# Will we have fusion power by 1988?

*The Sandia National Laboratory fires the world's most powerful particle beam. A report by Charles B. Stevens.*

Scientists at the Sandia National Laboratory in Albuquerque, New Mexico, on Dec. 11 successfully test-fired the world's most powerful particle beam accelerator, the PBFA-II (Particle Beam Fusion Accelerator). The 108-foot-diameter accelerator produces a 100-trillion-watt light ion beam, designed to achieve inertial confinement fusion. Given recent budget cutbacks in magnetic fusion research, the PBFA-II is now positioned to be the first facility to achieve net energy generation from igniting controlled nuclear fusion reactions in the laboratory, before the end of 1988. Compared to other inertial confinement fusion (ICF) drivers, such as lasers and heavy ion beam accelerators, the Sandia PBFA-II will definitely be the first to demonstrate significant fusion gain.

This means that, despite the general curtailment of funding for the U.S. fusion research effort, commercial fusion reactors could still be attained by the 1990s. And while substantial technical problems remain to be resolved for commercial electrical power production, the amazing rate of progress demonstrated by light ion beam accelerator technology over the past decade, makes such a development more than possible. The successful test-firing of PBFA-II, seven weeks ahead of schedule and within budget, reflects a broad revolution in particle beam accelerator technology, which promises to produce very soon a wide range of technological marvels beyond that of fusion energy. The prototype PBFA-I has already been converted into an x-ray research facility. X-ray laser experiments will also be carried out on PBFA-II.

## The march to fusion

The Sandia light ion beam program is among the youngest in the fusion field. Under the direction of Dr. Gerold Yonas, currently assistant director and chief scientist for the Pentagon's Strategic Defense Initiative Organization (SDIO), Sandia scientists began exploring electron beam diode accelerator technologies as possible ICF fusion drivers in the early 1970s. Previously, this technology had been developed to produce intense bursts of x-rays that would simulate the effects of nuclear weapons. For fusion, the idea was either to utilize the electron beams directly, or the powerful burst of x-rays they were capable of generating, for compressing and heating a small pellet of fusion fuel, much in the same manner as in laser pellet fusion.

To obtain significant ICF pellet fusion, the driver, whether it be a laser, heavy or light ion beam accelerator, must deliver several millions of joules within a few tens of nanoseconds (one nanosecond = one billionth of a second) onto a fusion fuel pellet a couple of millimeters in diameter. In other words, the beam must have a power level of 100 trillion watts and a power density of several hundred watts per square centimeter. Furthermore, the beam energy must be efficiently deposited within a thin layer of the outer skin of the pellet. In this way, most of the incident beam energy will go into driving an implosion of the fusion fuel, while not heating the interior fuel until maximum compression has been attained. This type of implosion, which does not pre-heat the interior fuel, is called isentropic compression, and is essential for achieving relatively large fusion energy outputs compared to beam energy inputs—"high-gain ICF."

*The interior of the PBFA-II central vacuum chamber hub is shown here. The water insulator has been removed in the outer sections. The 200-trillion-watt electrical current pulse, which will be directed into this central hub, will contain more energy than all of the world's power plants combined, for 50 billionths of a second.*

Electron beam diode technology has both advantages and disadvantages relative to other ICF drivers. In the first place, relativistic electron beam (REB) diode accelerators are based on the highly efficient and high-energy technology of electrical pulsed power. This means that REBs are most capable of attaining the necessary multi-megajoule energy and 100-trillion-watt power levels needed for ICF, and attaining these outputs at high system efficiency—upwards of 25% of the input electricity used to power the REB ends up in the beam, as compared to a fraction of a percent for the case of high-power glass lasers. (High-power lasers, such as the Lawrence Livermore National Lab Nova, are only now approaching the 100,000 joule energy level—see accompanying article.)

On the other hand, it is extremely difficult to focus REBs to the high power densities, and it is difficult to deposit the REB's energy within the short distance required for isentropic compression.

In the mid-1970s, REB technology proved capable of efficiently generating intense, high-current beams of light ions. (PBFA-II achieves 80% conversion from electron to ion beam; that is, 80% of the already high efficiency of the REB pulsed power technology is preserved.) Ions have even better pellet deposition properties than laser beams, in terms of meeting the stringent conditions needed for isentropic compression. 100% of the incident light ions are deposited within a very thin layer of the pellet, without pre-heating the interior fuel.

