Chapter 1 — Milestones in Cannon Launch to Space

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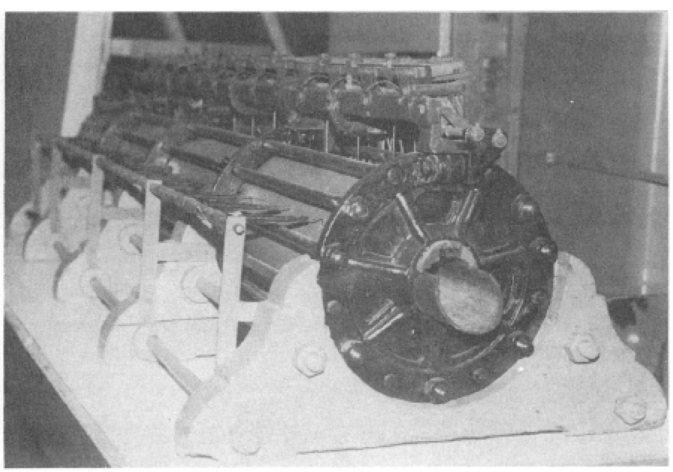
The first recorded mention of cannon launch to space is in the novel *From the Earth to the Moon*, written by Jules Verne in 1865. Research on the subject has an equally long history, and includes both explosively and electrically powered cannons. However, throughout this history, none of the concepts have been studied to an extent that could be considered exhaustive, compared to, for example, the amount of research and development that led to successful commercial aircraft. Because of contemporary improvements in materials and electronics, promising ideas from the past can be further advanced through experiments performed on a modest budget.

1901 Birkeland gun

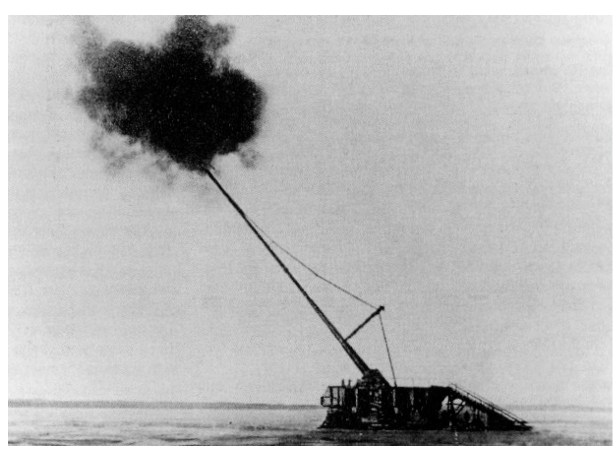


The first large effort to develop EM launch was undertaken by Kristian Birkeland. Birkeland's background was in electromagnetic waves, especially their role in energy transfer. He performed pioneering research on the aurora borealis, Saturn's rings, cosmology, and comets. Birkeland also conducted research on hydroelectric power stations. It was during the course of one of these experiments that he observed pieces of iron being pulled through coils, turning the iron into a projectile. Within a year, Birkeland had obtained funding to build his first electromagnetic gun, the patent for which was filed September 16, 1901. In this gun, a magnetized iron projectile is pulled by a series of solenoids. As the projectile passes each solenoid, an attached wedge pushes apart contacts, opening the circuit of each solenoid in succession. A few months after the first patent application was filed, Birkeland filed a second application, for the use of a coil instead of solid iron as the projectile. In April 1902, Birkeland filed his last patent related to electromagnetic gun research. It contained several improvements, the most significant of which was the switching method. The inductances of the projectile and drive coils would be matched so that the back EMF due to the drive coil would equal the voltage applied to the projectile coil as the projectile passed; the switches would then open at zero current. This idea was rediscovered in 1993 by Ingram.

