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Abstract

The Center for Electromechanics at the University of Texas (CEM-UT) at Austin has developed a velocity dependent friction model which accurately predicts the losses associated with a plasma armature railgun while performing research associated with several Defense Advanced Research Projects Agency (DARPA) contracts.

Test results from CEM-UT's 1 m long, 1.27 cm square bore, plasma-armature railgun have been used to determine the validity of the model. Deviation between calculated and measured performance is typically less than 5% at railgun currents below 500 kA; however, at currents greater than 500 kA, the deviation increases.

Experimental evidence suggests that the railgun's lack of stiffness and subsequent venting of driving pressure rather than the electromechanical model is primarily responsible for the divergence between predicted and measured results. To test this theory a railgun was built using external preloading rings (Ringfeder®) to increase its stiffness. On the first test of the Ringfeder® railgun, 700 kA was discharged into the gun and the projectile was accelerated to 5.9 km/s. Test data indicates that the projectile accelerated through the entire length of the railgun and that a minimum amount of plasma leakage had occurred during the test.

An analysis of the 700-kA test was done to compare the results of CEM-UT's frictional loss model to ablation and viscous drag loss models.

INTRODUCTION

A variety of loss models have been developed in the community to aid in predicting performance of electromagnetic (EM) railgun type launchers. At the Center for Electromechanics at The University of Texas at Austin (CEM-UT), computer programs were developed that predict shot performance and test theoretical models against experimental data after a railgun has been fired. Data has been accumulating which suggests that there are two loss mechanisms that are primarily responsible for lowering railgun performance: friction between the projectile and the bore of the railgun, and plasma leakage due to the railgun's lack of stiffness.

This paper will review three popular loss models currently used at CEM-UT in modeling EM launchers: friction, ablation, and armature drag, followed by the analysis of one railgun experiment in which the projectile obtained a measured velocity of about 6 km/s. The shot will be analyzed using the velocity dependent frictional loss, ablative loss, and armature drag both separately and combined for comparison's sake. Energy balances of each model will be compared to the energy fed into the railgun's breech.

ELECTROMECHANICAL MODEL

Lorentz Force

For a parallel geometry railgun, as shown in figure 1, drive force (Lorentz Force) without losses is:

$$F = \frac{1}{2} L'I^2 \tag{1}$$

where

F = force on the projectile
L' = inductance per unit length.[1]

Simulated projectile performance will be determined by calculating the projectile's acceleration, due to the Lorentz Force and integrating it over time.

Thermodynamic Force

When a metallic foil is used to initiate a plasma armature in a railgun, it imparts a thermodynamic force on the projectile caused by the rapidly expanding hot gases of the exploding foil. Rather than develop a complicated model, this effect is accounted for by an initial velocity of 400 m/s in pre-shot simulations. This value was chosen from the average values of the y-intercept of post-shot plots of the integral of current squared vs. observed velocity. In post-shot simulations, the observed intercept for each particular shot is used instead of the average value.

Friction Model

Projectile-to-bore friction forces have been modeled by light gas gun researchers using a velocity dependent friction model based on the work of Bowden and Tabor.[2] At velocities greater than 400 m/s, the friction coefficient scales according to:

$$h = AV^{-B}$$

where

h = velocity dependent friction coefficient
V = velocity (ft/s)
A = constant scale factor
B = power factor.

Bowden and Tabor's work was done by sliding nylon on steel where they found the coefficient B to be -0.4. In work published by Powell and associates, it was assumed that B was the same as in Bowden and Tabor's work but A was scaled by the ratio of the static coefficient of friction of Lexan® on steel and nylon on steel yielding A to be 4.0. Powell states that "This approach produces a realistic trend and reasonable values but is known to be approximate."[3] Since a variety of materials are used in railguns, the equation has been rewritten to eliminate the scaling done by Powell by dividing A by the static coefficient of friction for Lexan® on steel and introducing the coefficient of friction of the projectile material on the bore such that:

$$h = 4(\frac{h_1}{h_2})V^{-0.4} \tag{2}$$

where

h = velocity dependent friction coefficient
V = velocity (ft/s)
h_1 = static coefficient of the projectile on the bore
h_2 = static coefficient of the Lexan® on steel.

In CEM-UT railgun simulations, the force normal to the bore is determined by calculating the triaxial stress state that is established in the projectile due the drive pressure applied at the rear surface.[4] The component of stress that is normal to the bore surface is integrated over the projectile surface and then multiplied by the velocity dependent friction coefficient to determine the loss in driving force. A check is performed to insure that the frictional loss does not exceed the drive force and, in the event that it does, a message is printed to the screen indicating to the operator that it has. Table 1 lists the static coefficients of friction for materials used in CEM-UT railguns as determined in CEM-UT labs.

Ablation Model

Analysis of plasma armatures in EM launchers has revealed behavior that suggests the ablation of the railgun bore constituents and subsequent ionization of them into the plasma armature.[5] A simple worst-case model for predicting the material mass removed from the bore and consequently added to the armature is:

$$\frac{dm_a}{dt} = \alpha I V_a \tag{3}$$

where

m_a = arc mass
I = armature current
V_a = arc voltage
α = ablation constant.

The ablation constant α is material dependent and can be approximated by calculating the energy per gram required to ionize it. Since the dominant factor in determining the ablation constant is the average atomic weight of the material, a close approximate can be found using the following relation:

$$\alpha = \frac{3n}{4} \text{ g/MJ} \tag{4}$$

where

n = average atomic weight of bore materials.

Table 2 lists ablation constants for typical bore materials determined using the formula above.

Ablation affects the performance of a plasma armature railgun in at least two ways: the first is in the increase in the overall launch package mass which may be determined using equation (3), the second being the force associated with changing the launch package mass while moving at velocity, v, which can be determined by [5]:

$$F_A = v \frac{dm_a}{dt} = \alpha I V_a v \tag{5}$$

In CEM-UT railgun simulations, the ablation force is subtracted from the Lorentz force prior to calculating the normal force used in frictional loss calculation.

Armature Drag

The viscous drag of a plasma armature on railgun bore walls further decreases the acceleration force on the projectile. If the plasma armature is assumed to be uniform along its length, the viscous drag force in a square-bore railgun can be determined from: [5]

$$F_v = \frac{B\rho v^2 C l_a}{2} = \frac{B v^2 m_a (w+h)}{wh} \tag{6}$$

where

ρ = plasma density
B = drag coefficient
C = bore circumference
l_a = armature length
m_a = armature mass
v = armature velocity
w = width of bore
h = height of bore.

According to Tidman, Goldstein, and Winsor [6], the drag coefficient can be determined using the following equation:

$$B = [2\log(\frac{a}{\delta a_w}) + 1.74]^{-2}$$

where

$\frac{a}{\delta a_W}$ = the ratio of the bore size divided by the bore roughness.

For most smooth gun bores, $a/\delta a_W \approx 4000$, so by substitution B = 0.0125.

As with the ablation loss, the viscous drag force is subtracted from the Lorentz force prior to calculation of the projectile's velocity dependent friction loss.

EXPERIMENTAL RESULTS

Test results from CEM-UT's 1 m long, 1.27 cm square bore, plasma armature railgun have been compared to data generated using the velocity dependent frictional loss model. Deviation between calculated and measured performance is typically less than 5% at railgun currents below 500 kA; however, at currents greater than 500 kA the deviation increases.[4] During post-shot inspection of the railguns, a black soot was observed to have penetrated the bore seals in the region of the gun where the current exceeded 500 kA. Since the divergence between the calculated and measured data increased in the sooty areas, it has been suggested that the railgun's lack of stiffness and subsequent venting of driving pressure rather than the electromechanical model is primarily responsible for the divergence between predicted and measured results.[4] To test this theory, a railgun was built using external preloading rings (Ringfeders®) to increase its stiffness. Molybdenum flame sprayed copper rails and quartz glass insulators formed the bore of the gun. On the first test of the Ringfeder® railgun, 700 kA was discharged into the gun and a 2-g projectile was accelerated to 5.9 km/s. Test data indicates that the projectile accelerated through the entire length of the railgun and a minimum amount of plasma leakage had occurred during the test.

