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MELBOURNE, VICTORIA

REPORT

MRL-R-900

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D.D. Richardson & R.A. Marshall

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It is shown that relatively simple calculations presently give as much insight as detailed computer codes. This is expected to remain so until rigorous determinations of inductance per unit length of railgun rails have been obtained. We recommend that railgun simulation codes and plasma armature codes be developed separately until much greater understanding of railgun behaviour is available.

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C O N T E N T S

USE OF THE COMPUTER PROGRAM PARA 80 TO STUDY

RESULTS FROM FIRING THE RAILGUN ERGS-1M

1. INTRODUCTION

This paper describes simulation calculations of railgun performance using the computer code PARA 80 designed by Y.C. Thio [1]. The calculations are used to study the effectiveness of PARA 80 in simulating actual railgun results obtained from a series of firings of the ERGS-1M railgun. The program was originally used to design ERGS-1M, so the performance of the latter compared to the predictions is of much interest.

PARA 80 is a computer program written in FORTRAN which describes the entire railgun circuit. The most important aspect of the program is its description of the plasma armature. This is done with a one-dimensional model, described in some detail in ref. 1.

The hierarchy of subroutines for PARA 80 is shown in Fig. 1. Table I gives a brief explanation of the purpose of each subroutine. The calculation may be considered as divided into two parts. In the first part capacitor discharge dominates and in the second part the capacitor bank has been eliminated from the circuit and inductance dominates. Consider the railgun circuit diagram shown in Fig. 2. The capacitor bank C is initially charged to a nominated voltage. The main switch S1 is then closed and the simulation begins at this point. When the voltage on the capacitor bank drops below a specified value, the crow-bar switch S2 is closed, isolating the capacitors from the rest of the circuit. The simulation then switches to an inductively driven mode, the energy of the circuit being taken as now stored in inductor L. The program ceases calculation when the circuit current reduces to a specified value. (Other conditions on termination and crow-bar switching are allowed by the program). The calculation effectively progresses down the barrel from the plasma initiation point in discrete (input) timesteps. The distance it travels down the barrel is determined by the projectile motion and termination condition, and may vary under different simulation conditions.

The experimental railgun ERGS-1M is a small bore (6 x 8 mm) gun with Cu-0.6% Cd rails of length approximately 900 mm [2]. The insulation between the rails is a vulcanised cellulose fibre and the barrel casing is made of Micarta, a high-density glass reinforced resin material. A sketch of the gun is shown in Fig. 3, full specifications are given in Ref. 2.

Instrumentation of firing on ERGS-1M involved recording breech and muzzle voltages, circuit current (with a Rogowski belt) and projectile velocity, in the barrel using inductance coils and outside the barrel using a ballistic pendulum.

This paper reports calculations using PARA 80 to compare with a series of firings of ERGS-1M for initial capacitor voltages between 3.0 and 7.0 kV. The simulation program was run on a VAX 11/780 computer; Ref. 1 described the program structure for a DEC System 10 computer.

2. CHANGES NEEDED TO RUN PARA 80 ON VAX 11/780

To transfer the program from the DEC 10 to the VAX 11/780 it was necessary to make several changes. In order to make the data file containing the run specifications more legible, it was reformatted. This was done for all data read into the array CONDAT in subroutine SETUP; the nature of the input data is shown in Table II.

In addition, the subroutine used originally to solve the system of equations, NAG library routine DO2ABF has been removed from the library. The NAG routines on the VAX 11/780 are in double precision, and subroutine DO2BAF was found to be a suitable replacement. This required alteration of the arguments of the subroutine, particularly accuracy specification, and use of double precision variables where relevant. The facility for reducing the timestep size in the original program did not appear to be very effective, and was deleted. A check on the timestep size is now done through changing it in the input data. DO2BAF appears in subroutines CAPSEG and INDSEG, where it uses routines CAPAC and INDUCT, respectively. General adjustments to timestep and accuracy parameters were also required to operate PARA 80 on the VAX computer.