The highest speed achieved was 100 m/s, with a mass of 10 kg, fired from a 4 m cannon. Birkeland also appreciated the main obstacle to higher speeds, "the problem of finding an energy source that could deliver enough power within a fraction of a second." The experimental guns were powered by dynamos. A rotating wheel power supply, most likely a Faraday disc, appeared in the first patent application. This power supply would be important in electromagnetic launch research beginning in the 1970s.

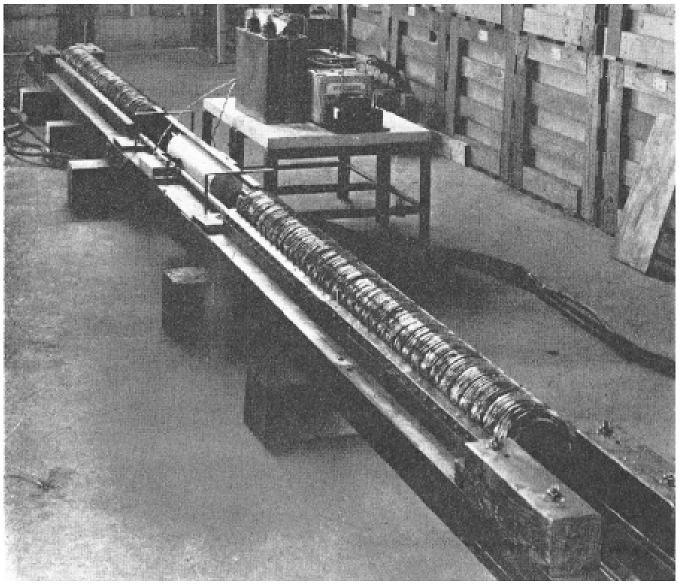
Birkeland's cannon design seemed poised for success. A well-funded public company, Birkeland Firearms, had been organized. In order to raise enough capital for other research, an electromagnetic gun demonstration was held in 1903. During this demonstration, before which Birkeland had promoted the gun as operating silently, a very high current short occurred, which was not at all silent, and the value of the company's stock decreased to zero.

1918 The Paris Kanonen



The so-called "Paris Guns" were built by the Krupp company during WWI for delivery of explosives to Paris from positions near the German front lines, a distance of about 130 km. The project was supervised by Fritz Rausenberger and Max Bauer, and was technically successful, although it had little strategic effect. The muzzle speed of the 106 kg shells was over 1500 m/s. All of the guns were destroyed at the end of the war to prevent capture.

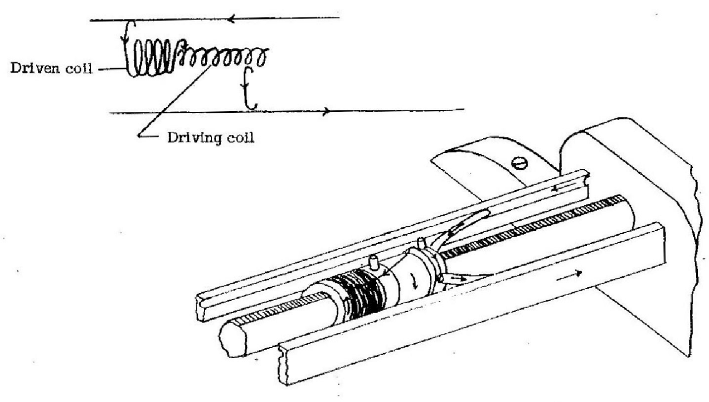
1936 Northrup coil gun



The next notable electromagnetic launch effort occurred during the 1930s, and was led by Edwin Northrup. Northrup was a professor at Princeton University, and founded a profitable induction furnace company. Unlike the Birkeland guns, which were intended for use by the military, Northrup advocated the use of EM launch for reaching orbit, as presented in his novel *Zero to Eighty*.

The Northrup design, several of which were constructed, used a three-phase AC power supply. The gun barrel was divided into sections, with each section consisting of six coils, connected so that each was 60 degrees out of phase with the next. The traveling wave of the drive coils induced a current in the projectile coil. A scheme was also presented for using a sliding contact attached to the projectile to energize one section of drive coils at a time. The coils were wound from copper tubing so that cooling water could be provided. Speeds were not published.

