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LA-UR-88-709

CONF-880418--7

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LA-UR--88-709

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TITLE THE SRS RAILGUN: A NEW APPROACH TO RESTRIKE CONTROL

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SUBMITTED TO 4th Symposium on Electromagnetic Launch Technology
The University of Texas at Austin
Balcones Research Center
Austin, Texas

April 12-14, 1988

Los Alamos National Laboratory
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THE SRS RAILGUN: A NEW APPROACH TO RESTRIKE CONTROL*

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Abstract

A Segmented Rail Surface (SRS) structure is described that eliminates restrike arcs by progressively disconnecting segments of the rail surface after the plasma armature has passed. This technique has been demonstrated using the Los Alamos MIDI-2 railgun. Restrike was eliminated in a plasma armature acceleration experiment using metal-foil fuses as opening switches. A plasma velocity increase from 11 to 16 km/s was demonstrated using the SRS technique to eliminate the viscous drag losses associated with the restrike plasma. This technique appears to be a practical option for a laboratory launcher at present and for future multi-shot launchers if appropriate switches can be developed.

Introduction

Parasitic current flow in the region previously traversed by the plasma armature is now understood[1,2] to be a major process limiting the performance of plasma armature railguns. This parasitic current flow occurs in a variety of forms ranging from a low current-density tail following the main plasma to an isolated plasma carrying a significant fraction of the total current in a region well separated from the main plasma (so-called "restrike arc"). Whatever the distribution, this parasitic current flow represents a substantial portion of the applied magnetic force which is not available for projectile acceleration.

The increasing evidence that restrike conduction is intimately related to ablation and viscous drag has sharply narrowed the strategies available for restrike control. The available strategies fall into two classes: those which eliminate ablation and the concomitant increase in viscous drag force and those which seek to inhibit conduction in the post-plasma region. The Segmented Rail Surface (SRS) railgun belongs to the latter category.

The SRS railgun is a new development related to the segmented railgun[3,4]. The second section of this paper explains the principle of the SRS railgun, describes the relationship between SRS and segmented railguns, and discusses the advantages of the SRS design.

Manuscript received March 11, 1988

*Work supported by the U.S. Department of Energy and the U.S. Army Research, Development and Engineering Center, Dover, New Jersey.

A practical realization of the SRS concept using the MIDI-2 railgun at Los Alamos is presented in the third section. The MIDI-2 experiments presented in the fourth section provide a direct comparison between the SRS configuration and a conventional railgun configuration. Measurements of rail current provide direct evidence that restrike conduction is suppressed in the SRS configuration and that substantially higher velocities are achieved as a result.

The last section discusses the application of the SRS technique to larger railguns. Opening switch requirements are summarized and potential mechanical and electrical fabrication issues are considered.

The SRS Concept

Since the first observations of restrike in plasma armature railgun[1,5], one recognized possibility for eliminating this loss mechanism has been the segmented railgun illustrated in Fig. 1a. In a segmented railgun, the barrel is divided into several electrically isolated sections, each with its own power supply and switching. As the projectile and plasma armature pass from one section to the next, there is no possibility of restrike because current from the down-stream section cannot flow into the previous section. Despite its conceptual simplicity, a segmented railgun has never been demonstrated because of several practical difficulties. First, the segmented railgun requires a multiplicity of power supplies. Second, the segmented design is inefficient because the stored magnetic energy in each section is wasted after the projectile exits. Finally, there are practical problems with muzzle arcing and electrical insulation between sections.

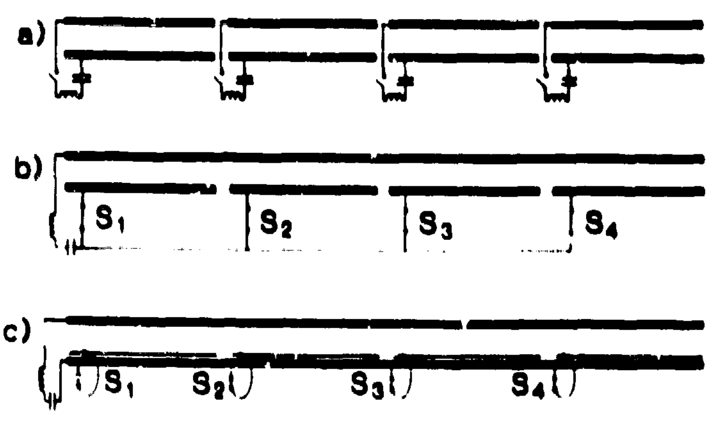

Fig. 1 Relationship between a conventional segmented railgun and the SRS railgun: a) segmented, b) segmented rail with external current bus, c) SRS railgun.