A check on the program was made by repeating conditions of a calculation previously made on the DEC 10 and comparing results. Although it was not possible to reproduce the timesteps exactly as before, agreement was sufficiently close to accept the program as working properly on the VAX 11/780. The disparity arises due to the different ways in which the original equation solver DO2ABF and the new one, DO2BAF, work. The former would change the stepsize if it needed to, while the latter left it fixed. This affected, therefore, the positions at which solutions were found along the barrel. As a result, crowbarring was also not possible at exactly the same position as before.

3. RESULTS

The experimental firings on the railgun ERGS-1M produced records of breech and muzzle voltage and circuit current as a function of time. Also recorded were projectile positions as a function of time, and from these, one can estimate velocity as a function of time.

PARA 80, on the other hand, produced curves of current, position and velocity versus time directly. Calculations were performed at the experimental capacitor voltages of 3.0, 4.2, 5.0, 6.0, 7.0 kV. For each of these initial conditions, we were therefore able to compare current profiles, but more interestingly position and velocity of the projectile in the gun.

The calculations were repeated twice : For one series we used gun parameters suggested by the author of the PARA program. These are shown in Table III. For the second series, we repeated the calculations using parameters thought by the present authors to be more realistic. These are also shown in Table III.

To effect a comparison we plot projectile displacement versus time for each of the firings. Results for the 3.0 and 7 kV cases are shown in Figs. 4 and 5.

The positions in the case of the "experimental" curve are determined from magnetic probe measurements, Ref. 3. Six probes were placed on top of the barrel and alternate probes connected together. From the measured induced voltages, the positions versus time were found. The accuracy of these measurements is subject to debate since it was found that the voltage characteristic of adjacent connected probes overlapped to some extent. This distorted the shape of the characteristic, and added to the difficulty of interpretation of the time when the plasma passed the probe. Corrections for the difference between plasma position and projectile position have not been made. It was found, however, that the velocity estimated from the probe positions agreed reasonably well with that determined from the ballistic pendulum displacement on projectile impact.

The results of Figs. 4 and 5 suggest that PARA 80 consistently under-predicts the projectile velocity. The same results were found for the 4.2, 5.0 and 6.0 kV simulations as well. In all cases projectile velocity was consistently lower than experiment. Changing the gun and plasma parameters shown in Table III had some effect - generally a further lowering of projectile velocity - but did not dramatically affect this overall conclusion.

4. DISCUSSION OF THE USE AND VALIDITY OF PARA 80

PARA 80 has been used by its author to predict the performance of various firings of railguns; the predicted data on armature volt drop, current, and projectile position as functions of time appeared to agree well with the experimental results [1,4]. The statement is made in the "User Notes" [1] included with PARA 80 that meaningful interpretations of the results obtained by running the code requires the skills of a plasma physicist. It is well known that computer codes tend to be very personal constructions and it would be truer to say, in this case at least, that meaningful interpretations require the skills of the code's author. The User Notes contain such statements as -

PI	Has the value of 1.0. This is a dummy parameter included for compatibility with future versions of PARA.
A3	Dummy parameter, for compatibility with future versions of PARA.
A5,A6	These should have the value 0.45. Included for compatibility with future versions of PARA.
B6	Dummy parameter
B7	Should have the value of 1.0E-9
B8	Should have the value of 1.0E+2
C1-C11	Dummy parameters for compatibility with future versions of PARA.
AB	Should have the value of 0.0
DU	Dummy variable.

