ELECTRON BEAM TIME-OF-FLIGHT POTENTIAL DIAGNOSTIC

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ABSTRACT

A time-of-flight method for measuring electrostatic potentials in plasmas using a modulated electron beam has been developed. The beam is injected along the magnetic field in a cylindrical plasma geometry. The phase of the electron beam modulation is detected using a Rogowski loop which encircles the beam and plasma, and the phase information is in turn related to the electrostatic potential. Measurements in vacuum and in plasma have been performed.

I. INTRODUCTION

There exists a need for an axially resolved electrostatic potential diagnostic for tandem mirror plasmas[1][2][3]. We demonstrate a technique for measuring potentials in plasma geometries in which the beam can be injected along a field line, or perhaps in plasmas with no magnetic field (e.g. DC or AC discharge plasmas). The experimental configuration is shown in Fig. 1.

A 1 mA electron beam that is modulated near 10 MHz is injected along the magnetic field in the Berkeley Ten Meter Multiple Mirror Experiment[4]. The beam has a diameter of approximately 2 mm, and the plasma diameter is approximately 5 cm. The beam is detected using a Rogowski loop which has a frequency response which is peaked at 10 MHz. The principle of the time-of-flight measurement is that the beam slows as it rides up a potential hill, and this retards the phase of the beam modulation at the detection point. Similarly, a potential well advances the phase at the detection point. Quantitatively, we consider a beam current which has a sinusoidal time dependence at its detection location $z = 0$:

$$I_{beam}(t) = I_{DC} + I_{peak} \sin(\omega t + \phi) . \tag{1}$$

The phase of the beam at axial position z is then given by integrating the wavenumber $k(z)$

$$\phi(z) = \int_0^z \frac{\omega}{v(z')} dz' = \omega \sqrt{\frac{m}{2e}} \int_0^z \left[-V(z')\right]^{-1/2} dz', \tag{2}$$

where ω is the modulation frequency, and the beam velocity $v(z)$ varies with z due to variations in the electrostatic potential. Here the potential

$V(z)$ is referenced to that of the electron gun filament. In this proof-of-principle experiment only one detection loop is employed, so that we measure $\phi(z = L)$.

Multiple detection loops could be employed to obtain a differential phase measurement, and hence an axially resolved potential profile. In this case the data is interpreted by differentiating (2) with respect to z, and solving for the potential so that

$$V(z) = -\frac{m\omega^2}{2e}\left[\phi'(z)\right]^{-2}. \tag{3}$$

This possibility of using multiple detectors located outside the plasma confinement region makes the present technique superior to that of Lieberman *et. al.*[5][8], in which a collector was inserted into a low temperature plasma to intercept the electron beam. It is not feasible to insert a collector into high temperature tandem mirror plasmas. Another advantage of the Rogowski loop technique is that transverse alignment of the electron beam is not critical, whereas when a collector is used, the beam may drift back and forth across the collector.

II. APPARATUS

The electron gun is enclosed in a stainless steel cylinder which extends into the center of the plasma[5]. The dimensions of the gun were made as small as possible in order to minimize the disturbance to the plasma. The cylinder is 4 mm in diameter, and encloses a heated tungsten filament, a wire mesh grid for modulating the current, and another wire mesh designed to prevent plasma electrons from entering the gun. A heater current of approximately 3 A is applied to the beam filament about 5 seconds prior to firing the magnetic fields and initiating the plasma discharge.

Great care was exercised in the design of the Rogowski loop (Fig. 2), as the detection of a 500 μA peak-to-peak beam signal in a noisy plasma environment which includes pulsed magnetic fields of large magnitude is not an easy task. The coil was wound from a coaxial line with a solid copper shield in order to provide maximum protection for the inner current-sensing conductor. The distributed capacitance of the coaxial line and the inductance of the coil can be modelled as lumped circuit elements of 141 pF and 1.0 μH, respectively. Since the coil geometry is constrained by our plasma and chamber dimensions, the main parameter we can vary is the number of turns in the loop. By varying the number of turns, we sought to peak the frequency response at 10 MHz, our gun modulation frequency. The response of the circuit was plotted for different numbers of turns, and on this basis the number of turns was chosen to be 48. The response of the loop was modelled using the SPICE circuit simulation computer code[6]. In the simulation, the loop was modelled as a voltage source exciting a transmission line which is terminated in 50 Ω. The SPICE simulation qualitatively reproduces the experimentally measured frequency response (Fig. 3), although the exact positions of the high frequency resonances differ. As expected, the lumped circuit model is quite accurate at low frequencies, but begins to fail at frequencies for which the propagation wavelength approaches the length of the transmission line.