1961 Thom and Norwood coil gun with sliding contacts



The traveling magnetic field in the Thom and Norwood accelerators was created by sliding contacts that moved with the projectile coil. They tried three configurations. In the first, four sliding contacts carried current from the power supply into the coils. One contact carried current from the supply rail into the driven coil. From the driven coil, another contact supplied the drive coil. A third contact picked up current from the drive coil, and a fourth contact carried current back to the return rail. In this way, only a section of the drive coil that moves with the driven coil is energized.

The second and third configurations used two sliding contacts, one to pick up current from the supply rail, and one to make a connection between the driven coil and the drive coil. The current returned to the supply through the drive coil. The length of the energized section of the drive coil therefore changes during the shot. In configuration two, the winding sense of the coils is such that the driven coil is pushed ahead of the energized drive coil. The energized section lengthens behind the driven coil. The third configuration is similar, but the driven coil is pulled, and the energized length decreases. These methods of brush commutation were investigated by Kolm et al. at the Bitter magnet lab at MIT in the 1980s and are now being studied at the U.S. Naval Research Laboratory. The sliding-coil accelerators were powered by a 2000 V, 5000 J capacitor bank. A capacitor bank of this size costs only about a thousand dollars today.

Thom and Norwood also derived a minimum mass for accelerators in which the projectile is a conductor in a magnetic field that is generated by another part of the circuit. The projectile is heated by ohmic losses. For a given speed, there is a minimum mass projectile that can absorb the losses without melting. Winterberg, in 1966, sought to circumvent this limit by using a superconducting solenoid with a persistent current as the projectile.

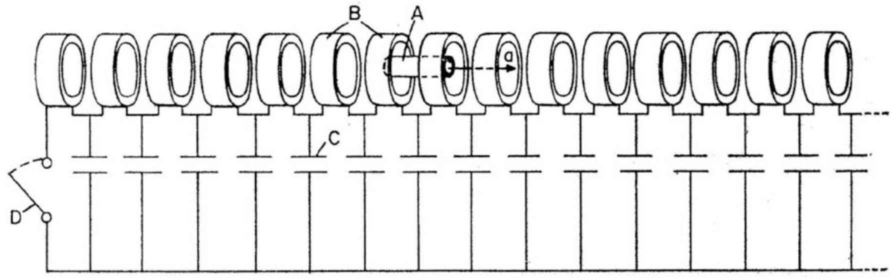
1960s High Altitude Research Program (HARP)

The High Altitude Research Program (HARP) was funded by McGill University, under the direction of Gerald Bull, and the U.S. Army Ballistic Research Laboratory, under the direction of Charles Murphy. The goal of the program was to develop a low-cost method of conducting atmospheric and space research.

HARP produced cannon launch altitude records that have yet to be broken. The highest apogee, achieved not just once, but 15 times during a four-day period in 1966, was 180 km. The mass of the rocket-shaped projectiles launched to this altitude was 100 kg, and the muzzle speed was 2100 m/s. This altitude is well above the conventional definition of the threshold of space, 100 km, and in fact above the altitude that is necessary for a satellite to orbit without excessive atmospheric drag, 150 km.

