 3), the monitoring resistors are exposed. In some situations this could pose a problem with radio-frequency interference, although we have not observed any problem here. If it should be a problem, the resistors could be enclosed in a moderate-sized housing (dashed lines of Fig. 1), possibly including ferromagnetic material.

Our arrangement with 100 resistors provides response of a nanosecond or so. If faster response is desired, one could consider an azimuthally uniform resistive band of, for example, some highly resistive material (e.g. carbon) or an evaporated metal coating. The time decay of the beam position signal can most easily be improved by lowering the value of the resistance of the band.

Conclusions

Clearly, the shunt may be used to measure currents in any coaxial system, whether the inner current is electrons in vacuum or in copper. The use of the monitor on a beam pipe has the benefits of not constricting the aperture or putting a large discontinuity in the beam pipe. The device is located outside of the vacuum area and is readily accessible.

References

1. W. Chupp, et.al., The ERA 4 MeV Injector, 1971 Particle Accelerator Conference, paper G-9.

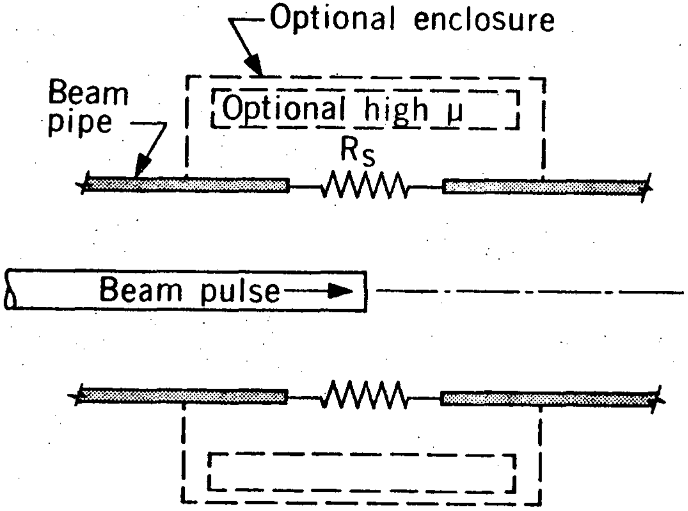
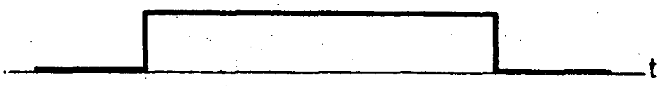
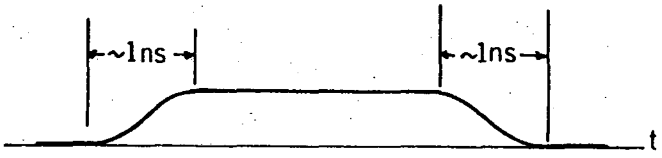


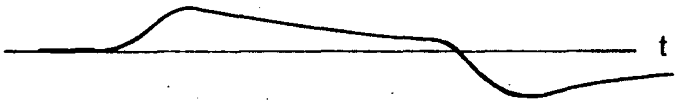
Figure 1 - Conceptual diagram showing beam pulse traversing monitor ring of resistance R_s.



a) Beam current



b) Monitor current



c) Monitor current, if L/R_S ratio is high.

Figure 2 - Anticipated monitor waveforms for "square" pulse of beam current.

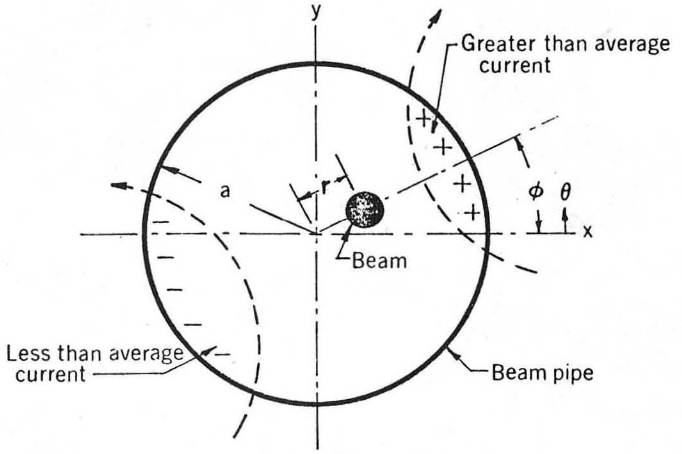


Figure 3 - Illustration showing beam off-center within beam pipe. Dashed lines indicate sense of magnetic field due to change in wall current densities.