The entire loop is enclosed in a stainless steel shell having a circumferential gap. The thickness of the shell was chosen such that the skin depth at 10 MHz is small compared to the shell thickness, yet large compared to the skin depth at 1 kHz, which is the characteristic frequency of the pulsed magnetic fields which confine the plasma. Furthermore, the gap in the shell was made on the outside of the loop, in contrast to the more typical Rogowski loop geometry[7]. This approach prevents the plasma from making direct contact with the outer shield of the loop windings and worsening our noise problems.

A block diagram of the modulation and detection electronics is shown in Fig. 4. A 100 MHz ECL clock signal is divided down to a 10 MHz TTL signal which is amplified and filtered to produce a 20 V peak-to-peak sine wave which is applied to the electron gun grid through a transformer. The output of the Rogowski loop is terminated at the 50 Ω input of a 10 MHz bandpass amplifier (BW = 2 MHz) which has a gain of 60 dB in the pass band. The amplifier output is passively added to a fiducial timing marker circuit, and the resulting signal is digitized on a Transiac 2001 transient digitizer. The digitizer clock is provided by the 100 MHz master clock signal. Since the modulation signal is produced from this same clock signal, the advantages of phase sensitive detection are realized. The fiducial timing marker is required because the transient digitizers do not reliably digitize the first sample when triggered. Often the first sample, or the first two samples are simply missed. This effect is probably due to noise in the system ground when the plasma is fired. Missing sample points give an apparent phase shift to the sampled data. The presence of a timing marker in the signal allows us to correct for this source of systematic error.

III. RESULTS

In a preliminary experiment we have varied the energy of the electron beam between 250 and 325 volts, and measured the resulting phase shift in the electron beam modulation both in vacuum and with plasma. The vacuum measurement is very straightforward and reproducible. There are two major problems with the plasma results, however. One is that there appears to be a density limit of about 2×10^{11} cm^{-3} above which the shielding of the beam by the plasma and the noise associated with the plasma obscures the signal[8]. The second problem is that for some discharges the detected signal is actually larger than the beam signal in vacuum. For these discharges, the measured phase is not correlated to the beam energy. This signal appears to be correlated with Langmuir probe breakdown which produces a powerful transient that causes the high gain bandpass amplifier to oscillate. The Langmuir probes are used to measure the plasma density and electron temperature upstream and downstream of the electron beam apparatus.

The results for vacuum and plasma discharges are shown in Fig. 5. Here we have plotted the measured phase shift against the reciprocal of the square root of the beam energy. According to (2), with $z = 113$ cm, this should be a straight line with slope 120 V$^{-1/2}$, and we have obtained a slope of 112 V$^{-1/2}$. Five different beam energies for the vacuum shots and two different energies for the plasma shots are represented in this figure. The error bars represent one standard deviation, based on the shot-to-shot variation. The phase measurements for the two results with plasma are plotted along this best-fit line, and the corresponding beam energy is read on the abscissa. Subtracting the known bias voltage on the gun, we obtain the plasma potential. For the two cases indicated in Fig. 5, the results obtained indicate a plasma potential Φ of +12 V, and +17 V. These are reasonable plasma potentials given our plasma temperature of about 3eV ($\Phi \sim 4kT$), and this is suggestive of an actual potential measurement. As indicated in the figure, however, the uncertainty in these measurements is quite large.

The shot-to-shot variation in the phase shift data may be due to low frequency phase drift in the signal amplifier. This variation has proven to be the major source of difficulty in this measurement. A larger beam signal would reduce the gain requirements on the amplifier, with corresponding reduction in the phase drift.

For geometries in which it is not practical to circumscribe the plasma with a Rogowski loop, a coil could be placed to one side of the beam near the chamber wall. This has the disadvantage of detecting currents which do not pass through the plasma. In a less noisy environment than ours, however, this disadvantage might not be prohibitive.

ACKNOWLEDGEMENT

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References

[1] G. Dimov, V. Zakaidakov, and M. Kishinevskii, Fiz. Plazmy **2**, 597 (1976) [Soviet J. Plasma Phys. **2**, 326 (1976)].

