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RAILGUNS AND PLASMA ACCELERATORS: ARC ARMATURES, PULSE POWER SOURCES AND U.S. PATENTS

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SUMMARY

Railguns and plasma accelerators have the potential for use in many basic and applied research projects, such as in creating high-pressures for equation-of-state studies and in impact fusion. A brief review of railguns and plasma accelerators with references is presented in Section I. Railgun performance is critically dependent on armature operation. In Section II, plasma arc railgun armatures are addressed. Pulsed power supplies for multi-stage railguns are considered in Section III. This includes brief comments on the compensated pulsed alternator, or "compulsator," rotating machinery, and distributed energy sources for railguns. References are given at the end of each section. Appendix A contains a brief review of the U.S. Patents on multi-staging techniques for electromagnetic accelerators, plasma propulsion devices, and electric guns.

I. RAILGUNS AND PLASMA ACCELERATORS

A. Introduction

Railguns and plasma accelerators have the potential for use in many basic and applied research projects. For example, hypervelocity projectiles are useful for characterizing reentry-vehicle drag and ablation on entering the atmosphere, and in creating high-pressures for equation-of-state studies. Laboratory simulation of meteoroid impact on spacecraft requires knowledge of impact phenomena occurring at velocities the order of 20 km/s. The ability to launch reentry configurations to 20 km/s is necessary to provide laboratory simulation of planetary reentry phenomena in which radiative heat transfer dominates the flow field. Other potential applications include a variety of weapons, impact, and penetration studies. Impact fusion is yet another potential application of railgun accelerators. For example, a projectile with a mass of 0.1 grams traveling at a speed of about 200 km/s carries the energy needed to ignite a fusion fuel pellet. Recently, space-launch railgun concepts have been studied.

In this section on accelerators, let us first review the background and then identify some of the available information on railguns and plasma accelerators. Second, let us outline an approach or plan to pursue for following the development/trends in railguns and plasma accelerators and their applications.

B. Background

Why study railguns and plasma accelerators? Because EM fields propagate at the speed of light and can exert force on projectiles. EM accelerators are not limited by gas sonic velocity of the accelerating medium, as with light gas guns and explosive launchers. Since electrostatic techniques have severe launch mass limitations, the investigations of high velocity (at and above 10 km/s) launch of projectiles of practical size have concentrated on magnetic techniques. (Investigations of magnetic acceleration techniques date back to the early 1900's where work was performed by Fauchon-Villeplee in France.) The first concentrated effort to build and experiment with electric guns was conducted by Hansler in Germany during World War II. In the U.S., electric gun activities began in the 1950's and intensified through the 1960's. However, two basic problems limited the performance of these guns; namely, (1) lack of adequate power supplies, and (2) inadequate armature design concepts. Recent developments in power supplies and in plasma arc armatures have helped remove these limitations.(1)*

An example of high-velocity explosively driven guns is the work performed by Physics International in the late 1960's and early 1970's. For example, a two-stage gun was used to launch intact 2 gram models to 12.2 km/s in several experiments.(2)

Electromagnetic launchers were reviewed recently.(3) The advances in energy storage, switching, and magnetic technology make EM acceleration a viable alternative to chemical propulsion for certain tasks, and provide a means to perform other tasks not previously feasible. Launchers reviewed included the dc railgun driven by energy stored inertially in a homopolar generator and transferred through a switching inductor. One application mentioned was that of launching space cargo or nuclear waste in one-ton packets using off-peak electric power.

A recent review of EM guns, a survey of the field, was reported in 1972 by A. F. Riedl of the Naval Weapons Laboratory, Dahlgren, Virginia.(4) The technical note describes the initial phase of NWL's investigation of the possibility of using EM forces to launch projectiles.

*Note: References are listed at the end of each section

Interest in EM launchers that use pulsed dc techniques to launch macroparticles to velocities the order of 10 km/s has grown considerably in the last couple of years. For example, a small laboratory system (ELF-1) has been assembled at Westinghouse.(5) The system comprises an inductive power supply (powered by a homopolar inertial storage system), an inductive storage coil, switching mechanisms, a launcher barrel and projectile, and a down-range diagnostic and catcher section. The Materials Science Office of DARPA funded the advanced current-collection program.

A mass accelerator system was analyzed theoretically and recently reported(6) that uses a series of imploded annular plasma pinches to propel projectiles of mass ranging from grams to kilograms to velocities of 10 to 100 km/s. Such a device would have applications ranging from basic materials and impact studies to space-probe launching and impact fusion.

C. Impact Fusion

As stated in FUSION in the December 1979 issue,(7) "researchers are taking a new look at the idea of impact fusion, a concept that some fusion scientists feel could soon demonstrate better than breakeven energy production with just a $20 million research investment today. The idea was first proposed in 1963 by Dr. Friedwardt Winterberg, now at the Desert Research Center of the University of Nevada." Recently, Winterberg proposed a new pellet design for inertial confinement fusion.(8) The reported preliminary calculations indicate that the necessary velocity of an impact fusion projectile is 50 km/s. An evaluation of impact fusion concepts was presented in a report(9) by F. L. Ribe and A. T. Peaslee, Jr. They state, "The segmented railgun as analyzed by Hawke(10) and by Muller, Garwin, and Richter(11) seems to offer the most promise of being developed into an impact fusion accelerator." Hyperfuse--a novel inertial confinement system utilizing hypervelocity--has been described(12) by Henry Makowitz of Brookhaven National Laboratory.

D. Mass Driver

The mass driver that converts electrical energy into kinetic energy for accelerating 0.001 to 10 kg slugs to high velocities has been studied and described.(13) For example, mass drivers were studied for launching lunar materials into free space. The mass driver conversion efficiency from electrical energy to kinetic energy was reported at 75 to 90%. The power source was either solar or nuclear.

E. Railguns

In addition to the recent (1979-80) hypervelocity railgun experiments conducted jointly with LANSL that will be identified and briefly reviewed below, other railgun work includes: (1) a transversely activated railgun (TARG) to accelerate metallic objects by EM body forces that works well for the acceleration of hollow shells or tubes(14) (it is possible to produce rotational forces with the TARG System for spin-stabilization of a projectile), (2) the hairpin ASE Shutter(15), (3) a compact railgun pulser for a laser plasma shutter,(16) and (4) a railgun plasma accelerator to drag a projectile to high velocity. The pellets were initially 0.006-in. diameter pyrex. The velocities achieved were about 15 km/s.(17, 18)

Now, let us briefly identify the available information on railguns and plasma accelerators.

F. Available Information

In addition to the reports cited in the preceding background section, the following reports have been published on the recent (1979-80) LLL/LLNL railgun work: (1) a brief report on the LLNL/LANSL hypervelocity railgun experiments,(19) (2) a progress report on projectiles launched from EM railguns,(20) (3) drag and erosion modeling for EM propulsion with railguns,(21) (4) railgun accelerators for launching 0.1-g payloads at velocities greater than 150 km/s,(22) (5) the design and capabilities of magnetic propulsion railguns,(23) and (6) the prospects for generating 1 to 10 TPa pressures with a railgun.(24) In February of 1980, a report on the applications and potential of electric guns was published.(25)

Available information on the Australian National University railgun work in Canberra includes: (1) the 1978 report on EM acceleration of macroparticles to velocities the order of 5.9 km/s,(26) (2) a 1975 report on the Australian National University railgun project,(27) (3) a 1972 article that describes the railgun device that was being developed at the Australian National University,(28) (4) an unpublished Ph.D. dissertation by J. P. Barber, dated 1972, the Australian National University,(29) (5) an unpublished proceedings of the seminar on energy storage, compression and switching, the Australian National University, in 1977.(30)

A study of a rail-type MHD hypervelocity particle accelerator was reported by D. E. Brast and D. R. Sawle.(31)

Recent reports by R. A. Marshall, et al, of The University of Texas at Austin include: (1) an analysis of the performance of railgun accelerators powered by distributed energy stores presented in June of 1980,(32) (2) a railgun overview presented at the DOE Impact Fusion Workshop in July of 1979,(33) (3) a report on work in progress presented at the DARPA/ARRADCOM Review on September 19, 1979,(34) and (4) a method of numerically simulating the performance of railgun powered by distributed stores.(35)

Recent reports by H. Kolm, et al, of the Massachusetts Institute of Technology include a review of EM launchers,(3) a report on EM propulsion alternatives,(36) and a paper on basic coaxial mass driver reference design.(37)

