

# Operational Requirements and Issues for Coilgun Electromagnetic Launchers

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**Abstract**—Coilgun electromagnetic launchers have capability for low- and high-speed applications. Through the development of four guns having projectiles ranging from 10 g to 5 kg and speeds up to 1 km/s, Sandia National Laboratories<sup>1</sup> has succeeded in coilgun design and operations, validating the computational codes and basis for gun system control. Coilguns developed at Sandia consist of many coils stacked end-to-end forming a barrel, with each coil energized in sequence to create a traveling magnetic wave that accelerates a projectile. Active tracking of the projectile location during launch provides precise feedback to control when the coils are triggered to create this wave. However, optimum performance depends also on selection of coil parameters. This paper discusses issues related to coilgun design and control such as tradeoffs in geometry and circuit parameters to achieve the necessary current risetime to establish the energy in the coils. The impact of switch jitter on gun performance is also assessed for high-speed applications.

**Index Terms**—Circuit analysis, coilguns, electromagnetic induction, electromagnetic launching, software verification and validation, statistics, switched capacitor circuits, timing jitter.

## I. COILGUN OPERATION

COILGUNS are electromagnetic guns that use the Lorentz ( $J \times B$ ) force to accelerate a projectile with a conducting armature. For low-speed applications, brush commutation coilguns use sliding electrical contacts to deliver current to the armature that reacts with the magnetic field generated by barrel coils [1], [2]. For high-speed applications, induction coilguns use magnetic coupling to drive current in the armature without requiring direct electrical contact between the barrel and projectile. Several geometries and power supply configurations have been proposed [1]–[6]. Coilguns with long barrel lifetimes have potential application in the next-generation long-range artillery guns for land-based and naval platforms.

Induction coilguns developed at Sandia National Laboratories consist of short-length, solenoidal electromagnets that are stacked end-to-end to form a barrel as shown in Fig. 1. The coils are energized sequentially to create a single wave of magnetic energy moving from breech to muzzle just slightly faster than the speed of the accelerated armature. The color density in the coil cross-section in Fig. 1 represents the magnitude of the current in each coil. This transient wave generates an induced current in the conducting armature coil attached to the

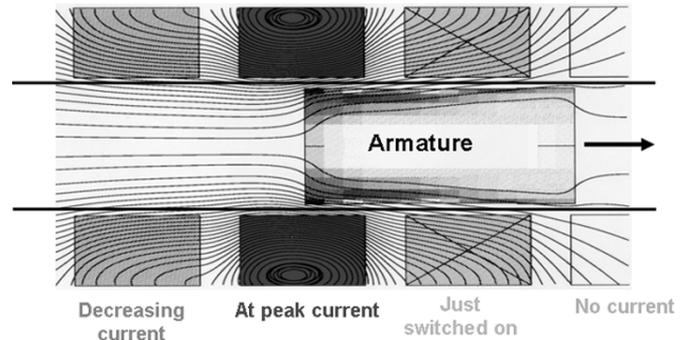


Fig. 1. Cross-section view of axisymmetric coilgun with contours of flux lines.

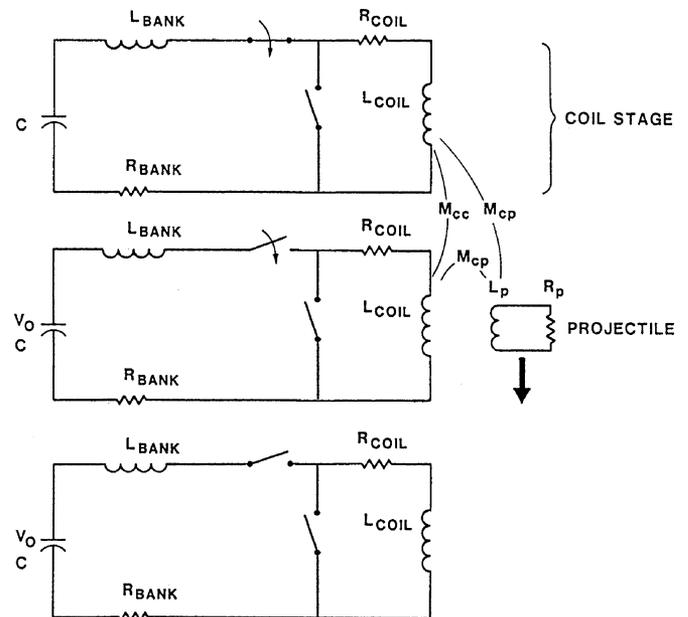


Fig. 2. Electrical schematic of a coilgun with three barrel coils where the current is flowing to the top coil, the switch of the second stage bank is about to close, and no current is flowing yet in the third stage coil.

launched projectile. The induced current and barrel coil's magnetic field generate Lorentz forces that accelerate and compress the armature.