The issue of multiple power supplies can be resolved by using a common power bus as shown in Fig. 1b. The rail sections are connected to the external power bus through opening switches S_1-S_4. These opening switches do not have to interrupt the main power supply current so efficiency is increased. However, there are still losses due to the loop inductance between sections and the problem of segment to segment arcing is not addressed.

The final step to the SRS railgun is illustrated in Fig. 1c. Now the usual rail serves as a current bus and thin conducting segments, insulated from the rail, replace the rail sections in the segmented design. Opening switches S_1-S_4 disconnect each segment after the plasma has passed to the next segment. The loop inductance is very small so there is practically no switching energy to be dissipated in the opening switches. Segment to segment arcing is reduced because it is not necessary to dissipate the magnetic field energy between the rails in order to turn off current conduction.

The SRS design eliminates restrike conduction with little impact on railgun efficiency but at a substantial cost in mechanical and electrical complexity. This issue is discussed in the last section. It is worth noting here that the opening switches have an uncommon set of performance requirements in the SRS railgun. Each switch conducts the full current only while the armature is passing over its segment. Thus the current requirements are large (~MA's) but the action (I^2dt) and the charge transfer are small. Each switch opens after the current has been commutated to the next switch by the armature so there is very little switching energy to be dissipated and the switching time and jitter are not critical. The voltage seen by each switch is the full inductive voltage of the launcher so the hold-off voltage requirement may be ten kilovolts or more.

SRS Demonstration on MIDI-2

To test the SRS railgun concept an experiment was performed using a modification of the MIDI-2 railgun[1]. The MIDI-2 device is a laboratory railgun with a 9.5 x 9.5 mm^2 bore and a useful length of 1.64 m. Built principally for precision magnetic probe diagnostics, the MIDI-2 device has been used for an extensive investigation of "free-arc" plasma armatures at high velocity (10-40 km/s).

The modifications made to MIDI-2 for the SRS tests are shown in Figs. 2-4.

Figure 2 is a cross-section of the MIDI-2 barrel configured as a conventional railgun. The rails and insulators are designed for easy replacement. Figure 3 shows an expanded view of the central region with the SRS modifications. The lower copper rail has been reduced in thickness from 9.53 mm thickness to 6.35 mm. A copper sheet 3.2 mm thick x 19 mm wide x 100 mm long is placed on top of this rail but insulated from it by three sheets of 0.05 mm Mylar plastic. Also shown in Fig. 3 is a thin metal foil located at the breech end of each segment. This foil is in contact with the rail at one end, passes out to the edge of the plastic sheet and then returns to make contact with the segment. The foil length is approximately 50 mm. The foil strip establishes an electrical connection between the rail and the overlying segment. During operation, the plasma current passing through this foil causes it to fuse and act as an opening switch. In this manner, the SRS design can be evaluated rather inexpensively without the need for many expensive opening switches. Refractory ceramic fiber pads protect the G-10 insulators from the high temperature fuse material.