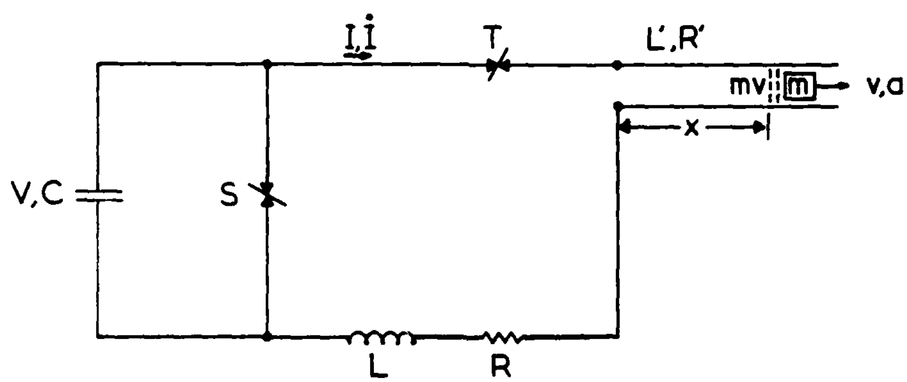
Educated guesses can be made about the purposes of some of these parameters, but the author's intention about others is not clear. In the case of parameter A6, this is probably the same as γ_2 (p.22 of Ref. 1) where it is stated that "$1-\gamma_2$ is the fraction of current lost through arcing ahead of the projectile; normally assume $\gamma_2 = 1$". This is at variance with the statement in the User Notes that a value of 0.45 should be used. In any event, there is *no* physical reason to assume that some fixed fraction of gun current is likely to pass the projectile.

We believe that there is little merit in combining an armature plasma code with a railgun performance code as has been done in PARA 80, particularly for small calibre railguns. The performance of a railgun is dependent on one plasma parameter only, namely the resistive voltage drop across it (the so-called muzzle voltage). It makes more sense to use two codes, one for railgun performance and another for the plasma. It is known experimentally (and "confirmed" by computation) that muzzle voltage is largely independent of current for a particular railgun design so to do a complete simulation of a firing, gun system performance would be predicted by assuming a constant value for muzzle voltage to give current as a function of time. Plasma behavior can be simulated using this function, to give in turn a computed value of muzzle voltage as a function of time. If desired, an iteration could then be made for gun performance using this computed muzzle voltage but further iterations are unlikely to be required because of the insensitivity of gun performance (including gun current) to muzzle voltage.

To make realistic design decisions about the parameters required for future railgun systems, simulation codes assuming a constant value for muzzle voltage are adequate. As noted above, experimentally it is found that muzzle voltage is essentially independent of armature current. This was first observed in the Canberra railgun [5] where the value 200 V was seen with armature current ranging from 300 kA down to the low values of tens of kiloamps. The same constancy was observed in the ERGS experiments [4]. Plasma codes may then be used to enable "fine tuning" to be done. As these simpler codes are refined by comparison with experimental results it should become possible to construct more comprehensive and accurate codes which could be used to calculate the performance of large calibre railgun systems. Large systems will be much too expensive to construct without having very advanced simulations on which to base the designs.

5. SIMULATED PERFORMANCE OF AN ERGS FIRING USING A HP 65 PROGRAMMABLE CALCULATOR

To demonstrate the adequacy of simple simulations for small calibre railguns we include the following model which can be programmed onto a small calculator. The circuit of the ERGS system is as follows -



where*

- m is the railgun projectile mass,
- v is the projectile velocity
- a is the projectile acceleration,
- MV is rail-to-rail voltage across the armature (muzzle volts),
- x is the distance the projectile armature has travelled,
- L' is the inductance per unit length of the railgun rails,
- R' is the resistance per unit length of the railgun rails,
- R is the resistance of the inductor and its leads,
- L is the inductance of the inductor,
- C is the capacitance of the energy storage capacitor,
- V is the voltage produced by the capacitor,
- T is the voltage drop across the main switch when it is conducting,
- S similarly, is the voltage drop across the crowbar switch,
- I is the current flowing in the railgun circuit,
- $\dot{I}$ is the time rate of change of the current,

and also

- t is the elapsed time,
- δt is the time increment used in the simulations.

The equations (in iterative form) which describe the performance of the system are

$$-\dot{I} = ((R + R'x + L'v)I + (MV + T - V))/(L + L'x) \quad (1)$$

$$I = I + \dot{I}\delta t \quad (2)$$

$$a = L'I^2/2m \quad (3)$$

---

* S.I. units are used throughout.

$$v = v + a\delta t \tag{4}$$

$$x = x + v\delta t \tag{5}$$

$$t = t + \delta t \tag{6}$$

$$V = V - I\delta t/C \tag{7}$$

After the capacitor is crowbarred, (MV + T - V) in equation (1) is replaced by (MV + T + S), and equation (7) is removed.