Each of the barrel coils shown in Fig. 1 is energized by its own capacitor bank. This is shown schematically in Fig. 2 for three barrel coils, and the armature of the projectile is shown as a single circuit comprised of a series inductor and resistor. This representation of the armature is valid if the armature is a shorted, wound coil, but if the armature is a thick solid single-turn conductor, the appropriate circuit representation is

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many parallel, series-inductor-and-resistor loops representing possible current conduction paths in the solid. The mutual inductance among all the armature loops and barrel coils is taken into account.

To create the traveling magnetic wave in the barrel that is near-synchronous with the location of the armature, a real-time detector locates the projectile and the gun's firing system generates the trigger to the main closing switches of the capacitor banks of the individual coils. The discharge of current into successive coils ideally creates a boundary condition of magnetic field for the armature that is near-constant, allowing the armature to be magnetized with near-dc currents. These induced currents therefore penetrate more deeply into the conductor resulting in less localized heating at the conductor surface than if higher frequency field variation occurred. To achieve such a field variation and a smooth acceleration, it is important to utilize coils whose length is short compared to the diameter, and the risetime of the current in the coil must be about the transit time of the armature length through that coil. As the armature speed increases from the breech of the gun to the muzzle, the current risetime, which is also the time to transfer the energy stored in the capacitor bank to the coil, decreases proportionally.

The launch thrust and acceleration can be tailored to the needs of the projectile since the stored energy in each bank is adjustable. However, a uniform acceleration profile that is near the projectile's maximum acceleration capability yields the desired muzzle velocity with the shortest length gun.

## II. DESIGN REQUIREMENTS

### A. Real-Time Monitor of Projectile Position

The energizing of the barrel coils synchronous with the position of the armature is critical for optimum performance of the coilgun. If coils are energized well before or after the armature is resident in a coil, no thrust will be generated since the magnetic coupling between coil and armature would be weak. If the armature is present but the coil is energized too early, the field may generate no thrust, or if the field fills the coil bore ahead of the armature, a braking force will be generated.

Controlling the firing sequence of the coils by pre-programmed timing from calculated performance is simple to implement, but not practical since any deviation from the calculated speed for each coil integrates to significant differences between the estimated and actual armature positions at the times of firing of subsequent coils. This significantly degrades the performance of the gun as the magnetic wave outruns the projectile position.

Both discrete sensors embedded between coils and external laser-based diagnostics have been successfully used to monitor the position and speed of the armature in the coilgun during launch. The energizing of each coil is then based on the true position of the armature with respect to the coil to provide optimum thrust. The coils are only energized if the projectile's speed falls within an accepted tolerance band around the pre-shot calculations. Precise muzzle velocity is then possible as the last coils can "trim" the projectile speed.

### B. Tradeoffs in Coil Geometry

There are several tradeoffs that must be considered in the selection of the geometry of the coil. The ideal, solenoidal, barrel coil has a very thin radial build and is very short in the axial direction. The thin radial build is desirable to keep the mean radius of the coil current as close as possible to the radius of the induced currents in the armature to maximize the magnetic coupling between them. This maximizes the magnitude of the induced armature current, and the thrust is proportional to that current. However, the thrust is also proportional to the axial gradient of the mutual inductance between the coil and armature loop currents. That is maximized when the coil's axial dimension is short compared to the diameter. Coils that are long compared to their diameter yield predominantly axial field and, therefore, inward radial forces on the armature. Of course, real coils also require feeds, support structure, and if repetitively energized, heat transfer coolant. The addition of these components to meet the coil's electrical, mechanical, and thermal requirements typically drives the coil design from the ideal geometry.