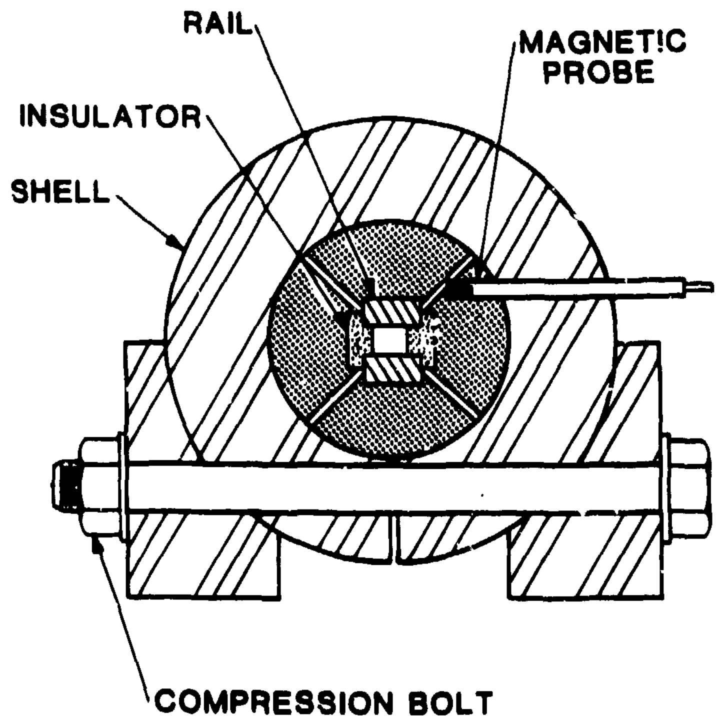

Fig. 2. Cross-section drawing of MIDI-2 configured as a convention railgun.

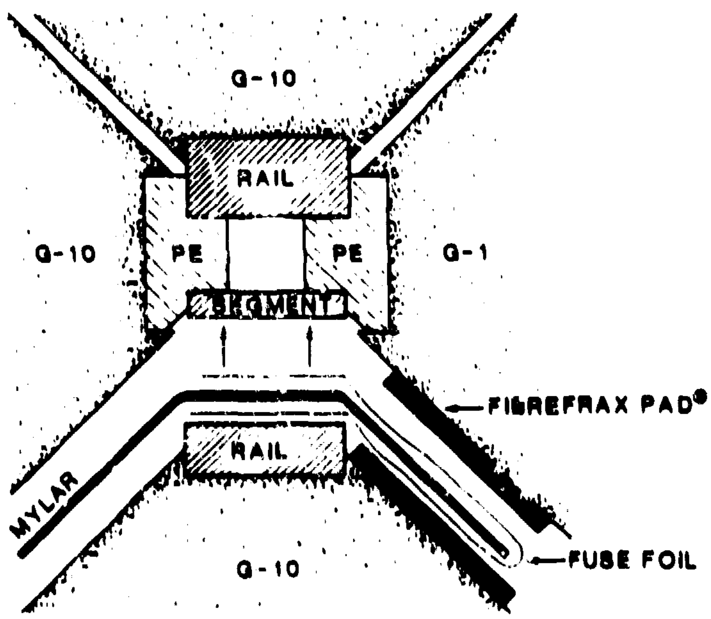

Fig. 3. Partially exploded view of the MIDI-2 core showing modification made for SRS experiments.

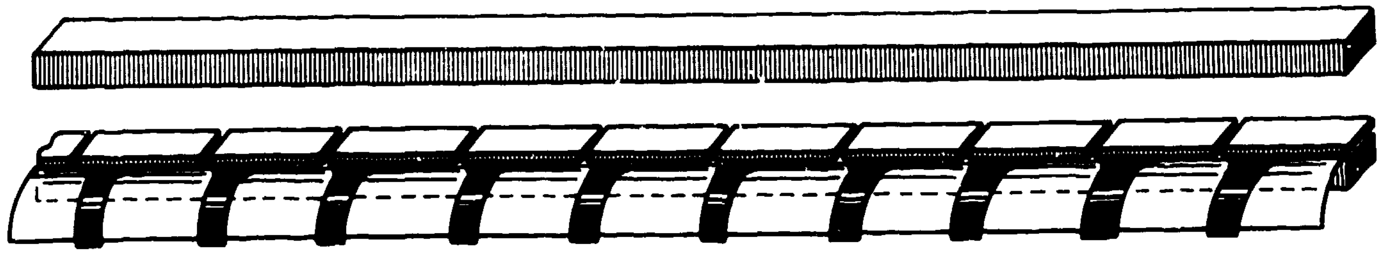

Fig. 4. Longitudinal cut-away drawing of MIDI-2 SRS railgun showing rail segments and connecting fuse links. Experimental configuration utilized 16 segments, 100 mm long x 3 mm thick, connected by 0.05 mm aluminum foil fuse links. The insulator is three sheets of 0.05 mm Mylar.