Simulations of the ERGS shot MIC9 (ref. 3) have been made with the following parameter values

$$C = 0.00614\ \text{F}$$

$$L = 6.8\ \text{E-6 H}$$

$$R = 0.011\ \Omega$$

$$MV = 180\ \text{V}$$

$$T = S = 200\ \text{V}$$

$$m = 0.0003\ \text{kg}$$

$$R' = 0.003\ \Omega$$

$$V_{initial} = 7000\ \text{V}$$

Crowbarring was assumed to occur when V = -500. The results of the two simulations with L' = 0.25 E-6 and L' = 0.15 E-6 are plotted in Fig. 5.

6. THE CRITICAL IMPORTANCE OF RAIL INDUCTANCE

It can be seen that the simulation performed with the lower value of L' matches the experimental data well. This value of 0.15 μH/m is very low. The value for L' obtained in the same way for the Canberra railgun [5] is 0.42 μH/m.

We believe that the difference between actual performance and measured performance has much to do with frictional drag on the projectile as it is being accelerated in the railgun. Lower values of L' indicate higher friction. Higher friction effects are to be expected in smaller guns and this is what the results show. The ERGS railgun has a bore size of 6 mm x 8 mm compared with the Canberra railgun bore of 12.7 mm square.

It can be argued that the selection of some particular value of L' to make a simulation match measured performance is a questionable procedure. The author of PARA 80 had a similar factor that he adjusted to get agreement, namely γ_2. The question then arises, how should the unknown factors be handled? The answer to this is, "In the manner which gives the greatest insight". Perhaps then we should be simulating by using a computed value of L' in equation (1) and modifying the acceleration equation (3) to read

$$a = (0.5 L' I^2 - F)/m$$

where F is the friction force. If friction force is proportional to the driving force, then the effect will be the same as using a modified value for L'.

It should be noted that, in any case, the area of greatest uncertainty in the simulation of railgun systems is the value to take for L', the rail inductance per unit length. Depending on the assumptions made, values can vary greatly. The three main possibilities are:

(1) current density uniform within the rails,

(2) current confined to the inner surface of the rails to the full rail height, and

(3) current confined to inner rail surface, the sheet width being equal to the bore height.

For the Canberra railgun these computed values [5,6,7] are 0.503, 0.493 and 0.628 μH/m. For ERGS, the respective values are 0.557, 0.552 and 0.732 μH/m.

Work recently reported gives hope that realistic computed values for L' will be available soon [8,9,10].

7. CONCLUSIONS

Fig. 5 contains two curves estimated by using a simple model of the railgun. With an empirically determined value of the rail inductance of L' = 0.15 μH/m, good agreement is found with experiment. Use of eqn 4.16 of ref. 1 indicates a value of L' = 0.8 μH/m, which is considerably larger. In PARA 80, it is thought that γ_1 of eqn 4.16 [1] is input rather than calculated. In this case, a value of $\gamma_1 = 0.45$ as recommended in the "User Notes" is much higher than the value of 0.24 obtained from Ref. 1 eqn (4.17).

Difficulties in interpreting the meaning of various aspects of PARA 80, such as this, considerably limit the usefulness of the program for the present work. The program is written in a convoluted manner, and uses unusual scaling of variables, both of which make it very difficult to understand from the source listing. The possibilities of modifying or improving aspects of the code are therefore limited.

We believe that for small calibre railguns quite simple simulation codes can be used to compute performance. Using such codes and experiments it will be possible to determine the critical physical parameters needed to construct more comprehensive codes. Large codes will be needed for design and analysis of large calibre railguns. At present a critical area in need of resolution is the value of inductance per unit length of rails in railguns and this is being addressed.