[2] T. Fowler and B. Logan, Comments Plasma Phys. Controlled Fusion **2**, 167 (1977).

[3] R. S. Hornady, G. W. Coutts, J. W. Colborn, J. W. Heefner, and D. H. Nelson, Plasma Potential in the TMX-U Central Cell, Bull. Am. Phys. Soc., 26th Annual Meeting of the Division of Plasma Physics, Abstract #8S20, (1984).

[4] J. C. Fernandez, C. P. Chang, A. J. Lichtenberg, M. A. Lieberman, and H. Meuth, Phys. Fluids **29**, 1208 (1986).

[5] C. P. Chang, Ph. D. dissertation, College of Engineering, University of California, Berkeley, 1986; submitted to **Physics of Fluids**, 1986.

[6] A. Vladimirescu, K. Zhang, A. R. Newton, D. O. Pederson, A. Sangiovanni-Vincentelli, **SPICE 2G.6 User's Guide**, EECS/ERL Industrial Support Office, Univ. of Cal. Berkeley (1982).

[7] D. G. Pellinen, M. S. Di Capua, S. E. Sampayan, H. Gerbracht, and M. Wang, Rev. Sci. Instrum. **51** 1535 (1980).

[8] M. A. Lieberman and C. P. Chang, Electron Beam Time-of-Flight Measurements of Plasma Potential in Tandem Mirrors, UCB Memorandum No. UCB/ERL M84/92 (1984).

Figure 1: Experimental configuration. The electron beam is injected axially and detected with a Rogowski loop.

Figure 2: Rogowski loop design. A solid shield coaxial cable is wound on a Teflon core, and the structure is enclosed in a stainless steel shell. There are 24 turns wound clockwise, and 24 wound counter-clockwise, so that no voltage is induced by time-dependent magnetic fields which are driven by external current sources.

Figure 3: Frequency response of Rogowski loop for the cases of a lumped analytical model ($-$), a SPICE model ($\triangle$), and the measured response ($\diamond$).

Figure 4: Block diagram of modulation and detection electronics. The 10 MHz gun modulation is derived from the same 100 MHz signal which clocks the transient digitizer.

Figure 5: Phase shift data for vacuum ($\square$) and plasma ($\triangle$) shots. The straight line is a fit to the vacuum data, and the data for the plasma shots are forced to lie on this line.