### C. Adjustment of Current Risetime for Energy Transfer

As seen in Fig. 1, to generate high thrust, energy is delivered to the coil when the magnetic field's radial component is large when the aft end of the armature passes through the coil. It is advantageous to start current flow to a coil as soon as the forward end of the armature has entered it. This allows the initial stored energy in the capacitor bank,  $E_s$  to transfer to the coil in the transit time of the armature length,  $l_a$  through that coil, defining the maximum risetime,  $\tau_r$  of the bank current.

A relationship for the bank and coil parameters can be derived with a few assumptions by equating the electrical power delivered by a capacitor bank averaged over the current risetime to the average power required to deliver the necessary thrust, based on an electrical-to-kinetic energy conversion efficiency,  $\varepsilon_{ek}$ . This is shown in (1) where  $V_o$  is the initial bank voltage,  $I_{pk}$  the peak current delivered to the coil,  $E_{KE-muzzle}$  the projectile kinetic energy at the muzzle,  $l_c$  the coil axial length,  $v$  the projectile velocity at that coil, and  $l_g$  the gun length. The total initial stored energy is assumed to be uniformly distributed over the length of the gun, and each bank's initial energy is proportional to the axial length of its barrel coil

$$\frac{V_o I_{pk}}{\pi} = \frac{E_{KE-muzzle} l_c v}{\varepsilon_{ek} l_g l_a}. \quad (1)$$

Most of the terms on the right side of this equation are given conditions based on projectile mass, muzzle speed, and maximum acceleration, and the gun efficiency can be estimated from coupling coefficients or similar previous designs. The coil length is typically maximized to reduce the number of stages and the armature length minimized to reduce launch mass, but the values must be self-consistent with the estimate for energy conversion efficiency which drives them in the opposite direction.

The selection of the initial voltage and maximum current is a tradeoff with the number of turns in the coil,  $N_t$  affecting the coil's apparent inductance at its terminals described in (2). It is also a function of  $r_c$  the coil radius,  $k_L$  a self-inductance form

factor,  $k_a$  the magnetic coupling to the armature, and  $k_e$  a factor relating the coil's self-inductance to the effective inductance of that coil in the presence of coupled barrel coils [7]

$$L = \frac{\mu_0 \pi \cdot r_c^2 k_L (1 - k_a^2) k_e N_t^2}{l_c}. \quad (2)$$

Using relations for bank energy and peak current, and with the factor  $k_e$  replaced by  $(1 + k_{cc})$ , where  $k_{cc}$  is the magnetic coupling to an adjacent barrel coil, a relationship for average voltage per turn can be derived

$$\frac{V_o}{N_t} = \frac{\pi v}{l_a} \sqrt{\frac{\mu_0 \pi \cdot r_c^2 k_L (1 - k_a^2) (1 + k_{cc}) E_{KE-muzzle}}{2 \varepsilon_{ek} l_g}}. \quad (3)$$

Often either the total voltage across the coil or the voltage per turn limit the design depending upon the construction, and the maximum voltage is selected for the muzzle coil within those limits with the largest number of turns to reduce the peak current in transmission lines. This assumes that the capacitance is arbitrarily available to meet the voltage and energy required. A balance between maximum voltage and peak current is also necessary based on the capability of the capacitor bank components. Once the voltage is selected, the peak current can be determined from (1), but with a correction for the effect of additional coupled barrel coils

$$I_{pk} = \frac{\pi \cdot E_{KE-muzzle} l_c v}{\varepsilon_{ek} l_g l_a (1 + k_{cc}) V_o}. \quad (4)$$

An example illustrates that reasonable voltages and current levels can be used to accelerate 20 kg masses to 2.5 km/s in a 15 m length gun with a 155 mm bore and 30% efficiency. The projectile uses an 84-mm-long armature with 60% coupling to 163 mm diameter, 27-mm-long coils and 56% coupling between coils. This results in 21 kV per turn, and using a 2-turn muzzle coil (consisting of many parallel conductors in several layers), keeps the total coil voltage near 40 kV with a predicted peak current of 488 kA. This value agrees well with gun simulations performed with our benchmarked, lumped-parameter circuit code, Slingshot, described in detail below. However, one is not limited to these parameters. Analysis with Slingshot shows that launch performance is not degraded (difference less than 5%) if the number of turns is increased to four with 37 kV banks resulting in 270 kA maximum current which shows that the estimates from (1)–(4) should be considered indicators within a range of possible values.