In 1984, a series of breakthroughs was achieved on PBFA-I in ion-beam focusing, which totally transformed the prospects for PBFA-II. When originally designed, PBFA-II was expected to at best *approach* fusion breakeven—production of as much fusion energy output as beam energy input—and to at least produce significant fusion burns. It was expected to produce multi-megajoule beams at a 100-trillion-watt power level, focusable to power densities of 100 trillion watts per square centimeter.

But light ion beam focusing experiments in 1984 and 1985 on the Sandia PBFA-I and Proto-I, experimentally demonstrated that much higher power densities were obtainable. It is now projected that PBFA-II will be capable of 3.5-million-joule energy pulses, produced in 50-nanosecond bursts at a delivered power level of 100 trillion watts, but with potential power densities of 10,000 trillion watts per square centimeter. This *100-fold improvement over original projections* is based on the scaling seen in beam focusing experiments on PBFA-I and Proto-I.

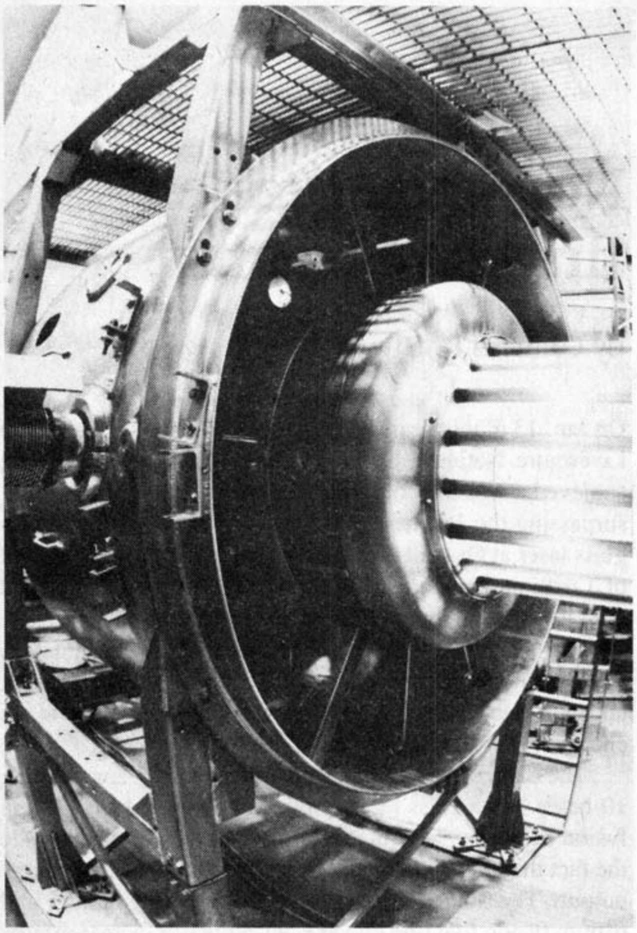
## Fusion budget slashed

On Aug. 25, 1980, the U.S. House of Representatives passed a 20-year plan to develop commercial fusion, introduced by Rep. Mike McCormack (D-Wa.) and cosponsored by 159 congressmen (the vote was 365 to 7). The bill, HR 6308, mandated the Department of Energy to develop a plan to demonstrate the commercial feasibility of magnetic fusion energy by the turn of the century. The total cost authorized by the Congress was $20 billion over the 20-year period.

The McCormack bill motivated the need for an aggressive fusion program as follows: "The early development an export of fusion energy systems will improve the economic posture of the United States and ultimately reduce the pressures for international strife by providing access to energy abundance for all nations."

The accompanying figures tell the story of what has actually happened to the fusion budget in the intervening period, and particularly with the current Gramm-Rudman legislation. President Reagan's proposed FY 1986 budget was $8 million more than the $436.9 eventually adopted by the Congress for magnetic fusion research (pre-Gramm-Rudman), and $85 million *less* than that adopted for inertial confinement fusion. In the case of inertial confinement, the Gramm-Rudman cuts are still being made as we go to press.