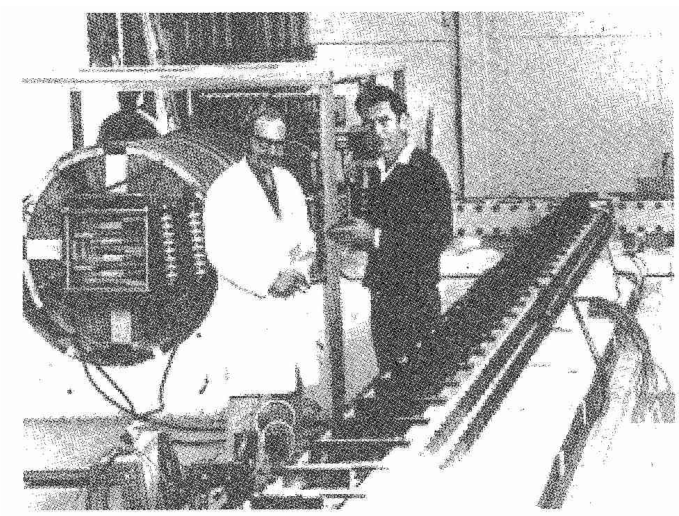
The barrels of the HARP cannons had smooth bores, so fin stabilization was necessary, and sabots were used to transmit the pressure of the combustion gases to the projectiles. Later projectile designs included fins that popped out of the projectile body after launch. Guidance and sensor electronics were developed that withstood the large initial accelerations.

1966 Winterberg transmission line coil gun



The driving coils in the Winterberg design are powered by capacitors, one capacitor per drive coil. For properly selected component values, the capacitors and coils act as a transmission line. Synchronization of the projectile with barrel is not necessary; other than the single initial switch, operation is passive. Unfortunately, no device based on this idea has been built. However, the term "collapsing field," which was to reappear at the University of Texas in 1993, was used by Winterberg.

1972 Marshall rail gun



The great interest in electromagnetic launch for military applications began in Canberra, Australia, in the early 1970s. Richard Marshall and others, including John Barber, attached a homopolar generator to a rail gun. Rail guns consist of two conducting rails with a sliding conductor between them. When current is applied to the rails, the magnetic field generated by the rails interacts with the current flowing through the sliding conductor, producing acceleration.

The Canberra generator, which was surplus from high-energy physics research, was two stories tall and stored 500 MJ. The system accelerated 3 g polycarbonate cubes to 6 km/s in 5 m. The current between the rails was carried by a metal vapor arc behind the polycarbonate cube.

The impressive speed generated by the Canberra group led to investigations by other groups. Although work continues on rail guns, and has increased projectile masses to the order of kilograms, rail guns have several disadvantages compared to other types of launchers. The plasma armature causes damage to the rails, which shortens their life. This problem can be overcome. However, a more serious drawback is the railgun's inherent inefficiency. Railguns operate at very high currents and relatively low voltages, so resistive losses are high. A large magnetic field is also left stored in the barrel at the end of acceleration. These problems can be mitigated by staging the gun, but doing this makes a railgun as complicated as a coil gun, negating out its main advantage, simplicity.

1970s Mass drivers

Gerard O'Neill gained a large amount of publicity for EM launch as part of his space colonization proposal during the 1970s. O'Neill rebuilt the synchrotron at Cornell University during work on his Ph.D., and his experience was directly applicable to EM launcher construction. The first of O'Neill's accelerators was constructed using surplus particle accelerator magnets. This accelerator was referred to as a mass driver.

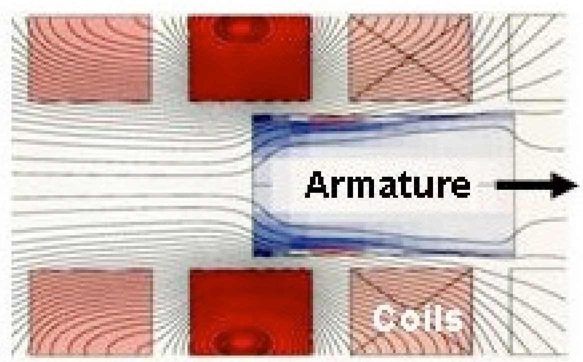
O'Neill was also involved in the construction of two more mass drivers. The mass drivers used superconducting driven coils. The goal of the research was achieving high accelerations, as opposed to high speeds, so only short test sections were built.

