# DEVELOPMENT OF HYPERVELOCITY ELECTROMAGNETIC LAUNCHERS

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## ABSTRACT

Interest has increased substantially during recent years in the application of electromagnetic launch (EML) technology for a variety of purposes. In part this increased interest is due to the recent availability of compact pulsed power supplies suitable for driving such launchers. Also, several successful EML experiments have provided encouraging results.

The history of electromagnetic launch is reviewed, the current status of the railgun is presented, and plans for the next generation of electromagnetic launchers are discussed.

## INTRODUCTION

The prospect of using electromagnetic rather than thermodynamic forces to accelerate projectiles has excited the imagination of scientists and engineers throughout the twentieth century. Of course the single stage induction accelerator capable of launching a copper or aluminum ring into the air was a popular demonstration in the physics laboratory before the turn of the century (Fig. 1). In 1882 C. A. Cheever was issued a patent for an "electromagnetic dispatch tube"[1] and in 1902 the Norwegian scientist Birkeland was issued several patents on an electromagnetic cannon.[2] Written by Arthur B. Reeve in 1915, the science fiction novel The War Terror gives a technically accurate description of an electromagnetic accelerator.[3]

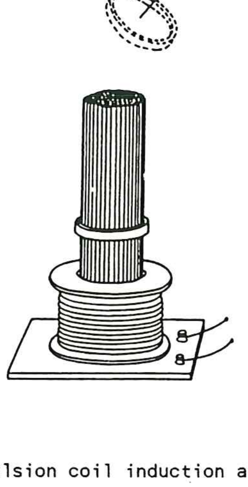

Fig. 1. Repulsion coil induction accelerator.

World War I stimulated a strong interest in the improvement of guns in general and in particular the first serious investigations of electrically-driven guns. In the period between 1917 and 1922 the Frenchman A. L. O. Fauchon-Villeplee was issued several U.S. patents on "electric gun apparatus for propelling projectiles"[4] (Fig. 2) and wrote a book on electromagnetic guns.[5] A magazine article published in 1921 indicates that during the war, Fauchon-Villeplee successfully accelerated a 50-g projectile to 200 m/s with his electric gun.[6] By 1918, Birkeland also had built an electromagnetic cannon (Fig. 3)[7] and in 1921 F. B. MacLaren was issued a quite detailed patent on an electric gun[8] (Fig. 4). Early efforts to demonstrate the electromagnetic acceleration of projectiles were limited by the availability of suitable sources of electric power. As electric power became more commonly available and its application better understood, experiments with electric guns became more common also; but the limited availability of suitable power sources has plagued the development of electromagnetic projectile accelerators to the present day.

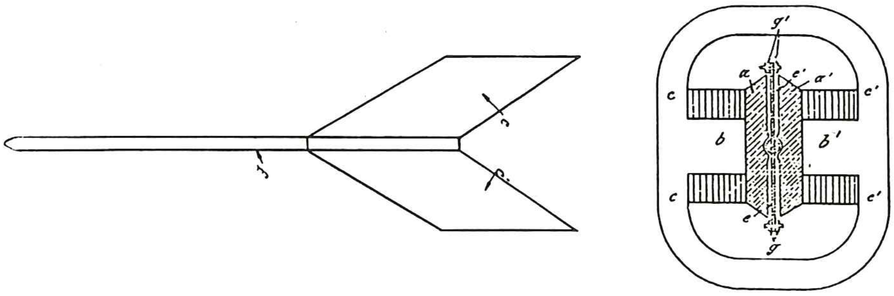

Fig. 2. Fauchon-Villeplee's electric cannon for launching finned projectiles.