Along the length of the MIDI-2 barrel there are 16 segments as shown in Fig. 4. Each segment has a foil fuse at the breech end. Selection of an appropriate fuse thickness and width is not straightforward. For a very short plasma (ℓ_p << 100 mm) each fuse sees a rectangular current pulse of duration $t = 0.1/V_p$, where V_p is in meters/second. For the more realistic case of a plasma length comparable to or greater than 100 mm, the current pulse amplitude and shape is a complication function of velocity and current density.

Experimental Results

Experimental evaluation of the SRS railgun was performed by repeating the operating conditions of an earlier MIDI-2 experiment so that a direct performance comparison could be made. The conventional MIDI-2 experiment was #16, one of a series designed to investigate the effects of insulator material on plasma characteristics. The experimental parameters for test #16 were:

Rails:	electrolytic copper
Insulators:	high density polyethylene
Gas Fill:	10 Torr of air
Current:	100 kA
Initiator:	2 mg copper wire fuse

The polyethylene test was chosen because polyethylene has the lowest average atomic weight among conventional plastics and thus provides the highest velocity for a given current and gas pressure.

A total of 6 tests (#22-27) were performed with the SRS configuration. The first test utilized a fuse width calculated on the assumption of a short armature (< 100 mm) traveling ~10 km/s. None of the fuse links opened during this test and the railgun performance was essentially identical to that of the non-SRS test (#16). Subsequent to test #21, an analysis of the interaction of current distribution and fuse action was performed and it was determined that the foil fuse action is not dynamically stable. That is, if a given fuse opens late, it allows the plasma length to increase. This reduces the peak current density and cause the next fuse to open even later and so forth. Since there is no "correct" solution for the case of passive fuses, the remainder of the SRS tests were conducted on a trial basis with progressively narrower fuses. Test #27 using 13 mm wide x 0.05 mm thick fuse links on all segments was the most successful of the tests performed. The switching action of the fuse links was less abrupt then desired so the armature current distribution had a substantial "tail" extending over several segment lengths. Nonetheless, as the results presented below illustrate, there was sufficient switching resistance developed to inhibit restrike current and the expected performance increase was obtained. In the following subsections the experimental data from test #27 will be reviewed and contrasted with the results of the non-SRS test #16.

Plasma Current Distribution

The current distribution in the railgun is observed by measuring the rail current at ten locations along the railgun. Details of the rail current diagnostics are presented in Ref. 1. Figures 5 and 6 show the measured rail current vs. time for tests #16 and #27 respectively. Test 16 has a pronounced secondary arc which develops early in the arc motion. For example, at 200 µs when the arc front is nearing probe 8, 57% of the input current is located between the arc front and probe 7, a distance of 20 cm. At the same time, nearly 20% of the current is flowing in the region between probe 5 and probe 7, about 10% between probes 4 and 5, and another 10% between probes 3 and 4. In terms of magnetic force distribution only 32% of the total forces is acting in the immediate vicinity of the arc front (~20 cm) while 42% of the total force is acting on ablated material located more than 55 cm behind the arc front.

This current and force distribution is in sharp contrast to the SRS result shown in Fig. 6. When the arc front is at the same position (t = 183 µs) 70% of the current is flowing between the arc front and probe 7, 21% between probes 5 and 7, and about 7% between probes 3 and 5. The force distribution has improved to 49% immediately behind the front, and less than 16% of the force acting on material more than 55 cm from the arc front.