8. ACKNOWLEDGEMENTS

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T A B L E I

PURPOSES OF PARA 80 SUBROUTINES

PAMPS (MAIN)	-	General control, files opened and closed.
SETUP	-	Reads input data, defines constants and constructs scaled quantities.
NORMAL	-	Normalises input data according to the scales from SETUP.
EXTRAC	-	Structures the array GUNDAT for the actual calculation.
SGUN	-	Controls simulation of the railgun itself.
INTERP	-	Interprets the data stored in GUNDAT.
CAPSEG	-	Controls the simulation of the capactively driven gun.
INDSEG	-	Controls the simulation of the inductively driven gun.
RESULT	-	Prepares data for output, calculates physical properties and outputs results.
DO2BAF	-	Solves (in double precision) a system of ordinary differential equations.
PHYCON	-	Calculates pressure behind projectile with radiation and magnetic terms only.
MAGCON	-	As for PHYCON but includes gas pressure term as well (for closed breech simulation).
CAPAC	-	Calculates the integrand for DO2BAF for the capacitively driven gun - i.e. finds the array F(10).
INDUCT	-	As CAPAC but for the inductively driven gun.
PLASMA	-	Calculates armature plasma properties.
VETROD	-	Gives electrode potential.
VRIAL	-	Calculates potential drop along the rails.

TABLE II

THE NATURE OF PARAMETERS INPUT TO PARA 80

PARA data meanings		Typical
Line 1:	Type of foil	ALUMINIUM
Line 2:		
	Ionisation potential of plasma ions (eV)	5.98
	Atomic weight of plasma ions	26.98
	Density of foil kg m^{-3}	2.7 E3
	Height of foil) metres	6.0E-3
	Width of foil) metres	44.0E-3
	Thickness of foil) metres	15.0E-6
Line 3:	CONDAT (n,1)	
n		
1	If > 0.5 entirely inductive simulation	0.0
2	Reference voltage for scaling (Volts)	10.0E+3
3	Reference capacitance (Farads)	4.E-3
4	Another dummy parameter (May be used in the NAG file routine?)	0.5E-6
5	Projectile mass (kg)	.31E-3
6	γ_1 = 0.45	0.45
7	γ_2 = 0.45 half of fraction of current not lost through arcing	0.45
8	Separation between the rails (m)	8.E-3
9	Height of the bore (m)	6.0E-3
10	Rail height (m)	10.E-3

Line 3 (contd)			Typical
11-20	Not used - set to zero		0.0

Line 4:

n			
1	If > 0.5 skips normalisation (in NORMAL) (Unit indicator) Indicates whether the quantities are in the same line		0.0
2	Electrode potential drop per electrode (Volts)		10.0
3	Magnetic permeability of the medium (Hm^{-1})		1.257E-6
4	Resistivity of rail material (Ωm)		2.E-8
5	Height of the bore (m)		6.E-3
6	Resistivity of armature (Ωm) (Dummy parameter)		4.E-8
7	Width of the bore (m)		8.E-3
8	Value 1.0×10^{-9}	) These are presumably more	1.E-9
9	Value 1.0×10^{-2}	) dummy parameters	0.5E+2
10	Resistivity of bus-bar material (Ωm)		2.7E-8
11	Length to width ratio of bus-bar		160
12	Resistance of the circuit other than bus-bar, rails & plasma (Ω)		10.9E-3
13-20	Not used - set to zero		0.0

Line 5: CONDAT (n,3)

n		
1	)	
2	)	
3	)	
4	) Not used - all set to zero	0.0
5	)	
6	)	
7	)	

		Typical
Line 6:	CONDAT (n,4)	
n		
1	Number of segments (should be 1.0) (NSEG)	1.0
2	0.0 for results in physical (SI) units, 1.0 for normalized units	0.0
3	Relative error of computed results	1.E-9
4	No. of timesteps skipped before computed results output to files	1.0
Line 7:		
n		
1	Unknown	0.0
2	Unknown	0.0
3	Inductance of storage inductor and stray inductance, excluding rail inductance (H)	6.6E-6
4	Capacitance of capacitor bank (F)	6.14E-3
5	Initial position of projectile relative to closed breech (m)	5.E-2
6	Initial current (usually zero) (A)	0.0
7	Initial velocity of projectile (kms^{-1})	0.0
8	Initial capacitor voltage (V)	3.E+3
9	Initial value of time (usually zero) (sec)	0.0
10	Time step of simulation (sec) (TINTLO, TINTVL)	1.3E-5
11	CONTYP - Controls which condition is used for crow-bar and termination (ICON)	8.0
12	CONVAR - Criterion to control crow-barring and final termination	-500