### III. RESULTS FROM PREVIOUS GUN EXPERIMENTS

Several coilguns based on the principles described above have been built and tested that cover a broad range of projectile masses, muzzle velocities, and topologies. In most of these guns listed in Table I the coils for each stage were identical (or similar), and for the smaller-scale projectiles, the capacitors banks were also identical with parameters selected to match the mean speed of the gun. The 131 × 112 mm dimensions

TABLE I  
COILGUNS DESIGNED AND TESTED AT SANDIA NATIONAL  
LABORATORIES [8]–[11]

Projectile		Coilgun		Maximum at muzzle	
Dia.(mm)	Mass (g)	Length(m)	# stages	Speed(m/s)	Energy(kJ)
25	10	0.44	10	317	0.5
131x112	139	2.3	14	1004	70
47	237	1.6	35	1000	119
140	5000	0.8	6	335	281

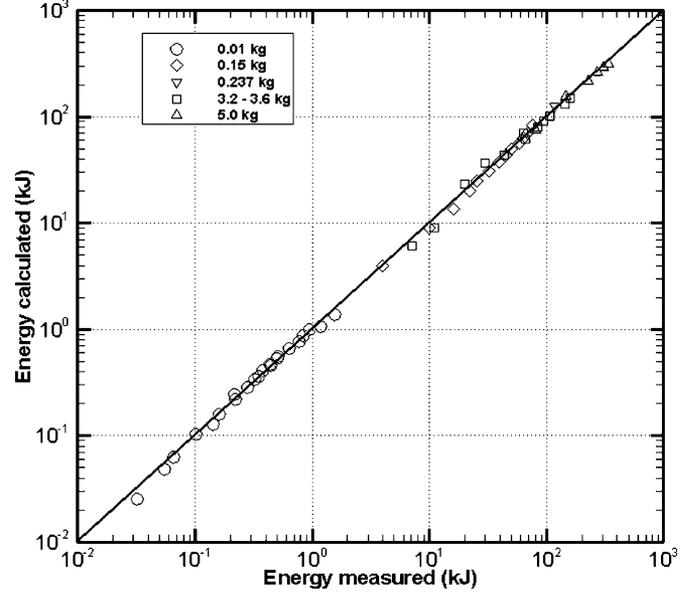


Fig. 3. Comparison of projectile energy calculated by the Slingshot circuit-based gun simulation code with measurements.

represent a rectangular plate that was launched edgewise. For the 140 mm gun, the bank capacitance was adjusted to tailor the current risetime to the projectile speed. Key accomplishments from these experiments include the demonstration of: 1) control of firing of coils with active feedback of projectile position to repeatedly achieve designed performance; 2) a scalable 30 T coil design that generates high thrust; and 3) validation of our gun simulation code.

A lumped-parameter circuit code, Slingshot, is used to model the performance of the gun based on the circuit representation shown in Fig. 2. The code self-consistently solves for currents in coils and the armature through a system of mesh equations with parameters that are position and temperature dependent. Forces are based on mutual inductance gradients, and temperature-dependent resistances are self-consistent with Ohmic heating and material properties [12]. The code has been used to model the coilguns described in Table I, and the calculated muzzle energies compare well to measured energies as shown in Fig. 3. For speed greater than 100 m/s, the difference in projectile energy between the simulation and experiments is less than 15%, and at 1 km/s, the energy difference less than 8%. The code also has reliably predicted the in-bore acceleration profiles which are documented in [10]. This firm theoretical capability enables confidence in designs of new systems.