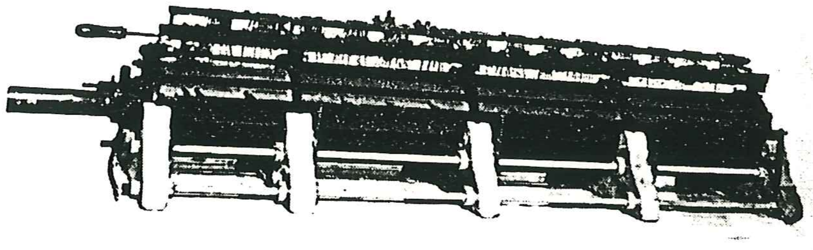

Fig. 3. Birkeland's cannon (1918), the earliest example of a tubular motor.

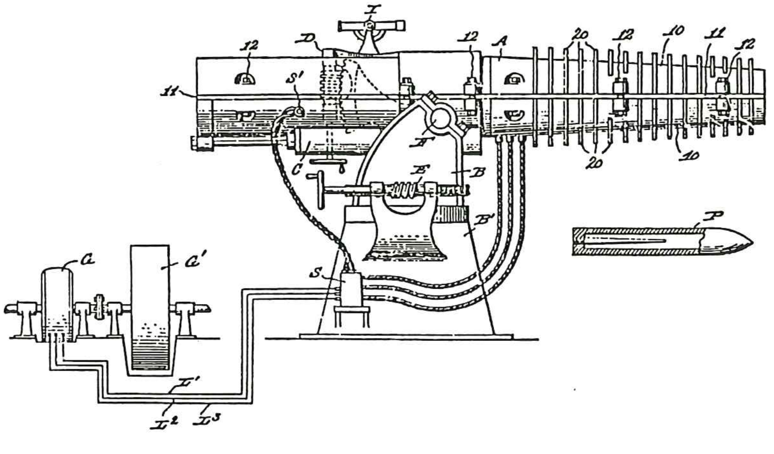

Fig. 4. MacLaren's electric gun.

The Russians reportedly built an electric cannon called "Ivan the Terrible" around 1929 although little is known of the device. In the early 1930's the Yugoslavian War Ministry reportedly repeated Fauchon-Villeplee's experiments. In 1934 engineers at The University of Texas at Austin (UT) demonstrated "a new type of machine gun, operated entirely by electromagnetic power and without the aid of gun powder."[9] In 1937 Professor Edwin Fitch Northrup of Princeton University published Zero to Eighty in which he described a series of electromagnetic gun experiments actually performed in his laboratory and then extrapolated this experience to an earth-to-moon launcher in the form of a fictional autobiography of an individual performing the work.[10] The book is illustrated with photos of electromagnetic guns built and tested by Northrup (Fig's. 5a and b) and includes a technical supplement which presents the scientific principles and calculations upon which both the actual experiments and extrapolations were based.

As did World War I, World War II again served as the catalyst for more ambitious electromagnetic gun experiments. The Japanese considered a linear induction motor for launching finned, 10 kg anti-aircraft projectiles at a velocity of 2 km/s. A model was built to accelerate a 2-kg projectile to a velocity of 500 m/s but only attained 335 m/s (Fig. 6).[11] As a result, the full scale launcher project was abandoned, but the model continued to be used for testing projectiles. The most intense effort during the war was that of Dr. Joachim Hansler in Berlin under contract to the German Air Force.[12,13] Although the project goal of developing an electric gun to accelerate a 40 mm, 6.5-kg projectile to a muzzle velocity of 2,000 m/s was not achieved, Hansler did electromagnetically accelerate 10-g projectiles to velocities up to 1,200 m/s. The work proceeded from 1943 until it was interrupted by the end of the war. Hansler's papers indicate that he anticipated most of the developments responsible for the recently renewed interest in electromagnetic guns.

