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A MULTIGIGAHERTZ BEAM-CURRENT AND POSITION MONITOR

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Abstract

A self-integrating magnetic-loop device having a risetime of less than 175 ps has been developed to monitor the temporal behavior of the electron beam current and position within each 3.3-ns micropulse generated by the PHERMEX rf linear accelerator. Beam current is measured with a 2-GHz bandwidth by combining these loops in a four-port hybrid summer. Another application of these loops uses two 180° hybrids to give 2-GHz time-resolved beam position to an accuracy of 1 mm. These sensors are nonintrusive to the propagating beam and allow ultrafast beam measurements previously restricted to the technique of recording the Cerenkov-light emission from an intercepting Kapton foil using a streak camera.

Introduction

The PHERMEX electron-beam facility at Los Alamos is being used to study the propagation of electron beams in gases at various pressures. This facility is a three-cavity standing-wave rf electron linac principally used for flash x-radiography and is described in [1] and [2]. The PHERMEX electron-beam pulse is a burst of ten 3.3 ns micropulses each separated by 20 ns with a peak current of 500 A and an energy of 30 MeV. This paper presents improved beam current and position monitors that are used to characterize the propagating electron beam. In particular, the emphasis has been on improving the monitors to resolve beam oscillations or disturbances that might occur with frequencies as high as 2 GHz. Most monitors whose bandwidth is extended to these extremes are plagued by self-resonances and artifactual responses. Excellent monitors for beam current and position referred to as "beam bugs" are described in [3] and [4], and increased positional resolution via Fourier-analyzing coil arrays is discussed in [5]. Neither of these types of monitors has the necessary bandwidth for resolving the sub-nanosecond details of a propagating PHERMEX micropulse. The new monitors described are non-intrusive to the propagating beam and allow ultrafast beam measurements previously restricted to the technique of recording the Cerenkov-light emission from an intercepting Kapton foil using a streak camera [6].

Theory

Consider a pipe of radius R in which a current I is flowing a distance r from the geometric pipe axis (see Fig. 1). The magnetic field at the cylinder wall can be derived by superposition of the fields produced by the current near the axis and an image current flowing a distance R^2/r from the pipe axis. The field at the wall is given by

$$B(R,\theta) = B_0 \frac{1-\rho^2}{1+\rho^2-2\rho\cos\theta}, \quad B_0 = \frac{\mu_0 I}{2\pi R} \qquad (1)$$

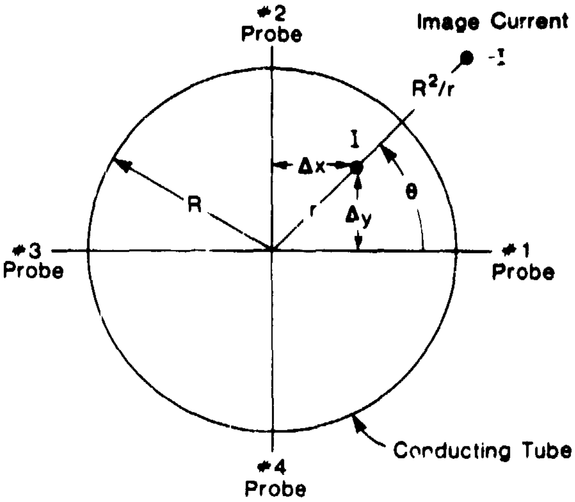

Fig. 1. Orientation of current probes monitoring the magnetic field of a filamentary current displaced from the axis of a conducting cylinder.