Available information on <u>plasma gun accelerators</u> includes the original, early work of the 1960's and recent reports, such as: (1) the performance of a hydromagnetic plasma gun by John Marshall,(38) (2) a coaxial plasma accelerator by Ralph Lovberg,(39) (3) pulsed plasma accelerators by Robert Jahn and colleagues,(40) (4) space-time resolved plasma properties of dynamical plasmas by Otto M. Friedrich, Jr. and colleagues at The University of Texas at Austin,(41) (5) plasma gun injectors for magnetic fusion experiments,(42) (6) plasma electron gun research for conceptual design of a large area, repetitively pulsed device,(43) (7) plasma guns for spraying,(44,45) (8) a coaxial plasma gun for use as a particle accelerator by E. L. Shriver of NASA Marshall Space Flight Center in Alabama(46) (This plasma gun accelerated glass beads of 0.66 millimeter diameter to 7 to 8 km/s. Glass beads of smaller diameter were accelerated to more than twice this velocity. This NASA report references the early work under NASA contract by Lovberg, Hayworth and Gooding on coaxial gun for plasma propulsion.),(47) (9) tapered coaxial plasma gun electrodes for improved gun performance(48) (This Air Force Weapons Laboratory technical report references the early work by Mather(49) of LASL and of Filippov/Fillippova(50) and researchers in the USSR), and (10) a plasma gun proposal by LLL to build and test a magnetized coaxial plasma gun for axial injection and trapping in a magnetic mirror.(51) (This LLL proposal references the LASL plasma gun work in Ref. 51, Appendix C. It also presents numerical MHD code calulations for field-reversed plasma rings by J. L. Eddlemen, C. W. Hartman, J. W. Shearer, and W. C. Turner.)

Additional technical reports on <u>EM accelerators and plasma guns</u> include: (1) a study of EM guns in 1957 by the Armour Research Foundation,(52) (2) the final report on an investigation of EM launcher for high-speed projectiles by the Armour Research Foundation in May

1958(53) (This report references the early work by General Electric on EM accelerator systems.), (3) a study of methods of producing high-speed particles by the Aeronutronic Division of the Ford Motor Corporation in 1959,(54) (4) a final report on EM mass accelerator by the Laboratories Division of Instruments-Electrical Laboratory, Detroit Arsenal(55) (preliminary investigations of induction and parallel-rail types of mass accelerators were made. A mass of 24.5 grams was accelerated at a velocity of 1157 ft/s using a three-stage induction accelerator with an efficiency of 23.4%.), (5) the linear acceleration of large masses by electrical means at Holloman Air Force Base in New Mexico,(56) (6) four electrical techniques--an exploding coil, an induction accelerator, an accelerated plasma, and a gas heating technique--were studied by Bolt Beranek and Newman, Inc. for the Wright Air Development Division, U.S. Air Force in 1960(57) (experimentally, speeds up to 14,500 ft/s were obtained with a 20 kJ energy input. Limitations and design considerations of the plasma system were described.), (7) an investigation of an arc gun by the University of Utah in 1960 (a 3.7 mg nylon projectile was accelerated to 5 km/s with a 6 kJ capacitor bank power supply.),(58) (8) theory of an EM mass accelerator for achieving hypervelocities by K. Thom and J. Norwood of NASA-Langley Research Center,(59) (9) the development of hypervelocity guns using a capacitive energy source(60) (velocities of up to 12 km/s were obtained with an exploding foil gun powered by a 50 kJ capacitor bank. Also, microparticle, glass balls 75 microns diameter were accelerated with a coaxial plasma gun to velocities up to 15 km/s.), and (10) a report on EM propulsion of ordnance by NSWC/DL in August 1976.(61)

G. Outline of a Plan

What is a good method for following the developments, the trends in railguns and plasma accelerators and their applications? Also, what instrumentation and diagnostics are useful for studying the railgun--the plasma arc in particular? What power supplies (homopolar, compulsator, capacitor, inductor, etc.) and electrical circuits are available and what are the trade-off considerations for railguns? What additional analyses are required and tests necessary for developing the multistage railgun accelerator? And, what electrode and insulator materials are available for railguns? Let us briefly consider these questions and look at available approaches, or a plan to answer these questions.

In order to follow developments and trends in a high-technology area (such as railguns), a continuing effort of literature searches, analytical studies, technology assessment and forecasting is best. Thus, a continuing review of the literature, study of reported test data and calculations is recommended.

As stated in May 1980 by I. R. McNab of the Westinghouse R&D Center,(62) "... *in our view, it is most important that future* experiments of this type (EM macroparticle acceleration by a high pressure plasma, arc armature) should employ diagnostic instrumentation capable of directly measuring as many of the plasma parameters as possible. Only in this way will it be possible to investigate these interesting plasma conditions more closely and to make more accurate evaluations of the plasma conditions." Up to now, most EM macroparticle accelerators measure projectile velocities with magnetic flux loop probes placed near the rails and external velocity by time-of-flight, such as with down-range laser "fences" or with flash x-ray shadowgraphs. In Ref. 62, spectroscopic techniques were used to determine the plasma temperature. Also, the electron density in the muzzle arc was determined with stark broadening. Thus, instrumentation recommended for future railgun plasma arc measurements include: (1) optical fibers for space-time resolved measurements along the railgun. This optical data can provide spectroscopic (plasma temperature) and stark broadening (plasma density) information in addition to the time-of-flight, velocity information. (2) Voltage-current, input terminal and output muzzle data can provide information on the plasma arc's dynamic inductance--a measure of position vs. time and of plasma structure, current sheet or pinch. (3) Rail electrode markings can provide information on plasma arc burning, movement, tracks, etc. Erosion in the breech of the railgun is an indicator of arc dwell, etc. And, (4) Projectile markings can provide information on arc burning, plasma blow-by (electrode coating on projectile), and erosion (such as a concentrated arc and not a uniform current sheet). On the railgun tests with the 400 kJ capacitor bank, it is recommended that optical fiber data, voltage-current waveforms, and visual inspection of the railgun captured projectile be performed to obtain information on the plasma arc armature. Also, optical interferometry and/or holography are extremely valuable for space-time resolved(41,63,64) visual data recording.

As stated in Ref. 1, "... the successful operation of a high velocity electric railgun requires a power supply which can supply very large currents (typically hundreds of thousands of amperes) for relatively short durations (typically milliseconds), and can provide the energies required (typically hundreds of kilojoules). Power supply requirements are further restricted by the impedance characteristics of a railgun ... Conventional electrical generators are not capable of supplying the required current ... capacitors are capable of storing the required energy and delivering the required currents ... (however) direct capacitor drive makes successful operation of a railgun very problematical ... inductive energy storage is very attractive for railgun driving ... (however) the inductor must be charged and switched into the accelerator at high current ... (switching problems) ... Homopolar generators, because of their low intrinsic internal impedance, are ideally suited for inductor charging." The compensated pulsed alternator(65) "compulsator", with its dynamic impedance/flux compression properties, and the distributed inductive energy store railgun(32) afford alternative approaches. Thus, circuit analysis, computer simulation of these nonlinear systems need to be performed for trade-off, performance analysis.

As stated in Ref. 66, "... The 'classical' homopolar/inductor driven railgun is a fairly inefficient process. About half the homopolar energy can be transferred to the inductor and about one-third of that can be delivered to the projectile making a transfer efficiency from homopolar to projectile of around 15 percent ... The biggest inefficiency in this process is the charging of the inductor and it is possible that the use of a compulsator would eliminate the inductor charging stage. This could bring the transfer efficiency to above 80 percent. The compulsator also has the great advantage that because it is an 'active' device (compared with an inductor which is 'passive') its output can be tailored to match the load. This means that for a specific railgun design, a compulsator can, in principle, be designed to maintain constant current in the gun ... it could then be arranged in such a way that magnetic energy in the gun at projectile exit can be fed back into the compulsator. This would be very energy efficient ... Finally, a possibility which has not yet been ruled out is the use of distributed energy stores along the gun ... This would be a good arrangement because each homopolar/inductor along the gun would be completely discharged during firing ..." Thus, distributed energy stores and multistage railguns should be analyzed.