In 1957 General Electric published the results of their study of electromagnetic accelerators concluding that there was no fundamental limitation preventing the attainment of velocities of 7.6 km/s by either the ac or dc accelerators that they had analyzed.[14] They further observed "however, practical limitations must be solved to increase the conversion efficiencies." The 1960s and early 1970s saw a flurry of interest in electromagnetic accelerators both as potential hypervelocity weapons and as a means of investigating hypervelocity impact of meteorites.[15,16,17] Most of these studies were primarily analytical in nature until the landmark experiments performed under the direction of Dr. R. A. Marshall at the Australian National University (ANU) during the mid-1970s.[18] Marshall and his colleagues succeeded in accelerating a 3 g plastic projectile to a velocity of 5.9 km/s in an electromagnetic railgun 4-m long.

The principle of the railgun accelerator is shown simply in Fig. 7. Basically, the current flowing in the rails produces a magnetic flux density between the rails and this magnetic field interacts with the current J flowing in the armature which, for the ANU railgun, was an arc. The resulting J x B or Lorentz force accelerates the armature together with the projectile along the rails. The magnitude of this driving force is given by $\frac{1}{2}L'I^2$, where L' is the inductance per unit length of the parallel rails and I is the current. A typical value for L' is $0.4 \times 10^{-6}$ H/m, so that the driving force for a typical railgun may be expressed as $2 \times 10^{-7}$ N/A$^2$. For currents in the kA range, the forces produced in a railgun are uninteresting, but as current levels approach a megamp, extremely large forces result. Thus, only with the advent of pulsed megamp power supplies has this type of electromagnetic gun become of interest for practical applications.

In the ANU railgun circuit (Fig. 8) the homopolar generator, having been brought up to speed by an external power source, is the source of the total electrical energy required by the circuit as well as the high electrical current required. However, the output voltage of the homopolar generator is not high enough to produce the necessarily rapid rise of current in the railgun armature, nor can it drive the requisite current against the rising back electromotive force (speed voltage) of the armature. This then is the function of the storage inductor in the circuit. Once charged to the required current, it produces the voltage necessary to maintain that current in the dynamically changing railgun discharge circuit. The switching armature is large and heavy by comparison with the railgun armature so that it can carry the inductor charging current without overheating. It also serves to rapidly introduce the railgun into the circuit so there is no heating and/or creeping of the railgun armature until peak current is reached in the circuit, and therefore maximum acceleration can be achieved.

The important technical contributions of the ANU railgun are the use of a homopolar generator to provide the required high energy and current (originally proposed by Hansler to the Germans during WW II), the use of a storage inductor rather than the capacitors used in earlier experiments to provide the voltage necessary to maintain the driving current against the rising back electromotive force or speed voltage of the railgun and, perhaps most important, demonstrating that the sliding metallic armature of earlier railgun experiments could be replaced with a metal-vapor arc allowing much higher velocities to be reached.

Early railgun experiments, including the first experiments at ANU, used a sliding metal armature to carry the current between the rails of the accelerator. The armature was typically designed so

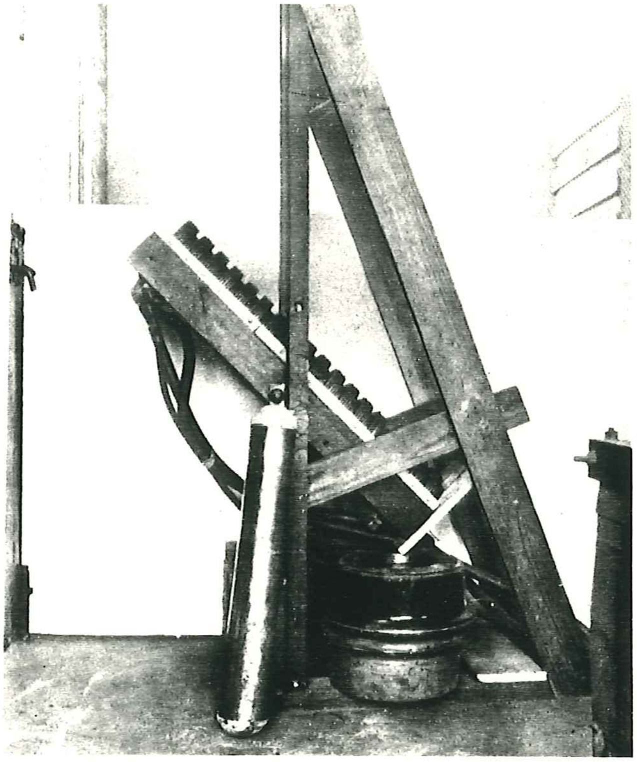

Fig. 5a. Northrup's electric gun.