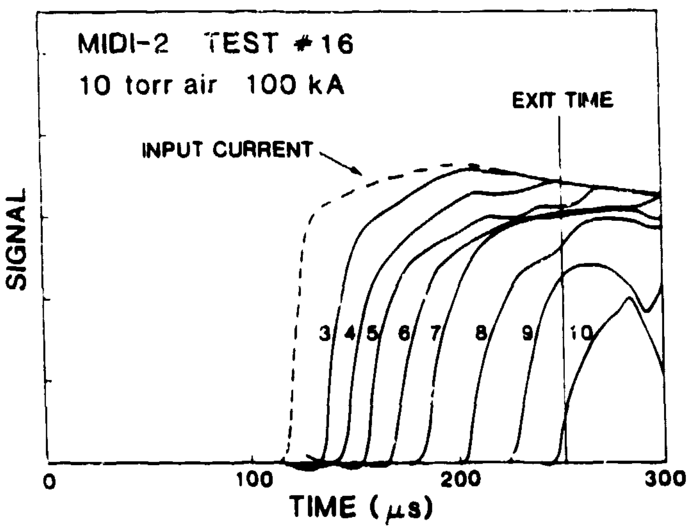

Fig. 5. Rail current data for a MIDI-2 "free-arc" test using polyethylene walls and copper rails.

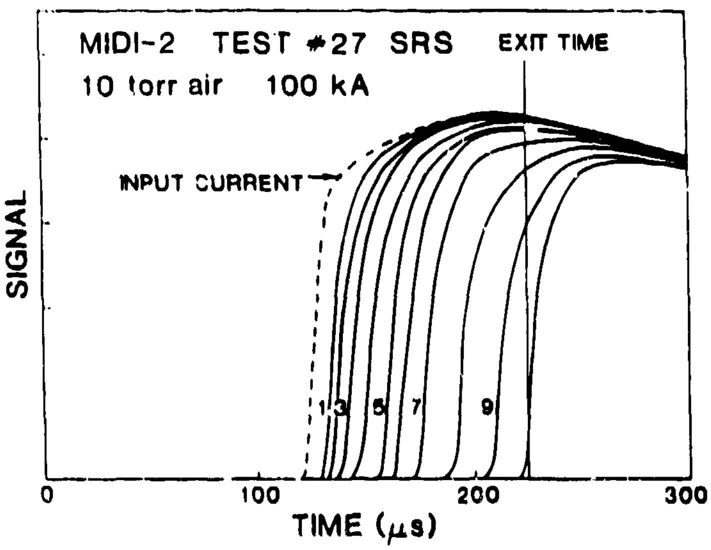

Fig. 6. Rail current data for a MIDI-2 SRS test using polyethylene walls and copper rails.

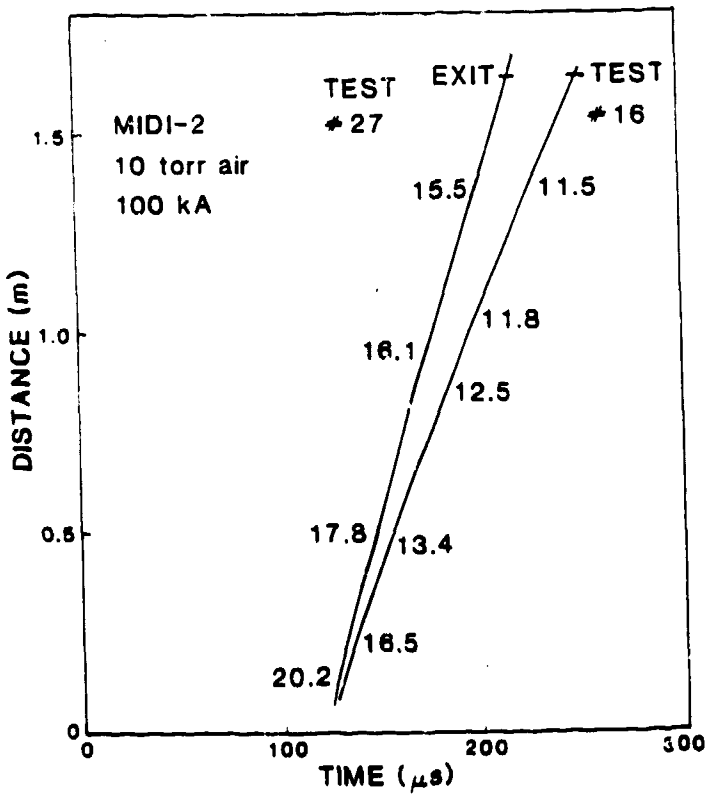

Fig. 7. Comparison of arc position vs. time for tests 16 and 27. Arc front velocity in km/s shown next to each curve.