The multiple stage railgun affords improved performance, efficiency as shown in Refs. 23, 67. The total energy loss in the rails is proportional to $1/N^{1/2}$ where N is the number of modules. As indicated in Ref. 32, there are two disadvantages to using a single energy store. First, it is generally desirable to keep gun currents as nearly constant as possible and this is difficult to achieve without making the store excessively large. And, second the coil resistance also becomes a dominating factor as higher velocities are reached because higher velocities require greater gun lengths and correspondingly large gun resistances. Thus, the distributive energy store, multiple stage railgun needs to be developed further. This requires railgun test, circuit analysis, computer simulation (nonlinear elements in system), electrical switching, and inductive storage trade-off studies. A switch for a projectile-accelerating system with distributive stores, multiple stages was described in U.S. patent #3,613,499 dated October 19, 1971.(68)

The selection of electrode and insulator materials is critical for the successful operation of the-plasma arc, armature railgun. Results with copper electrode plasma arc railguns in the recent LLNL/LANSL, railgun tests are very encouraging. (In the past, some railguns have used tungsten and graphite electrodes, such as POCOACF-10Q).(69) Available insulator materials include ceramics and glass-bonded mica, such as MYCALEX(70) and MYKROY(71), which is arc resistant and non-tracking. Materials are improved and new materials are developed. Thus, the materials technology must be monitored, studies performed, and tests made as required.

References for Section I

1. John P. Barber and Hallock F. Swift, "Modern Electric Railgun Technology, "International Congress on Instrumentation in Aerospace Simulation Facilities, ICIASF '79 Record, IEEE, pp. 141-145, September 24-26, 1979.

2. J. D. Watson, "High-Velocity Explosively Driven Guns," Physics International Company, PIFR-113, report on NASA NAS 2-4903 contract, 101 pages, July 1969.

3. Henry Kolm, Kevin Fine, Peter Mongeau, and Fred Williams, "Electromagnetic Launchers," Proceedings of the 14th Intersociety Energy Conversion Engineering Conference, American Chemical Society, pp. 2004-2012, August 5-10, 1979.

4. Albert F. Riedl, III, "Preliminary Investigation of an Electromagnetic Gun," NWL Technical Note No. TN-E-10/72, Naval Weapons Laboratory, Dahlgen, Virginia, about 40 pages, July 1972.

5. I. R. McNab, "Recent Advances in Electrical Current Collection," Wear, Vol. 59, pp. 259-276, 1980.

6. D. A. Tidman and S. A. Goldstein, "Acceleration of Projectiles to Hypervelocities using a Series of Imploded Annular Plasma Discharges," Journal of Applied Physics, Vol. 51, No. 4, pp. 1975-1983, April 1980.

7. John Schoonover, "Impact Fusion--A New Look at an Old Idea," Fusion, pp. 47-52, December 1979.

8. "Winterberg Proposes New Pellet Design for Inertial Fusion," Fusion, pp. 65-66, September 1980.

9. F. L. Ribe and A. T. Peaslee, Jr., "Evaluation of Impact Fusion Concepts," University of Washington, Final Report UWFPP-7, p. 4, January 30, 1980.

10. R. S. Hawke, "Railgun Accelerators for Launching 0.1-G Payloads at Velocities Greater than 150 km/sec," LA-8000C, p. 167, Proceedings of Impact Fusion Workshop, July 10-13, 1979 (also Lawrence Livermore National Laboratory Report UCRL-82762).

11. R. A. Muller, R. L. Garwin, and B. Richter, "Impact Fusion With a Segmented Railgun," LA-8000C, p. 156, Proceedings of Impact Fusion Workshop, July 10-13, 1979.

12. Henry Markowitz, James R. Powell, and Richard Wiswall, "Hyperfuse: A Novel Inertial Confinement System Utilizing Hypervelocity Projectiles for Fusion Energy Production and Fission Waste Transmutation," Second International Conference on Emerging Nuclear Systems, Lausanne, Switzerland, April 1980; Brookhaven National Laboratories, BNL-26965, preprint.

13. Brian T. O'Leary and Gerard K. O'Neill, "Space Manufacturing, Satellite Power and Human Exploration," Interdisciplinary Science Reviews, Vol. 4, No. 3, pp. 143-207, September 1979.

14. B. Carder, "Transversely Activated Railgun," EE#80-128, 4276P, 4 pages, July 10, 1980.

15. B. Carder, "The Hairpin ASE Shutter," EE#78-191, December 4, 1978.

16. L. P. Bradley, E. L. Orham, and I. F. Stowers, "A Compact 5 x 10^{12} amp/sec Railgun Pulser for a Laser Plasma Shutter," preprint UCRL-82539, 14 pages, June 12, 1979.

17. David R. Sawle, "Hypervelocity Impact in Thin Sheets and Semi-Infinite Targets at 15 km/sec," AIAA Journal, Vol. 8, No. 7, pp. 1240-1244, July 1970.

18. David R. Sawle, "A Plasma Railgun Accelerator for Projectile Velocities Greater than 10 km/sec," UCRL-71321, (no date on report).

19. "Brief: Hypervelocity Railgun Experiments," Energy and Technology Review, LLNL, pp. ii-iv, June 1980.

20. "Projectile Launched from Electromagnetic Railgun Achieves Fastest Velocity to Date," Electronics Engineering Department Quarterly Report No. 1 -- 1980, pp. 1-4, April 1980.

21. A. C. Buckingham, "Electromagnetic Propulsion: Drag and Erosion Modeling," preprint, UCRL-83721, 9 pages, April 25, 1980.

22. R. S. Hawke, "Railgun Accelerators for launching 0.1-g Payloads at Velocities Greater than 150 km/s," preprint, UCRL-82762, 14 pages, June 15, 1979.

23. R. S. Hawke and J. K. Scudder, "Magnetic Propulsion Railguns: Their Design and Capabilities," preprint, UCRL-82677, 39 pages, May 8, 1979.

24. R. S. Hawke and J. K. Scudder, "Prospects for Generating 1-10 TPa Pressures with a Railgun," preprint, UCRL-82296, Rev. 2, 5 pages, October 2, 1979.

25. "Electric Gun: Applications and Potential," Energy and Technology Review, LLNL, pp. 28-37, February 1980.

26. S. C. Rashleigh and R. A. Marshall, "Electromagnetic Acceleration of Macroparticles to High Velocities," Journal of Applied Physics, Vol. 49, No. 4, pp. 2540-2542, April 1978.

27. R. A. Marshall, "The Australian National University Railgun Project," Atomic Energy, pp. 16-19, January 1975.

28. "Fast Propulsion," The Indian and Eastern Engineer, pp. 29-31, Vol. 114, No. 1, January 1972.

29. J. P. Barber, "The Acceleration of Macroparticles and a Hypervelocity Electromagnetic Acceleration," Ph.D. dissertation, The Australian National University, Canberra, Australia, 1972 (unpublished).

30. R. A. Marshall, "Proceedings of the Seminar on Energy Storage, Compression and Switching," the Australian National University, Canberra, Australia, 1977 (unpublished).

31. D. E. Brast and D. R. Sawle, "Study of a Rail-Type MHD Hypervelocity Projectile Accelerator," Proceedings of the Seventh Hypervelocity Impact Symposium, Vol. 1, p. 187, 1964.

32. R. A. Marshall and W. F. Weldon, "Analysis of Performance of Railgun Accelerators Powered by Distributed Energy Stores," 14th Pulse Power Modulator Sympossium, Orlando, Florida, 5 pages, June 3-5, 1980.

33. R. A. Marshall, "Railgun Overview," presented at the DOE Impact Fusion Workshop held at LASL, July, 1979.

34. W. F. Weldon and R. A. Marshall, "Work in Progress at U.T., C.E.M.," presented at the DARPA/ARRADCOM Review, Washington, D.C., September 19, 1979.

35. R. A. Marshall, "A Method of Numerically Simulating the Performance of Railguns Powered by Distributed Energy Stores," presented at the DARPA/ARRADCOM Review, Washington, D.C., April 9, 1980.

36. H. Kolm, et al., "Electromagnetic Propulsion Alternatives," presented at the Princeton Symposium on Space Manufacturing, 1979.

37. H. H. Kolm, "Basic Coaxial Mass Driver Reference Design," Proceedings of the Princeton Conference on Space Manufacturing, May 1977.