| Fiscal year | Magnetic fusion ($M) Budget line | Magnetic fusion ($M) Constant 1972 dollars | Inertial confinement ($M) Budget line | Inertial confinement ($M) Constant 1972 dollars |
|---|---|---|---|---|
| 1977 | 219.1 | 163.6 | 103.0 | 77.1 |
| 1978 | 316.3 | 224.3 | 111.9 | 79.4 |
| 1979 | 332.4 | 222.0 | 130.6 | 87.2 |
| 1980 | 355.9 | 224.1 | 144.1 | 90.8 |
| 1981 | 350.2 | 207.1 | 194.9 | 115.3 |
| 1982 | 394.1 | 219.6 | 208.8 | 116.3 |
| 1983 | 453.8 | 247.8 | 209.1 | 114.2 |
| 1984 | 447.1 | 259.0 | 190.0 | 110.1 |
| 1985 | 468.5 | 270.1 | 169.7 | 98.0 |
| 1986 | 436.9 | 254.6 | 254.6 | 98.7 |
| Before Gramm-Rudman: | | | | |
| | 379.9 | 221.4 | 155.0 | 90.3 |
| After Gramm-Rudman: | | | | |
| | 365.5 | 213.0 | n.a. | n.a. |



*The wide-angle photo shows the new Sandia fast-opening gas switch that has just been experimentally demonstrated. This switch could double the beam power level of the PBFA-II to 200 trillion watts.*

If this scaling is successfully demonstrated on PBFA-II, it will mean that the facility will be capable of going far beyond simple ICF breakeven. Conservatively, PBFA-II could shoot targets with fusion energy outputs 10 times greater than beam energy inputs. More significantly, PBFA-II could reach high-gain ICF, in the range of 20 to 100 times greater output than input—the level needed for commercial ICF electric power plants.

The technical success of the Sandia light ion beam program can be judged by the fact that as little as two years ago it was thought that a facility for experimentally demonstrating high-gain ICF would cost on the order of one billion dollars. The PBFA-II, which clearly has the potential for attaining high-gain ICF, has cost only $48 million—20 times less than the previous projection.

Further improvements have been achieved in the PBFA-II design. "PBFA-II is a state-of-the-art accelerator with 1985 technology, even though we've been building it for the past three years," pointed out Dr. Pace VanDevender, who has replaced Dr. Gerold Yonas as Sandia Director of Pulsed Power Sciences. "We achieved that by fast-tracking the design, at the same time that we were constructing the accelerator. The successful first shot demonstrated that the risky fast-track process works beautifully." Dr. VanDevender explained that "fast-tracking" means that accelerator design research continues during the construction process, making it possible to modify yet-uninstalled portions of the machine without impeding the construction process.

One example of such design improvements is the newly developed gas switch (see photo). This fast-opening power switch, which has just been experimentally demonstrated, may make it possible to double the PBFA-II power level to 200 trillion watts.

## The PBFA-II

The $48-million PBFA-II consists of 36 pulsed power modules which are arranged around a central experimental hub and which deliver electric power pulses to it from all directions. These modules are arranged in four layers. Each level is arrayed like the spokes of a 108-foot-diameter wheel. Each module consists of capacitors, switches, and transmission lines, submerged in oil and water in separate sections of a 20-foot-tall tank.

During a test firing, the capacitors are charged up by Marx generators which receive their power from ordinary electric power lines. The switches release the capacitor banks' electrical energy in a short burst, which then travels down the water- and oil-insulated transmission lines. The transmission lines shape and compress this initial electrical current pulse and deliver it to the central hub, toward which all of the modules converge. The hub consists of a vacuum chamber containing the Applied-B diode. When the electrical pulses arrive simultaneously at the diode, intense lithium ion beams are generated and converge at the very center of the hub. It is here that the fusion fuel pellet will be placed.

These lithium ion beams will be utilized to compress a pellet of hydrogen fusion fuel to 1,000 times solid density—a density greater than that found in the core of the sun—and temperatures greater than 100 million degrees Celsius. Under these conditions, the hydrogen nuclei fuse to form helium, releasing fusion energy before the pellet disassembles. The resulting burst of energy could be directly used to generate fuel for nuclear fission reactors and heat liquid lithium, which is then used to produce electricity. (The most recent reactor designs at Livermore National Laboratory envision utilizing the liquid lithium in a magnetohydrodynamics—MHD—channel to directly generate electricity at the highest efficiencies. In this way, ICF could generate electricity at less than half the cost of existing nuclear fission and coal electric power plants.)