		Typical
Line 7: (contd)		
13	CONSUP - termination control + Simulation terminates after the current has fallen below a given fraction of the current at the contact of crow-bar	0.8
14	Initial Plasma temperature (K)	2.6E+3
15	ABSORB (zero), meaning unclear	0.0
16-20	Not used - set to zero	0.0
Line 8: CONDAT (n,6)		
n		
1	Unknown	0.0
2	Unknown	0.0
3-15	No. of simulations required on varying the relevant (n,5) parameter	1.0
16-20	Not used - set to zero	0.0
Line 9: CONDAT (n,7)		
n		
1	Unknown	0.0
2	Unknown	0.0
3-15	Increments of parameters (n,5) if relevant, (n,6)>1.0 [(n,5) gives starting value].	not used
16-20	Not used - set to zero	0.0

T A B L E III

CHANGES TO INPUT PARAMETERS FOR PARA 80 BETWEEN THE ORIGINAL AUTHOR AND THE PRESENT AUTHORS' ESTIMATES

CONDAT PARAMETER	SIGNIFICANCE	ORIGINAL	NEW*
(2,2)	Electrode potential drop	60 V	10 V
(4,2)	Resistivity of rail material	4×10^{-8} Ωm	2×10^{-8} Ωm
(10,2)	Resistivity of busbar material	4×10^{-8} Ωm	2.7×10^{-8} Ωm
(12,2)	Resistance of circuit ex busbar, rails, plasma	0.005 Ω	0.0109 Ω

