search & discovery

Pellet fusion with heavy-ion beams attracts attention

Heavy-ion fusion, a late entry in the inertial confinement sweepstakes, has been gaining a good deal of ground lately. Accelerator people as well as those involved in inertial confinement, have been thinking for several years that if a beam of energetic heavy ions at sufficiently high current could be delivered to a deuterium–tritium pellet in ultrashort bursts, a successful fusion implosion could occur. In particular, during the past few years Alfred Maschke of Brookhaven National Laboratory and, independently, Ronald Martin and Richard Arnold of Argonne National Laboratory did some calculations that made the prospects for using heavy ions appear to be within reason. Interest in the possibility has become more widespread: In July 1976, the US Energy Research and Development Administration (now the Department of Energy) sponsored a two-week study of heavy ions for inertial-confinement fusion, attended by about 90 people.[1] Money for research was put in the ERDA–DOE budget, and early last spring funding and experiments began at several laboratories in the US.

This past October, a second workshop was held,[2] with about the same attendance as the first, plus some observers from laboratories in Europe and the UK. Out of this session came a new set of accepted goal parameters and a program that calls for the detailed design of a 100-kilojoule demonstration experiment in accelerator technology and the rough

PHOTO MORTON ROSEN

Looking into Brookhaven xenon linac, designed to accelerate 750-kV xenon ions. It is a folded quarter-wavelength resonator with twelve accelerating gaps. Output energy is 1.15 MeV, and the particle velocity is 0.0036 *c*.

design of a 1-MJ accelerator system appropriate for commercial power. Both designs are to be completed by the spring of 1979, and the demonstration accelerator is to be built by the mid-1980's, assuming adequate funding is made available.

Toward this end, accelerator development work, from ion sources to final beam transport, is going on at Argonne, Brookhaven and the Lawrence Berkeley Laboratory. Each of these laboratories has a history of experience invested in a particular acceleration scheme for heavy-ion fusion, but each is also now working on solving more general problems, as we found in a series of interviews with participants and observers.

In addition, groups at the Lawrence Livermore Laboratory are working on targets, reactor-chamber design and the focussing of the beam across the reaction chamber to the target. Problems connected with the effects of gaseous "debris" from previous explosions within the reaction chamber are being studied by plasma physicists at the University of Maryland and at Cornell University, as well as at Livermore.

The research is being supported by two DOE divisions, Laser Fusion (about $3.5 million for FY 1978) and High-Energy and Nuclear Physics (about $1.4 million). The Division of Basic Energy Sciences has also provided about $100 000 to study ion–ion cross sections.

Why the interest in accelerators as "drivers" for fusion power plants? Much larger efforts have long been underway in magnetic confinement and (rather more recently) in inertial confinement with lasers and with electron beams or light ions. And accelerators have the disadvantage, at least at first glance, that no one before has ever tried to produce high-energy heavy ions at the high peak power (100–600 TW; 1 TW = 10^{12} watts) nor to deliver them in the short bursts (1–10 nanosec) required. They are very

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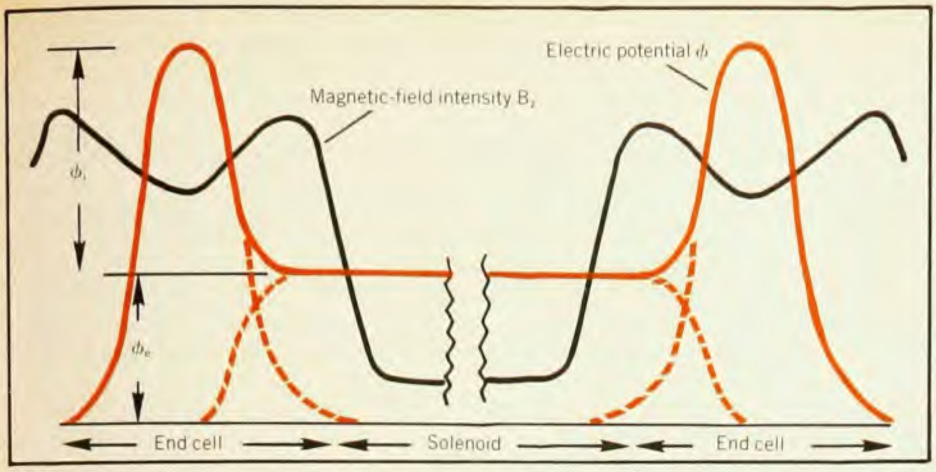
Panel recommends pulsed high-flux neutron facility

The creation of a national high-flux pulsed spallation neutron facility is one of the major recommendations of the Panel on Research Facilities and Scientific Opportunities in the Use of Low Energy Neutrons. The panel was established in early 1977 by the Solid State Sciences Committee of the Assembly of Mathematical and Physical Sciences, National Academy of Sciences-National Research Council. Gordon K. Teal, formerly chief scientist at Texas Instruments, served as chairman and Clifford G. Shull of MIT was vice-chairman.