where $\rho = r/R$ and the displaced filamentary current is at an angle θ relative to probe #1. B_0 is the magnetic field for the case with the filamentary current flowing on axis. Expression (1) can be expanded as

$$B(R,\theta) = B_0 \, (1+2\rho\cos\theta+\ldots) \qquad (2)$$

where the error of dropping the higher order terms will be discussed later. The fields B_i at each of the probe locations are given by

$$B_1 \approx B_0 \, (1+2\rho\cos\theta) \qquad (3)$$

$$B_2 \approx B_0 \, (1+2\rho\sin\theta)$$

$$B_3 \approx B_0 \, (1-2\rho\cos\theta)$$

$$B_4 \approx B_0 \, (1-2\rho\sin\theta)$$

The present monitors consist of a wire loop protruding from the wall of the propagation pipe. The voltage induced in the loop is proportional to the time-rate-of-change of the net electron beam current and loop area and must be integrated to recover the fields and hence the net current as a function of time. Typically this integration can be accomplished by digitization or by using passive external RC networks. Neither of these techniques is appropriate for multigigahertz bandwidths. The present monitor is shown in Fig. 2 and consists of a wire loop terminated in a radial resistance. If the wire loop and radial resistor can be considered lumped elements over the desired bandwidth, the monitor can be modeled as an inductor in series with a resistor driven by the beam

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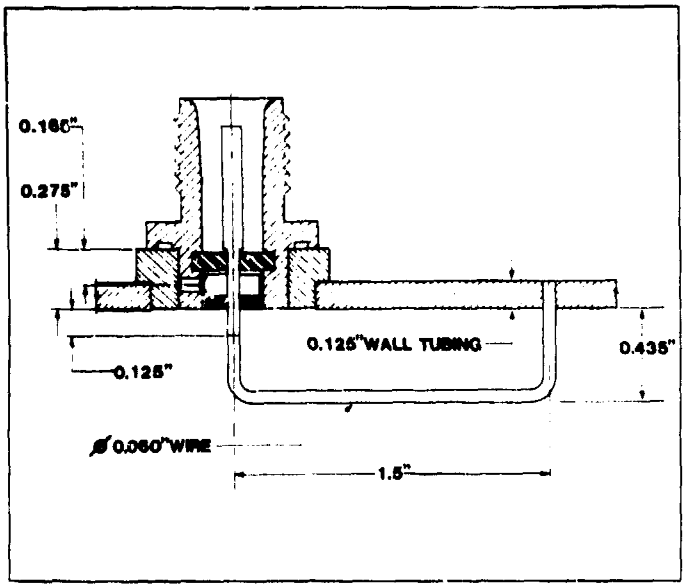

Fig. 2. Cutaway of a self-integrating probe monitor shown mounted in the propagation tube wall.

current induced voltage. Such a network has the solution

$$V(t) = \frac{1}{\tau}\frac{\mu_0 A}{2\pi R}\,I(t) - \frac{1}{\tau}\int V(t)\,dt \qquad (4)$$

where $V(t)$ is the voltage output of the probe, τ is the ratio of the loop inductance to the radial resistance, A is the loop area, and $I(t)$ is the net electron beam current. For large τ and current pulses short relative to τ, the integral term (typically referred to as "droop") can be made acceptably small as compared to the desired beam current term. There is an optimization of the loop area, resistance, and probe sensitivity that must be balanced against droop, self-resonance, and the upper bandwidth at which the circuit elements can be considered lumped versus distributed. Referring to Fig. 1 and using equations 3 and 4, the net beam current I and displacements $\Delta x, \Delta y$ are given by

$$I = \frac{2\pi R}{4\mu_0 A}\,\tau\,V_T,\quad V_T = V_1 + V_2 + V_3 + V_4 \qquad (5)$$

$$\Delta x = R\,\frac{V_1 - V_3}{V_T} \qquad (6)$$

$$\Delta y = R\,\frac{V_2 - V_4}{V_T}$$

where V_i are the voltage outputs from identical probes. By summing and differencing the four probes the beam current and position are resolved. This analysis neglects the errors associated with a four probe discrete array monitoring large beam displacements and the range effects due to the probes being responsive to both local and distant axial displacements (see [5] for a further discussion).