An analysis of the 700-kA test was done to compare the results of CEM-UT's frictional loss model to ablation and viscous drag loss models. Friction and ablation coefficients corresponding to the rail and insulator material were selected from Table 1 and Table 2. Data for the projectile's position and velocity in the gun and the gun input energy are plotted against time in figures 2 through 13 for each of the models separately and for the three models combined. In figures 2 through 13, "computed" refers to data calculated from the measured railgun current. Measured data was obtained using the methods discussed by Cook.[7] Measured railgun input energy represents the integral over time of the product of gun current and breech volts. Computed railgun input energies represent the sum of energy stored in the gun's inductance, integral of the product of voltage times current in electrical dissapative elements, the integral of force times velocity in mechanical dissapative elements, and the kinetic energy of the projectile.

The comparison of measured data to data calculated using the friction model alone is shown in figures 2 through 4. Figure 2 shows good correlation between measured and calculated position data. The greatest error occurs at early times and is probably due to a slight inaccuracy in thermodynamic force model (the thermodynamic model is used to account for an initial velocity and does not include a displacement). Since the projectile is moving very slow at this time, the accuracy of the velocity dependent frictional model may suffer. In figure 3, good correlation is seen throughout the shot between measured and calculated velocity. Some deviation is seen in the first 0.1 m of the gun but is most likely attributable to an insufficient magnetic probe density to give required resolution. Figure 4 shows reasonable correlation between the calculated input energy and the measured input energy.

The comparison of measured data to data calculated using the ablation model alone is shown in figures 5 through 7. In figure 5, the measured position deviates from the calculated position at the beginning and end of the experiment. Figure 6 clearly shows the measured velocity being significantly higher than that calculated in the simulation. In terms of energy, there does not appear to be much deviation between the measured and calculated data.

In figures 8 through 10, measured data was compared to data calculated using the viscous armature drag model. Deviation between measured and calculated position and velocity is small at early times in the test and gets larger near projectile exit. Once again, the calculated gun input energies do not differ significantly from the measured input energy.

In figures 11 through 13, data calculated using all three models combined is compared to measured data. Deviation between measured and calculated position, velocity, and input energy greatly exceed that obtained by applying the models individually.

ANALYSIS

All three loss models (velocity dependent, frictional drag, ablation, and armature drag) when evaluated individually, produce realistic results; yet when the models are evaluated together, the total loss is overpredicted. It is probable that most of the error is in the values chosen for the various coefficients used in the models.

At CEM-UT, the velocity dependent friction model is used in simulations because it is an accepted model in light gas guns. Ablation and armature viscous drag have been included into simulations for completeness, however; in experiments where plasma leakage was not observed the best correlation between simulated and measured performance was obtained using the friction model alone. It is believed that reducing frictional losses and plasma leakage will be instrumental in achieving velocities greater than 6 km/s.

CONCLUSIONS

Railgun performance simulations at CEM-UT were modified to include the effects of friction, ablation, and viscous drag. On experiments at currents below 500 kA using existing railgun design, the friction model alone was acceptable in predicting performance. In an experiment incorporating a railgun structure modified for higher stiffness and a measured peak railgun current of 700 kA, the effects of each of the loss models were compared to the measured results and the greatest success at predicting the final projectile velocity and exit time occurred using the velocity dependent friction model. Future plans include the construction of ceramic re-enforced railgun structures that can be operated at currents in the 800 kA regime with bore deflection of less than 0.13 mm (0.005 in.) to further test these theories.

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[7] R. W. Cook, "Observation and Analysis of Current Carrying Plasma in a Railgun", Master of Arts' Thesis, The University of Texas at Austin, December 1985.

Table 1. Static coefficients of friction of polycarbonate on various bore materials

BORE MATERIAL	COEFFICIENT OF FRICTION ON POLYCARBONATE
Steel	0.23
Copper 110	0.34
Quartz Glass	0.22
Plasma Sprayed Molybdenum	0.24
40% Glass Filled Polycarbonate	0.68

Table 2. Average ablation constants for various bore materials.

BORE MATERIAL	ABLATION COEFFICIENT
Steel	41 g/MJ
Copper 110	47 g/MJ
Quartz Glass	21 g/MJ
Plasma Sprayed Molybdenum	71 g/MJ
40% Glass Filled Polycarbonate	8 g/MJ

FIGURE CAPTIONS

Figure 1. Railgun basic concept

Figure 2. Measured and calculated projectile position data using velocity dependent friction model only

Figure 3. Measured and calculated projectile velocity data using velocity dependent friction model only

Figure 4. Measured and calculated railgun input energy using velocity dependent friction model only

Figure 5. Measured and calculated projectile position data using ablation model only

Figure 6. Measured and calculated projectile velocity data using ablation model only

Figure 7. Measured and calculated railgun input energy using ablation model only

Figure 8. Measured and calculated projectile position data using armature viscous drag model only

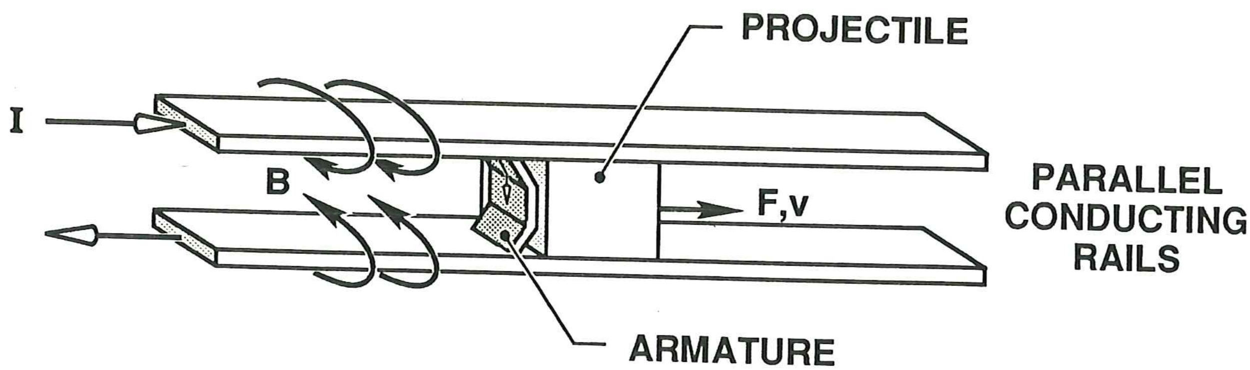
Figure 9. Measured and calculated projectile velocity data using armature viscous drag model only

Figure 10. Measured and calculated railgun input energy using armature viscous drag model only