The panel, with 18 members representing a wide range of scientific disciplines, issued its report, "Neutron Research on Condensed Matter: A Study of the Facilities and Scientific Opportunities in the United States," in October. This followed after an extensive study over a six-month period with numerous meetings of the core panel and various subpanel groups. This study was undertaken in response to desires by both ERDA and NSF to formulate guidelines for future activity in an area where they provide the major amount of federal support.

Neutron characteristics. The use of neutrons as a tool for investigating all forms of condensed matter has several advantages. First, by examining how neutrons are scattered, the experimenters can obtain information on a microscopic scale of the positions of atoms in a material and of how these atoms will move when thermally excited. Similarly, magnetic scattering experiments provide information on an atomic scale of the locations of spins in a magnetic material, the relative alignment of the spins, and their motion.

One further advantage of low-energy neutrons (those with energy on the order of 1 eV or smaller) is that their momentum and kinetic energy are ideally matched to the equivalent quantities characteristic of atomic excitations and fluctuations in matter. The panel explained that "these neutrons possess so little kinetic energy that they have mini-



Tandem-mirror electric and magnetic fields. Plasma-confinement devices built on this principle have two minimum-**B** magnetic-mirror pairs separated by a long uniform-field solenoid. Peaks of positive ambipolar potential (color) occur in each end cell, trapping ions in the solenoid.

tive potential barrier can amount to several times T_e. Electrons will be contained by the overall positive potential end-to-end (a potential well of depth ϕ_e). The overall length of TMX is about 15 meters; estimates for a future reactor indicate a length of 100 meters.

The density of hot ions will be maintained in the end cells by the injection of energetic neutrals at energy E_0, which could be several hundred keV in a reactor. These hot ions will heat electrons in the end cells to a temperature T_e, which is less than E_0 but could amount to several tens of keV. These electrons, which communicate readily throughout the system with an approximately constant energy everywhere, will in turn ionize and heat cold fuel continuously injected into the solenoid.

According to Fowler and Logan's calculations, thermonuclear burning will occur in a fuel of deuterium and tritium if reasonable assumptions for the operating parameters are met. Pure deuterium fuel (for the d–d fuel cycle) is also feasible but at more stringent conditions. The calculations suggest that Q (defined as the ratio of fusion power produced to input power necessary to sustain the reaction) could be as high as 5. By contrast, traditional mirror machines could only yield a Q very close to 1—a net power output will demand very efficient conversion of energy.

One advantage of the tandem mirror, Logan told us, is a result of the separation of the solenoid (where thermonuclear burning is expected) from the magnetic mirrors serving as end plugs. Development will be begun with a relatively short solenoid to determine its stability properties. Then progressively longer solenoids may be substituted in turn; for high efficiency the plasma volume in the solenoid should be much greater than that in the end cells. Conversely, if in the course of time better end plugs are found (for example, when experience with the Mirror Fusion Test Facility becomes available), they could be substituted for the currently proposed ones without disturbing the solenoid and energy extraction system.

Tandems at other laboratories. Dimov intends to build a tandem mirror machine at Novosibirsk, although construction has not yet begun. The final design is still flexible within an overall concept very similar to Livermore's TMX; it will be of a comparable size and employ the same type of fast neutral injection.

Two other machines currently under construction differ from the Livermore design principally in the manner in which the plasma is to be heated. At the University of Wisconsin at Madison, Richard S. Post is principal investigator of a tandem mirror project that will use ion-cyclotron radiofrequency heating. Construction started in late 1977; tests of trapping techniques with one mirror-pair only are expected at the end of 1978, with the complete machine ready a year later. Post told us that he believes he can maintain better control over plasma heating by energizing ions directly, either in the end plugs or in the solenoid, at the ion-cyclotron resonance frequency. Then the energy requirement for the neutral beams is considerably reduced; they function only as a particle source, not an energy source as at Livermore. They need only have sufficient energy at injection (2 keV in the plugs in the Wisconsin experiment) to ensure proper trapping.