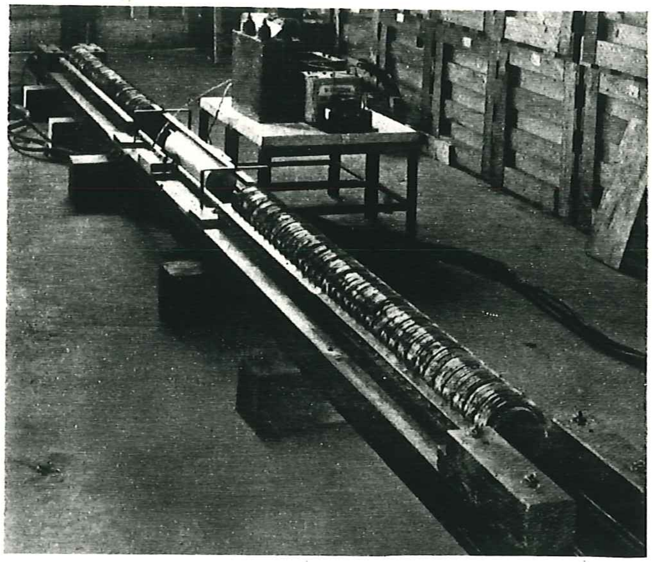

Fig. 5b. Horizontal gun coils in Northrup's laboratory.

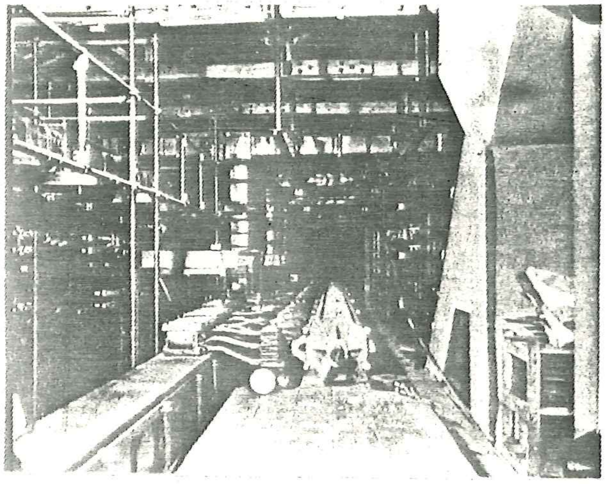

Fig. 6. Japanese linear induction accelerator.

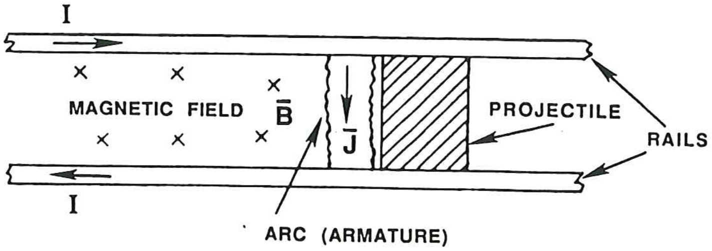

Fig. 7. Principle of the railgun.