Design, Testing, and Calibration of Monitors

The electron-beam propagation experiments utilize 305 mm diameter aluminum, brass, and stainless steel pipe. The current monitors as well as other diagnostics are mounted on removable 101.6 mm long flanged pipe sections. For development and calibration of the current monitors, a coaxial test stand was built. This consists of a 500-mm-long biconic input transition from a type N connector to 570 mm of coaxial transmission line, the 101.6 mm monitor section, another 570 mm of transmission line, and lastly a 500 mm biconic exit transition back to a type N connector. The inside diameter of the test stand coaxial line is 305 mm with a 127 mm outside diameter center conductor giving a calculated characteristic impedance of 52.5 ohms but a measured value of 51.5 ohms. The test line was driven by either of two reed pulsers: one has a risetime of 270 ps at 400 volts and the other has a slower risetime of 500 ps up to 5000 volts output. The measurements were made using a 4.6 GHz sampling scope while simultaneously recording the same data on a Tektronix 7104 oscilloscope. The 7104 type oscilloscopes are used to record the beam current monitors during propagation experiments. This class of scopes is advertised to have a bandwidth of at least 1 GHz but most are usable beyond 1 GHz and exhibit an amplitude decrease of a factor of 2 at 1.5 GHz, a factor of 4 at 2 GHz, and no output at 3 GHz. The output of the test stand when driven by either pulse exhibited no measurable degradation in pulse rise time or shape.

Referring to Fig. 2, a probe consists of a modified type N connector (UG-30 D/U) terminated with two 1-ohm ceramic radial resistors in parallel. The probe was tested without the resistors and had a risetime of 170 ps with a slight self-resonance at 2.6 GHz. The inductance of the loop was measured to be 32 nh, which should give a probe droop of about 10 percent for the nominal 6 ns test pulse. Note that an external integrating network would need to have a bandwidth in excess of 2 GHz to recover the integral of the loop response. The self-integrating probe exhibited no observable difference in risetime as compared to the 270 ps pulser but had a self-resonance of 2.8 GHz producing a 10 percent modulation across the flat-topped portion of the test pulse.

In order to extract beam current and position from the probes of Fig. 1, opposing pairs are connected to a pair of 2 MHz to 2000 MHz, 0°/180° hybrids (Anzac Model H-9). This gives the two desired difference signals, but additionally the 0° ports are summed using a 1 MHz to 2000 MHz 0° hybrid (Anzac Model H-8-4) to give the sum of the four probes. The signals are then transmitted over 23 m of 12.7 mm foam flex cable to the 7104 oscilloscopes in the diagnostics area. Figure 3 shows a comparison of the test stand output voltage using the 500 ps pulser and the summed output of the four probes using the above hybrid combination as recorded on the 7104 oscilloscope. It is evident that there is about a 10 percent droop as expected due to the L/R ratio of 64 ns/ohm and that the slight 2.8 GHz self-resonance of each probe has been rejected primarily by the cutoff of the 7104 oscilloscope and to a lesser degree by the conservative bandwidth of the hybrid summing combination. The pulse can be corrected to first order for the droop by a simple linear correction in time; a passive network that accomplishes this at the oscilloscope input is now being designed.

The positional response of the probes was tested by replacing the center conductor of the test stand with a 19 mm diameter copper rod terminated in a movable shorted end plate. Figure 4 plots the measured displacement indicated by the monitor system versus the

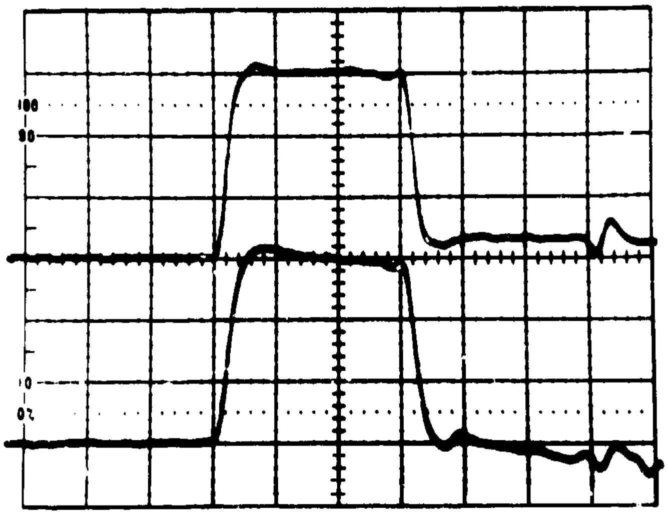

Fig. 3. Top trace: test stand output voltage (2 ns/div).
Bottom trace: current as recorded by monitor (2 ns/div).