1990s Quench guns and collapsing field accelerators

Mongeau and Kolm proposed storing energy in the barrel of a superconducting accelerator in 1991. They referred to the accelerator as a quench gun, and planned to use a magnetic attachment leading the projectile to induce a quench. Although the accelerator was never constructed, this is the first appearance of the idea of combining long-term energy storage with the structure of the accelerator.

Independently, Samuel Ingram noted in a paper on a collapsing field accelerator using copper coils that, if the coils were superconducting, a very small power supply could be used to energize them before launch. Ingram also published the condition necessary for inductive commutation.

1990s Sandia coil guns



At Sandia National Labs, under the direction of Bill Cowan, several launchers were constructed. The first launchers had an unusual design that uses the main field of solenoidal coils rather than the fringing field. The projectile is a flat plate, which fits between two similarly-sensed drive coils. As the plate reaches the drive coils, current is switched on in them. Currents are induced in the plate that oppose the increase in magnetic field. The Lorentz force propels the plate. This can be visualized as magnetic lines of force being stretched behind the plate, and straightening as the plate passes. The launcher was therefore called the "reconnection gun".

The reconnection idea was later applied to more conventional coaxial geometries. In these launchers, the projectile is tubular, and fits inside solenoidal magnets. The best performing guns were one flat-plate type, which achieved a speed of 1 km/s with a 150 g projectile, and two cylindrical guns, which both achieved speeds of 335 m/s (Mach 1), one with a 10 g projectile, and the other with a 5 kg projectile. A similar device, reaching a speed of 100 m/s with a 1 kg projectile, has been constructed by a group in Chengdu, China.

1990s Light gas guns

John Hunter, while reviewing possible improvements in EM launch technology for study at Los Alamos National Laboratory, noticed that a light gas gun developed by NASA in the 1960s had outperformed all more recently constructed railguns. This NASA design had accelerated projectiles to speeds up to 11 km/s. In the two stage light gas gun, a combustible gas (such as methane) first drives a piston in a cylinder that compresses a light gas (such as hydrogen). At a certain pressure, a valve ruptures to let the now very high pressure hydrogen into the second stage, smaller diameter barrel of the gun, accelerating the projectile.

Guns constructed by Hunter's group included a 3 meter version that reached 8 km/s, and a 130 m gun that accelerated a 5 kg projectile to 3 km/s. This project was referred to as the Super High Altitude Research Project (SHARP), and an unsuccessful commercial spin-off was called the Jules Verne Launcher Company.

2000 NASA Maglev tracks

A project at Lawrence Livermore uses a special array of permanent magnets, called a Halbach array, to provide levitation for a projectile that can be accelerated by a linear electric motor. In a Halbach array, magnets are tiled with orientations such that their magnetic fields reinforce to create a sinusoidally varying field on one side, and cancel on the other. As the array travels above a conductor, the sinusoidal field induces currents in the conductor, resulting in a repulsive force. The force is large enough that permanent magnets can be used for magnetically levitated trains or rocket assist. Because the force is dynamic, the system can be stable without feedback.

A demonstration track has been constructed that uses capacitors (and, according to the LLNL web site, a bungie cord) to reach 10 m/s. The power source in a full-scale version would probably be existing power lines. Marshall Space Flight Center had two test tracks, one of them using the Halbach technology from LLNL. The first track was built by PRT Advanced Maglev Systems (Park Forest, IL). Originally developed at the University of Sussex, a linear induction motor provides both thrust and lift. A 14 kg mass can be accelerated to 25 m/s. The second track was constructed by Foster-Miller Inc. (Wortham, MA). It is 14 m long, with 7 m of acceleration and 7 m of passive braking. Acceleration is provided by a linear synchronous motor, while levitation is by means of a Halbach array. A sled and payload with a combined mass of 5 kg reaches 25 m/s. According to press releases, there were plans to build larger test tracks at Kennedy Space Center, but these appear to have been cancelled.