38. John Marshall, "Performance of a Hydromagnetic Plasma Gun," The Physics of Fluids, Vol. 3, No. 1, pp. 134-135, January 1960.

39. R. H. Lovberg, "Schlieren Photography of a Coaxial Accelerator Discharge," The Physics of Fluids, Vol. 8, No. 1, pp. 177-185, January 1965.

40. Neville A. Black and Robert G. Jahn, "Dynamic Efficiency of Pulsed Plasma Accelerators," AIAA Journal, Vol. 3, No. 6, p. 1209-1210, June 1965.

41. Otto M. Friedrich, Jr. and Arwin A. Dougal, "Comparison of Numerical Calculations and Measured Space-Time Resolved Plasma Properties of a Dynamical Theta Pinch, " AIAA Journal, Vol. 4, No. 12, pp. 2159-2165, December 1966.

42. N. Inoue, Y. Kawasumi, and K. Miyamoto, " J x B Type Plasma Gun for Closed Magnetic Trap Experiment," Plasma Physics (GB) Vol. 14, No. 9, pp. 891-895, September 1972.

43. D. B. Cohn, J. E. Thompson, and B. B. O'Brien, "Plasma Electron Gun," Final Report NRTC 75-19R by Northrop Corporation on Contract DAAH01-74-C-0350, 80 pages, 1975.

44. V. S. Klubnikin and E. G. Pukhov, "An Analysis of Plasma Guns for Spraying," Soviet Journal/Welding Production, Svar. Proiz., Vol. 25, No. 12, pp. 28-30, December 1978.

45. A. V. Donskoi, V. S. Klubnikin, and R. I. Kenkhi, "The Energy Characteristics of Plasma Guns," Soviet Journal/Welding Production, Svar. Proiz., Vol. 25, No. 2, pp. 8-10, February 1978.

46. Edward L. Shriver, "Analytical and Experimental Investigation of the Coaxial Plasma Gun for Use as a Particle Accelerator," NASA Technical Note, NASA TN D-6687, 77 pages, April 1972.

47. R. H. Lovberg, B. Hayworth, and T. Gooding, "The Use of Coaxial Gun for Plasma Propulsion," Report No. AE62-0678, NASA-Lewis Research Center, 1962.

48. John G. Clark, "Tapered Coaxial Plasma Gun Electrodes," Air Force Weapons Laboratory, Technical Report AFWL-TR-72-39, 34 pages, June 1972.

49. J. W. Mather, "Formation of a High Density Deuterium Plasma Forms," The Physics of Fluids, Vol. 8, No. 2, p. 366, 1965.

50. N. V. Filippov, T. I. Fillippova, and V. P. Vinogradov, "Dense, High-Temperature Plasma in a Non-Cylindrical Z-Pinch Compression," Nuclear Fusion Supplement, Part 2, p. 577, 1962.

51. T. C. Simonen, "Plasma Gun Proposal, "LLL-Prop-156, 203 pages, August 18, 1978.

52. K. W. Miller and R. M. Bergslien, "Study of Electromagnetic Gun," Technical Note No. 1, AFOSR-TN-57-244, ASTIA Document No. AD 126-541, 39 pages, July 1957.

53. J. L. Radnik and A. Bak, "Investigation of Electromagnetic Launcher for High-Speed Projectiles," Final Report, AFOSR-TR-58-84, AD 158-393, 67 pages, May 1958, (Armour Research Foundation).

54. T. Bergstralh, D. Krucoff, N. Meyer, and J. Worcester, "Final Report on Study of Methods of Producing High-Speed Particles," AFOSR-TR-59-181, AD 229-718, 65 pages, November 1959.

55. Petro Shajenko, "Electromagnetic Mass Accelerator," Final Report No. 4725, Detroit Arsenal, AD 234-351, 55 pages, March 14, 1960.

56. Knox Millsaps and Karl Pohlhausen, "The Linear Acceleration of Large Masses by Electrical Means," Holloman Air Force Base, AFMDC-TR-60-11, AD 241=375, 23 pages, June 1960.

57. Jordan J. Baruch, Denis V. Noiseux, Jay H. Ball, and Creighton M. Gogos, WADD Technical Report 60-468, AD 246-350, 139 pages, August 1960.

58. T. Fujii, E. P. Palmer, and R. W. Grow, "Investigation of an Arc Gun," Technical Report UU-6, AFBMD-TR-60-217, AD 604-499, 36 pages, August 3, 1960.

59. Karlheinz Thom and Joseph Norwood, Jr., "Theory of an Electromagnetic Mass Accelerator for Achieving Hypervelocities," NASA Technical Note, NASA TN D-886, AD 257-855, 35 pages, June 1961.

60. John E. Myrberg and William H. Clark, "Development of Hypervelocity Guns Using a Capacitor Energy Source," Final Report, AFML-TR-66-252, AD 807-538, 58 pages, September 1966.

61. G. Kourouklis and E. M. Lerner, "EM Propulsion of Ordnance (U)," NSWC/DL, AD C0072031, 94 pages, August 1976.

62. I. R. McNab, "Electromagnetic Macroparticle Acceleration by a High Pressure Plasma," Journal of Applied Physics, Vol. 51, No. 5, pp. 2549-2551, May 1980.

63. Max L. A. Gassend and Wolfgang M. Boerner, "Hypervelocity Particle Measurements by Holographic Method," SPIE, Vol. 97, High Speed Photography, pp. 104-112, 1976.

64. S. Denus, et al., "Application of Multiframe Laser Interferometry to the Study of Plasma Dynamics in a Plasma-Form Device," Journal of Technical Physics, Vol. 18, No. 4, pp. 381-394, 1977.

65. "Compulsator," Final Report by The University of Texas at Austin's Center for Electromechanics, LLNL, March 1980.

66. R. A. Marshall and W. F. Weldon, "Final Report on Comparison of Linear Induction, Synchronous and Homopolar Accelerators for Accelerating 25- and 700-Gram Projectiles to Velocities of One and Four Kilometers per Second," NSWC/DL, 39 pages, December 1979.

67. J. N. Brittingham and R. S. Hawke, "Magnetic Gradient and Railgun Accelerators for Launching 0.1-g Payloads at Velocities Greater than 150 km/s," UCRL-52778, 1979.

68. Frank T. Hubbard, "Switch for Projectile-Accelerating System," U.S. Patent #3,613,499, patented October 19, 1971.

69. POCO Graphite, Inc., "Standard Grades", 1601 South State Street, Decatur, Texas, 5 pages, Catalog dated 2-1-80.

70. MYCALEX, "Glass-Bonded Mica, Electrical and Electronic Insulation," Clifton Boulevard, Clifton, N. J. about 20 pages, catalog, papers, 1980.

71. MYKROY, "Glass-Bonded Mica," Mykroy Ceramics Corporation, Orben Drive, Ledgewood, N. J., about 20 pages, catalog, 1980.

II. PLASMA ARC RAILGUN ARMATURES

A. Introduction

Railgun performance is critically dependent on armature operation. Successful metallic armature operation with solid-on-solid sliding becomes difficult at speeds above about 1.1 km/s because of contact sliding instability.(1,2)* Plasma arc armatures provide a possible solution to this railgun problem area, performance limitation. However, now the questions of plasma arc stability, structure, uniformity, formation and movement, and of plasma arc-surface interactions (such as erosion, electrical breakdown) must be addressed.

B. Background

As recently stated(3), with plasma armatures in railguns the contact problems and the ohmic heating limitations of metallic armatures are eliminated. Ablation of the projectile and containment of the plasma are potential problems with this concept. For short accelerations typical of many hypervelocity applications, ablation may not be a significant problem. Plasma containment (similar to the gas blow-by problem in a gas gun) can be controlled by the construction of the gun and the fit of the projectile. If sufficient plasma leakage, or blow-by occurred, electrical arcing could occur in front of the projectile and these arcs would reduce the acceleration of the projectile. The problems of plasma leakage and mechanical breakup of the projectile are greatly reduced with inductively driven railguns. Recently, projectiles were accelerated up to approximately 9.9 km/s using plasma armatures in the LLNL-LANSL program.(4,5)

*Note: References are listed at the end of each section.