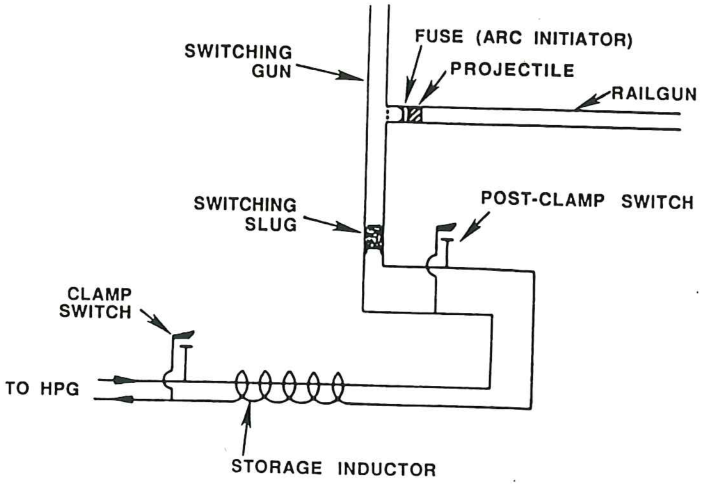

Fig. 8. Schematic circuit of the ANU railgun.

that the magnetic field produced by the current passing through it forced the armature into contact with the rails. Marshall and others found that at sliding velocities around 1 km/s a phenomenon known as "gouging" occurred wherein the rail and armature material apparently welded together -- resulting in substantial amounts of material being pulled off of the rails, degrading the rail surface, and effectively limiting the velocities attainable.

Marshall, et al., began experimenting with thin metal fuses which were vaporized by the rapidly rising current as the railgun was switched into the circuit and formed a metal-vapor arc with relatively low voltage drop (about 160 V in the ANU gun). This technique successfully drove nonmetallic projectiles (typically polycarbonate plastic) to much higher velocities than had previously been achieved.

In the late 1970s and early 1980s, reports of the ANU experiments inspired several small scale railgun experiments in the U.S. With one exception, these experiments were powered by capacitor banks, but all used the storage inductor, parallel rail geometry, polycarbonate projectiles, and fuse initiated arc armatures pioneered so successfully at ANU. Capacitor-driven railguns were built and operated at Westinghouse Electric Corporation, Vought Corporation, The University of Texas at Austin, and Lawrence Livermore National Laboratory (LLNL). The Vought railgun, designed at UT and using an existing capacitor bank originally built for shock-tube research, accelerated a 6 g polycarbonate projectile to 8 km/s in a 4 m long railgun in 1981 (Fig. 9). This represented a mass/speed record for capacitor-driven railguns at that time.

In 1980, a unique team was formed with a cooperative effort between LLNL and Los Alamos National Laboratory (LANL). The LLNL/LANL team combined an LLNL group interested in railgun development with an LANL group having the expertise to design and build explosive flux compression generators or magnetocumulative generators (MCG) capable of delivering megampere currents at reasonably high voltages. Although it is not attractive for many applications because of the explosive driver and because the MCG and often the rear portion of the railgun are destroyed with each shot, the MCG-driven railgun did allow the LLNL/LANL team to explore a very high-performance regime for railguns early in the program before more conventional power supplies were available. In 1980, the LLNL/LANL experiments succeeded in accelerating 3 g polycarbonate projectiles to velocities in excess of 10 km/s.[19]

In 1980-82, a system quite similar in concept to the ANU railgun, but operating at much higher currents and accelerating heavier projectiles, was built by Westinghouse Electric Corporation under joint sponsorship and direction of the Defense Advanced Research Projects Agency (DARPA) and the U.S. Army Armament Research, Development, and Engineering Center (U.S. Army ARDEC). This laboratory demonstration electromagnetic launcher, called EMACK, is now located at the Picatinny Arsenal near Dover, NJ (Fig. 10). The EMACK railgun is reported to have accelerated a 317-g projectile to 4.2 km/s at a peak current of 2.1 MA early in 1982.[20]