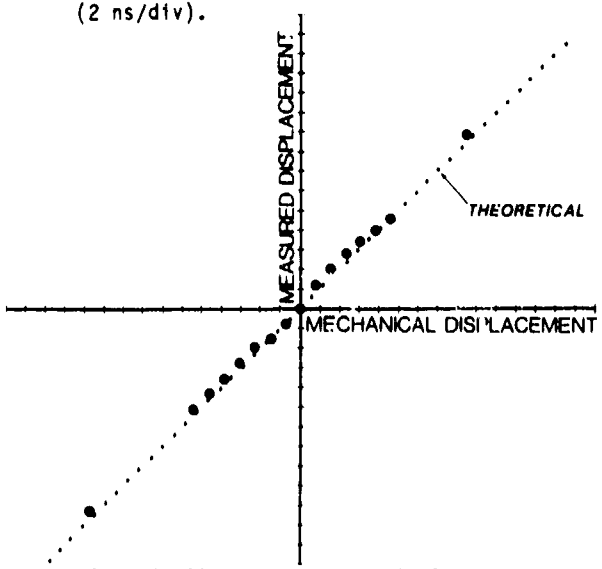

Fig. 4. Electrically measured displacement versus actual mechanical displacement of a current carrying rod in coaxial test stand. (1 mm/div both axes)

actual displacement of the rod along the axis of an opposing pair of probes. This test at $\rho=0$ results in an error of 2 percent for $\rho=0.1$ in making the approximation from equation (2) to (3); however, the electrical signals and mechanical displacements were not read to better than 10 percent for motions of less than 3 mm. For $\rho<0.2$ the approximation has a maximum error of less than 10 percent.

Results Using PHERMEX

The monitor system was tested using the PHERMEX electron-beam and the beam current is shown in Fig. 5. The droop in the beam current is as predicted and the monitor system is essentially free of noise, resonances, and artifacts as compared to previous monitors deployed for propagation experiments at PHERMEX. The positional capability of the monitor array was verified by moving the propagation pipe and array relative to the few millimeter diameter and collimated electron-beam at the output of PHERMEX. The positional sensitivity is limited in practice to several millimeters by the signal to noise ratio of the difference signal. This is entirely acceptable for monitoring the expected excursions of the beam centroid associated with the propagation experiments. In summary, this monitor system allows non-instrusive beam current and position measurements at a bandwidth of 2 GHz.

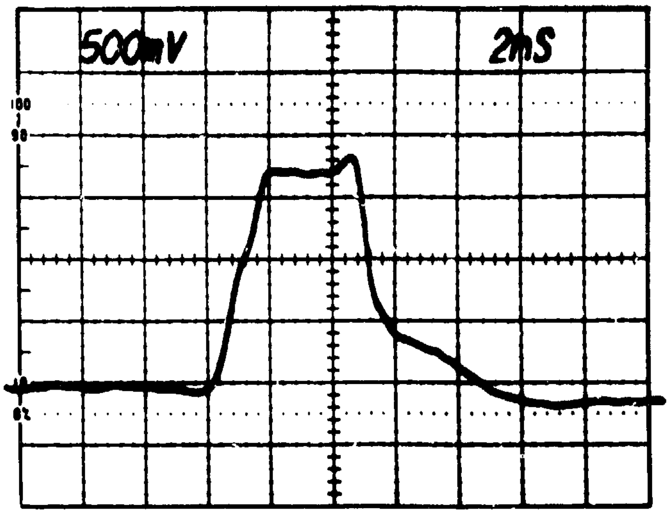

Fig. 5. PHERMEX Electron-Beam Current at 450 amps using Monitor System. (signal has been attenuated, 2 ns/div)

Acknowledgements

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