Over the coming year, extensive pulsed-power testing will be conducted on the PBFA-II. The first year of operation will be devoted to characterization and optimization of the accelerator. In the second year, experiments will concentrate on ion beam formation and focusing. In the spring of 1985, PBFA-I delivered an 8-trillion-watt pulse of hydrogen ions onto a spot 4 to 4.5 millimeters in diameter. This represented a power density of 50 trillion watts per square centimeter and a 33-fold improvement in focusing over the .5 trillion Proto-I experiments in 1984. These experiments demonstrated that beam focus scaling increased beam current, .4 million amperes on Proto-I to 4 million amperes on PBFA-I. PBFA-II will demonstrate beam focusing with increased beam voltage. PBFA-II will have 30-million-volt lithium ions, as compared to 2-million-volt hydrgen ions in PBFA-I.

Many of these beam-focusing experiments will be directed at demonstrating alternative applications of the PBFA-II and new beam-focusing geometries. Among the alternative applications of PBFA-II will be the demonstration of ion beam-driven x-ray lasers. Recent developments with particle beam weapons could also be included in the PBFA-II experiments. For example, following up research originally carried out at Sandia, Livermore scientists have recently shown that intense particle beams can be focused and transported over long distances, through specially prepared plasma channels. A low-energy excimer laser pulse was utilized in these experiments to successfully produce such a plasma channel.

Beam transport through laser-produced plasma channels could provide the solution to one of the only major technical problems remaining for use of the light ion beam accelerator in commercial ICF power plants—"accelerator stand-off." Currently, the beam-generating diode is placed in close proximity to the fusion pellet. As a result, the pellet implosion-explosion damages this diode and it must be replaced after each shot. By utilizing plasma channels for beam transport, the pellet could be located at a sufficiently great distance, that no diode damage would result—known as accelerator stand-off. Given the current projections for PBFA-II's extraordinarily high beam power density, proposals to experimentally demonstrate beam stand-off are currently being considered by Sandia researchers.

## Fusion experiments

By 1988, PBFA-II will begin experiments with actual fusion fuel pellets. These will include both direct and indirect drive pellet target designs. If PBFA-II attains the power densities currently indicated by existing experiments, it will produce significant and possibly high-gain ICF fusion. Throughout the 1970s, electrical pulsed power made tremendous strides forward, outpacing all other high-energy technologies, as PBFA-II demonstrates. This was achieved with shoestring levels of funding. But now electrical pulsed power has become a major focus of President Reagan's Strategic Defense Initiative. The Sandia pulsed-power fusion program is only now beginning to benefit from this several-orders-of-magnitude increase in research funding for pulsed power research. Therefore, the prospects for light ion beam fusion are quite bright.

# Nova laser takes first fusion shot

by Charles B. Stevens

On Jan. 13 of this year, U.S. fusion researchers at Lawrence Livermore National Laboratory in Livermore, California, achieved a world record for laser fusion energy production, surpassing the Japanese, whose experiments on the Gekko glass laser at Osaka University had held the previous record of 1 trillion fusion neutrons generated. But with anticipated cuts in funding for the American program under the new Gramm-Rudman "balanced budget" regime in Washington, the Livermore achievement could rapidly be undermined, and with it one of the best prospects for achieving the limitless energy resources of laser fusion.

The Livermore researchers fired their newly constructed, 10-beam Nova glass laser, producing more than 10 trillion fusion neutrons. The successful result was achieved despite the fact that this was not an optimal design for fusion energy output. The small glass sphere containing deuterium and tritium fusion fuel (the two heavy isotopes of hydrogen) was primarily designed to test the various Nova fusion system diagnostics and measuring instruments. Only 18,000 Joules of the 100,000-Joule capability of the 10-beam, 100-trillion-watt Nova laser was used in the shot. The 10 ultraviolet (.35 millionths of a meter) Nova laser beams were directed onto a small sphere for one-billionth of a second, and produced 28 Joules of fusion neutrons.

In a 1984 study, laser fusion pioneer and Livermore Associate Director for Physics, Dr. John Nuckolls, showed that laser fusion has the potential of providing a virtually limitless source of electricity at half the cost of existing nuclear fission and fossil fuel energy sources. Dr. Nuckolls based his analysis on:

1) The cheap cost of fusion fuel and ready availability of hydrogen fusion fuel. One gallon of sea water contains enough fusion fuel to produce the equivalent energy of 300 gallons of gasoline.

2) The high quality and extreme concentration of fusion energy, which makes possible the efficient direct conversion of the fusion output to electricity.

As Dr. Nuckolls detailed in his study, given the fuel costs, of almost zero, and the almost-double electrical output per unit fusion input, nuclear fusion reactors would provide electricity at half the cost of existing types of nuclear fission