* Prepared with the advice of Dr V. Kowalenko

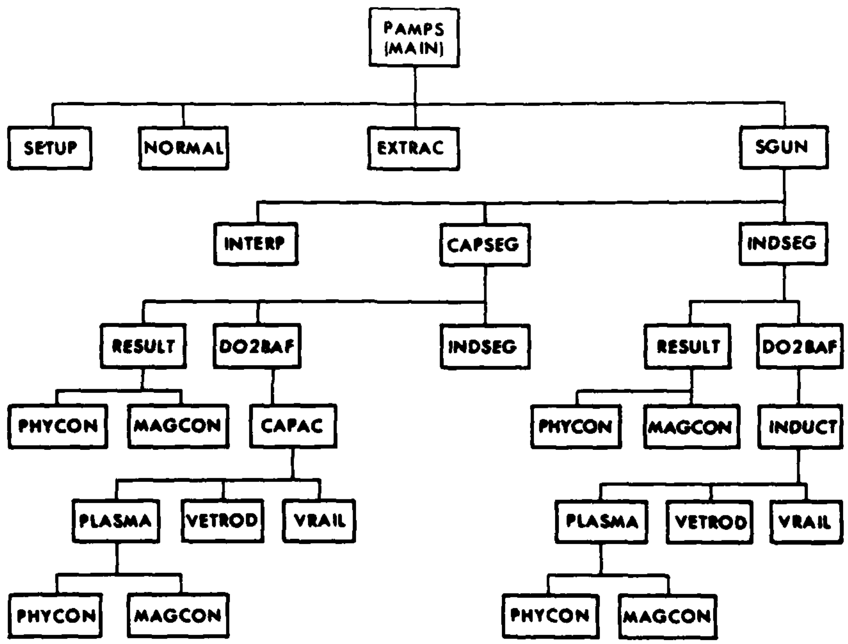

FIG. 1 Hierarchy of subroutines used in PARA 80

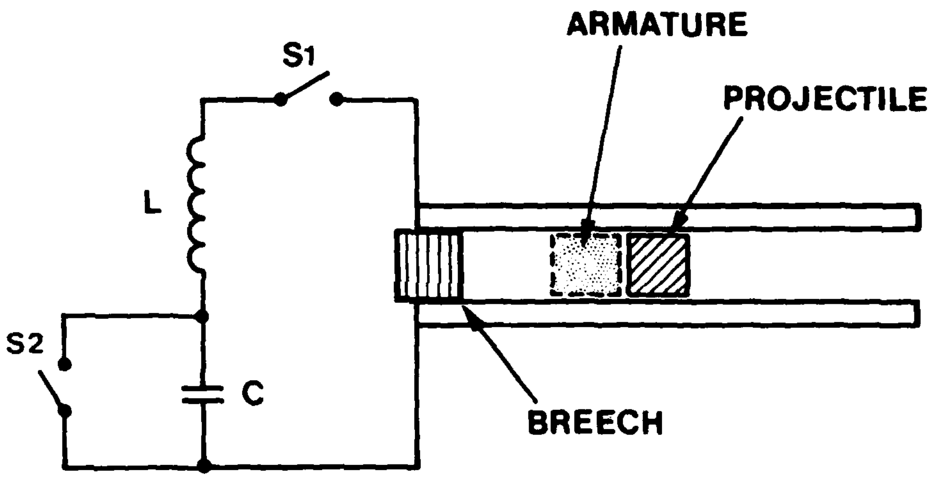

FIG. 2 Circuit diagram of the ERGS-1M experiment

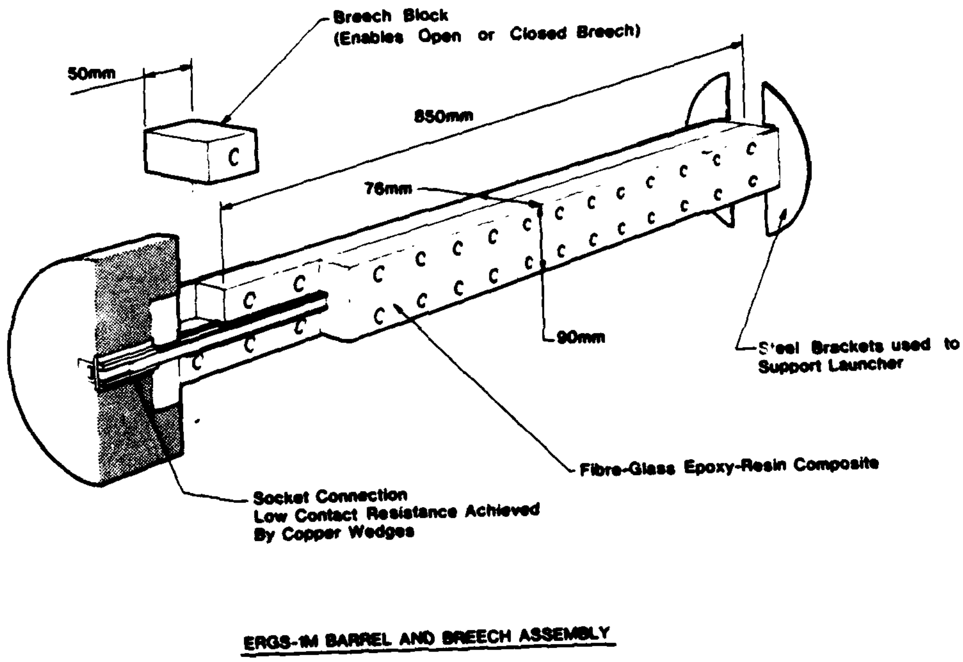

FIG. 3 Sketch of the ERGS-1M railgun

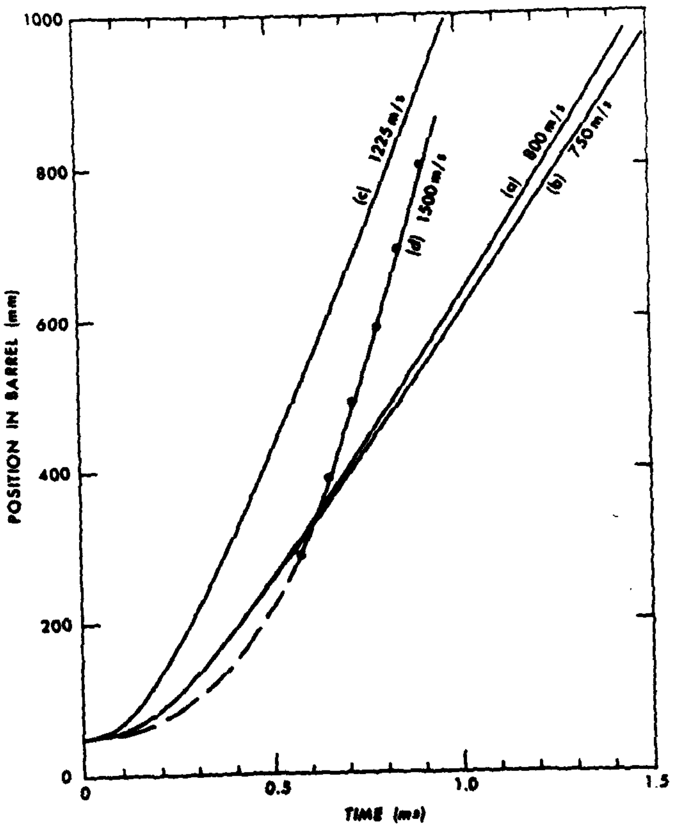

FIG. 4 Plots of position vs time for initial capacitor voltage of 3.02 kV. (a) Results of the author of PARA 80, (b) Results for the "improved" parameters shown in Table III, (c) Results as for (a) except for a foil mass of 0.036 gm (compared to 0.0104 gm for (a) or (b). (d) Experimental (MIC 