The Wisconsin tandem is less than half the size of TMX; overall length is about six meters. Magnetic fields are lower, being 4 kG peak mirror field in the current design with the capability of increasing to 8 kG.

The University of Tsukuba in Japan has a strong program in fusion research, principally with mirror machines of various kinds. The series of experimental devices called "Gamma-1," "Gamma-2" and so on is already up to Gamma-6, a tandem mirror on which work started in the spring of 1977, with completion due in March 1978 and experiments likely to start in April. Shoichi Miyoshi coordinates the whole program. Takaya Kawabe, one of the principal investigators for Gamma-6, explained to us that the speed of construction is the result of much "borrowing" of components from earlier devices in the series. He is very pleased that Japanese industry is taking a great interest in the project; a considerable amount of funding comes from industrial sources, and the remainder from the national government.

Gamma-6 differs from the Livermore and Wisconsin projects in its use of relativistic electron beams for plasma heating in the solenoid (or in the end plugs if this proves desirable). A 400-keV, 80-kA electron beam injected into the mirror is expected to be trapped by plasma turbulence within 50 nanoseconds, to stay in the mirror field for more than 1 millisec. Magnetic field intensity will be 6 kG in the mirrors, 2 kG in the solenoid; plasma density is expected to be 10^{13} in the end plugs and 3×10^{12} in the solenoid.—JTS

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reliable, typically operating over 90% of the time: This is less "down" time than a typical conventional power plant. Accelerators also are durable; they have lasted for decades and are usually shut down only for budgetary reasons. They have the required fast pulse rates and efficiency. Although accelerators have never been designed to produce the required currents of heavy ions, they have been designed to produce protons at the required total power (for example, the CERN Intersecting Storage Rings, Isabelle at Brookhaven and Fermilab). And the short, well-defined range of heavy ions appears to suit them well for thermonuclear ignition.

The pellet designers are in a slightly awkward position in relation to their accelerator-building colleagues because some of the pellet details are classified. However, sufficient work has been done in pellet design, under the general direction of John Nuckolls at Livermore, to set "moderate confidence levels" for commercial power. The demonstration experiment is to deliver 0.1 MJ of ions at a peak power of 3–30 TW in two or more simultaneous beams. The pilot reactor plant, aimed toward the pellet designer's moderate confidence level, is to deliver at least 1 MJ with a peak power of at least 100 TW in a pulse length of about 10 nanoseconds every 1–10 seconds. Roger Bangerter, who has done most of the heavy-ion pellet calculations, noted that for 1 MJ, and for uranium ions (the ion being used in most calculations for this project), ion energies should be no higher than about 25 GeV, rather than the 40 GeV once believed useful. The maximum ion energy is determined by the minimum allowable specific energy deposition (about 20 MJ per gram of target) and the calculated range of the ion.

At the accelerator labs. The Argonne effort, directed by Martin, has been centered around a synchrotron as the main element. Synchrotrons have an economic advantage here, because they are cheaper to build than the long rf linac required. However, they have a significant potential technological disadvantage in that acceleration in a synchrotron takes 0.1–1 sec, a relatively long time. Ion–ion cross sections for collision followed by the exchange of an electron may be so large for the heavy ions at high currents that the resulting beam loss (both ions would be lost, because the ions must be singly charged) during this time would be too great. The Argonne synchrotron would raise the energy to about 20–30 GeV and would be followed by several storage rings, filled sequentially to build up to 1 MJ and then dumped simultaneously into the target chamber.

Martin told us that they are also developing an initial accelerating section, applicable for nearly any likely accelerator arrangement. Their aim is to develop an ion source with very large current and put it through a dc preaccelerator and the beginning section of an rf accelerator. With the Hughes Research Laboratory, they are scaling up the power of an existing very bright 2.5-mA xenon source to 100 mA. The dc preaccelerator is a "Dynamitron," (acquired as surplus from the NASA–Goddard Space Flight Center) which is being rebuilt as a high-energy physics machine. The current-carrying capacity will also be doubled. Initial goal is a beam of 50–100 mA of Xe^+ ions at 1.5 MeV, with the possibility of increasing the current and of going up to 2 MeV. This would be the highest current of heavy ions yet produced of a quality that could be further accelerated, continued Martin, and if a substantial fraction of such a beam could be transformed into a stable rf accelerator beam, "then we will have demonstrated that the initial part of such an accelerator is feasible." Argonne also plans to use these still fairly low-energy Xe^+ beams to study the vacuum effects of bombarding metal surfaces with heavy ions and the transport of these highly space-charge dominated beams. They are also working on the idea of a rapid cycling synchrotron that would cycle as often as 60–100 times per second.