Figure 11. Measured and calculated projectile position data using combined model

Figure 12. Measured and calculated projectile velocity data using combined model

Figure 13. Measured and calculated railgun input energy using combined model



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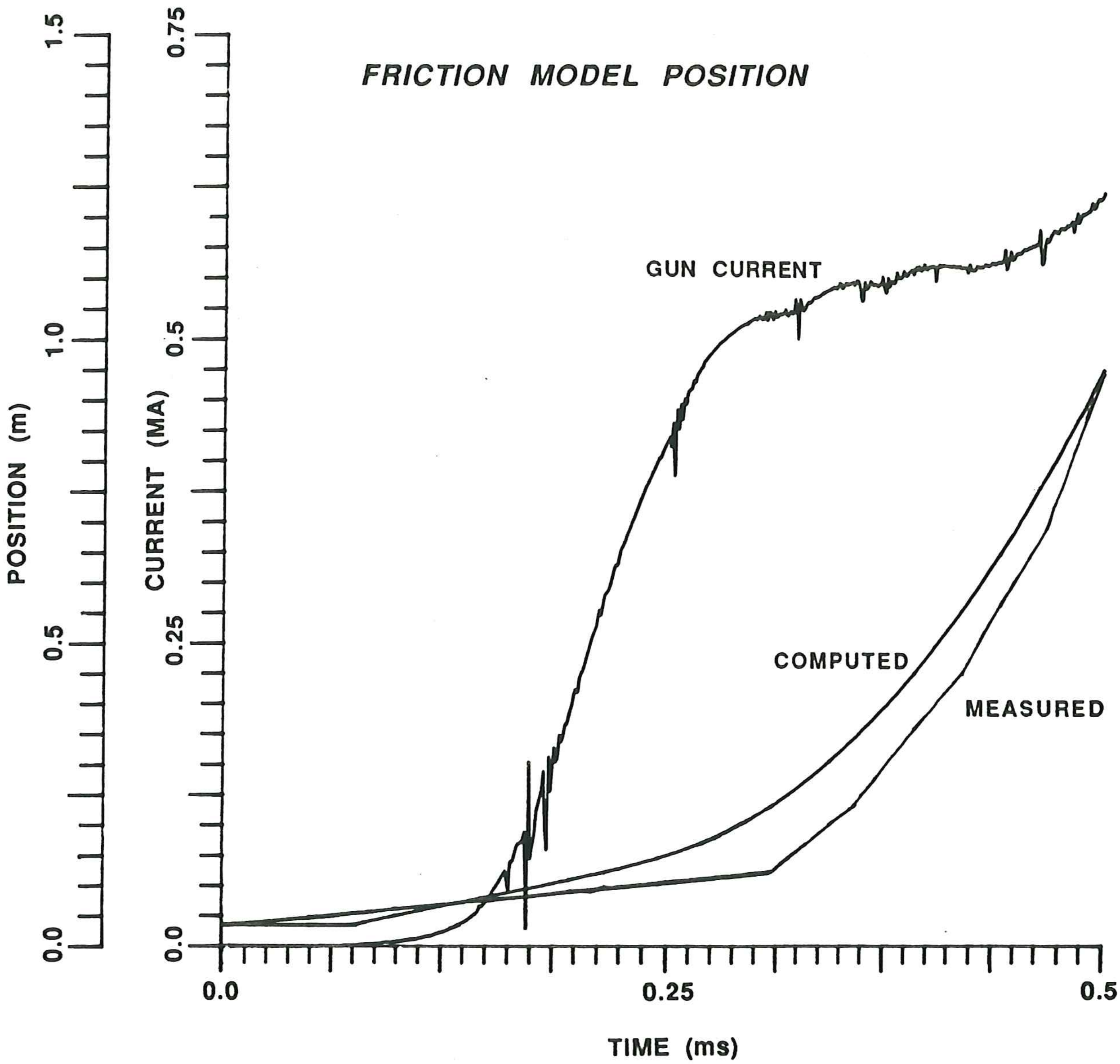
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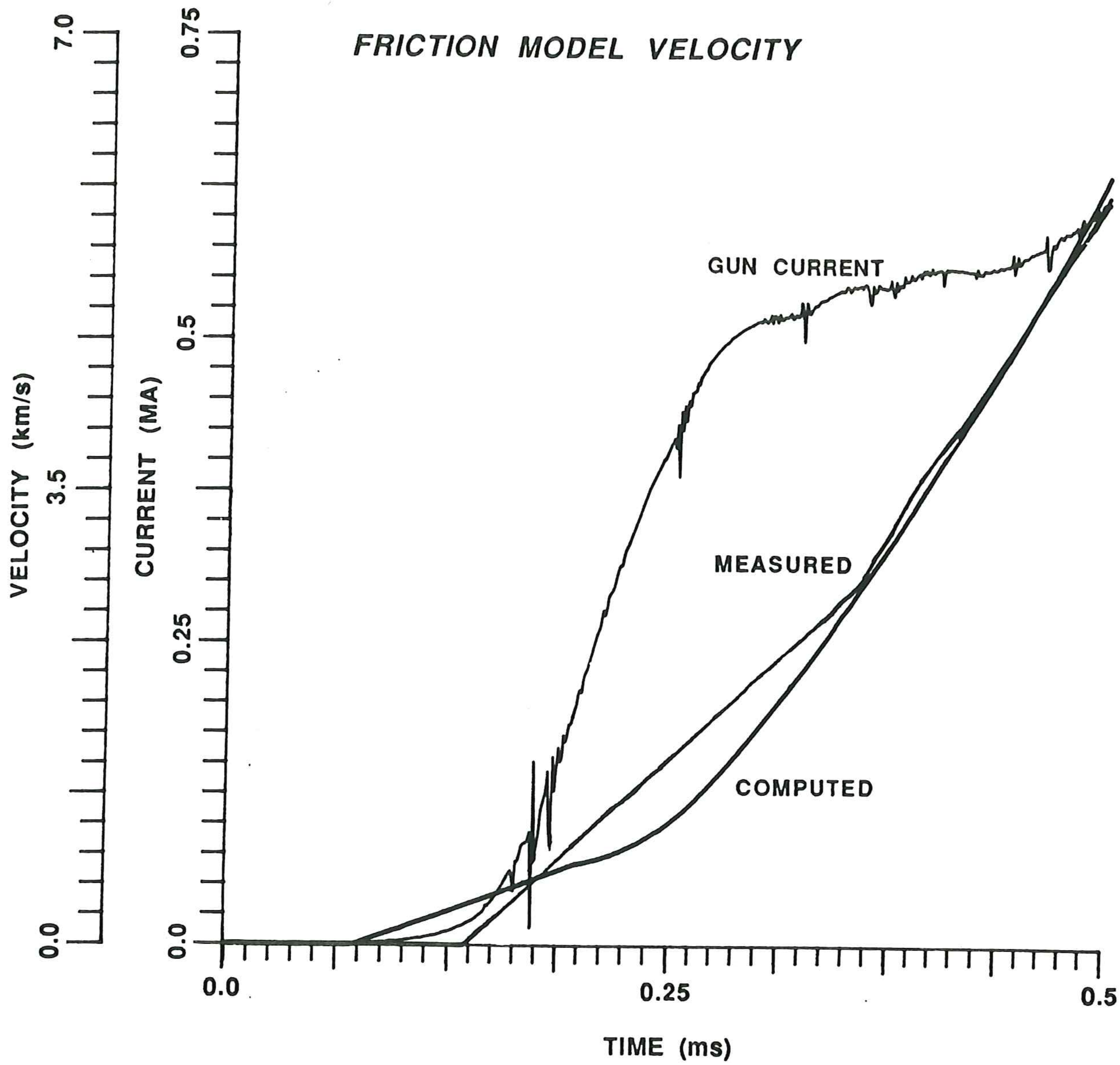
GUN CURRENT
COMPUTED
MEASURED
POSITION (m)
0.0
0.5
1.0
1.5
CURRENT (MA)
0.0
0.25
0.5
0.75
0.0
0.25
0.5
TIME (ms)