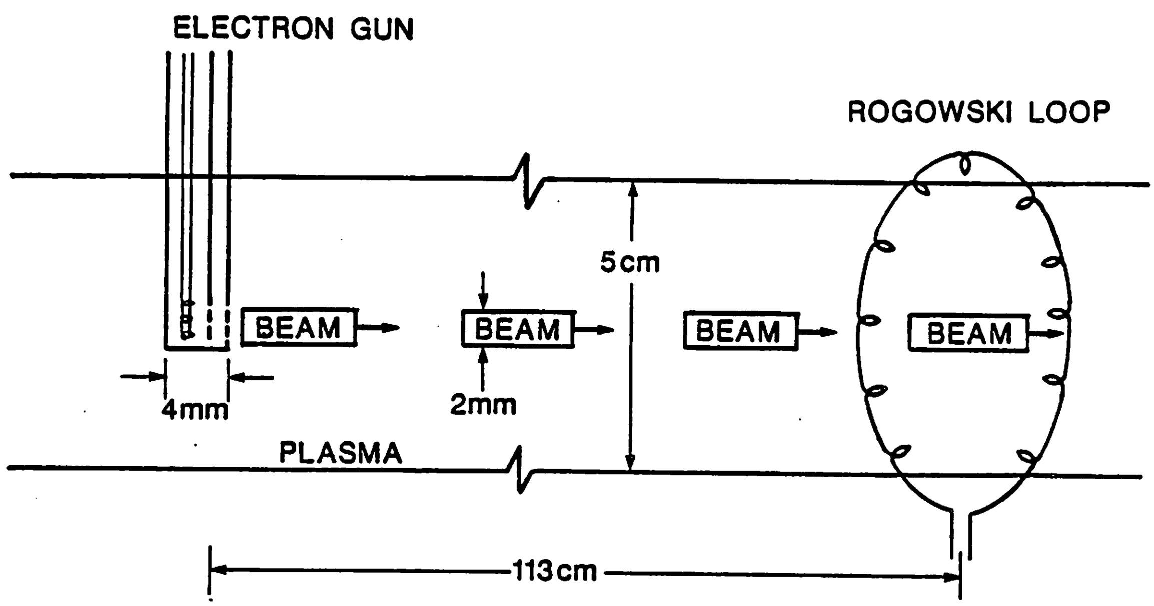
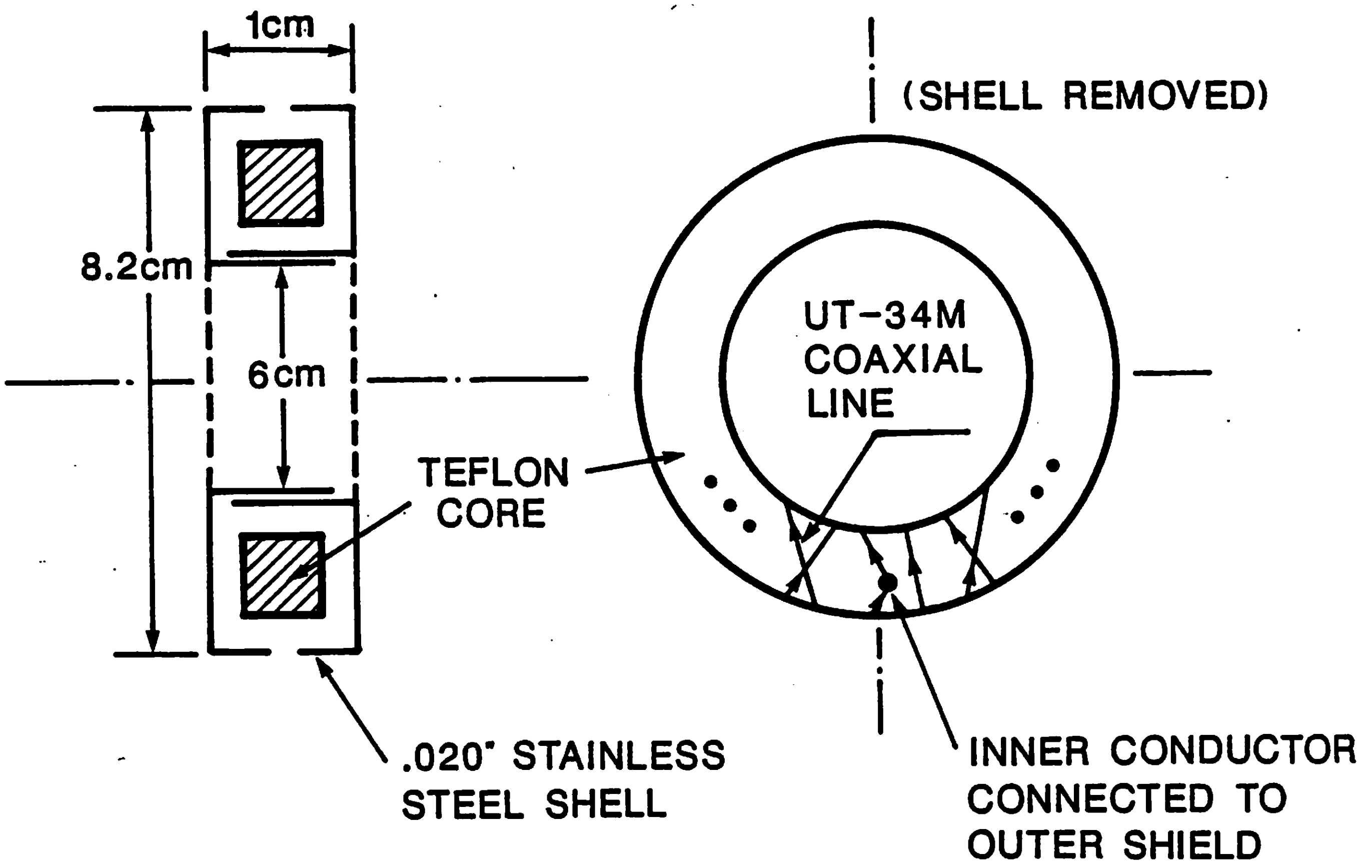