Plasma Velocity

Increased magnetic force near the arc front should translate into increased plasma velocity. For a "free-arc", limited by the shock velocity in the initial gas fill, the velocity scales as the square root of the applied pressure or approximately linearly with the current in the plasma immediately behind the shock front. Figure 7 presents position vs. time for the arc front as obtained from the magnetic probe data. Displayed next to each curve is the best fit velocity in km/s. The SRS railgun arc moves faster than the conventional railgun arc by about 32% for the entire length of the barrel.

Breech Voltage

Figure 8 shows a comparison of the measured breech and muzzle voltages for test 16 and 27. The breech voltage records are denoted 16B and 27B. Many of the details of the breech voltage, for example, the initial voltage spike, are determined by dI/dt effects which are not of interest here. The relevant difference is the consistently higher breech voltage observed on test #27. During the motion of the plasma this voltage difference averages about 480 volts. Correcting for the average muzzle voltage difference of 140 volts gives a voltage of 340 volts which arises primarily from the inductive term L Iv. Using the theoretical value of L = 0.324 μH/m and the average measured current of 95 kA, this voltage difference translates into a velocity difference of 11 km/s. A velocity difference of 11 km/s is substantially greater than the measured difference in arc front velocity, about 4 km/s. This discrepancy arises because the velocity which enters into LIv is the average velocity of the plasma nearest the breech. For the SRS railgun, most of the current carrying plasma is moving at a velocity nearly equal to the plasma front velocity. In the conventional railgun test, the restrike arc current is moving more slowly than the arc front. The measured velocity of the back surface of the restrike arc is only 6 km/s in test 16. The difference between the restrike arc velocity in test 16 and the plasma velocity in test 27 is about 9 km/s, in reasonable agreement with the 11 km/s inferred from the breech voltage.

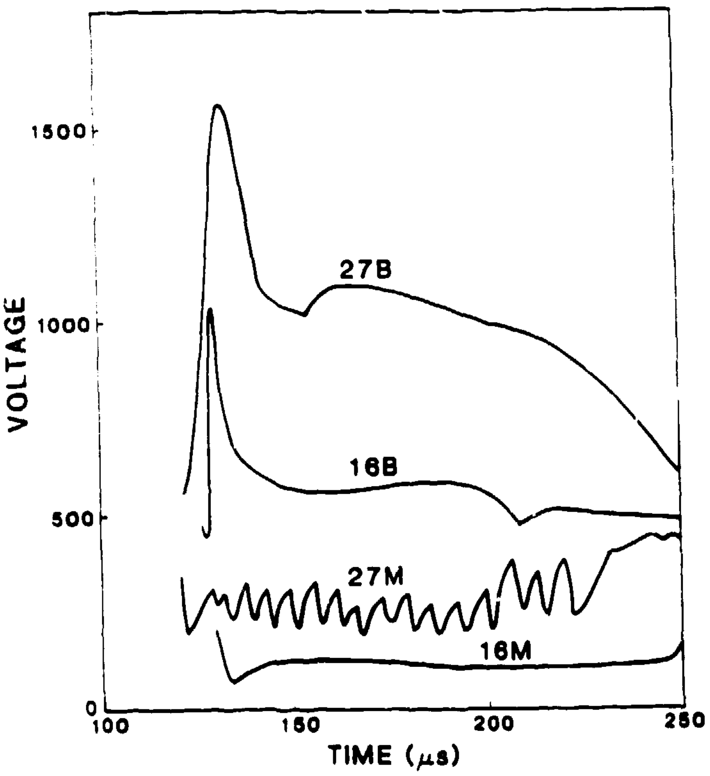

Fig. 8. Breech voltage (B) and muzzle voltage (M) for tests 16 and 27.

