mal 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

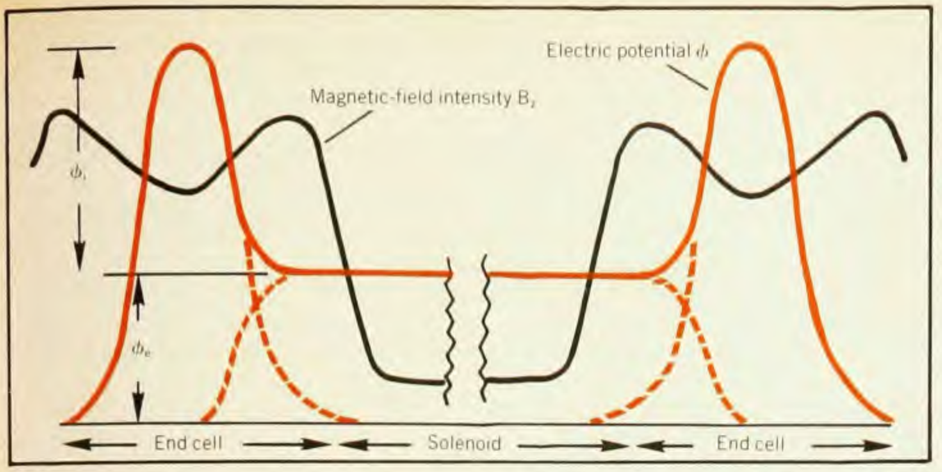
Tandem-mirror machines promise better efficiency

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-



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

References

1. G. G. Kelley, Plasma Physics **9**, 503 (1967).
2. T. K. Fowler, B. G. Logan, Comments on Plasma Physics and Controlled Fusion **2**, 167 (1977).
3. G. I. Dimov, V. V. Zakaidakov, M. E. Kishinevsky, Fizika Plasmy **2**, 597 (1976).

Pellet fusion with heavy-ion beams

continued from page 17

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