Energy Research: Accelerator Builders Eager to Aid Fusion Work

Useful fusion energy may be generated by means of heavy ion accelerator driven implosions if the contraints dictated by the physics and economics of thermonuclear targets and reactors can be satisfied.—JOHN H. NUCKOLLS, Lawrence Livermore Laboratory.

Accelerator builders have compiled an enviable success record. Whereas large technical projects in other fields have sometimes failed and often piled up cost overruns, the accelerators built in the United States within the last 30 years have almost all met or exceeded their design specifications within the projected budget. The sophistication of the postwar accelerators has served as a measure of the nation's technical progress, and the accelerator effort has supported a distinguished record of basic research.

The one thing that has eluded high energy physicists has been the opportunity to contribute something practical. It has been a bothersome omission to many, and may explain the current enthusiasm for applying accelerator know-how to the solution of the fusion problem. "There is a strong feeling that it would be nice to do something useful," says one high energy physicist about his colleagues' proposals to use an accelerator to drive an inertially confined fusion reaction. "There may be enlightened self-interest behind the plan," he says, "but there is nothing wrong with that if it works."

The plan in question is to produce an intense beam of heavy ions at an energy of many giga-electron volts (Gev). By splitting the beam into a number of components, the ions would be made to strike a small fuel pellet from a number of directions and thereby ignite a thermonuclear explosion. With a yield between 0.1 and 1 ton equivalent of TNT, such an explosion could be contained in a 10-meter-diameter chamber and the energy of the explosion products could be converted to heat in order to produce electricity in a turbogenerator. If a pellet with a 1 ton yield were ignited every second, it is estimated that the energy released would be enough to generate 1000 megawatts of electrical power.

Like other proposals for inertially confined fusion, the heavy-ion scheme has not been proved and may not work. But it offers a considerable advantage over laser fusion—the most widely publicized competing method, that is receiving $107 million in research support in fiscal 1977. That advantage was succinctly stated in one of the planning documents for a summer (19 to 30 July) conference on heavy-ion pellet fusion sponsored by the Energy Research and Development Administration (ERDA): "Present accelerator technology is within sight of the requirements to ignite a fusion pellet."

The requirements for pellet fusion are uncertain at best and seem to grow more stringent with each year's computer calculations, but they are formidable. In 1972, it was predicted that 1 kilojoule of laser energy would be sufficient to show the feasibility of laser fusion and perhaps 100 kilojoules would be sufficient to drive a practical laser fusion reactor. Now the experts are hedging their bets on the capability of a 10-kilojoule laser to show feasibility, and talking about 1 to 10 megajoules of energy for a practical reactor. Whereas most laser builders agree that the present large lasers could never be scaled to megajoule energies, accelerator technology has already shown the ability to produce the needed amount of energy in one burst. The Intersecting Storage Rings at CERN, in Geneva, Switzerland, can hold two beams with 2 megajoules of energy each, and a larger storage ring machine ISABELLE being designed at Brookhaven National Laboratory would have 20 megajoules in each ring. The energy requirement could be somewhat less for lasers, but how much less is difficult to evaluate.

Accelerator technology is considered to be much closer than laser technology to the point where it could be utilized for inertial fusion because the many complex processes in an accelerator—such as the forces that cause beam instability—are for the most part well understood. By contrast, a large research and development program will be needed to invent new types of lasers and scale them to megajoule energies—if indeed that is possible. Thus the roles for lasers and heavy-ion accelerators could be complementary. The lasers now nearing completion could demonstrate the feasibility of pellet fusion and large accelerators could carry the concept to the scale needed for electricity production.

The design of the pellet is crucial to the success of the endeavor, and it is nearly impossible for researchers outside the weapons community to evaluate the likelihood that a particular pellet will perform as predicted. Although some laser fusion pellets have been declassified, those planned for the relatively high yield "microexplosions" initiated by heavy ions are still classified, and likely to remain so because of their similarity to thermonuclear bomb designs.

Various researchers emphasize that if pellet ignition works as predicted in the upcoming laser experiments, it should be even more certain to work with an accelerator. The confidence level depends on the amount of energy that can be deposited on the pellet, according to the head of laser fusion design work at Livermore, John Nuckolls. At the July workshop, Nuckolls estimated that the chance of success was high for pellets ignited with a 10-megajoule ion burst and moderate if the pellet were only hit with 1 megajoule. More than half of the 50 high energy physicists who attended the summer workshop were given a classified briefing on the details of the pellet design.