C. Plasma Pressure

In a railgun with a plasma armature, the accelerating current is carried by an ionized gas, plasma arc behind the projectile. The $\vec{j} \times \vec{B}$ Lorentz forces generated with the plasma arc are applied to the projectile. Thus, the plasma arc stability, magnetic pressure distribution uniformity, and the arc-surface effects are very important. The total pressure is exerted by a three-component plasma -- atoms, electrons, and ions. As recently stated, (2)... "the paucity of measured information on the plasma in this case necessitates the use of simplifying assumptions ..." including the assumption of a homogeneous plasma.

First, let's briefly review the available information on plasma arcs, plasma sheaths, current sheets, and then briefly review plasma simulation with computer codes. Second, let's outline an approach, or a plan to obtain the required data on plasma arcs for railgun armatures in envisioned railguns.

D. Available Information

Plasma arcs, plasma sheaths, and current sheets were experimentally investigated by several people in the 1960's. For example, at The University of Texas, experimental and analytical work was performed on an inverse plasma pinch, a theta-pinch, a parallel-plate railgun, and a plasma-focus.(6) This research was on plasma sheath dynamics -- computer calculations with a two-fluid, MHD code based on LASL plasma simulation models, and experimental diagnostics (including new laser techniques) developed under contracts with NASA-Headquarters, the Air Force (W-P AFB and AFOSR), the NSF, and the Texas Atomic Energy Research Foundation (TAERF). In the 1960's, Ralph Lovberg published(7) results on a pulsed plasma accelerator with parallel-plate electrodes operated in a mode that produced a flat sheet of current with one-dimensional variation of field and plasma parameters over most of its area. The plasma sheath was examined from the side with fast Schlieren photography. Earlier, magnetic and electric probe data indicated that the current sheet was nearly a perfect magnetic snowplow. It was then expected that the current sheet would leave in its wake a very dense layer of gas highly compressed against the cathode (negative electrode in the railgun). (In 1963-64, using space- and time-resolved laser interferometry, at The University of Texas, the electron density was measured in these plasma sheaths and cathode layers.(8)) In 1964, after prolonged railgun accelerator operation, a certain irregular behavior of the plasma arc discharge was noted -- instabilities were reported (7)... "a pronounced departure of the current sheet from planarity, with a tendency of those parts of the sheet nearest the electrodes to move ahead of the central region ... the cause of this phenomenon is not understood, and our control over it is poor; what is known for certain is that it can be eliminated if new electrode and insulator surfaces are used." The spacing of the railgun accelerator electrodes was increased from 3.8 cm to 5 cm in order to determine if overall stability of the configuration would suffer. Figure 14 of Ref. 7 shows the current sheet formed with increased electrode spacing (spacing of 5 cm) -- it is relatively planar and appears to be stable. The operating voltage was 16 kV, the current was 100 kA.

More recent reports on plasma arcs, plasma sheaths, and current sheets include the following:

(1) A theory of the current sheath dynamics for a plasma focus including finite thickness effects.(9) A filamentry structure was shown to be necessary for the sheath stability.

(2) In a theta-pinch with strong and fast-rising magnetic field, flute instabilities were observed during the stage of fast radial collapse of the cylindrical plasma sheath.(10)

(3) In a plasma focus, the plasma cylinder expands to a relatively long-lasting (30 to 70 ns) quiescent phase before instabilities occur.(11)

(4) From laser scattering experiments on a dense plasma focus, radial motions of the entire column that might be associated with kink MHD instabilities (M=1) were ruled out.(12)

(5) In a partially preionized high voltage theta-pinch, a hybrid computer model that combines a fluid numerical treatment and ionization predicted a differential rotation of the imploding plasma column that affects the radial density distributions.(13) And,

(6) ... "in recent years it has become increasingly clear that the vacuum arc possesses a high degree of instability ... (recent) investigations of vacuum arcs have revealed new and sometimes surprising information concerning the products of erosion from arc cathode spots ... A major cause of the presently poor understanding of vacuum arc emission process is the lack of fundamental information concerning the energy balance at the cathode ... A major limitation in the ability of a vacuum device to interrupt current is the tendency for the high-current vacuum arc to constrict at the anode junction producing surface melting and the formation of an anode spot ... There have been several attempts to describe anode spot formation theoretically."(14) There are 171 references on arcs and electrical breakdown in the reference and bibliography of Ref. 14.

The basic physics of electric propulsion, including a description of plasma arcs, the parallel-plate accelerator, and the current sheets was reviewed in a book by Robert Jahn in 1968.(15) Normally, the initiation of the plasma arc is in the minimum inductance configuration (this is associated with the high-frequency skin effect wherein a rapidly changing current tends to be excluded from the interior of a conductor. If the dynamic minimum inductance condition continues to be satisfied during normal railgun operation, then we would expect the curent sheet to be planar -- plasma pinches, constricted arcs, instabilities would be precluded.

Available reports on erosion of rails in a railgun, and on plasma arc-surface interactions include the following:

(1) The ablation or erosion of rails in a rail accelerator was ..."not thoroughly understood. Joule heating seems to contribute part of the effect, although ion bombardment of the surface may also contribute. Copper rails appear to work as well or better than anything else which has been tried. In addition, (in) small diameter railguns the skin friction of the plasma on the wall can have a large effect.(16) In Ref. 17, the first demonstration that a current sheet can be produced on an insulator and driven from it with negligible desorptive mass loading from the material surface was reported.

(2) Surface effects in a pulsed plasma accelerator were discussed briefly in Ref. 18. Experimental studies of several pulsed plasma accelerators on a thrust stand were reported, including the plasma impulse for varying electrode materials, insulator materials, background gas pressures, initial surface preparation, etc. Surface effects mentioned were outgassing of adsorbed and absorbed gas; mass removal from the electrodes and insulator assembly due to the various erosion effects, resistive changes at the electrode surface and deposition of ablated insulator material, and viscous boundary-layer and current boundary-layer effects.

(3) Electrode erosion in a repetitively pulsed plasma accelerator was considered in the acceleration of metal plasmas.(19)

(4) The current sheet structure in a parallel-plate railgun was ... "found to be very sensitive to impurities in the gas in the discharge chamber ... The first half-dozen shots were irreproducible and irregular ... This was due to the fact that for good breakdown the insulator surface had to be conditioned by the discharge."(20)

(5) Curent sheet tilt in a parallel-plate railgun was stated as a requirement to allow the ions to carry the discharge current near the cathode, there being a mass motion of the ionized gas towards the cathode.(21)

(6) In a neutral-gas accelerator using a railgun, near the insulator a discharge consisting of a current sheet driving a shock was found.(22)

Available plasma simulation with computer codes includes:

(1) Numerical calculations using a two-fluid MHD model programmed in Lagrangian coordinates for dynamic plasmas,(6)

(2) A two-dimensional MHD Eulerian code for a plasma focus developed at LLNL(23), and

(3) Simulations of the implosion of a reversed field pinch using a one-dimensional hybrid code called AURORA at LANSL.(24) As stated in Ref. 25, computer simulations concerned with plasma dynamics and current sheath structure are done in one- and two-dimensions and do not cover the full parameter range of the experiments.

In a Soviet publication, an approximate solution was reported for the system of equations describing the processes in nonlinear [illegible]ized systems for the acceleration of plasma bunches in rail-type accelerators.(26) In another Soviet report, a study was made on the effect of friction on the distribution of currents, magnetic field, and velocity in a pulsed erosion accelerator.(27) Snowplowing in a plasma railgun has been analyzed, for example in Ref. 28.

Recently, at LLNL an axisymmetric Eulerian MHD code called CODA was used to calculate the production of field-reversed plasma rings by means of a plasma gun.(29) A code called HAM is also now available at LLNL that can handle partially ionized plasmas.(30)

A nonlinear, two-dimensional, MHD, Eulerian code has been developed by J. Killeen and colleagues at LLNL.(31,32,33) In a report dated October 1978, the authors state that with the advances in speed and memory size of modern computers, it has become feasible to study plasma instabilities by numerical techniques.

Other available computer codes at LLNL include: HEMP(34), LASNEX(35), ZFUSE, WOLF, and codes through the National MFE Computer Center, such as MHD2D, TRANSPORT, 2D LINEAR, 2D NONLINEAR, AND 3D NONLINEAR

E. A Plan

Let's outline an approach, or a plan to obtain the required data on plasma arcs for railgun armatures. An analytical, numerical, and experimental approach is recommended for investigating the plasma arc in the envisioned railguns. This plan includes:

1) Continued analytical studies and analyses on the dynamic plasma arc, plasma sheath, and current sheet produced in the railgun.