FRICTION MODEL VELOCITY
VELOCITY (km/s)
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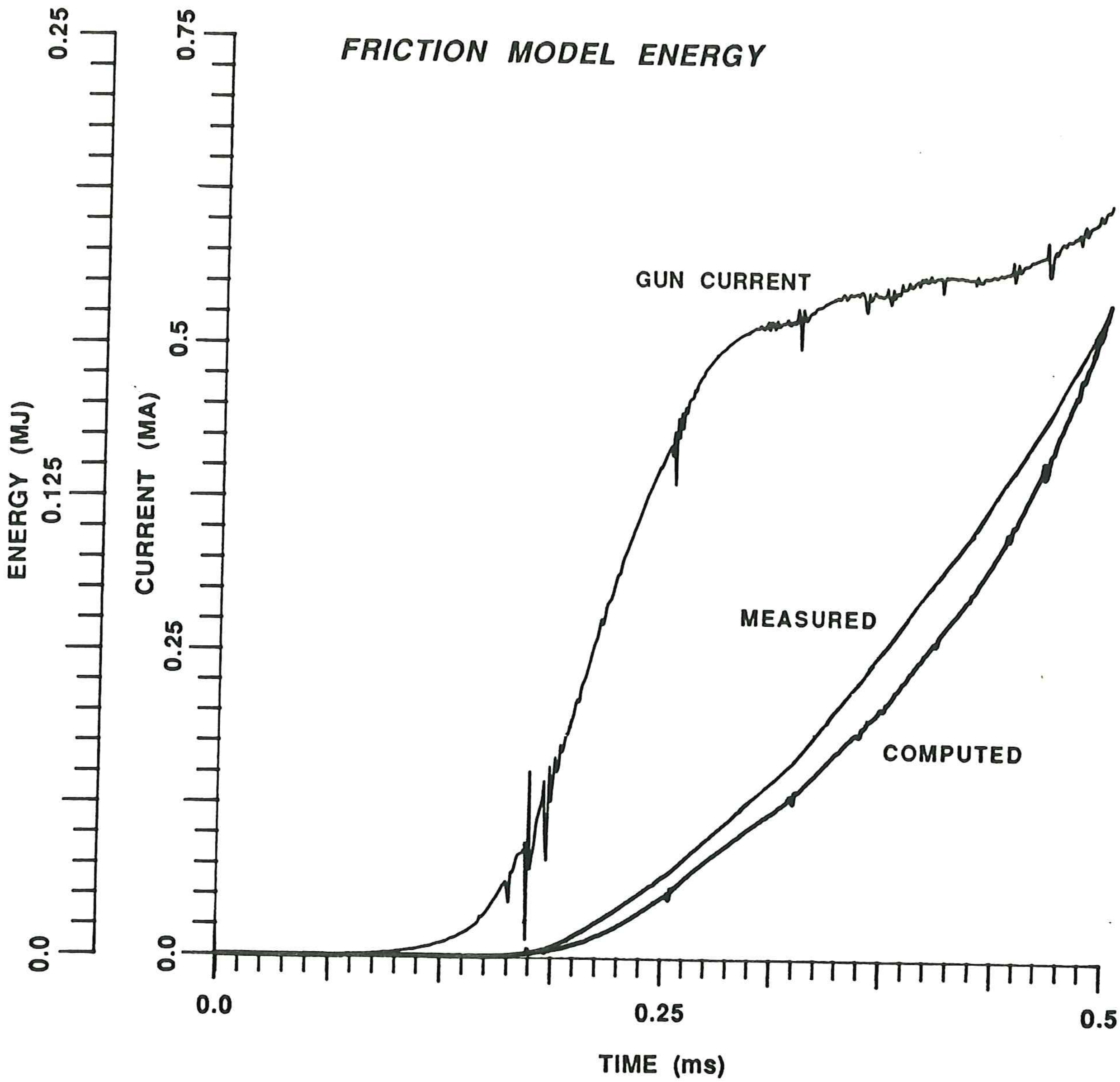
3.5
7.0
CURRENT (MA)
0.0
0.25
0.5
0.75
GUN CURRENT
MEASURED
COMPUTED
0.0
0.25
0.5
TIME (ms)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GUN CURRENT
MEASURED
COMPUTED