Accelerator technology is attractive to the designers of inertial fusion pellets because it can not only deliver the required high-powered burst of particles, but it can also do so rapidly and efficiently. The reactor would require either a 10-megajoule burst of ions every second or a 1-megajoule burst every tenth of a second, estimated Nuckolls. The accelerator would have to be from 1 to 10 percent efficient in converting electrical energy to ion energy. Accelerators routinely produce many pulses per second and the Stanford 2-mile linear accelerator converts electricity to beam energy with 5 percent efficiency. Accelerator builders say there is no reason why better efficiencies cannot be obtained.

On the other hand, glass lasers currently used in inertial fusion research can be fired only a few times per day and they have an efficiency of only 0.1 percent. To produce 1 megajoule of light from such lasers would require not tens but thousands of beams. Almost all laser fusion laboratories have one research group vigorously searching for "brand X," an undiscovered high-powered laser that is efficient at a short wavelength and rapid-firing.

Accelerators can of course energize any species of charged particles, and the principal drawback of the accelerator fusion idea is that it will require heavy ions—specifically, ions ranging in mass from iodine (127) to uranium (238). Accelerator builders have relatively little experience with such heavy ions [*Science* **192**, 986 (1976)], and none at the multi-Gev energies and intense currents that will be required to drive inertial fusion.

Heavy Ions Instead of Standard Fare

The reason that heavy ions are favored over the standard fare of accelerators—protons and electrons—is that ions alone stop in a short enough distance to vaporize the outer surface of a pellet without appreciably heating the interior. Quick energy deposition over a short range is essential to achieve a high energy gain (high ratio of the explosion energy to beam energy). Only a small fraction of the deuterium-tritium mixture in a fuel pellet needs to be ignited by the impinging beam for a large fraction of the mixture to burn, if the pellet is highly compressed. And compression requires much less energy than heating. So if the whole pellet interior is heated to ignition temperature, more beam energy than necessary is consumed and, in a correlated effect, the amount of compression is reduced, reducing the amount of fuel that burns before the pellet flies apart. With more energy in and less out, implosion methods that heat the whole pellet can achieve only limited energy gain and are thus not well suited for a practical reactor.

Long-wavelength infrared lasers, such as CO_2 lasers, also suffer this deficiency, just as accelerators of electrons and protons do. On the other hand, a uranium ion with an energy of 25 Gev will stop within a fraction of a millimeter.

About 18 months ago, researchers at the Argonne National Laboratory made the first detailed proposal for an accelerator system that could be used to drive an inertial fusion reactor. Although not the oldest idea, the Argonne concept is the most explicit. Using a 600-Mev linear accelerator followed by a 40-Gev synchrotron, the Argonne system would store as many as 100 beam bunches in a small superconducting storage ring and then quickly eject them so they would simultaneously strike the fusion pellet. To make the ion beam as bright as possible when it is focused onto the target, Argonne researchers found it best to accelerate hydrogen iodide ions $(HI)^+$ and then dissociate them to I^+ before injecting into the storage ring. The scheme, which is named Hearthfire,* relies as much as possible on existing technology, according to Ronald Martin, who together with Robert Arnold is directing the Argonne project. Just before being ejected from the storage ring, the iodine atoms would be stripped of all electrons to I^{+53}, and the cumulative current of 100 beams hitting the target would be 400,000 amperes. The total energy would be 2.4 megajoules. Just to dissociate the hydrogen iodide would require 2 megawatts of light, to be supplied by xenon flashlamps in one version of the plan.

Another proposal is to use a linear accelerator with a simplified storage ring. A large number of beams may not be required: spherical illumination is not essential for the newest pellet designs, according to Nuckolls, and the accelerator may focus as few as two ion beams on the pellet. One of the problems with a storage ring is that the mutual repulsion of the many particles in an intense beam tends to blow it apart—a phenomenon called the space charge effect. As a limitation to the current, the space charge effect is considerably less restrictive in a linear accelerator than in a circular one.

The most widely used type of linear accelerator is one in which radio frequency (RF) electric fields, produced in many conducting cavities laid end to end, propel the charged particles along. Al Maschke at the Brookhaven National Laboratory proposed that such an accelerator be used to produce a 100-Gev beam of uranium ions (U^+). With a source current of 50 milliamperes, one burst of particles could deliver 5 megajoules to the target. However, the well-tested RF accelerator would not necessarily be the best choice for a linear device.

