tion has only shown up in the K^0 meson, which has two states separated by 10^{-5} eV. Such a nearly degenerate system is expected to be sensitive to extremely weak effects. The B^0 meson is a similar system, and one might expect to see mixing between B^0 and $\bar{B}^0$, just as in K^0 and $\bar{K}^0$. By colliding-beam experiments in the vicinity of $\Upsilon(4S)$ one can manufacture pairs of B mesons and hope to find CP violation in this system, perhaps with a charge asymmetry.

Another object of intense interest is the putative electric dipole moment of the neutron. It is expected to be nonzero if time reversal is violated. Over the past three decades, Norman Ramsey and his collaborators, using cold neutrons, have set ever better limits on the electric dipole moment of the neutron. More recently V. M. Lobashov and his collaborators have done similar experiments.

The present limit on the neutron electric dipole moment is about 10^{-24} e·cm. The model due to Lee and Weinberg predicts the electric dipole moment to in fact be about 10^{-24} e·cm. Kobayashi and Maskawa predict a value of 10^{-30}–10^{-31}. Ramsey's next experiment, scheduled to operate at Grenoble next year, might be able to check the Lee and Weinberg prediction.

Cronin earned a BS from Southern Methodist University in 1951, and an MS in 1953 and PhD in 1955 from the University of Chicago. After three years at Brookhaven, he joined the Princeton physics department, rising to professor. In 1971 he went to the University of Chicago, where he is now University Professor of Physics. Fitch earned a BE at McGill University in 1948 and a PhD at Columbia University in 1954. In that year he went to Princeton, where he is now Cyrus Fogg Brackett Professor and chairman of the physics department. —GBL

Electromagnetic guns and launchers

While we accelerate elementary particles and ions by the most advanced electromagnetic means, our standard techniques for propelling macroscopic objects—from birdshot to interplanetary vehicles—are not very different from those in use since the introduction of gunpowder from China. But propulsion by chemical combustion suffers from severe limitations that are keenly felt by people interested in space travel, inertial-confinement fusion, and even such prosaic pursuits as artillery.

The Germans made an abortive attempt to use a "rail gun," a kind of linear dc motor, as an antiaircraft launcher during World War II. But for the next three decades very little was done about electromagnetic acceleration schemes for macroscopic projectiles. Now we are seeing a surge of interest and activity in this field, attested to by a DOD-sponsored conference on electromagnetic guns and launchers, held last month in San Diego.

Although such "guns" do have military applications, they are also of particular interest to solid-state physicists interested in the behavior of materials at extreme pressures, and to those thinking about initiating thermonuclear fusion with beams of "macroparticles." This latter was the subject of the DOE-sponsored Impact Fusion Workshop at Los Alamos last year.

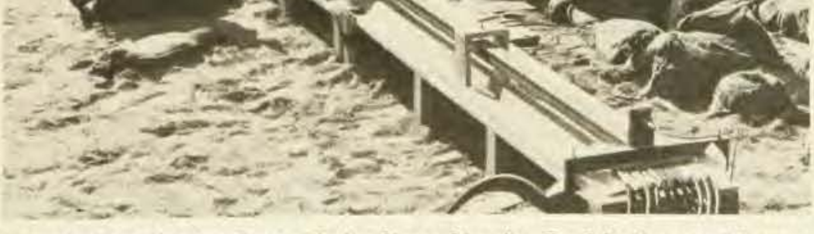
Using rail guns a few meters long, groups at the Australian National University (Canberra), Los Alamos (in collaboration with Livermore), and Westinghouse have in the past few years succeeded in accelerating projectiles weighing a few grams to speeds approaching 10 km/sec—the escape velocity from the Earth. Attaining such a speed in so short a distance involves a steady acceleration on the order of a million *g*.

A Princeton–MIT collaboration is currently building a "mass driver," a 2½-meter-long travelling-magnetic-wave accelerator, intended to accelerate a 1-kilogram vehicle to about 110 meters/sec (250 miles/hr). Although this device is thought of as a prototype launcher for interplanetary transport, the same ac linear-synchronous-motor scheme is being considered for the ignition of thermonuclear fusion—by accelerating small superconducting projectiles to speeds in excess of 100 km/sec.

Conventional artillery is limited by the chemical energy of the explosive (about 1 electron volt per atom) to muzzle velocities of one or two km/sec. One can't push the projectile in the gun barrel to speeds higher than those of the molecular combustion products. Rockets, though they are also driven by chemical combustion, do not suffer this velocity limitation, because the combustion takes place in the projectile itself. But one pays for this by having to carry aloft a great mass of propellant. The useful payload put into the Earth orbit turns out to be less than one percent of the launched weight, with a correspondingly horrific cost. Henry Kolm, head of the mass-driver group at MIT, looks forward to reducing the cost of putting payloads into Earth orbit to less than a dollar per pound—three orders of magnitude less than today's cost, and fifty times less than the early promises of the space-shuttle program.