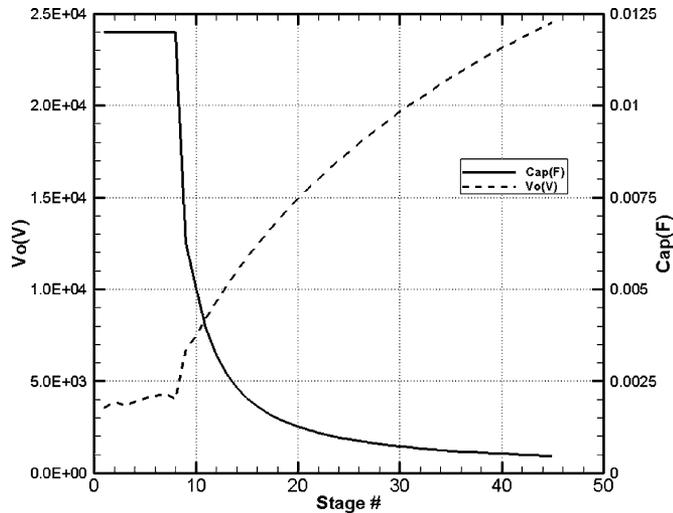


Fig. 4. Variation of bank capacitance and voltage from Stage 1 at breech to Stage 45 at muzzle to tailor current risetime with projectile speed in gun. The stored energy in each bank after Stage 8 is 140 kJ.

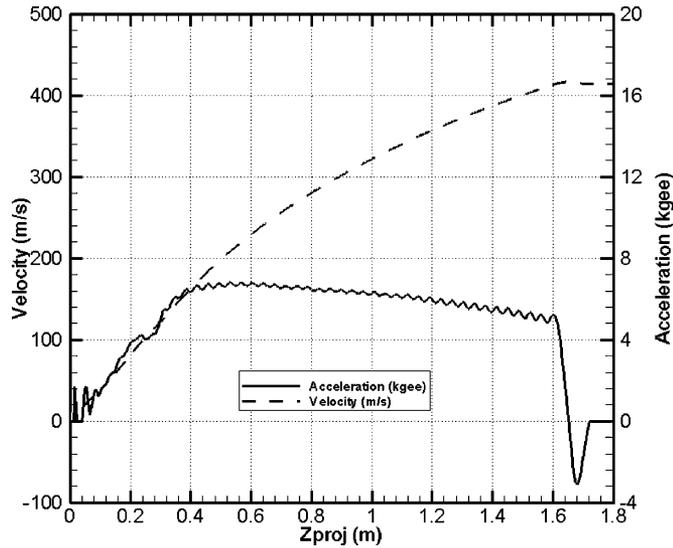


Fig. 5. Velocity and acceleration profiles for low-speed coilgun launching 18 kg mass.

IV. ESTIMATES OF GUN PERFORMANCE FOR APPLICATIONS

Two gun designs are considered here that may have future military applications: a low-speed gun for nonlinear of sight fires at ranges greater than that of existing battalion mortars, and a high-speed gun for fire support at hundreds of kilometers range. The low-speed gun consists of 45 identical 13-turn coils forming a 1.6-m-long barrel. The 18 kg, 120 mm diameter projectile consists of a warhead fitted with a solid copper armature. The 6 MJ total initial stored energy is uniformly distributed among the capacitor banks, except for the first few stages where the energy is reduced to minimize coil heating. To adjust the current risetime consistent with the projectile speed, the capacitance is decreased for the banks at the muzzle compared to the breech as shown in Fig. 4. The resulting velocity and acceleration profiles are shown in Fig. 5 as a function of armature position in the barrel. A sample of the coil currents from selected stages is shown in Fig. 6, where the delivered current is limited to one-half cycle

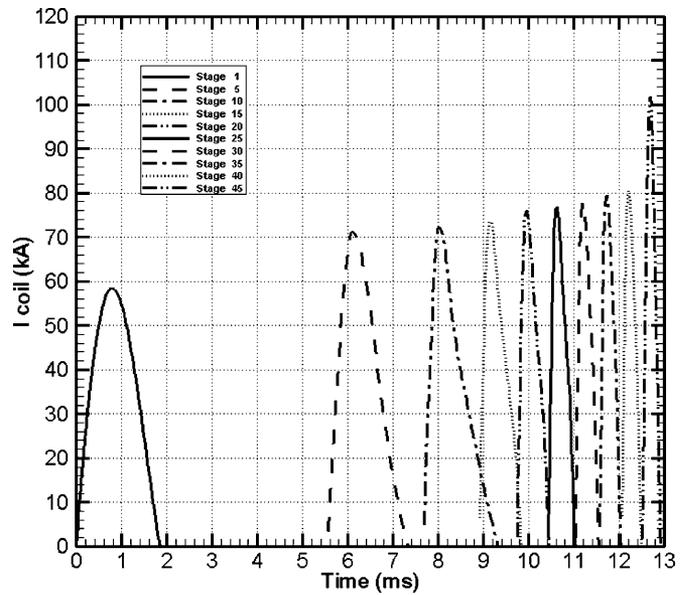


Fig. 6. Currents in selected coils from 45-stage low-speed gun.