Physical models based upon fundamental physical principles can be developed for plasma arcs produced in pulsed plasma devices, such as the railgun, the plasma-focus, the theta-pinch, the z-pinch, etc. Recent test data and reported literature provide the required inputs for developing these models.

2) Numerical modeling, computer simulation, plasma MHD code calculations. In order to fully model the resistive, dynamic plasma arc -- to determine its stability -- a 3D MHD code is required. The recently developed computer codes by John Killeen and colleagues at LLNL should be examined for this work.

3) Experimental tests and data collection with well-instrumented laboratory railguns. The required instrumentation for diagnostics on the plasma arc/plasma sheath/current sheet includes: space- and time-resolved optical-fibers and magnetic-probes; voltage-current circuit measurements; high-speed photography, laser interferometry, etc. when and where possible, time-of-flight, velocity, and energy measurements. Examination of the fixed projectiles that can be captured without severe damage will provide visual data, materials analyses, etc. on the plasma arc-surface interaction. The rail erosion and other markings on the rails of the railgun are important for determining how the plasma arc operated during the tests.

To achieve optimum results, the above steps in this plan need to be pursued in parallel, with information exchanged between the workers on each topic. Experimental test data that soon will be available from the 400 kJ capacitor-driven railgun in Bldg. #141, the test data available from explosive-driven shots in 1979-1980 (in particular, the recent data with the large-bore railgun) and other reported data is the basis for input and analytical physical models and for computer calculations, plasma simulation. Since the plasma arc's shape and stability are critical for an efficient operation of plasma arc railgun armatures, a 3D computer code, plasma simulation would be extremely valuable at this time. Also, space- and time-resolved plasma data on the arc's shape, structure, stability is needed.

References for Section II

1. J. P. Barber, "Aeroballistic Range Association 1973 Meeting," Arnold Engineering Development Center, Tennessee (unpublished).

2. I. R. McNab, "Electromagnetic Macroparticle Acceleration by a High Pressure Plasma," Journal of Applied Physics, Vol. 51, No. 5, pp. 2549-2551, May 1980.

3. John P. Barber and Hallock F. Swift, "Modern Electric Railgun Technology," International Congress on Instrumentation in Aerospace Simulation Facilities, ICIASF '79 Record, pp. 141-145, September 24-26, 1979.

4. "Hypervelocity Railgun Experiments," Energy and Technology Review, LLNL, pp. ii-iv, June 1980.

5. "Projectile Launched from Electromagnetic Railgun Achieves Fastest Velocity to Date," Electronics Engineering Department Quarterly Report No. 1--1980, LLNL, pp. 1-4, April 1, 1980.

6. Otto M. Friedrich, Jr. and Arwin A. Dougal, "Comparison of Numerical Calculations and Measured Space-Time Resolved Plasma Properties of a Dynamical Theta-Pinch," AIAA Journal, Vol. 4, No. 12, pp. 2159-2165, December 1966.

7. Ralph A. Lovberg, "The Measurement of Plasma Density in a Rail Accelerator by Means of Schlieren Photography," IEEE Transactions on Nuclear Science, NS-11, pp. 187-198, January 1964.

8. A. A. Dougal, R. F. Gribble, J. P. Craig, and O. M. Friedrich, Jr., "Infrared Maser Coupled Resonator and Faraday Rotation Techniques for Experimental Ionized Gas Diagnostics," Proceedings of the Seventh International Conference on Phenomena in Ionized Gases, Gradevinska Knjiga Publishing House, Belgrad, Yugoslavia, 1965.

9. F. Gratton and M. Vargas, "Magnetic Tension and Thickness in the Current Sheath Dynamics," Nuclear Fusion Supplement 1977, Vol. III, pp. 489-490, IAEA, 1977.

10. V. A. Burtsev, A. B. Berezin, A. P. Zhukov, L. A. Zelenov, V. A. Kubascv, V. N. Litunovskij, B. V. Lyublin, A. G. Smirnov, and V.G. Smirnov, "Study of Linear Theta Pinch with Strong and Fast-Rising Magnetic Field," Nuclear Fusion Supplement 1979, Vol. II, pp. 205-215, IAEA, 1979.

11. G. Decker, B. Nahrath, T. Oppenlander, G. Pross, B. Ruckle, H. Schmidt, M. Shakhatre, and M. Trunk, "Dynamics of 120 kV and 20 kV Plasma Focus Devices with Respect to Density and Current Distribution, and Neutron and X-Ray Emission," Nuclear Fusion Supplement 1977, Vol. III, pp. 441-446, IAEA, 1977.

12. J. N. Downing and M. Eisher, "Dynamics of the Dense Plasma Focus as Determined From an Analysis of Laser Scattering Spectra," The Physics of Fluids, Vol. 18, No. 8, pp. 991-1001, August 1975.

13. A. G. Sgro, "Calculations of the Effects of Incomplete Preionization in High Voltage Theta Pinches," The Physics of Fluids, Vol. 21, No. 8, pp. 1410-1416, August 1978.

14. G. A. Farrall, "Condition and Breakdown in Vacuum," General Electric Report No. 78CRD149, 17 pages, September 1978.

15. Robert G. Jahn, Physics of Electric Propulsion, McGraw-Hill, Inc., Chapters 6, 8, and 9; 1968.

16. David R. Sawle, "Hypervelocity Impact in Thin Sheets and Semi-Infinite Targets at 15 km/sec," AIAA Journal, Vol. 8, No. 7, pp. 1240-1244, July 1970.

17. R. H. Lovberg, "Investigation of Current-Sheet Microstructure," AIAA Journal, Vol. 4, No. 7, pp. 1215-1244, July 1966.

18. William J. Guman and William Truglio, "Surface Effects in a Pulsed Plasma Accelerator," AIAA Journal, Vol. 2, No. 7, pp. 1342-1343, July 1964.

19. T. L. Rosebrock, D. L. Clingman, and D. G. Gubbins, "Pulsed Elecromagnetic Acceleration of Metal Plasmas," AIAA Journal, Vol. 2, No. 2, pp. 328-334, February 1964.

20. G. J. Pert, "Current Sheet Structure in a Parallel Plate Railgun," The *Physics of Fluids*, Vol. 13, No. 8, pp. 2185-2192, August 1970.

21. G. J. Pert, "Current Sheet Tilt in a Parallel-Plate Railgun," Plasma Physics, Vol. 13, No. 1, pp. 63-69, January 1971.

22. G. J. Pert, "Neutral-Gas Acceleration by an Electromagnetic Plasma Gun," Nuclear Fusion, Vol. 11, No. 4, pp. 371-375, August 1971.

23. Stephen Maxon and James Eddleman, "Two Dimensional Magnetohydrodynamic Calculations of the Plasma Focus, LLL, preprint UCRL-79087 Rev. 1, 46 pages, February 1978.

24. A. G. Sgro, "Simulations of the ZT-S Reversed Field Pinch," The Physics of Fluids, Vol. 23, No. 5, pp. 1055-1061, May 1980.

25. K. Hothker, "Plasma Dynamics and Current-Sheath Structure in a Collision-Free Theta Pinch," Nuclear Fusion, Vol. 15, No. 2, pp. 253-261, April 1976.

26. D. M. Kazarnovskii, A. A. Kulandin, and A. V. Khoroshavin, "Approximate Analysis of Processes in a Capacitance Accumulator -- Rail-Type Accelerator System," Magnetohydrodynamics, Vol. 8, No. 4, pp. 541-544, October-December 1972.

27. A. S. Gastev, Yu M. Grishin, N. P. Kozlov, and V. I. Khvesyuk, "Effect of Viscous Friction on Plasma Flow in an Electromagnetic Plasma Gun," Soviet Physics - Technical Physics, Vol. 20, No. 9, pp. 1256-1258, September 1975.

28. C. T. Chang, "Comments on Snowplowing in a Plasma Railgun," The Physics of Fluids, Vol. 14, No. 18, pp. 1819-1820, August 1971.

29. J. W. Shearer, J. L. Eddleman, C. W. Hartman, and W. C. Turner, "Numerical Calculations of Plasma Gun Operation and Formation of Field Reversed Plasma," 1979 IEEE International Conference on Plasma Science, June 4-6, 1979.