The rail gun is conceptually the simplest electromagnetic launcher currently under consideration—and the one that has thus far achieved the highest velocities. It consists of two conducting rails mounted in a gun barrel. A pulsed dc current is sent down one rail and comes back along the other. In the original rail-gun design, the conducting bridge between the rails is a sliding metal conductor, analogous to the armature of a dc motor. The armature is propelled forward by the Lorentz force of the magnetic field generated by the current in the rails acting on the current in the armature. The propelling force is thus proportional to the square of the current. The problem is to achieve sufficiently high and steady currents—and to keep the armature from disintegrating.

Several important steps toward the solution of these problems were taken between 1968 and 1977 by Richard



Livermore–Los Alamos rail gun at the Los Alamos firing site. Two 8-foot-long parallel copper strips (foreground) constitute the magnetic-flux-compression generator. Sheet explosive driving the upper strip down generates a megawatt current pulse in the 6-foot-long small-bore rail gun (background). The ½-inch plastic cube is launched at speeds up to 5.5 km/sec.

Marshall and his colleagues at the Australian National University.[1] The Canberra group had access to the world's largest homopolar generator, a 500-megajoule dc storage generator built by Sir Mark Oliphant with parts cannibalized from a synchrocylotron that was never completed. The rotors of this generator are giant Faraday disks that act as flywheels to store energy accumulated from an external source over several minutes. When the rotor is up to speed, the generator can dump its stored energy in about a second—as a half-megampere dc current pulse. Marshall's student John Barber found that one could compress this output into a few milliseconds by interposing an inductive storage between the homopolar generator and the rail gun. It is important that the current remain roughly constant over the several milliseconds during which the armature is accelerated in the gun barrel—to maximize the final muzzle velocity and to prevent the device from blowing apart. Earlier attempts to energize rail guns by discharging capacitor banks had failed because the current was dumped too precipitously.

The original idea of using a sliding metal armature to complete the circuit between the rails and push a projectile turned out to have difficulties in practice. The mass of the accelerating armature limited the speeds that could be achieved, but if one tried to reduce the mass of accelerating metal, the armature would melt under the high currents to which it was subjected. The Canberra group demonstrated that one could dispense with the metal armature, replacing it by a plasma discharge arc between the rails. A nonconducting (plastic) projectile is pushed ahead of the plasma by the Lorentz force on the discharge current.

With a rail gun 5 meters long, the Canberra group was able in this way to accelerate half-inch Lexan cubes to speeds up to 6 km/sec in a square-bore rail gun. The gun barrel serves to keep the projectile from bursting under the acceleration stress of half a million *g*, and to keep the rails from flying apart despite the strong magnetic repulsion produced by the 300-kA current. Marshall is now at the University of Texas (Austin), working on rail guns with distributed energy storage. If one feeds the current into the rail gun only at the breech end, as was done with the Canberra homopolar generator, one suffers a lot of resistive energy loss in the rails. He is therefore building a system that will feed energy into the gun from capacitors and inductors arrayed all along the length of the barrel. The primary application he has in mind for such rail guns is inertial-confinement fusion.

Westinghouse and Los Alamos. Experimental rail guns are currently in operation at Westinghouse and Los Alamos. The small and large-bore guns at Los Alamos were built by a Livermore–Los Alamos collaboration headed by Max Fowler and Dennis Peterson (Los Alamos), and Ronald Hawke (Livermore). The current in these guns is generated by explosively driven magnetic-flux compression rather than by a homopolar generator. This flux-compression generator is an inductor consisting of two parallel conductors, one of which is lined with a sheet of explosive. After the inductor is energized from a capacitor bank, the explosive is detonated, propelling the one conductor toward the other, thus compressing the magnetic flux and inducing a longer and more powerful current pulse than one could get directly from the capacitor bank.

The small-bore Livermore–Los Alamos gun is 2 meters long and has a $\frac{1}{2}$-inch square bore. With a plasma-arc armature and a peak current of 800 kA, it has succeeded in launching a 3-gram plastic projectile at 5.5 km/sec. At a still higher current (1.2 MA), Hawke told us, the group believes it has recently achieved a projectile velocity of 10 km/sec. This would be the world's speed record for electromagnetic macroparticle accelerators. But Hawke points out that they were unable to verify this speed because the projectile disintegrated under the acceleration stress $(5\times10^6\ g)$ as it departed the muzzle. In order to have the projectile survive such a stress (15 times its elastic limit), he told us, they will have to arrange things so that acceleration ceases well before the projectile leaves the protective confines of the barrel. But the group was pleased to find that the plasma-arc armature continued to function well at four times the highest currents employed in the Canberra gun.