11). Ballistic pendulum measurements give 1500 ms^{-1} as the final velocity. Rough estimates from the curves give the following velocities near the end of the barrel:

(a) 800 ms^{-1}
(b) 750 ms^{-1}
(c) 1225 ms^{-1}
(d) 1500 ms^{-1}

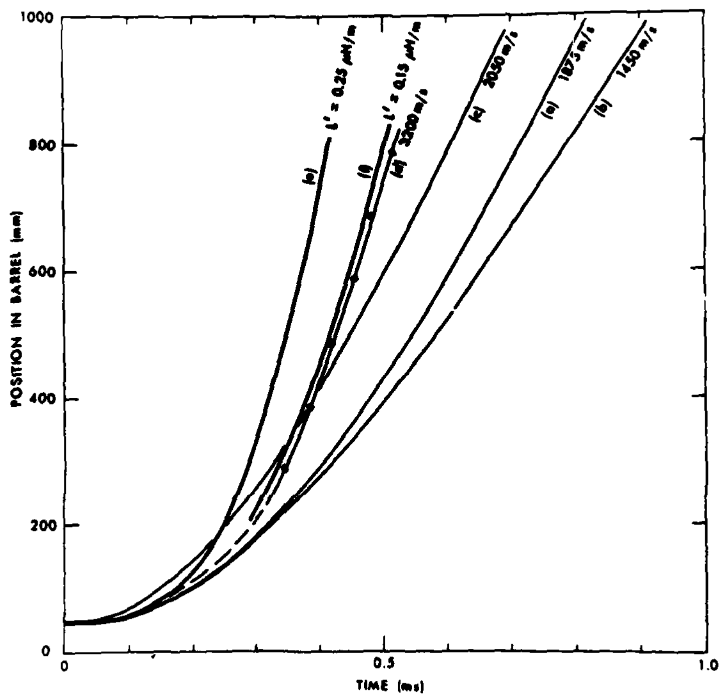

FIG. 5 As for Fig. 4 but at an initial capacitor voltage of 7 kV. Velocity estimates are:

Ballistic Pendulum 3300 ms^{-1} (MIC 2)

(a) 1875 ms^{-1}
(b) 1450 ms^{-1}
(c) 2050 ms^{-1}
(d) 3200 ms^{-1}

Curves (e) and (f) are calculated from the simple model given in the paper for (e) L' = 0.25 μH/m, (f) L' = 0.15 μH/m.

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