Unusual Constraints

The constraints on a driver for inertial fusion would be considerably different from the constraints on a research accelerator. Whereas the present machines—both circular and linear—are designed to deliver a large number of particles in milliseconds or microseconds, the ion fusion scheme will require a large number in nanoseconds. To develop the energy to ignite the pellet, 10^{15} particles will be needed, and to compress the pellet properly they must be delivered in 10 nanoseconds. A research experiment would be swamped with data if the beam were bunched into such a short pulse with such a high instantaneous current.

Present accelerator technology would have to accelerate particles for about 1 millisecond, then compress the resulting long bunch of particles to make a very short bunch. More than 100,000-fold compression would be needed. This is a rigorous challenge, and all the tricks of the accelerator trade would have to be employed in concert to achieve it.

A linear induction accelerator could be better suited to the problem. Although physicists have less experience with the concept—only three small versions have been built in the United States—the induction accelerator can provide high-current pulses of nanosecond duration, with a suitable repetition rate. The beam passes through a long sequence of laminated iron rings, and just as the beam pulse arrives at each stage a high voltage is applied to the metal cavity housing the ring. As the magnetic field builds up in the ring, it induces a voltage gradient in the center, which boosts the beam along. Denis Keefe at the Lawrence Berkeley Laboratory is the chief proponent of the induction accelerator. In one example, he estimates that a 25-Gev uranium beam could be produced with an 800-meter induction accelerator.

Since the induction accelerator characteristically produces 20-nanosecond pulses, compression of the beam would not be a problem. But to get 10^{15} particles into the accelerator in such a short time, a very intense source of heavy ions—producing about 10,000 amperes—would be needed. No such sources exist, and considerable development would be needed for any source technology to produce kiloamperes of heavy ions.

A problem that all heavy-ion accelerators have is that the ions may recombine with electrons when they strike other ions in the beam or the residual gases of the vacuum chamber in which the beam travels. The cross sections for uranium ions to recombine are unknown at Gev energies, and such recombination effects could scuttle some proposals. Ions that changed charge would be quickly lost from the beam, prohibiting attainment of the high currents needed. The problem is particularly severe in storage rings, where the beam would pass through the residual gas many times. Preliminary estimates are that the vacuum in the storage rings would have to be 10^{-11} or 10^{-12} torr, but only 10^{-7} torr would be needed for linear accelerators.

Another approach to the problem of producing intense ion beams is to use pulsed diode technology. Primarily used for the simulation of nuclear weapons effects up until now, this technology produces huge peak currents of relatively low energy particles. The largest example of pulsed power technology is the Aurora machine located outside Washington, D.C., which produces a 2-megajoule pulse of electrons with an instantaneous power of 10^{13} watts (10 terawatts). Until about 2 years ago, the pulsed power technology was limited to electrons,

*Hearthfire is an acronym for High Energy Accelerator and Reactor for Thermonuclear Fusion with Ion Beams of Relativistic Energies.

but recently the diode technology has produced very high ion beam currents as well. The ion diode technology could provide a suitably intense ion source for a linear induction accelerator scheme, or possibly be used directly to produce ion beam fusion.

The limitation that makes most ion diode machines unattractive for an inertial fusion reactor is the same factor that constitutes a major disadvantage of electron beam fusion. The focal length of the diode is so short—generally less than 1 meter—that the beam could not be focused onto the pellet from a point outside the reaction chamber.

A variation of the ion diode concept called a collective ion accelerator would not be so limited in focal length. One proposal, by Craig Olson at Sandia Laboratories, would employ an intense beam of relativistic electrons to form a moving potential well in the accelerating tube. The moving electromagnetic pocket would trap and accelerate positive ions. Such an accelerator would have a higher effective voltage gradient, and thus shorter length, than more conventional machines.

A major problem that has received far too little attention is the design of the reaction chamber. According to Nuckolls, the reactor would be nearly the same for accelerator fusion or laser fusion and—with the balance of plant—would be analogous to a present-day power plant. If a 1000-megawatt power station is projected to cost $1 billion, then the investment allowed for the accelerator would be about $100 million, Nuckolls says. The factory for producing pellets is expected to be equally expensive—and presumably just as complex—costing another $100 million.

The amount of power that needs to be recirculated to operate the accelerator depends on the accelerator efficiency and the target gain. Nuckolls envisions a system in which the product of efficiency and gain is greater than 10. At such a level, the recirculated power in a 1000-megawatt station would be about 300 megawatts with present accelerator efficiencies, but an accelerator with an efficiency of 50 percent would reduce the recirculating power tenfold.