The Westinghouse group, led by Ian McNab, Dan Deiss and John Mole, has a 2-meter-long gun driven by a capacitor bank, with an intervening inductor to lengthen the discharge current pulse. With plasma-arc and metallic armatures they have accelerated half-inch plastic projectiles to 1 km/sec, and heavier metallic projectiles to a few hundred m/sec. The group is now building a 15-megajoule homopolar generator for a rail gun that is expected to accelerate 3/4-pound projectiles to 3 km/sec by next year. At such intermediate speeds McNab believes that metal armatures will prove to work better than plasma arcs. The rail-gun work at Los Alamos, Livermore and Westinghouse is funded by the DOD, which is interested in electromagnetic accelerators as an alternative to conventional launchers and guns in applications where high velocity is important.

The mass-driver was suggested in 1974 by Gerard O'Neill (PHYSICS TODAY, September 1974, page 32), as a device for launching raw materials from the Moon. Because the mass driver concept is quite similar to the Magneplane superconductively levitated train developed by Kolm and his collaborators at MIT (PHYSICS TODAY, July 1977, page 34), O'Neill and Kolm have undertaken a collaborative effort to build a prototype mass driver, a traveling-magnetic-wave dipole accelerator. A persistent superconducting current loop on the projectile is propelled by magnetic-dipole interaction with a closely spaced row of synchronously activated current loops on the launcher. Each accelerating loop is activated as the projectile approaches. The projectile thus rides a magnetic wave—much like a surfer, Kolm told us. A similar linear dipole accelerator had been suggested in 1929 by the rocket pioneer Hermann Oberth—with ferromagnets rather than superconducting coils.

In O'Neill's conception, payloads are launched from a train of reusable "buckets" (each with superconducting coils) that circulate through the system. Though the original idea was to launch cargoes of aluminum-rich soil from the airless Moon, Kolm's group has recently calculated, rather surprisingly, that one could launch a vehicle as light as a ton ("in the shape of a telephone pole") from the Earth with only a 3% ablation loss as it traverses the atmosphere in about a second.

Mass drivers for space launchers are envisioned as being several kilometers long. Three years ago, Kolm and his students built the first prototype—Mass Driver I. The 2-meter-long device accelerated a half-kilogram bucket to about 100 miles/hr. Mass Driver II, now being constructed by the Princeton–MIT collaboration, may eventually accelerate kilogram vehicles to about the speed of sound.[2]

Impact fusion. Fifteen years ago Friedwardt Winterberg (University of Nevada, Reno) suggested using a traveling-magnetic-wave accelerator to propel small superconducting projectiles to speeds high enough to ignite thermonuclear fusion in deuterium–tritium targets. The use of macroparticle accelerators for "impact fusion" has recently been looked at in some detail by a number of investigators. To deposit the requisite megajoule of impact energy in a one-cm^3 target volume in about 10 nanoseconds requires, it is generally agreed, impact velocities of between 150 and 200 km/sec—an order of magnitude faster than anything that will be achieved in the immediate future.

In a critical review of the various impact-fusion options,[3] based on the 1979 Impact Fusion Workshop, Fred Ribe (University of Washington) and

Alfred Peaslee (Los Alamos) conclude that segmented rail guns with distributed energy stores appear to offer the greatest promise. Richard Muller (Berkeley), Richard Garwin (IBM) and Burton Richter (SLAC) had proposed to the workshop a kilometer-long segmented rail gun firing 0.05-gm projectiles at 200 km/sec. Hawke presented a similar impact-fusion gun design at the Workshop.

Ribe and Peaslee believe that rail guns are well suited to deliver 10–100 MJ to a fusion target with a relatively simple and inexpensive technology. Unlike light-ion and electron beams, macroparticles are very easy to focus on a target pellet, and the accelerating apparatus is easily shielded from the thermonuclear explosions in a reactor. Hawke believes one may be able to ignite fusion targets with a pair of rail guns firing from opposite sides—each only 30 meters long.

Garwin, somewhat cynically, told us that the main virtue of impact fusion is that it will teach us faster and cheaper than any other technology that inertial-confinement fusion won't work—at least in an economic sense. The basic problem, he believes, is that all such schemes require the concentration of large amounts of energy into 10-nanosecond pulses. Winterberg is skeptical that rail guns can achieve velocities high enough to ignite conventional fusion targets, because friction-generated radiation losses increase as v^8. Magnetic-wave accelerators, with superconductively levitated projectiles, suffer no such friction losses, but they provide significantly less acceleration. He points out, however, that with magnetized target designs one might achieve ignition at impact velocities less than 50 km/sec. Magnetized targets have been suggested by Ribe and his Seattle colleague George Vlases, and independently by Shyke Goldstein and Derek Tidman of Jaycor (Alexandria, Va.). In such fusion targets, a 10-megagauss pulsed magnetic field would thermally insulate a plasma from the walls of its confining cavity. —BMS

