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

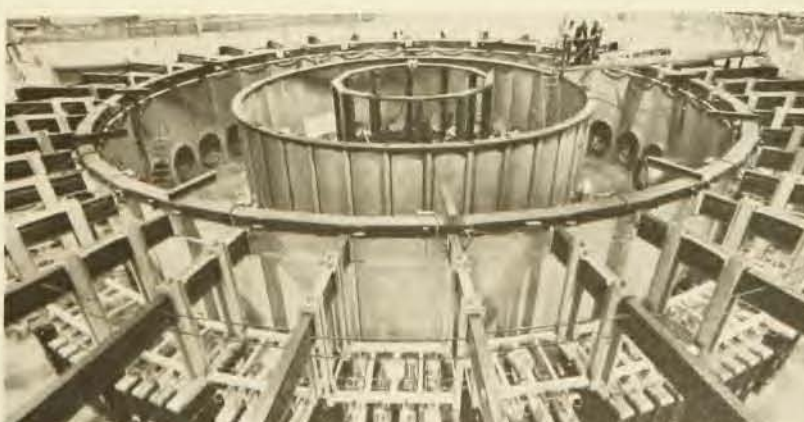
It would presumably take an order of magnitude less beam energy to run an inertial-confinement thermonuclear reactor with ion beams than with electron beams. But until last year the technological problems of producing and focusing a sufficiently intense light-ion beam have kept the emphasis of particle-beam 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.

beams of most of the input energy if it is not somehow curbed.

Since 1973 Ravi Sudan and his colleagues at Cornell have been experimenting with ion-accelerating diode designs that suppress this undesirable electron current by magnetically insulating the electrodes from one another.[1] Pulsed magnet coils in various configurations near the cathode divert the electrons away from the anode while permitting the more massive ions, drawn from dielectrics on the anode surface, to pass on toward the target. Such a magnetic insulation scheme had originally been proposed by Friedwardt Winterberg (University of Nevada, Reno) in 1969. Constructing a series of magnetically insulated diodes of this kind, David Johnson at Sandia has succeeded in delivering 80% of the diode's input power to the ion beam. The achievement of a proton beam focused down to a power density of 1 TW/cm$^2$ last year[2] with one of these diodes mounted in Sandia's Proto-I pulsed-power accelerator, Yonas told us, was central to the decision to convert the EBFA into a light-ion machine. Pellet ignition, requiring a power density on the order of 100 TW/cm$^2$, will depend crucially on the successful overlap of a large number of such ion beams—a feat that remains to be demonstrated.

**PBFA-I.** A diode similar to Johnson's will soon sit at the heart of PBFA-I, at the confluence of the 36 transmission lines that activate it with megajoule pulses of 40 nanoseconds duration. The two electrodes are in the shape of squat, closely spaced, concentric barrels, 50 centimeters in diameter. The intense electric field generated by the 2-megavolt potential difference in the few millimeters of accelerating gap between electrodes draws a plasma source of protons from the dielectric lining of the (outer) anode, and electrons from the metallic mesh of the (inner) cathode.

The focusing of the disk-shaped proton beam onto the target pellet (about a centimeter in diameter) at the central focus of the barrel, is essentially ballistic. A clean focus depends crucially on the smoothness of the plasma drawn from the spherically curved dielectric surface. A sufficiently uniform plasma is hard to achieve with the present anode design, which has a mosaic of dielectric ion emitters set in a metallic surface. The Sandia group is working on improving the uniformity of the anode plasma, but in the end, Yonas told us, one may have to resort to injector guns as the ion source. The hydrocarbon dielectrics used thus far at Sandia produce only protons in abundance, and one ultimately wants to accelerate heavier ions—$He^{+1}$ and $C^{+4}$.

Experiments with pellets are expected to begin at PBFA-I some time next year. With 30-TW proton-beam pulses in the first phase, one hopes for significant fusion neutron yields; but breakeven will have to wait for PBFA II. The main purpose of PBFA-I, which will operate for three years, is to study beam focusing and the coupling of the bombarding energy to target pellets of various designs.

