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

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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 minimal effect on what is being probed, whether it be a biological molecule involved in a life process or an organic substance undergoing catalytic reaction at a surface."

In performing neutron scattering experiments, however, investigators must face some major difficulties. Due to factors such as spatial collimation, incident energy selection and final energy analysis, the flux available to the detector at the end of the spectrometer is many orders of magnitude lower than the isotropic flux at the neutron source; thus long periods of data collection are required.

Additionally, the weak interaction of neutrons with matter (advantageous in other applications) can be a handicap in that it generally necessitates coin-sized samples for getting useful scattered intensity. In some cases (biological specimens, surface films and esoteric materials), such sizes may be unobtainable. In others, the requirements of a special environment, such as in high-pressure work, may place restrictions on sample size.

Funding recommendations. The panel recommended the formation of a national center with a high-flux (10^{16} thermal neutrons/cm^2 sec peak) pulsed spallation neutron facility as a way of overcoming the apparently characteristic practical limitations in neutron flux available from steady-state reactor sources. In the latter, neutrons are produced by fission reactions; in the pulsed type of source, high-energy charged particles (such as protons or electrons) are used through various nuclear reactions to produce neutrons. The panel states that the pulsed type of source has the potential of producing a thermal neutron flux that is a whole order of magnitude, and an epithermal neutron flux nearly three orders of magnitude, higher than that produced by any existing reactor source; thus many new areas of experimentation can be envisioned.

Three proposals for developing pulsed-neutron sources in the US have already been made: the Intense Pulsed Neutron Source at Argonne, the Weapons Neutron Research Facilty at Los Alamos, and the Pulsed Neutron Booster at the Oak Ridge Electron Linear Accelerator (PHYSICS TODAY, January 1976, page 17). Although they discussed these projects in detail, the panel made no recommendation for any particular proposal.

The panel urged, moreover, that continued support be given to 13 presently operating steady-state reactors that are serving as neutron sources for research studies in low-energy neutron scattering and radiation damage. Those in the US with the highest thermal neutron flux include the High Flux Isotope Reactor (13×10^{14} n/cm^2 sec) at Oak Ridge and the High Flux Beam Reactor (8×10^{14} n/cm^{2}sec) at Brookhaven.

The US preeminence in the world in the quality of its low-energy neutron research is threatened by several factors, according to the panel. Some of the oldest US neutron facilities (such as the Bulk Shielding Reactor commissioned at Oak Ridge in 1951 and the CP-5 reactor commissioned at Argonne in 1953) are now approaching the end of their generally expected lifetime (about 30 years).

Also, after a high amount of facility expenditure in the US during the mid-to-late 1960's, only a relatively small amount of money has been spent during the past eight years for new neutron sources. In that period, approximately $2 million each was spent on the reconstruction of the MIT Research Reactor and the installation of a pulsed neutron source on a satellite Los Alamos Meson Facility beam.

These expenditures are minute when compared to those spent on major neutron facilities outside the US that are currently either under construction or have been approved for construction. The panel listed ten such facilities that will require a total building cost of $505 million. Among this group, the ones expected to have the highest flux are the IBR-II Pulsed Reactor in Dubna, USSR (5×10^{16} n/cm^2 sec peak flux), the Rutherford Pulsed Neutron Spallation Source in the UK (5×10^{15} n/cm^2 sec peak flux) and the Leningrad Research Reactor (3×10^{15} n/cm^2 sec flux).

Use. The panel's recommendations about the use of the major neutron research facilities include:

- The major neutron sources should be treated as national facilities (requiring central funding of general operating costs), rather than strictly mission-oriented research centers.
- The group of users should be broadened in order to fully realize the research opportunities available in broadly distributed areas of science; efforts should be undertaken to identify, educate and encourage such users.
- The education of scientists and engineers in the neutron field, the accessibility of intermediate-flux facilities to the national community and the housing of independent, home-based research groups should all be encouraged through continuing support to university neutron research centers. —CBW

Tandem-mirror machines promise better efficiency

A major problem with magnetic-mirror devices for plasma confinement has always been the leakage of particles out of the ends of the machine. An experiment now under construction at Lawrence Livermore Laboratory, known as the Tandem Mirror Experiment (TMX), proposes to turn this failing neatly to advantage by employing two mirror-pairs, one at each end of a long straight solenoid. Each pair of mirrors confines positive ions by minimum-**B** magnetic-field wells, and the excess positive charge that develops in these "end cells" confines ions within the solenoid. In other words, the two mirror pairs act as plugs for the ends of the solenoid. Calculations for a reactor based on this concept predict that, under appropriate neutral injection conditions, a plasma of a density and temperature sufficient for controlled fusion will build up in the solenoid. The purpose of the TMX experiment is to test the principles of the concept. Other tandem-mirror experiments are planned or already under construction at Novosibirsk in the Soviet Union, at the University of Tsukuba in Japan, and at the University of Wisconsin at Madison.

Following a suggestion by George Kelley (Oak Ridge) published in 1967,[1] the tandem-mirror concept in its present form was proposed by T. Kenneth Fowler and B. Grant Logan of Livermore[2] and, independently, by G. I. Dimov of Novosibirsk.[3] The project at Livermore got under way in the spring of 1977, with $11.4 million of funding from ERDA (now DOE); construction is expected to be complete by late 1978. Fred Coensgen is head of the project. The device will use much of the technology already established at Livermore with the 2XII-B mirror machine (PHYSICS TODAY, November 1976, page 17). Future tandem-mirror devices will gain from technology to be established with the Mirror Fusion Test Facility, a $94 million project at Livermore. MFTF is designed to determine plasma conditions in a large magnetic mirror, yielding data that can be applied to all kinds of mirror machines.

The tandem mirror concept exemplified by TMX is illustrated schematically in the figure. Magnetic flux flows out of one end plug, through the solenoid and into the other end plug with an intensity shown there as $B(z)$. Each end plug is a complete minimum-**B** mirror machine, with additional field coils to join the end-plug field lines smoothly to the low-field uniform solenoid flux. In TMX the peak mirror field will be 20 kG, produced by "baseball-seam" coils. Hot neutrals with energy around 40 keV will be injected into the end cells to maintain a hot plasma there.

In conventional mirror machines, electrons with their higher velocities are more poorly confined than are ions—or they would be but for the net positive charge, or "ambipolar potential," that develops due to the positive-ion excess in the center of the mirror. In such machines the magnetic mirror confines the ions, and the ions confine the electrons. Our figure shows how positive ambipolar potential peaks occur in each end cell. The result in a tandem mirror is that ions in the solenoid will be prevented from escaping by the potential difference ϕ_i between the solenoid and the end cells. If T_e is the electron temperature this posi-