ENERGY (MJ)
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0.125
0.0
CURRENT (MA)
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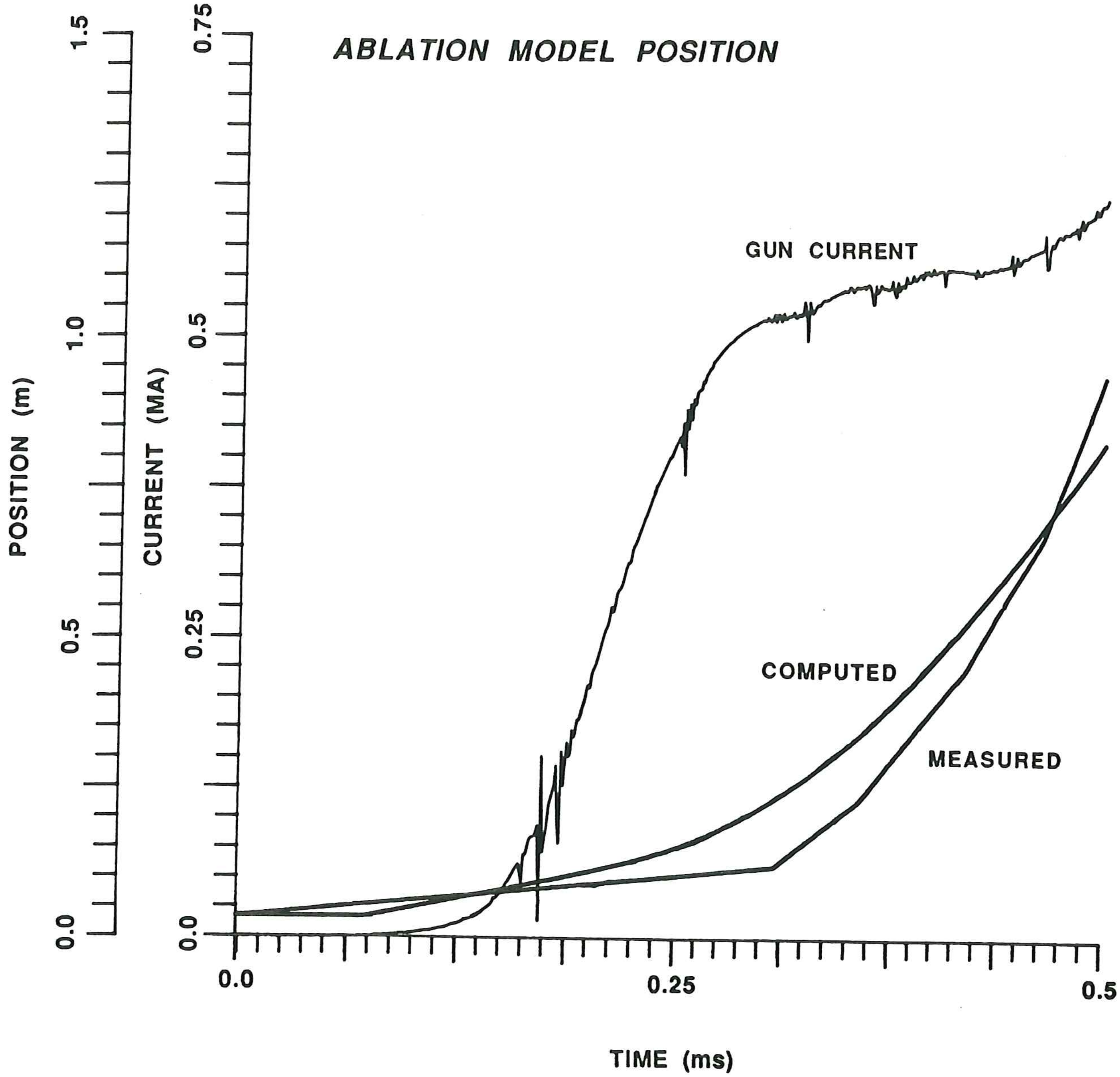
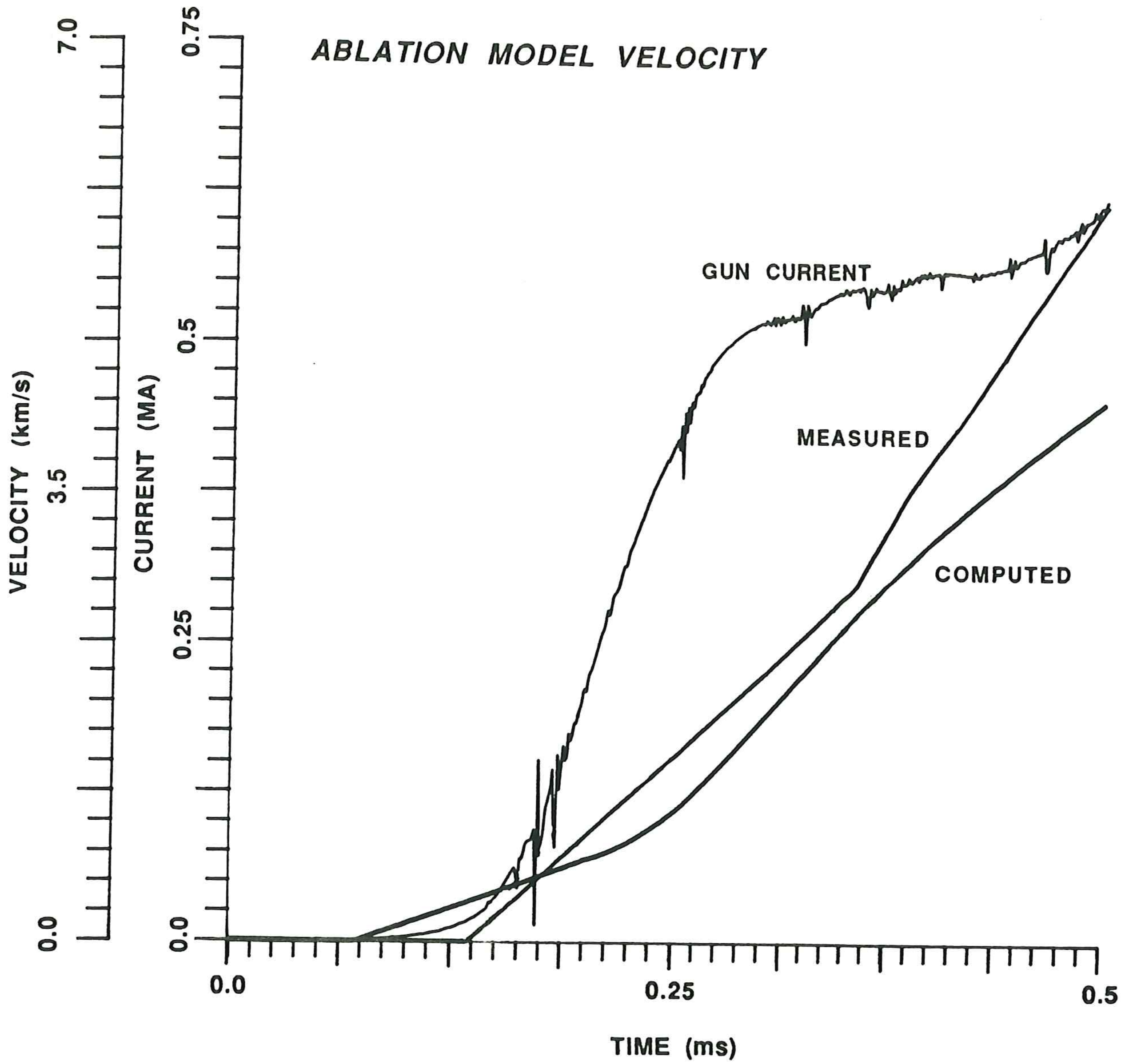
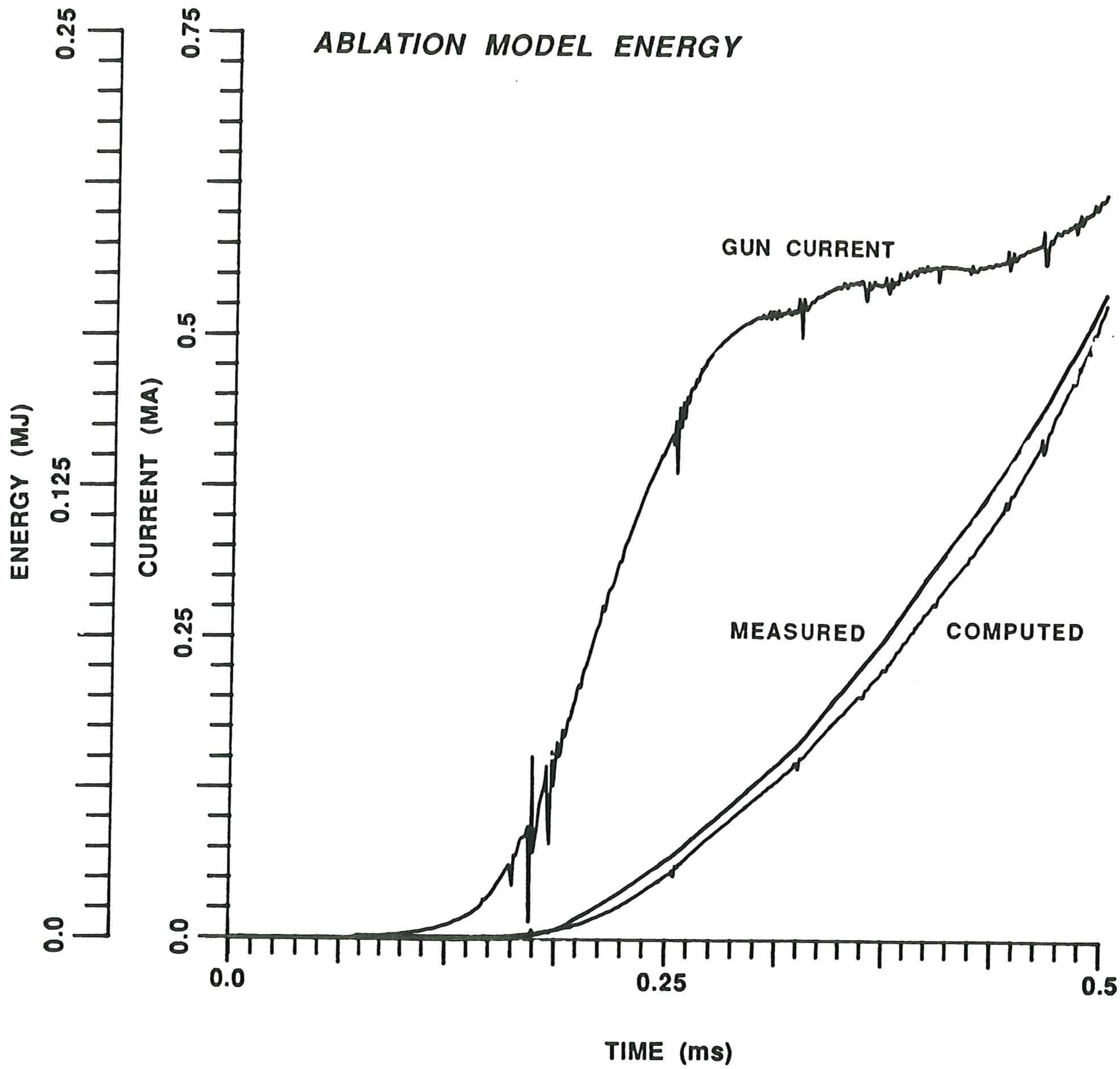
0.5
0.25
0.0
0.0
0.25
0.5
TIME (ms)