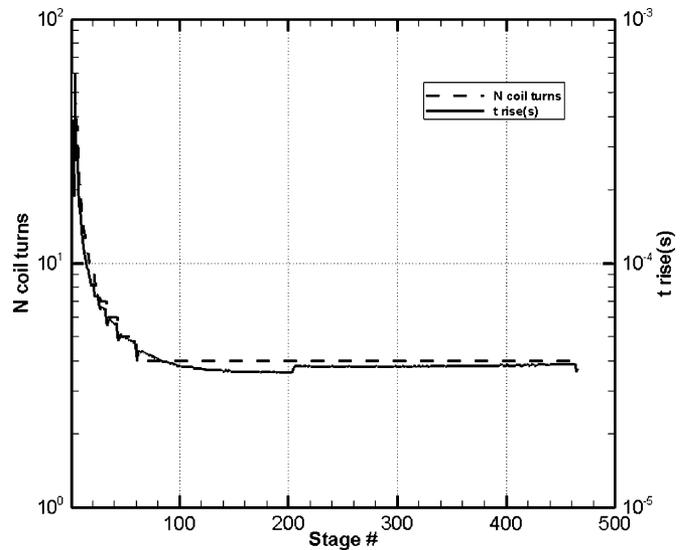


Fig. 7. Variation in number of turns and current risetime in coils from breech at Stage 1 to muzzle at Stage 466 of high-speed coilgun.

by using reverse-blocking thyristor switches to recover the magnetic energy back to the bank. The average energy conversion efficiency from the total initial stored energy in all the capacitors to projectile kinetic energy is 26%, but with energy recovery, the kinetic energy is 54% of the bank energy consumed in the shot.

The high-speed gun consists of 466 coils with variable turns forming a 15-m-long barrel. The 20 kg, 155 mm diameter launch package consists of a flight vehicle fitted with a prechilled, wire-wound armature. The 203 MJ total initial stored energy is roughly uniformly distributed among the capacitor banks, but has been tailored such that each coil works at the same maximum radial force. For this gun the capacitance was held constant at 600  $\mu$ F for each stage, and to adjust the current risetime consistent with the projectile speed, the coil inductance tailored by changing the number of turns as shown in Fig. 7. While more optimum, shorter risetimes could be

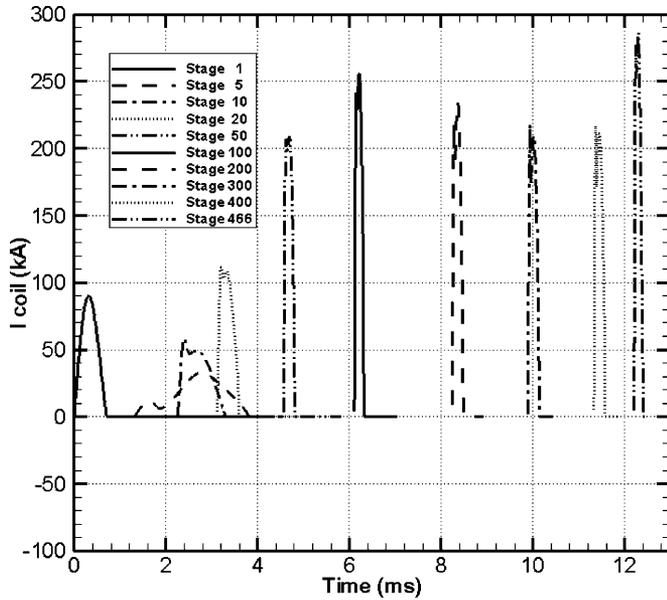


Fig. 8. Currents in selected coils from 466-stage high-speed gun.

achieved near the muzzle with lower inductance coils, the minimum number of turns was held at four to reduce the peak currents in muzzle stages. The resulting velocity and acceleration profiles are shown in Fig. 10 as a function of position of the armature position in the barrel. A sample of the coil currents from selected stages is shown in Fig. 8, where again the delivered current is limited to one-half cycle by solid-state switches. The average energy conversion efficiency from the total initial stored energy in all the capacitor banks to projectile kinetic energy is 31%, but with energy recovery, the kinetic energy is 74% of the bank energy consumed in the shot.