ELECTRON GUN
ROGOWSKI LOOP
5cm
BEAM
BEAM
BEAM
BEAM
4mm
2mm
PLASMA
113cm

Figure 1



1cm
8.2cm
6cm
TEFLON
CORE
.020" STAINLESS
STEEL SHELL
(SHELL REMOVED)
UT-34M
COAXIAL
LINE
INNER CONDUCTOR
CONNECTED TO
OUTER SHIELD

Figure 2

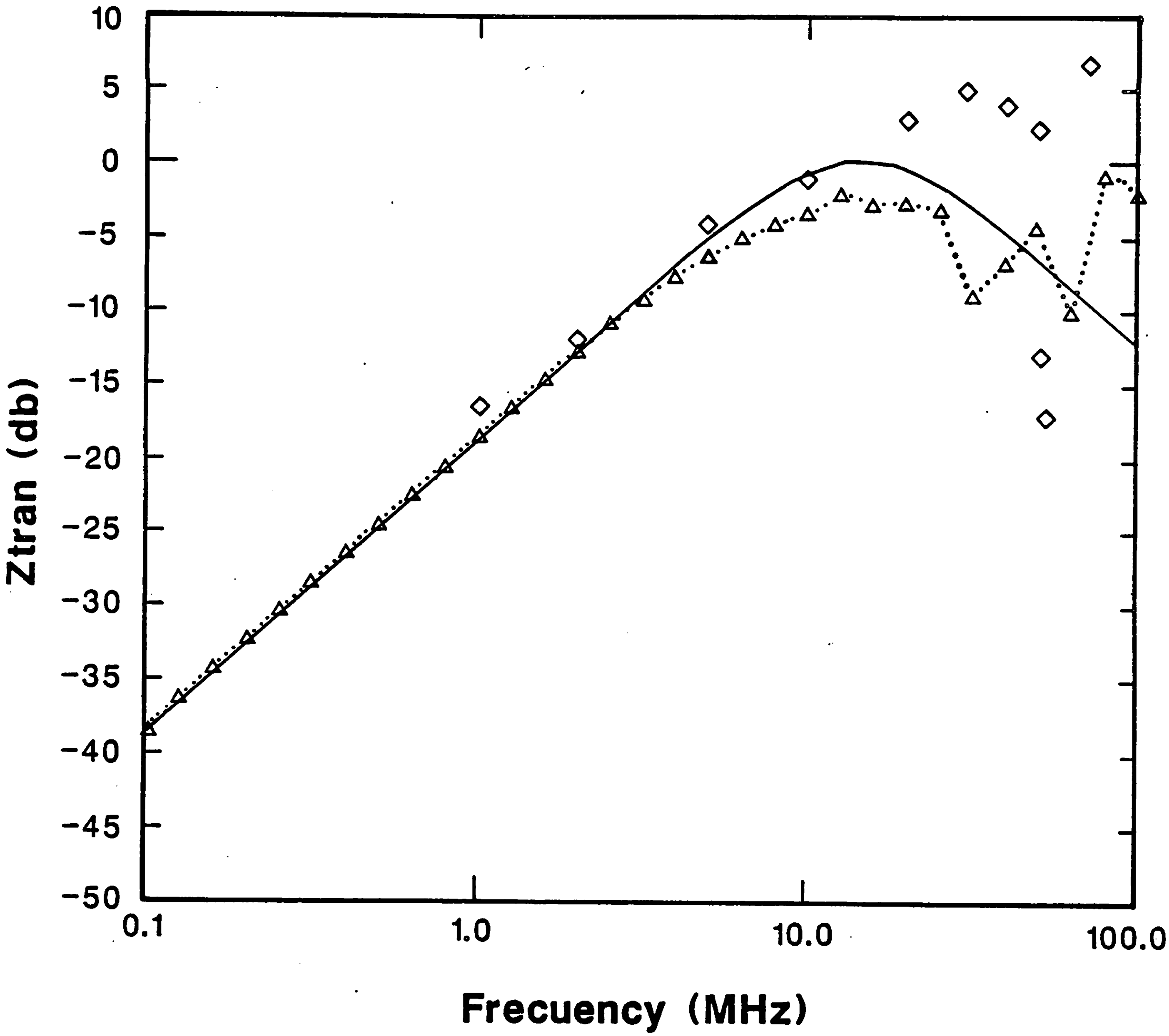

10
5
0
−5
−10
−15
−20
−25
−30
−35
−40
−45
−50
Ztran (db)
0.1
1.0
10.0
100.0
Frecuency (MHz)