References

W. Ying, R. Marshall, and C. Shukang, *Physics of Electric Launch*, Science Press, Beijing, China, 2004.

R. Marshall and W. Ying, *Railguns: Their Science and Technology,* China Machine Press, Beijing, China, 2004.

G.V. Bull and C.H. Murphy, *Paris Kanonen — the Paris Guns (Wilhelmgeschütze) and Project HARP*, Verlag E.S. Mittler & Sohn, Herford, Germany,1988.

I.R. McNab, "Early Electric Gun Research," *IEEE Trans. Mag.*, vol. 35, no. 1, pp. 250–261, 1999.

A. Egeland, "Birkeland's Electromagnetic Gun: A Historical Review," *IEEE Trans. Plasma Sci.*, vol. 17, no. 2, pp. 73–82, 1989.

E.F. Northrup, *Zero to Eighty*, Princeton, N.J: Scientific Publishing Co., 1937.

K. Thom and J. Norwood, "Theory of an Electromagnetic Mass Accelerator for Achieving Hypervelocities," *NASA Tech. Note* D-886, 1961.

F. Winterberg, "Magnetic Acceleration of a superconducting solenoid to hypervelocities," *Plasma Physics*, vol. 8, pp. 541–553, 1966.

H. Kolm and P. Mongeau, "An alternative launching medium," *IEEE Spectrum*, vol. 19, no. 4, pp. 30–37, 1982.

H.D. Fair, "Electromagnetic Launch: A Review of the U.S. national Program," *IEEE Trans. Mag.*, vol. 33, no. 1, pp. 11–16, 1997.

M. Cowan, E.C. Cnarre, B.W. Duggin, R.J. Kaye, and T.J. Tucker, "The Reconnection Gun," *IEEE Trans. Mag.*, vol. Mag-22, no. 6, pp. 1429-1434, 1986.

M. Cowan, M.M. Widner, E.C. Cnare, B.W. Duggin, R.J. Kaye, and J.R. Freeman, "Exploratory Development of the Reconnection Launcher 1986–1990," *IEEE Trans. Mag.*, vol. 27, no. 1, pp. 563–567, 1991.

S.-S. Gao and C.-W. Sun, "The Test and Analysis of a 3-Stage Reconnection Coilgun," *IEEE Trans. Mag.*, vol. 35, no. 1, pp. 142–147, 1999.

P. Mongeau, "Inductively commutated coilguns," *IEEE Trans. Mag.*, vol. 27, no. 1, pp. 568–572, 1991.

S.K. Ingram, "Theoretical Analysis of a Collapsing Field Accelerator," *IEEE Trans. Mag.*, vol. 29, no. 1, pp. 675–679, 1993.

R.F. Post and D.D. Ryutov, "The Inductrack: A Simpler Approach to Magnetic Levitation," *IEEE Trans. Appl. Superconductivity*, vol. 10, no.1, pp. 901–904, 2000.

R.F. Post, "Maglev: A New Approach," *Scientific American*, vol. 282, pp. 82–87, 2000.

K. Halbach, "Application of Permanent Magnets in Accelerators and Electron Storage Rings," *Journal of Applied Physics*, vol. 57, pp. 3605–3608, 1985.

M.R. Palmer, R.X. Lenard, "A Revolution in Access to Space Through Spinoffs of SDI Technology," *IEEE Trans. Mag.*, vol. 27, no. 1, pp. 11–20, 1991.

F. Kuznik, "Battle of the Big Shots," *Air and Space*, pp. 55–61, Aug./Sept. 1993.

J.A. Morgan and E.Y. Robinson, "A Long Shot for Satellite Launch," *Aerospace America*, vol. 36, no. 4, pp. 32–39, 1998.

R.A. Marshall, "Railgunnery: Where Have We Been? Where Are We Going?" *IEEE Trans. Mag.*, vol. 37, no. 1, pp. 440–444, 2001.