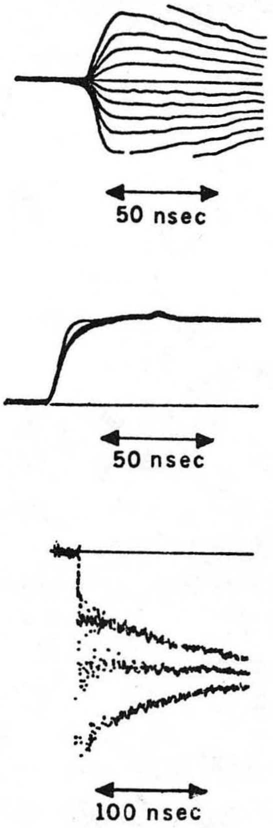


Figure 6 - Calibration waveforms for ERA Injector beam monitor: a) "difference" signal for center conductor at 12 lateral positions 2 cm apart, with input pulse rise time of ~ 10 ns; b) superimposed "sum" signals for same conditions; c) signal from one quadrant monitor connection for center conductor at + 5, 0 and - 5 cm lateral position with input pulse rise time of ~ 1 ns which demonstrates rapid response time of monitor.

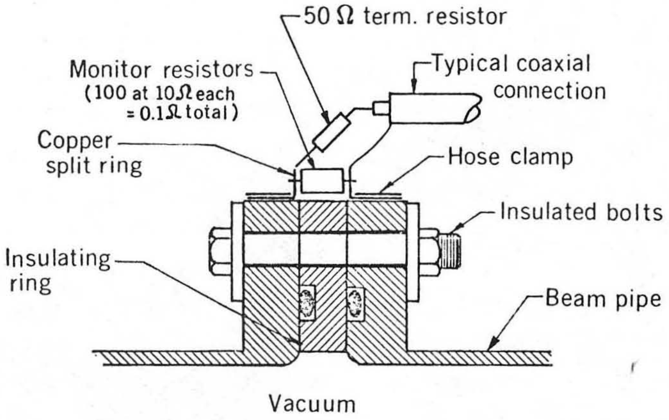


Figure 4 - Typical section through ERA Injector beam monitor.

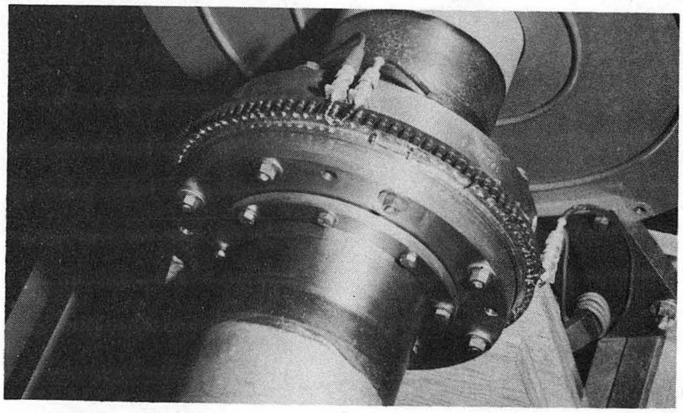


Figure 5 - Photo of installed ERA Injector beam monitor.

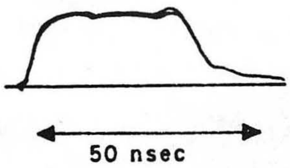


Figure 7 - "Sum" beam current waveform from ERA Injector beam monitor.

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