ABLATION MODEL POSITION
GUN CURRENT
COMPUTED
MEASURED
POSITION (m)
CURRENT (MA)
TIME (ms)
0.0
0.5
1.0
1.5
0.0
0.25
0.5
0.75
0.0
0.25
0.5


ABLATION MODEL VELOCITY
GUN CURRENT
MEASURED
COMPUTED
VELOCITY (km/s)
0.0
3.5
7.0
CURRENT (MA)
0.0
0.25
0.5
0.75
0.0
0.25
0.5
TIME (ms)


ABLATION MODEL ENERGY
GUN CURRENT
MEASURED
COMPUTED
ENERGY (MJ)
0.25
0.125
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CURRENT (MA)
0.75
0.5
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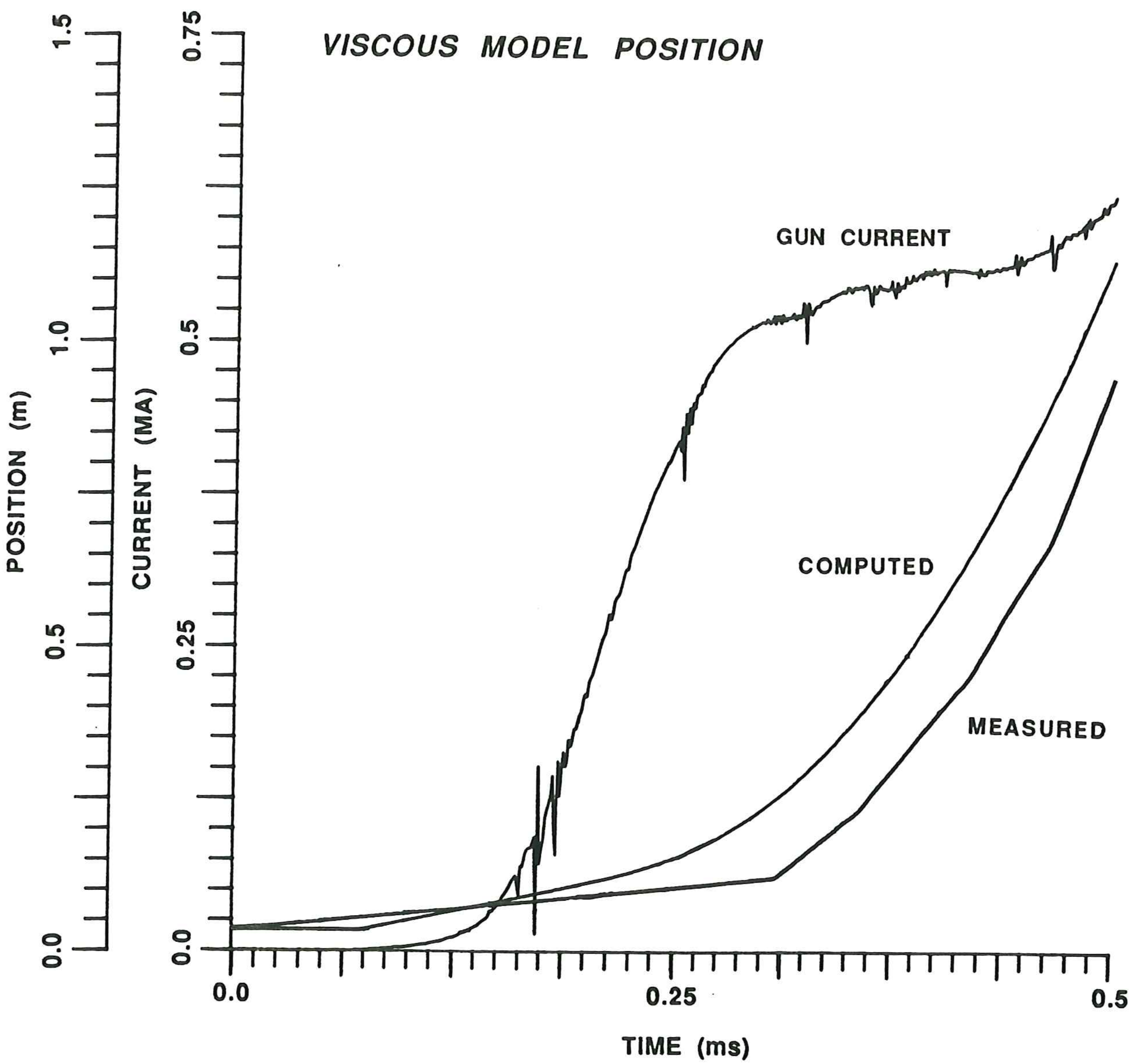
0.25
0.5
TIME (ms)


VISCOUS MODEL POSITION
GUN CURRENT
COMPUTED
MEASURED
POSITION (m)
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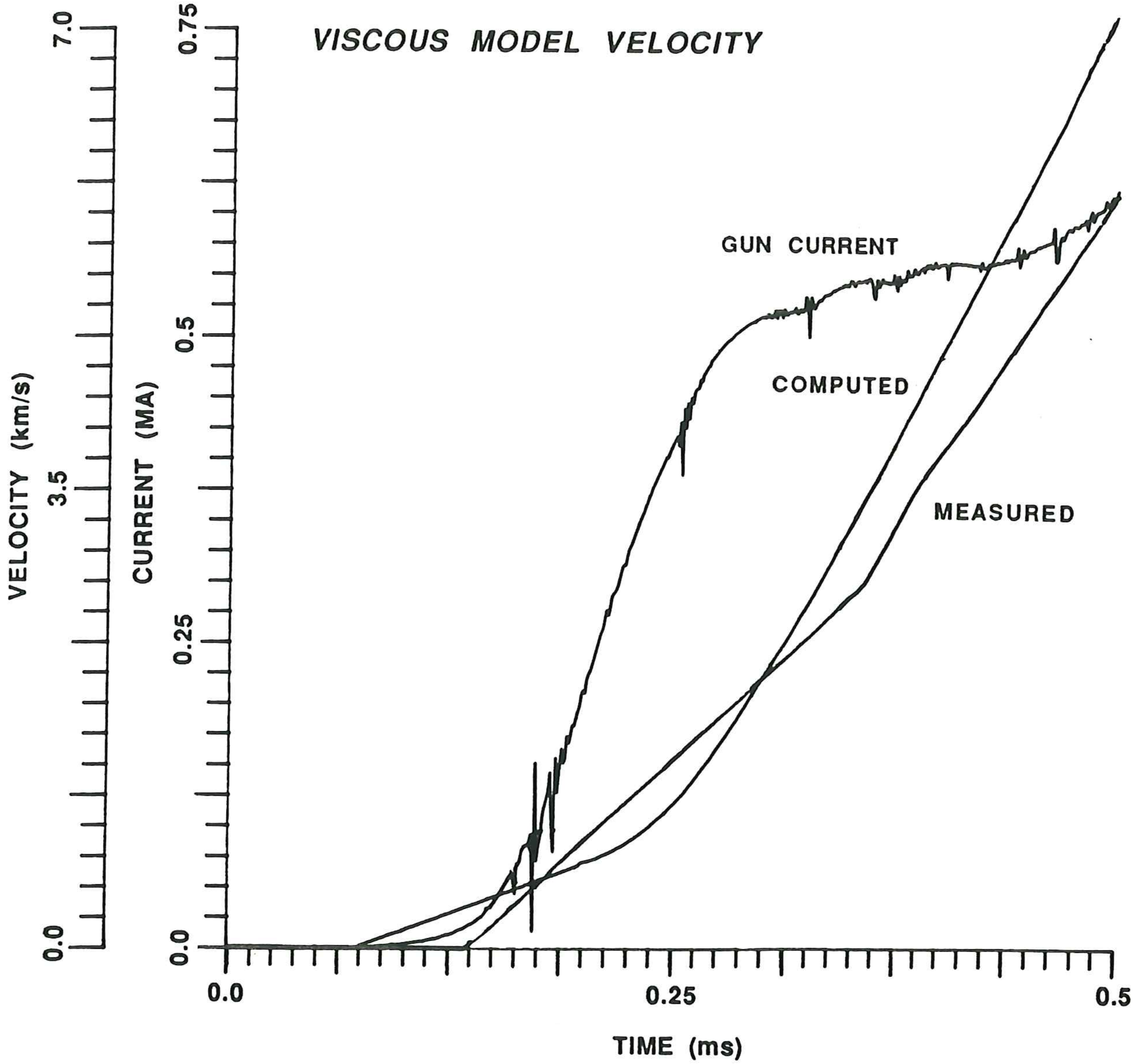
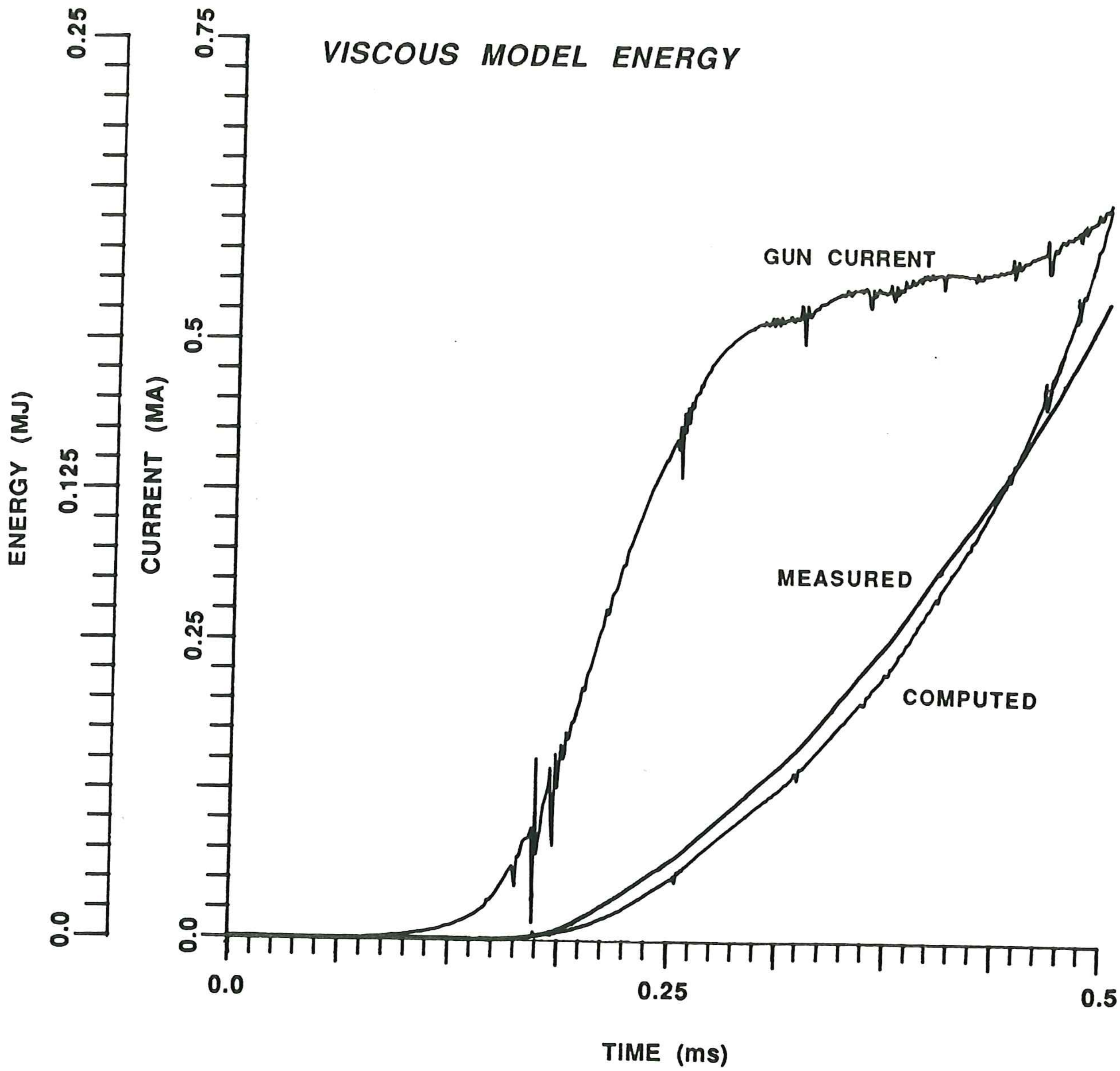
0.5
1.0
1.5
CURRENT (MA)
0.0
0.25
0.5
0.75
TIME (ms)
0.0
0.25
0.5