The difficulty of choosing adequate materials for the reactor chamber is determined by the projected power level inside the reactor. Although the average power would not be much greater than that planned for magnetic fusion reactors (a few megawatts per square meter), the instantaneous power would be enormous—10^{20} watts—because the explosion products (neutrons, x-rays, and alpha particles) are produced in a 10^{-11} second burst. Each burst would produce more than 10^{19} neutrons.

Since many scientists invited to the summer study were already committed to the design of inertial fusion pellets or had already proposed specific heavy-ion machines as drivers, it is not surprising that the consensus was optimistic. No fatal flaws were found in the idea, and the study found many of the technical requirements to be within reach. The meeting was "expected to have an optimistic output and it did," says one ERDA official. The summer study urged that an R & D program be launched immediately, with some people calling for a $10 million annual research budget.

Such a program is improbably large for the present, but ERDA officials in both the laser fusion division and the physical research division, from which high energy physics is funded, are in favor of a small program starting in the coming year. According to Glenn Kuswa, who has been coordinating the project for the laser fusion office, up to $1 million may be designated for the purpose.

Many Options, Severe Requirements

Before the summer study, two proposals were on the board, both based on storage rings. By the end of the study, the participants concluded that a broader range of accelerator technologies deserved consideration, and many researchers seemed disposed to go back to work for another year before committing themselves to specific designs. The key technical factors in this shift of opinion were apparently the question of the ion recombination cross sections that would be relevant for storage rings and the suggestion of a linear induction-type accelerator, which was unfamiliar to many high energy physicists.

None of the accelerator systems were able to project costs within the limitation of $100 million suggested by Nuckolls. Estimates ranged from $500 million to more than $1 billion. Thus the question of the economics of heavy-ion fusion is up in the air—just as with every other proposed method of controlling fusion.

Perhaps the strongest appeal of heavy-ion inertial fusion is that the outstanding technical questions can be answered—either negatively or affirmatively—with relatively few experiments and a modest amount of study. The summer study estimated that 100 to 200 man-years should be sufficient to determine the feasibility.

But the accelerator requirements are still "mind boggling," says one experienced accelerator designer familiar with the difficulties peculiar to heavy ions. At present only one accelerator in the world has successfully produced a beam of uranium ions. That one, the Gesellschaft für Schwerionenforschung (GSI) near Frankfurt, West Germany, is only energetic enough to serve as the injector for one of the heavy-ion fusion accelerator systems. It falls short of the required average ion current (10^{15} particles per second) by a factor of 10^7. The current in the Berkeley Bevalac is too weak by the same factor. It typically produces 2×10^8 particles per second, the heaviest ion being argon (40) at an energy of 80 Gev.

The proposed union of efforts by inertial fusion investigators and high energy accelerator designers could be beneficial to both parties. Major accelerator centers are likely to shut down in the next few years (*Science*, 1 October 1976) and it is probably no coincidence that the two centers that have invested the most effort in accelerator fusion—Argonne and Brookhaven—are the oldest and lowest-energy accelerator laboratories. With a relatively constant budget of $200 million per year, the number of opportunities for high energy researchers is decreasing.

Laser fusion researchers have had rapidly expanding budgets in the 1970's, which are only now beginning to level off. While large laser installations have a reasonable chance of fulfilling the military goals of the program, some researchers would like to have a backup to test the feasibility of civilian power generation. The pellet designers in particular think they have an outstanding idea—"a black box" as one described it—which they want to have ways to test. Not only the expertise but also the credibility of the high energy physics community would be a great asset if the project reaches the stage of a large demonstration plant.

Many other approaches to controlling fusion have looked promising when first studied. Only 5 years ago laser fusion was touted as a way to bypass the problems uncovered in 20 years of research on magnetic fusion methods. Few speak of the laser approach as a shortcut anymore, and many of the problems of laser fusion will be encountered in heavy-ion fusion. It is possible that heavy-ion fusion is being similarly oversold, in order to get the program started.

Nevertheless, the community of high energy researchers is a body of considerable talent that has not previously bent its efforts to the solution of the techniques of energy supply. Whether the proposed union of technologies will make new progress toward practical fusion power is still undetermined. But if the recommendations of the summer study are followed, high energy physicists will get a chance.

—William D. Metz