30. Jim Shearer, LLNL (telephone conversation, June 13, 1980).

31. D. Schnack and J. Killeen, "Nonlinear Two-Dimensional Magnetohydrodynamic Calculations," LLL, Preprint UCRL-81821, 64 pages, October 1978.

32. J. A. Dibiase, J. Killeen, D. C. Robinson, and D. Schnack, "Linear and Non-Linear Calculation of the Tearing Mode in Reversed Field Pinches," in Pulsed High Beta Plasmas, Pergamon Press, Oxford, pp. 283-289, 1976.

33. J. A. Dibiase and J. Killeen, "A Numerical Model for Resistive Magnetohydrodynamic Instabilities," Journal Comp. Physics, Vol. 24, 1977.

34. Mark L. Wilkins, "Magnetohydrodynamics of HEMP," LLL, UCRL-51715, 50 pages, March 1973.

35. George B. Zimmerman, Documentation on LASNEX, (June 9, 1980 Computer printout).

III. PULSED POWER SOURCES FOR RAILGUNS: A Brief Progress Report

A. Introduction

The objectives of these studies are: 1) to assess the suitability of compensated alternators for use in powering a multi-stage railgun accelerator, and 2) to assess the role of rotating machinery in pulsed power technology. Several recent technical reports and papers have been studied to pursue these objectives. The results of these studies will be presented in this progress report.

First, let's briefly review the multi-stage railgun accelerator, power supplies required by railguns, the compensated pulsed alternator, or "compulsator", and then report on the results of engineering analyses for using rotating machinery in railgun and pulsed power technology.

B. Multi-Stage Railgun Accelerator

As stated in Ref. 1*, in a single-stage railgun approximately 50% of the energy stored in the inductor is lost in resistive heating of the rails. However by dividing the accelerators into several shorter, modular sections, or stages, one can: 1) reduce the amount of energy loss in heating the rails, 2) allow the current to be re-established at the highest usable value in each section, 3) reduce the resistive voltage drop, and 4) provide a convenient division of the total amount of required energy into smaller units. The total energy loss in the rails is proportional to $1/(N)^{1/2}$, where N is the number of modules.

C. Power Supplies Required by Railguns

Based on circuit analyses of pulsed accelerators, one finds(2) that railgun accelerators require very large currents. In general,

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*Note: References are listed at the end of each section.

railguns present extremely low dynamical impedance to the electrical driving circuit. Power supplies with extremely low external inductance and resistance and with very high capacitance and voltage are needed. This places severe demands on the power supply. The dynamical plasma arc aspects are important, since these determine the rate of increase of inductance which must be the dominant circuit load in an efficient accelerator. Specific design criteria cannot be developed until the plasma arc dynamics are included in the circuit analyses. Also, power conditioning equipment is required to drive the accelerators -- namely, energy storage and switching. Thus, the need for energy storage units with exceedingly high performance, storage units to provide optimum driving - current waveforms for the discharge, the need for an impedance match between the source circuit and the particular discharge characteristics, and the critical nature of the switching mechanism must be determined.

D. Compensated Pulsed Alternator, or "Compulsator"

The compensated pulsed alternator, or "compulsator"(3), is an active device (compared with an inductor which is passive) that can have its output tailored to match a load, such as a railgun accelerator. The test results and design analyses for a prototype compulsator were presented in a final report dated March 1980 -- Ref. 3. Electrical circuit analyses and simulations have been performed using the compulsator to drive resistive loads. Now, additional studies are required with dynamical, inductive and resistive loads as are typical of railgun accelerators.

The "classical" homopolar/inductor driven railgun is a fairly inefficient process.(4). As stated in Ref. 4, about half of the homopolar energy can be transferred to the inductor and about one third of that can be delivered to the projectile. Thus, the overall transfer efficiency from homopolar to projectile may be about 15%. The largest inefficiency in this process is the charging of the inductor. It is possible that the use of a compulsator would eliminate the inductor charging stage. This could bring the transfer efficiency to above 80%.(4) In effect, the compulsator has a fast inductor built into it.

E. Rotating Machinery in Railgun and Pulsed Power Technology

Rotating machinery affords new opportunities as a power supply in railguns and for pulsed power technology. Its high energy storage density is an advantage for many applications. Rotating machinery may be more compact and lightweight than other energy storage units -- except explosives. Also, rotating machinery may be less expensive for certain applications. As mentioned above, the compulsator also has the great advantage that its output pulse can be tailored to match the load -- it is an active device. For a specific railgun design, a compulsator can in principle be designed to maintain a constant current in the railgun. It can then be arranged in such a way that the magnetic energy in the railgun at projectile exit can be fed back into the compulsator. Thus, this can be a very energy efficient system.(4) For example, in a single pulse, about 5% of the compulsator's energy may be extracted. Thus, to deliver a 2 MJ single pulse, the rotating machine would have to store 40 MJ initially. Rep-rated switching may be easier with a pulsed, rotating machine.

F. Distributed Energy Sources for Railguns

An analysis of the performance of railgun accelerators powered by a distributed energy source was recently presented.(5) This permits inductive energy to be transferred down the railgun rather than being dissipated resistively in the rails.

G. Concluding Remarks

As additional test data becomes available for the compulsator, these pulsed power feasibility studies need to be performed. Also, as new designs and information are obtained for rotating machinery, one must update the pulsed power feasibility studies. Presently, rotating machinery affords new, unique capability for a number of pulse power technology requirements.

References for Section III

1. R. S. Hawke and J. K. Scudder, "Magnetic Propulsion Railguns: Their Design and Capabilities," LLNL, preprint UCRL-82677, 30 pages, May 8, 1979.

2. Robert G. Jahn, Physics of Electric Propulsion, McGraw-Hill, Inc., Chapter 9 "Unsteady Electromagnetic Acceleration," pp. 257-316, 1968.

3. "Compulsator," Final report by The University of Texas at Austin's Center for Electromechanics, LLNL, March 1980.

4. R. A. Marshall and W. F. Weldon, "Final Report on Comparison of Linear Induction, Synchronous and Homopolar Accelerators for Accelerating 25 and 700 Gram Projectiles to Velocities of One and Four Kilometers per Second," NSWC, Dahlgren, Virginia, 30 pages, December 1979.

5. Robert A. Marshall and William F. Weldon, "Analysis of Performance of Railgun Accelerators Powered by Distributed Energy Sources," paper at the 14th Pulse Power Modulator Symposium, Orlando, Florida, 5 pages, June 3-5, 1980.

APPENDIX A

U.S. PATENTS on MULTI-STAGING TECHNIQUES for EM ACCELERATORS, PLASMA PROPULSION DEVICES, and ELECTRIC GUNS

A.1 Introduction

U.S. Patents have been awarded, starting in the 1920's on "electric gun or apparatus for propelling projectiles,"[1,2,3]* for electromagnetic accelerators, plasma propulsion devices, and electric guns. Let's identify and list some of the patents filed in the U.S. on these and related topics.

In the following paragraphs, some of the U.S. Patents on EM accelerators, plasma guns, etc., are briefly reviewed. References are provided at the end.

A.2 U.S. Patents Awarded

U.S. Patent No. 1,370,200, patented March 1, 1921 by A. L. O. Fauchon - Villeplee is entitled, "Electric Gun or Apparatus for Propelling Projectiles."[1] The following advantages are given: (1) economy, fuel weight (explosives compared to gasoline driven generators), (2) simple construction, (3) low wear, (4) rapid fire, (5) high power (only limited by sources of electric supply), (6) no smoke and little noise or light, and (7) adaptable for mobile or coast defense: useful for . . . "attacking airships by means of arrows, or for rockets as well as for torpedo launching, etc." The fifteen claims define the various electric gun geometries. On July 4, 1922, another U.S. Patent No. 1,421,435 was awarded to A. L. O. Fauchon - Villeplee entitled, "Electric Apparatus for Propelling Projectiles."[2] This patent relates to a gun construction based upon the same principles as the earlier patent (No. 1,370,200), but this patent (No. 1,421,435) has a projectile of circular cross section--not wings as in patent No. 1,370,200. In this patent (No. 1,421,435),

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*Note: References are listed at the end of this Appendix the projectile may be hollow or solid, rifled or smooth and made of magnetic or a nonmagnetic material. On July 11, 1922, a third U.S. Patent, No. 1,422,427, was awarded to A. L. O. Fauchon - Villeplee entitled, "Electric Apparatus for a gun construction based upon the same principle (patent No. 1,421,435) but again uses winged projectiles. The projectile shell is cross-shaped and provided with wings, which allows for reducing the magnetic gap and obtaining a better contact with the rails. A rotary (spin) movement could be imparted to the projectiles.