Muzzle Voltage

The muzzle voltage for test 27 (curve 27M) is measured between the upper rail and the lower current bus. This voltage includes not only the discharge voltage but the resistive and inductive voltages developed in the fuse elements. The spiky nature of trace 27 is the result of inductive voltage generated when the arc front passes from segment to segment. The steady voltage difference between curves 27M and 16M is about 100 V, in reasonable agreement with the voltage drop in the fuse links (~2 mΩ x 35 kA/segment). The inductive spikes average about 90 volts peak to peak. The average loop inductance from segment to segment can be calculated from this voltage amplitude using the measured dI/dt at the arc front. For dI/dt ~ 9×10^9 A/s the loop inductance for one segment plus two fuses is ~10 nH.

Summary and Conclusion

A new railgun structure has been proposed which can entirely eliminate restrike conduction and the concomitant performance loses. A practical demonstration of the SRS rail gun was carried out using the MIDI-2 railgun equipped with a 16 segment rail surface and passive fuse elements for opening switches. Despite non-ideal opening behavior exhibited by the fuse links, the expected benefits predicted for the SRS railgun were realized. Current flow in the region far behind the arc was substantially reduced and arc front velocity was increased by over 30%.

The electrical efficiency of the SRS railgun is not substantially reduced by the added switching circuitry. From the muzzle voltage trace, the resistive energy dissipated in the fuse elements was about 500 Joules and the magnetic energy dissipated during switching was about 6 Joules/fuse or a total of 100 Joules. These extra losses are about 12% of the input energy, a small price to pay for a 74% increase in the plasma kinetic energy.

The major question now is "what are the implications for 'real' railguns?" It is clear that this technique has the potential to improve railgun performances substantially when velocities greater than 6 to 8 km/s are needed. However, there are substantial practical difficulties.

For example, passive fuses are not suitable for a practical railgun. Some form of command triggered opening switch is needed to provide better opening action and lower resistance in the conducting phase.

There are no obvious candidate opening switches for a multiple-shot railgun at this time. None of the switch parameter are particularly difficult to achieve individually but they do not appear to be available in a single device. Typical switch requirements for a 3 MA launcher operating at 10 km/s with 2 meter segments are:

Peak Current:	3 MA
Conduction Time:	200 μs
Charge Transfer:	600 C
Current at Opening:	≤ 0.5 MA
Switching Time:	~10 μs
Jitter:	~10 μs
Switching Energy Dissipation:	~20 kJ
Inductance:	< 50 nH
Opening Voltage:	~10 kV

It appears that a single-shot laboratory or demonstration launcher could be built using current explosively actuated fuse technology.

A careful trade-off study is needed to determine the best segment length as a function of bore diameter and projectile velocity. The MIDI-2 results suggest that a 100 mm segment is shorter than necessary for a 1 cm bore railgun. If segment length scales with bore diameter, then it may be possible to utilize segments as long as 1 to 2 meters in a large-bore railgun (50-100 mm). The number of switches and current connections required for a practical launcher would thus be 20 to 40. Twenty to forty switches and their associated connections do not appear to be a major cost objection compared to the typical hardware costs of a major launcher system. For the near term, a demonstration railgun with 20 to 40 explosive opening switch appears practical if the shot rate is low (1-3 shots/week).

The other major issue is the mechanical and electrical design of the launcher barrel. The SRS demonstration on MIDI-2 was carried out at a pressure of 1.24×10^7 Pa (1940 PSI). To achieve similar performance at pressures of 10^8 Pa or higher will require careful design of the segments and segment-rail insulator to maintain adequate stiffness. The insulated gap between segments presents a new design problem whose solution will require careful experimental evaluation.

Despite these practical problems, we believe that the SRS technique is the only demonstrated method for reaching velocities greater than 8 km/s with a conventional railgun. The best competing technology at present is high-velocity injection using a two-stage light gas gun, an approach with its own practical limitations. Further developments in materials technology (ceramic insulators, refractory rails) may provide a simple alternative to the SRS structure but these new materials may not be available for five to ten years.

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