#### V. EFFECT OF SWITCH TIME JITTER ON GUN PERFORMANCE

The time of firing of individual coils in the gun is based on the position of the projectile's armature, not a preprogrammed time. However, once the correct position has been sensed for a given coil, there will be a time delay until current flows from that coil's capacitor bank. The total delay, which has contributions from the firing system hardware and software as well as the main closing switch, can be considered the sum of a constant mean value and a random jitter. The mean delay can easily be accounted for through a correction of the desired projectile firing position with assumptions of normal-operation velocity profiles, and will not impact gun performance. The random jitter component results in a deviation from the desired projectile's position at the time the coil is energized, which can affect performance. The position error is proportional to the projectile speed, so the effect is most pronounced for the high-speed gun.

To assess the effect of such a jitter, the Slingshot code was modified to apply a position error to the desired projectile firing position for each stage of the gun. The error is based on a sampling of a uniform random distribution of jitter times with equal maximum (positive) and minimum (negative) delay values. Complete gun simulations were performed with single sampling of the same distribution for each stage of the gun. Complete simulations were replicated to obtain a distribution

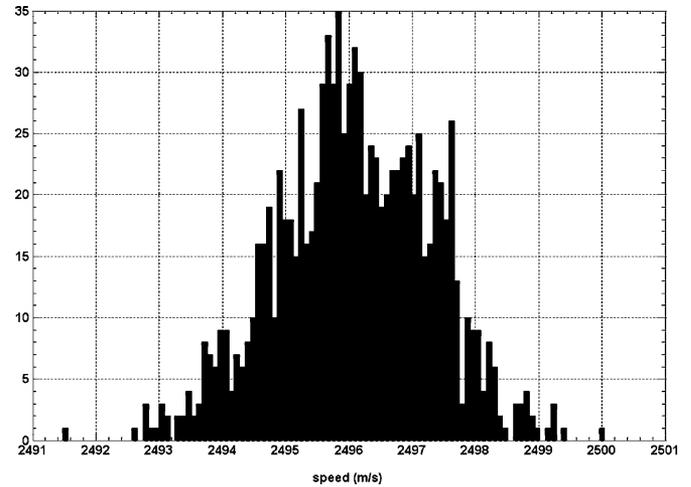


Fig. 9. Histogram of muzzle velocities of high-speed gun from 1000 independent calculations with a jitter time distribution  $\pm 2 \mu\text{s}$ .

TABLE II  
INFLUENCE OF WIDTH OF JITTER DISTRIBUTION ON MUZZLE SPEED  
AND ACCELERATION IN HIGH-SPEED GUN

	Switch Time Jitter Distribution Width			
	$0 \mu\text{s}$	$\pm 1 \mu\text{s}$	$\pm 2 \mu\text{s}$	$\pm 5 \mu\text{s}$
Mean muzzle velocity (m/s)	2498.4	2496.9	2496.1	2489.7
Std. Deviation (m/s)	na	0.68	1.08	2.56
Std. Dev./Mean velocity (%)	na	0.027	0.043	0.103
Change in mean velocity from no-jitter case (%)	na	-0.06	-0.09	-0.35
Pk-pk acceleration ripple/avg acceleration (%)	10	12	15	35

of velocities at each stage of the gun, with the most important being the muzzle velocity.

The high-speed gun described above was used as a test case where the width of the random jitter time distribution was parameterized for  $\pm 1 \mu\text{s}$ ,  $\pm 2 \mu\text{s}$ , and  $\pm 5 \mu\text{s}$ . Previous experience with our coilgun developed in 1993 with ignitron switches exhibited jitters of a few microseconds. Solid state switches with very low jitter are anticipated for new applications, but other components in the firing system may have contributions. The distribution of muzzle velocity for the  $\pm 2 \mu\text{s}$  width jitter distribution is shown in Fig. 9, and the mean velocity and standard deviation of the muzzle velocity for the three jitter distribution widths are shown in Table II. Statistics are based on 1000 independent calculation replicates.