VISCOUS MODEL VELOCITY
VELOCITY (km/s)
7.0
3.5
0.0
CURRENT (MA)
0.75
0.5
0.25
0.0
GUN CURRENT
COMPUTED
MEASURED
0.0
0.25
0.5
TIME (ms)



VISCOUS MODEL ENERGY
ENERGY (MJ)
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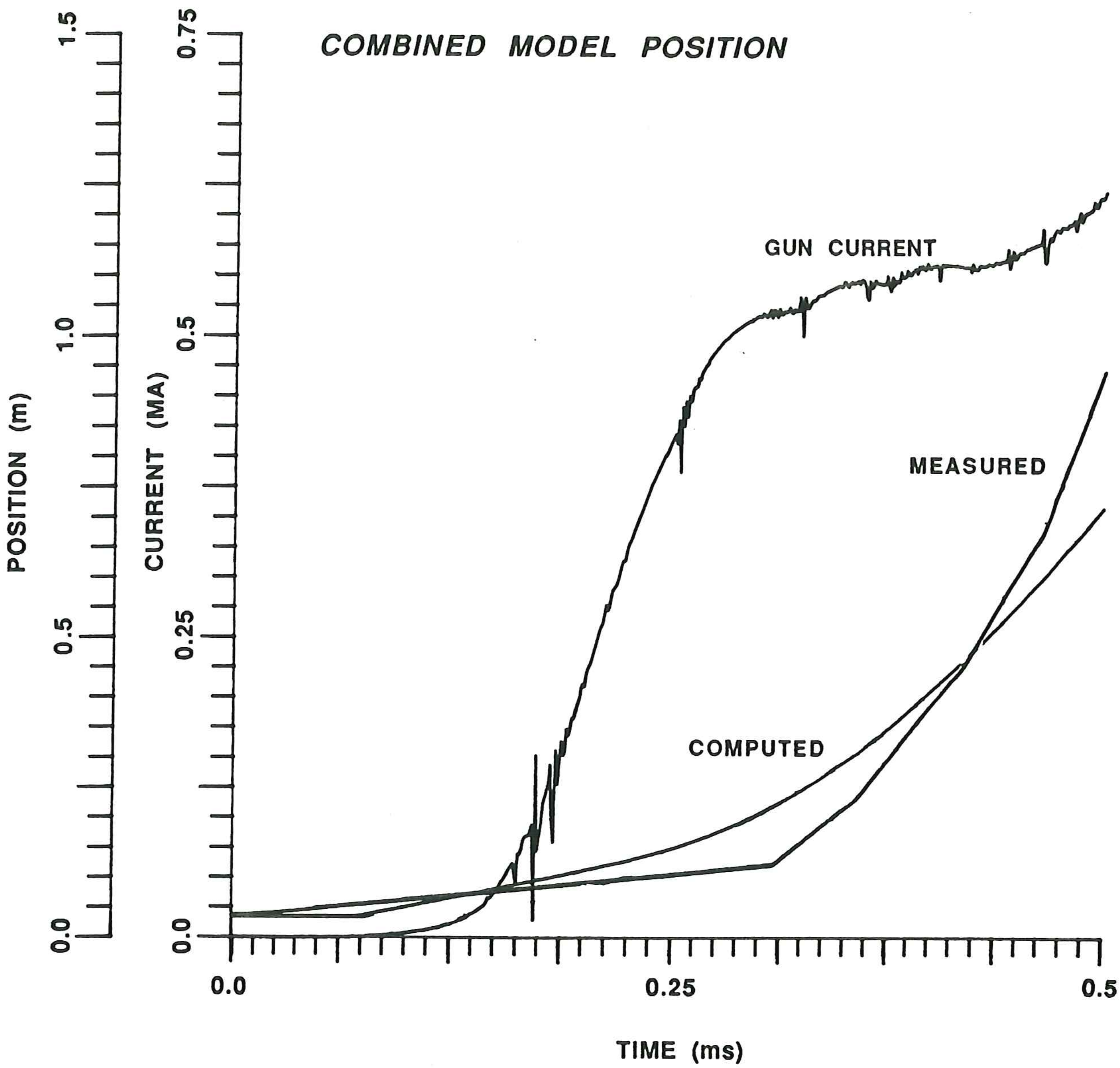
0.125
0.0
CURRENT (MA)
0.75
0.5
0.25
0.0
GUN CURRENT
MEASURED
COMPUTED
0.0
0.25
0.5
TIME (ms)