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Sandia to use light ions for fusion

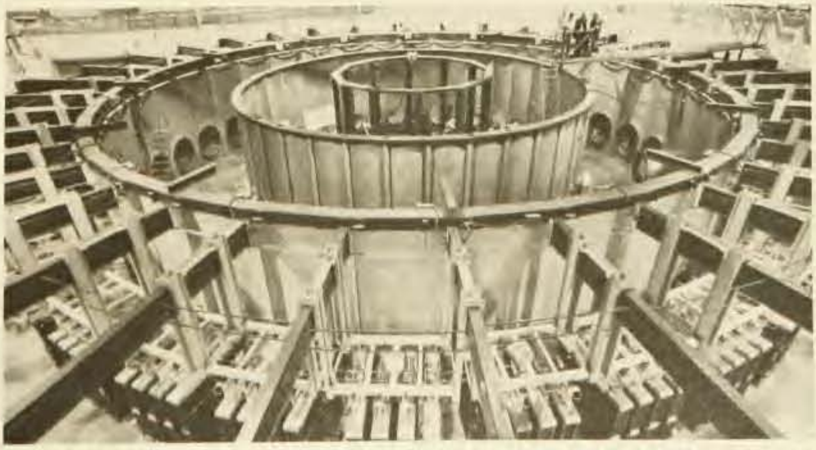
It would presumably take an order of magnitude less beam energy to run an inertial-confinement thermonuclear reactor with ion beams than with electron beams. But until last year the technological problems of producing and focusing a sufficiently intense light-ion beam have kept the emphasis of particle-beam fusion research on electron-beam devices. The largest particle-beam fusion machines, at Sandia in Albuquerque and at the Kurchatov Institute in Moscow (still under construction), were originally designed to implode deuterium–tritium pellets with beams of 2-MeV electrons.

But light-ion beam developments during the past few years at Sandia, Cornell and the Naval Research Lab (Washington, D.C.) have proven so encouraging that the large Electron Beam Fusion Accelerator under construction at Sandia was renamed Particle Beam Fusion Accelerator in July 1979, and modified to accelerate light ions instead of electrons. Its first 36-module phase, PBFA-I, began operation this past summer, and Congress has just authorized the second phase, PBFA-II, which, it is hoped, will produce net fusion-energy output by mid-decade, with 72 beams delivering a total of 100-terawatts to the target pellets.

Electron beams are easier to produce, but they are much less efficient than ions at delivering energy to the deuterium–tritium fuel in the pellets. The energy of the beam pulse is ideally deposited entirely in the shell of the pellet, whose consequent ablation and implosion drives the fuel to a pressure and temperature sufficient for thermonuclear ignition. This is more easily accomplished with ions, whose stopping range in material is much shorter than that of electrons at the same energy. To achieve the 1000 times liquid density needed for ignition, one wants to avoid heating the fuel before it is compressed by the imploding shell. But electrons, being much lighter than ions, do preheat the fuel by brehmsstrahlung and straggling through the shell. Furthermore, electrons waste energy by backscattering off the pellet. It is also more difficult to overlap multiple electron beams on a target, because electrons are more readily deflected than ions by the strong mutual magnetic and electrostatic forces in such an overlap.

Gerold Yonas, head of the Sandia project, told us that whereas one expects to achieve "scientific breakeven" (fusion energy output equal to beam energy input) with about 1 megajoule of light-ion beam energy, an electron machine would require about 10 MJ. A laser-fusion device would also require only about a megajoule, Yonas estimates. But he points out that laser machines cost hundreds of dollars per joule, while light-ion pulsed accelerators can be built for only $10 a joule.

The very ease with which electron beams are generated points up a major problem that arises when one wants to accelerate light ions. In the Sandia machine, the ions are accelerated to several MeV by much the same procedure originally designed for electron beams—except that all polarities are reversed. The single stage of acceleration takes place in a diode fed by 36 magnetically insulated high-voltage transmission lines, carrying pulses from a bank of capacitors and pulse-forming devices. (In later versions, each line will terminate in its own diode.) But as the ions generated at the anode pass through the cathode on their way to the target, an unwanted countercurrent of electrons tends to flow back across the accelerating gap from cathode to anode, robbing the ion



The PBFA-I light-ion fusion accelerator under construction last spring at Sandia. Thirty-six high-voltage transmission lines will converge on a central diode that directs a megajoule pulse of 2-MeV protons onto a deuterium–tritium target pellet. Energy is accumulated in the capacitor banks of the Marx generators (foreground) and then formed into 20-nanosecond pulses.