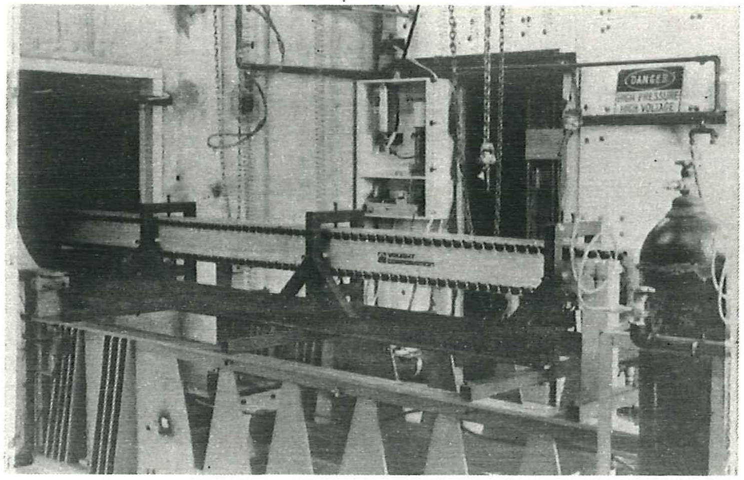

Fig. 9. Vought railgun.

The technical achievements of the electromagnetic gun program during the past eight years are documented in the proceedings of the three symposia.[21,22,23] At the present time, several railguns around the country are routinely operating in the 3- to 5-km/s range with projectile masses of a few grams to a few hundred grams. Research on these guns at present generally centers around rail and insulator material investigations, projectile/armature design, and plasma armature studies although some are occasionally used for impact studies. Of more interest for hypervelocity impact studies are the next generation of electromagnetic guns now being designed and built.

The DoE sponsored SUVAC gun at Westinghouse Research and Development Labs has accelerated 1 g to around 8 km/s in a 3.2-m barrel and is being expanded with the goal of reaching 20 to 30 km/s. The SUVAC power supply is a 6-MJ capacitor bank. The GEDI facility under construction at UT, supported by SDIO, DARPA, and U.S. ARDEC, has a goal of accelerating a 1-g projectile to 50 km/s, (Fig. 11). The power supply for GEDI is a system of six, 10-MJ homopolar generators, each charging an individual inductive store to an energy of 4.6 MJ at a current of 1.2 MA. The inductive stores will then be sequentially switched into the railgun, using explosively driven opening switches, to provide an essentially constant driving current during the launch. Average projectile acceleration levels of 2 x $10^6$ gees or more are anticipated. The power supply and range should be completed by the end of 1986 with the first experiments in the early part of 1987.

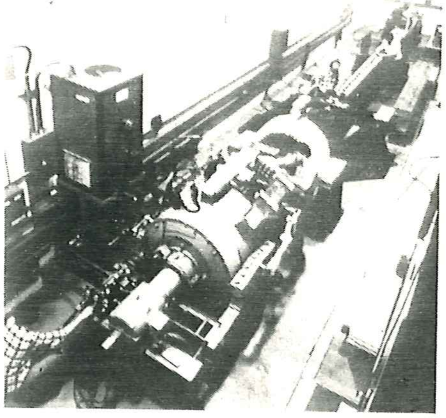

Fig. 10. EMACK railgun.