Figure 3

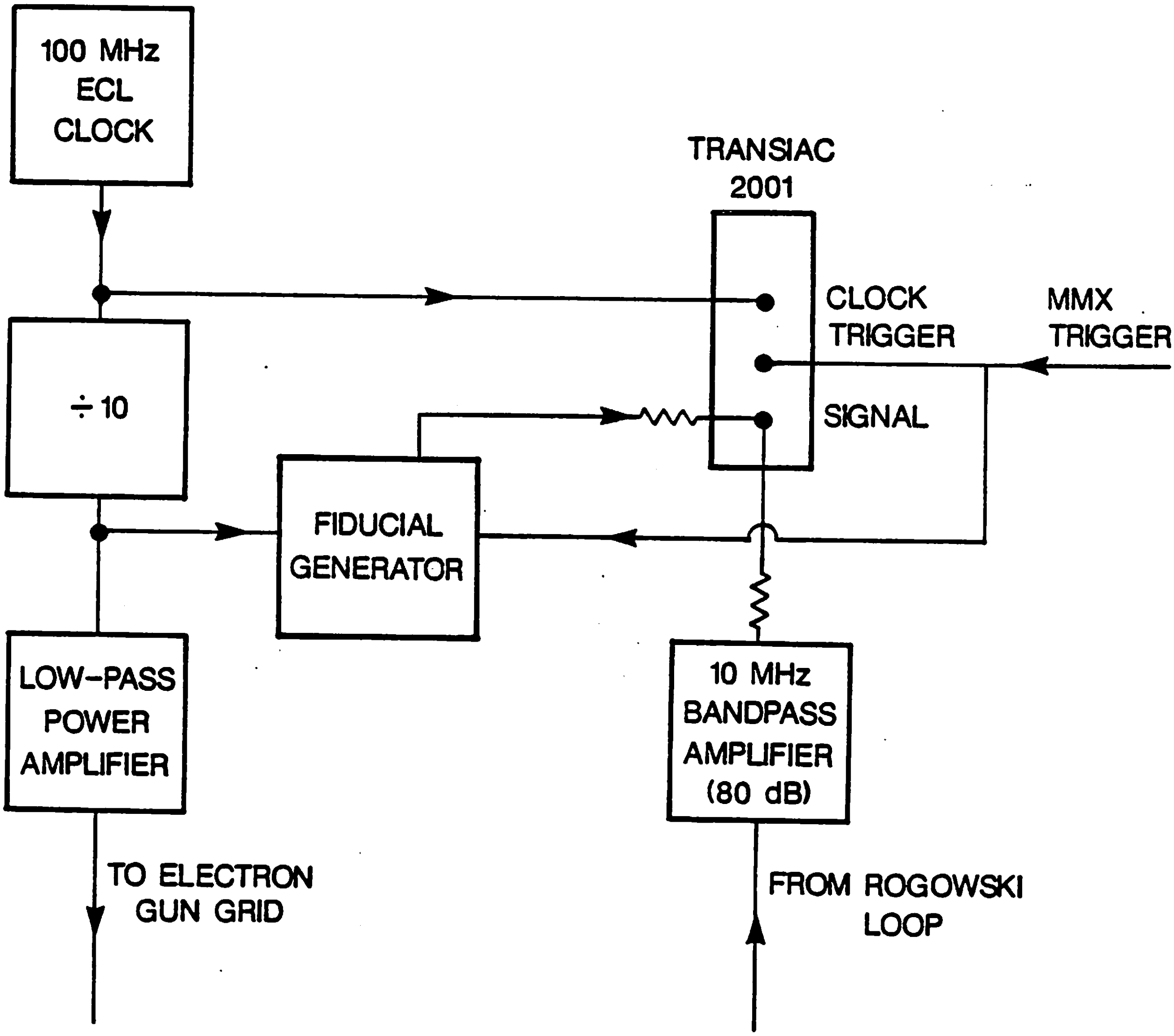
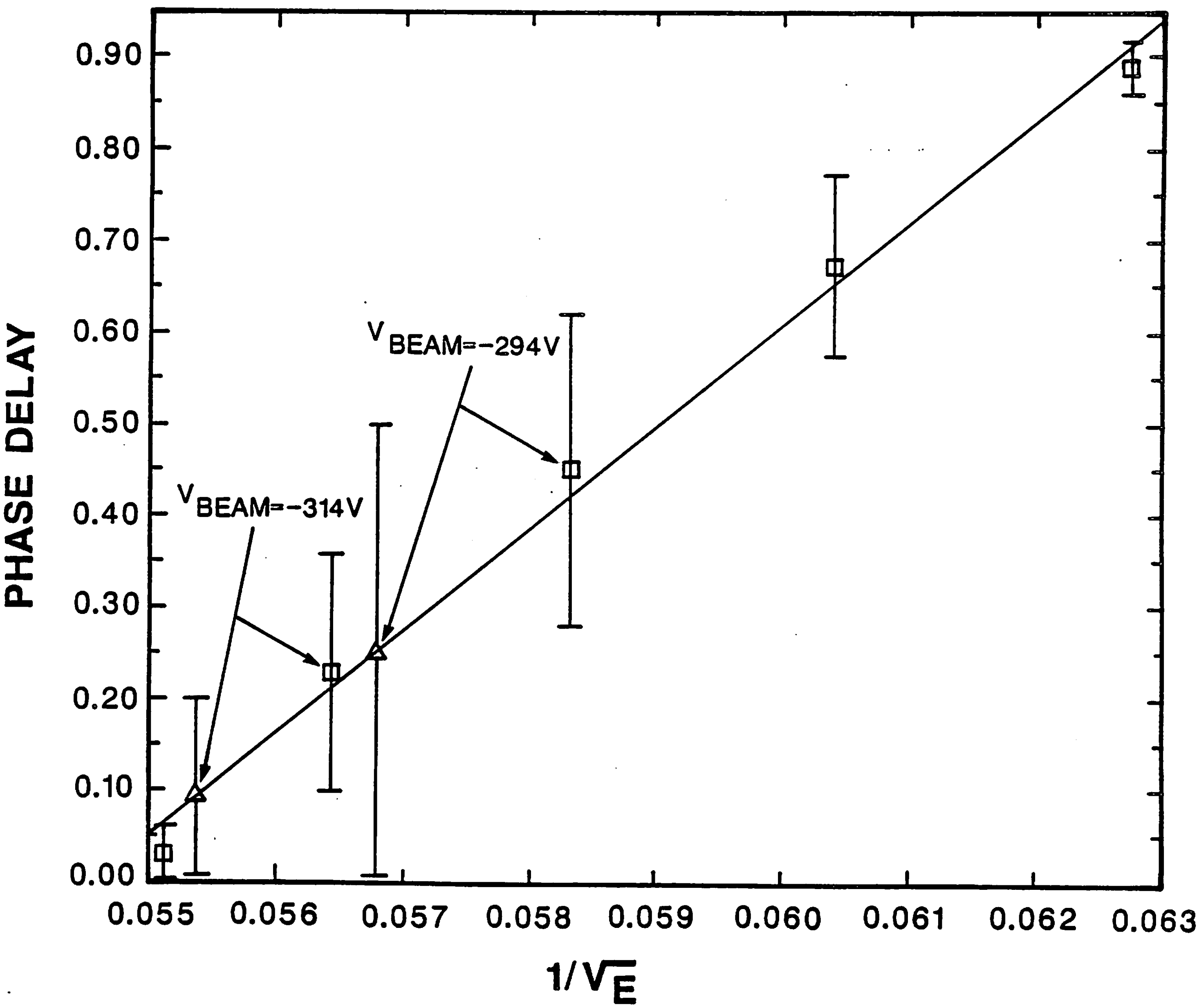

100 MHz ECL CLOCK
TRANSIAC 2001
CLOCK
TRIGGER
SIGNAL
MMX TRIGGER
÷10
FIDUCIAL GENERATOR
LOW-PASS POWER AMPLIFIER
10 MHz BANDPASS AMPLIFIER (80 dB)
TO ELECTRON GUN GRID
FROM ROGOWSKI LOOP

Figure 4


PHASE DELAY
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0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
V_{BEAM}=-294V
V_{BEAM}=-314V
0.055
0.056
0.057
0.058
0.059
0.060
0.061
0.062
0.063
$1/V_E$

Figure 5