U.S. Patent No. 2,783,684, patented March 5, 1957 by Yusuf A. Yoler is entitled, "Method and Means for Propagating a Mass."[4] This patent is assigned to General Electric Company of New York. One objective of this invention was to provide an improved method and apparatus for propagating a shock wave or for propelling a projectile at greater speeds than heretofore attainable. A second objective was to provide an improved method and apparatus for successively releasing energy in a spaced manner within an enclosure for maintaining controllable and distributed energy level or accelerating force along the length of the enclosure (gun). A third objective was to provide a more efficient method and apparatus for applying electrical energy to accelerate a mass. A fourth objective was to provide a less expensive and simpler method and apparatus for accelerating masses. What is claimed is: (1) a method of sequentially generating energy to propagate a shock wave or propel a projectile down the length of the gun with sequential initiation of electrical arc discharges, and (2) methods of propagating a shock wave for propelling a projectile down the length of the gun. Thus, a unique method and apparatus was evolved for maintaining a high pressure and temperature continuously behind the projectile or shock wave as it passed down the length of the gun. As the shock wave was accelerated down the length of the gun, this ionized gas (plasma) enables (triggers) an arc to form across the electrodes and additional electrical energy is supplied into the gun. On April 30, 1957, Yusuf A. Yoler and James D. Cobine were awarded U.S. Patent No. 2,790,354, entitled, "Mass Accelerator."[5] This invention provided a means for releasing large quantities of gas when subjected to heating by the passing arc.

U.S. Patent No. 3,613,499, patented October 19, 1971 by Frank T. Hubbard and Gaston Demers, is entitled, "Switch for Projectile-Accelerating System."[6] This patent relates to a method and apparatus for accelerating projectiles to hypersonic velocities and more particularly relates to a scheme involving the discharge of electrical energy into gas accelerating the projectile. A simple switch is provided that applies the electric voltage from a capacitor bank to electrodes to form an arc discharge. Multiple stages (a plurality of spaced-apart stations) or sections along the gun barrel are used to increase the projectile velocity. This patent (No. 3,613,499) refers to the prior art for switching that used pressure sensors, ionization gauges, break wires and an initially created ionized gas mass to trigger spark-gaps or ignitions for producing the arc discharge to drive the projectile. For example, the ionized gas mass itself permits an assisting discharge to occur between electrodes and then the arc to form.

U.S. Patent No. 3,279,320, patented October 18, 1966 by Theodore L. Rosebrock is entitled, "Magnetoplasmadynamics."[7] This patent is assigned to General Motors Corporation, Detroit, Michigan. This patent relates to an improved method and apparatus for generating and utilizing a plasma. The plasma itself produces the required switching. A unidirection explosion is achieved with high propellant mass utilization. Space propulsion is mentioned as an application. Various values and materials were suggested in the description. For example, a firing pulse rate of 100 pps was mentioned. To achieve maximum contact velocity while avoiding rail electrode evaporation, an example material was given--namely: silver Elkonite, Mallory 1,000 or some similar alloy. Claims include: (1) a method of producing a high velocity plasma at a repetition rate (such as 100 pps) and (2) a method of producing a plasma with unidirectional velocity component with a railgun device.

U.S. Patent No. 3,417,273, patented December 17, 1968 by Duane C. Gates and John F. Detko is entitled, "Apparatus for Accelerating Plasma by a Static Magnetic Field and a Traveling Wave."[8] This patent is assigned to Aerojet-General Corporation, El Monte, California. It relates to the acceleration of a plasma (electrically charged particles) along an elongated acceleration path. The objective of this apparatus was to provide for the acceleration of a high conductivity plasma by establishing a static, magnetic field in the plasma and subsequently accelerating the plasma by a traveling magnetic wave.

U.S. Patent No. 3,441,798, patented April 29, 1969 by Didier Veron is entitled, "Plasma Gun Utilizing Successive Arcs for Generating and Accelerating the Plasma."[9] This patent relates to a new process for the production and acceleration of a puff of plasma and to a gun that has been used in CTR research and for the propulsion of plasma. Basically, a plasma gun of the coaxial type is described. But this coaxial gun has another (a third) coaxial cylindrical electrode that is used to preionize the gas. A process with successive arcs is described. It is stated that "Laplace" (sic) forces eject the plasma.

U.S. Patent No. 4,010,396, patented March 1, 1977 by Thomas I. Ress and George V. Nolde is entitled, "Direct Acting Plasma Accelerator."[10] This patent is assigned to Kreidt Chemico Physical K. G., Schaan, Liechtenstein. It relates to a particle accelerator in which ions and electrons (plasma) are driven along a predetermined path and accelerated. (The purpose of the high velocity particles is to induce chemical or nuclear reactions.) A traveling magnetic field is used to accelerate the plasma.

A U.S. Patent No. 3,431,816, patented March 11, 1969 by John R. Dale is entitled, "Mobile Gas-Operated Electrically - Actuated Projectile Firing System."[11] Projectiles are propelled through the bore of the gun barrel and into free-flight by "electro-thermionic energy" (sic). An electrical energy discharge through a light gas load in the chamber behind the projectile provides an explosive force to move and accelerate the projectile. A second electrical energy discharge travels through the bore with the expanding gas and provides additional force to overcome system losses and enhance projectile acceleration. A mobile, small arms weapon system is mentioned with a power level of 100 kW and an energy level of 1 megajoule.

U.S. Patent No. 3,459,101, patented August 5, 1969 by John J. Scanlon, Jr. and Joseph B. Quinlan is entitled, "High Velocity Weapon."[12] This patent is assigned to the United States of America, Secretary of the Army. The objective of this invention is to provide means for increasing the velocity of a projectile as much as 15% by using secondary charges (explosives) along the path of the gun barrel.

A.3 Concluding Remarks

In the U.S. Patents referenced, one finds descriptions of EM accelerators, plasma propulsion devices, and electric guns. There are claims for new switching methods, power supplies, and guns with distributed energy stores. However, a multi-stage magnetic railgun *per se* is not described in the patents searched. Also, side track railgun arc staging and laser initiated plasma arcs in railguns were not reported in the patent literature.

References for Appendix A

1. A. L. O. Fauchon - Villeplee, "Electric Gun or Apparatus for Propelling Projectiles," U.S. Patent No. 1,370,200 patented March 1, 1921.

2. A. L. O. Fauchon - Villeplee, "Electric Apparatus for Propelling Projectiles," U.S. Patent No. 1,421,435 patented July 4, 1922.

3. A. L. O. Fauchon - Villeplee, "Electric Apparatus for Propelling Projectiles," U.S. Patent No. 1,422,427 patented July 11, 1922.

4. Yusuf A. Yoler, "Method and Means fcr Propagating a Mass," U.S. Patent No. 2,783,684 patented March 5, 1957.

5. Yusuf A. Yoler and James D. Cobine, "Mass Accelerator," U.S. Patent No. 2,790,354 patented April 30, 1957.

6. Frank T. Hubbard and Gaston Demers, "Switch for Projectile - Accelerating System," U.S. Patent No. 3,613,499 patented October 19, 1971.

7. Theordore L. Rosebrock, "Magnetoplasmadynamics," U.S. Patent No. 3,279,320 patented October 18, 1966.

8. Duane C. Gates and John F. Detko, "Apparatus for Accelerating Plasma by a Static Magnetic Field and a Traveling Wave," U.S. Patent No. 3,417,273 patented December 17, 1968.

9. Didier Veron, "Plasma Gun Utilizing Successive Arcs for Generating and Accelerating the Plasma," U.S. Patert No. 3,441,798 patented April 29, 1969.

10. Thomas I. Ress and George V. Nolde, "Direct Acting Plasma Accelerator," U.S. Patent No. 4,010,396 patented March 1, 1977.

11. John R. Dale, "Mobile Gas-Operated Electrically-Actuated Projectile Firing System," U.S.Patent No. 3,431,816 patented March 11, 1969.

12. John J. Scanlon, Jr. and Joseph B. Quinlan, "High Velocity Weapon," U.S. Patent No. 3,459,101 patented August 5, 1969.

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