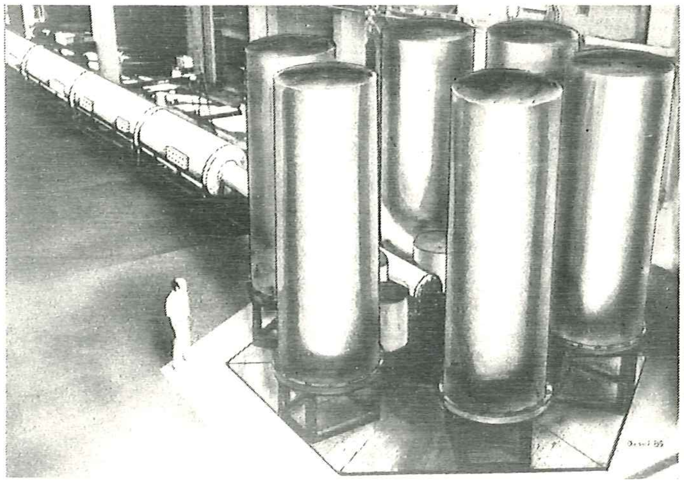

Fig. 11. GEDI facility at The University of Texas at Austin

This same 60-MJ power supply will be used to power a single shot laboratory gun capable of providing 9 MJ of kinetic energy to projectiles in the 2.5 to 4.0 km/s range, (Fig. 12). This facility which is scheduled to become operational in August, 1987 is being built under the sponsorship of the DARPA/Army/USMC Armor/Antiarmor Program. A capacitor powered facility with similar goals is to be constructed at Maxwell Laboratories. Both systems will be used for development and testing of antiarmor projectiles.

The Lethality Test System under construction at LANL has the goal of accelerating 20-to 30-g projectiles to velocities upto 15 km/s, (Fig. 13). This railgun will be powered through pulse transformers by 28 commutated dc machines with external flywheels. The total energy stored inertially is 95 MJ. A similar facility called <u>Thunderbolt</u> is under construction by Westinghouse. Both facilities are supported by SDIO, DNA, and SDC.

Electromagnetic gun technology has developed to a point that railguns now offer repeatable hypervelocity performance. The next generation of electromagnetic guns, now under construction, promises to extend the capabilities for hypervelocity impact research into regions not previously available.

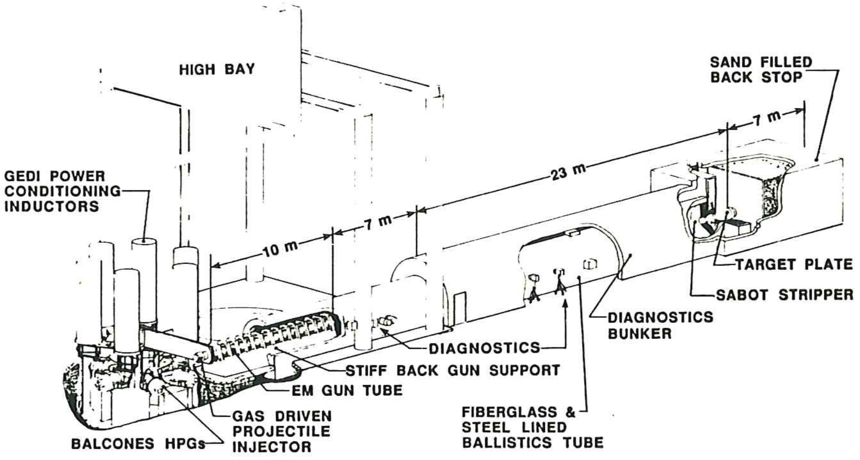

Fig. 12. The University of Texas at Austin single shot laboratory gun.

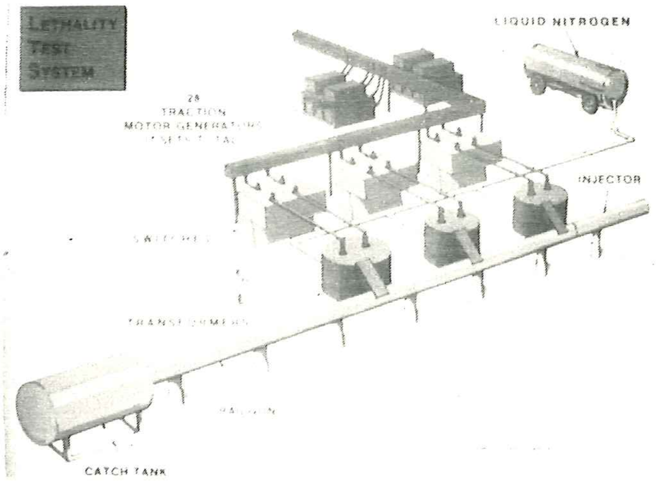

Fig. 13. Los Alamos National Laboratory Lethality Test System.

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