COMBINED MODEL POSITION
GUN CURRENT
MEASURED
COMPUTED
POSITION (m)
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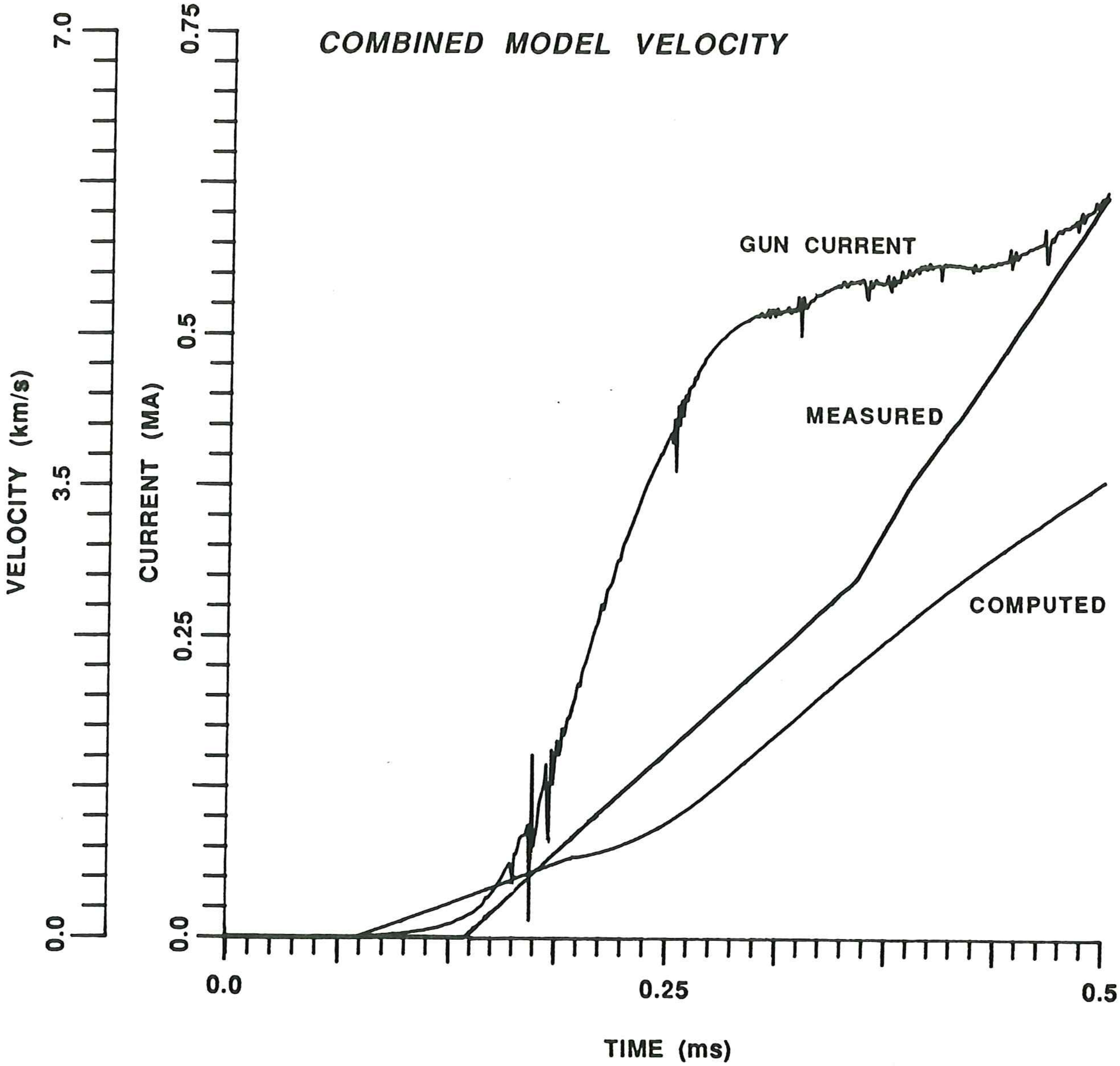
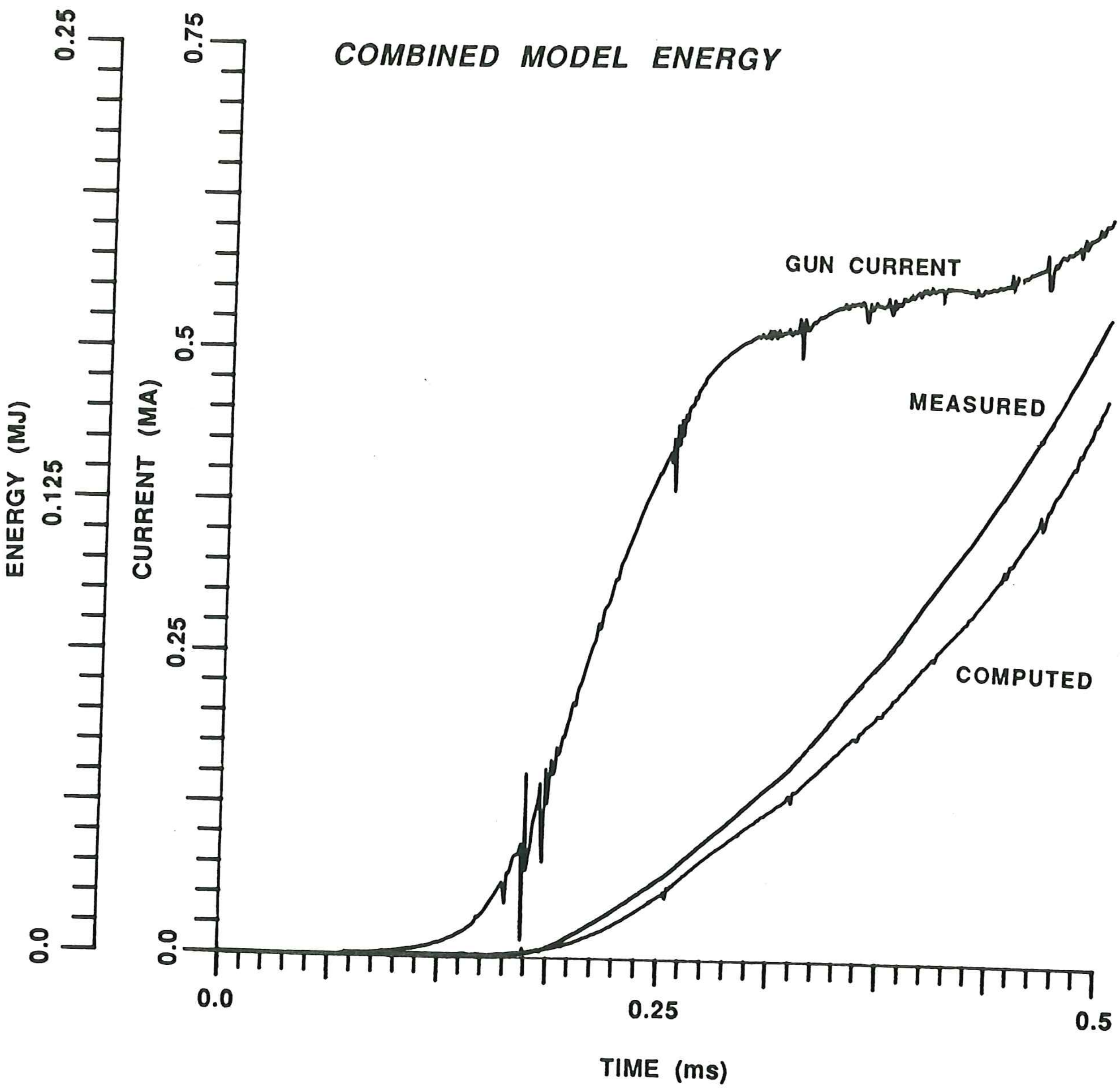
0.5
1.0
1.5
CURRENT (MA)
0.0
0.25
0.5
0.75
0.0
0.25
0.5
TIME (ms)


COMBINED MODEL VELOCITY
VELOCITY (km/s)
0.0
3.5
7.0
CURRENT (MA)
0.0
0.25
0.5
0.75
GUN CURRENT
MEASURED
COMPUTED
0.0
0.25
0.5
TIME (ms)


COMBINED MODEL ENERGY
GUN CURRENT
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CURRENT (MA)
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0.75
TIME (ms)
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0.25
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