**PBFA-II.** The Particle Beam Fusion Accelerator is scheduled to shut down in 1983 for conversion to its second phase. With twice as many accelerating modules, and twice the accelerating voltage (4 MV) of its predecessor, PBFA-II will deliver 3.5-megajoule pulses to the target, with a peak power of 100 TW.

To deliver so much more power to the pellet, the accelerating system will have to back off further from the target, just to provide elbow room for the 72 separate diodes that will now generate 72 separate ion beams—probably $He^{+1}$ or $C^{+4}$. (In PBFA-I the single barrel diode provides one continuous radially converging beam.) Transporting these ions more than a meter from the diodes cannot be done simply by ballistic focusing. The beam quality would be insufficient to permit focusing over so large a distance, and the mutual magnetic interaction of the fast-moving ions would make the beams diverge. Gerald Cooperstein, Shyke Goldstein and David Mosher at NRL have been working to develop the "plasma channels" that are expected to solve the beam transport problem. Laser beams running from the focus of each diode to the target are to delineate channels of highly magnetized plasma, produced by high-voltage discharge in the gas that fills the beam chamber. The discharge current running down the channel generates an azimuthal magnetic "pinch" field that should serve to keep each ion beam well collimated on its way to the target. The NRL group has already succeeded[3] in transporting proton beams of 400 kiloamps/cm$^2$ over $1\frac{1}{2}$ meters in plasma channels.

The ambition for PBFA-II is more than simply achieving breakeven—a criterion that ignores the energy cost of producing the ion beams. Yonas hopes that PBFA-II will achieve "net energy gain." That is to say, if the beams are produced by the pulse generators with an efficiency of about 25% (a realistic estimate, he tells us), one needs a gain of four times breakeven at the target before the fusion energy output equals the total energy expended. Sandia hopes to achieve breakeven by 1985–86—and then to pursue the further goal of net gain. Laser-fusion devices, apparently limited to beam-production efficiencies well below those of light-ion accelerators, would require correspondingly higher target gain to reach net energy output.

**Heavier ions.** With $He^{+1}$ or $C^{+4}$ ion beams, the focusing problems engendered by electrostatic and magnetic self-deflection are less severe than they are for the lighter protons. Once one goes to "welterweight" ions heavier than carbon, a single-stage accelerating scheme such as PBFA no longer suffices. The more massive the projectile, the greater the energy required to provide sufficient penetrating range in the shell of the fusion pellet.

For the real heavyweights (atomic weights above about 100) one can use conventional accelerator technology to produce GeV beams. For beams of such high momentum, focusing is no great problem. One doesn't need the plasma channels or space-charge neutralizing gases required for light ions. One simply focuses the beam onto the pellet with large quadrupole magnets, as is done in high-energy physics. Therefore one finds preliminary studies for heavy-ion fusion beams under way primarily at high-energy laboratories, such as Berkeley, Brookhaven and Argonne (PHYSICS TODAY, February 1978, page 17).

For all its advantages, the entry costs for heavy-ion fusion are high. PBFA-I was built for $8 million, a very modest sum on the scale of the massive devices needed to accelerate and focus GeV beams. Yonas believes that high capital costs would make heavy-ion fusion suitable only for very large-scale power plants, whereas the relatively small-scale technology of light-ion fusion would be attractive for small plants, with capacities less than 300 megawatts. But Denis Keefe of Berkeley points out that heavy-ion accelerator technology is unique among inertial-confinement schemes in that "it comes complete with instant engineering solutions for the high repetition rates a practical power plant would require."

**Abroad,** a group at the University of Karlsruhe in Germany is soon to begin light-ion beam fusion experiments with a $1-million accelerator they are buying from Physics International (San Leandro, California), and a Japanese group has built a comparable machine at Osaka University. The Russians, Yonas told us, "are taking a wait-and-see position." Their large accelerator, being built at Kurchatov under the direction of Leonid Rudakov, is for the moment staying with electron beams. —BMS

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