The results in Table II show that switching time jitter has a nearly negligible effect on the muzzle velocity for the maximum time error limits considered here. Switching and control jitters are expected to fall well within a  $\pm 2 \mu\text{s}$  sampling distribution. Under that condition 95% of the muzzle velocities fall within a band that is  $\pm 0.086\%$  of the desired velocity.

Another important result of the switch jitter time and subsequent position error is the effect on the acceleration profile. A  $2 \mu\text{s}$  time error at 2.5 km/s generates a 5 mm position error which is 16% of the length of a barrel coil. The magnetic fields from adjacent, energized coils overlap to smooth the acceleration, but the position error does produce a ripple in the acceleration shown in Fig. 10. The peak-to-peak ripple in acceleration increases with increasing width of the jitter distribution, and will

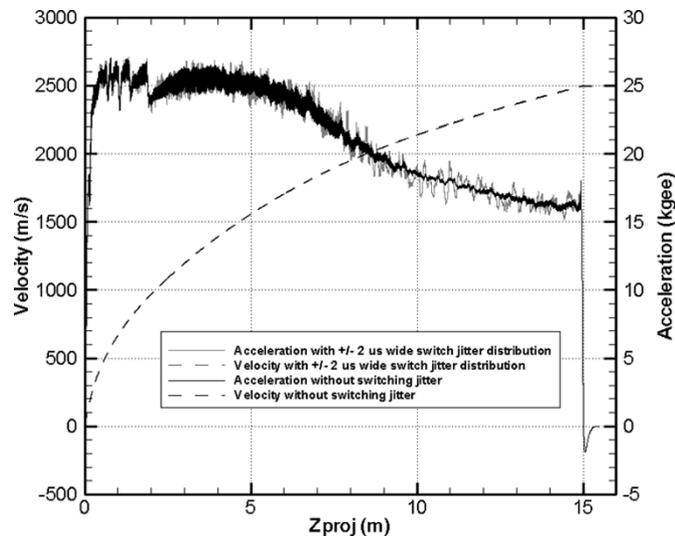


Fig. 10. Acceleration and velocity as function of position of 20 kg projectile in a 466-stage high-speed coilgun. Calculations shown with and without influence of random switching jitter delays in each stage sampled from a uniform distribution with  $\pm 2 \mu\text{s}$  extent.

be considered in the design of the launch package. However, the ripple is small for anticipated switch jitter levels. Should the level of oscillation be an issue, mechanical damping can be incorporated in the armature-flight vehicle interface to mitigate the effect.

The calculations discussed above are based on prescriptive projectile positions for the firing of each stage of the gun determined prior to launch. Firing systems currently being developed will have the ability to modify projectile firing positions of individual stages during launch. This will permit tuning of gun performance for precise muzzle velocity and modification of acceleration profiles.

Performance of the low-speed coilgun was also analyzed with switch jitter for the same parameter range as the high-speed gun. At the lower speeds the standard deviation of muzzle velocity is reduced to 0.02% of the mean velocity using a  $\pm 2 \mu\text{s}$  wide switch jitter distribution, and the peak-to-peak ripple in acceleration is 8% of the mean acceleration compared to 7.8% without jitter.

## VI. CONCLUSION

Coilguns have previously been considered applicable primarily for low-speed launch, partially because speeds of

1.5 km/s or less are demonstrated, but also due to concern of the peak power necessary to drive coils at the muzzle of high-speed guns and the precision of switching energy into these coils [13]. Analytic estimates presented here show that reasonable voltage and current levels are possible for launching tens of kilograms to 2.5 km/s. Calculations with the Slingshot coilgun simulation code indicate that there is flexibility in selection of the capacitor bank and coil parameters without severe degradation in gun performance giving the designer latitude in component selection. Simulation of the effect of switching jitter shows negligible effect on muzzle velocity for a 400 m/s gun, and for a 2.5 km/s gun, muzzle velocities vary with a standard deviation less than 0.1% of the mean. These results indicate that the coilgun has significant potential for precise, repeatable muzzle velocities that will enable precise targeting for low- or high-speed projectiles.

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