The Brookhaven group, under Maschke, has been working on a scheme in which rf linacs get the beam up to full energy. The linac is followed by small storage rings, as in the Argonne plan. The BNL group has been given a 750-kV Cockcroft–Walton, formerly a spare injector for the Alternating Gradient Synchrotron, and has been working with it since their funding began in April. Maschke described to us two of the ongoing experiments with the Cockcroft–Walton.

One is directed at improving the space-charge limit at the high-energy, high-current end of the acceleration, where the ions are extracted from the ring. They are neutralizing the proton beam with electrons and finding that they get eight times higher current with neutralization than without. With the addition of rf cavities and the resulting beam bunching, they hope to get even better results for this simulation study.

In the second experiment, due to begin last month, they are putting xenon gas into their proton source and accelerating it through 750 kV. This beam is to be run through the front portion of a xenon linac, which is about one-half meter long and will add about 400 kV.

Another group of experiments is being done with the AGS. One study tests the hypothesis that, for a beam bunched in a circular machine, peak instantaneous currents greater than the space-charge limit can be achieved for a revolution or two. Results with 200-MeV protons confirm this; the peak current is eight times the space-charge limit. The second set of experiments with the AGS has shown that the bunching factor can be increased. They have achieved a ratio of 60 to 1, compared with the usual 10 to 1, Maschke told us.

Induction linac. According to one Berkeley design, developed under the guidance of Denis Keefe, an induction linac is being examined as the main accelerator. This linac consists of a series of singly pulsed accelerating cavities, phased so that only a portion is energized at any one time. The energized region moves down the accelerator synchronously with the particle bunch. The advantage here is that this type of linac is built for high current and short pulses. An injector is needed to supply about 5% of the needed kinetic energy to get the beam up to reasonably high current, Keefe told us, and this injector could be an rf linac feeding a low-energy accumulator ring or a pulse-power driven drift-tube linac. However, very few induction linacs have been built, and these have been electron machines. One of the few places that does have experience with such machines is LBL. Right now, Keefe says, as part of an alternative scheme, they are working on the early part of the acceleration, on a beam to be injected into an rf linac. Two ion sources are being studied—a scaled-up multiaperture source, of the type developed for the magnetic-confinement program, that could provide 50 mA now and possibly 100 mA of heavy ions in the future, and a large (12-inch diameter) contact-ionization cesium-ion source that could produce one ampere. The cesium beam is to be accelerated through pulsed-power drift tubes to about 2 MeV, and then sent through a long sequence of magnets to study intense-beam propagation in magnetic focussing systems. Other groups at LBL are doing wholly theoretical analyses.

A sidelight of the sudden growth of interest in heavy-ion fusion has been the reemergence of interest in accelerating "B-B's"—microscopic material pellets—as an alternative to ions or laser beams. The development of this idea is still in its earliest stages, says Richard Garwin (IBM, Yorktown Heights) who, along with Richard Muller (University of California, Berkeley) and Burton Richter (Stanford Linear Accelerator Center], is now working on it. (The idea is not new, as Garwin pointed out to us. Similar ideas, they found, were published as long as ten years ago by Friedwart Winterberg of the University of Nevada and by Juri G. Linhart of Frascati.) According to Garwin, they were concerned that as much as a billion dollars would be spent before one could begin to determine the feasibility of heavy-ion fusion. A superconducting or ferromagnetic pellet, on the other hand, might be accelerated to a few times 10^7 cm/sec with a delay-line accelerator (a kind of magnetic rifle) about 10 km long and only a few cm in diameter. The point is, stresses Garwin, that the feasibility of this idea could be tested relatively cheaply.

The components of the accelerator for the heavy-ion demonstration project, then, are still uncertain, but one arrangement appeared to be gaining favor as of the Brookhaven meeting: an initial rf linac, followed by some sort of accumulator-buncher and an induction linac for the main acceleration. However, many questions remain. Among the most serious technical problems are those at the front end of the accelerator and in pulse compression and beam handling at the high-current end. The identity of the heavy ion is not decided; candidates range from mass 150 through U^{238}. And funding for the demonstration project is not certain, nor is it likely to be for another two years or so.

—MSR

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