Ionic Push Toward Nuclear Fusion

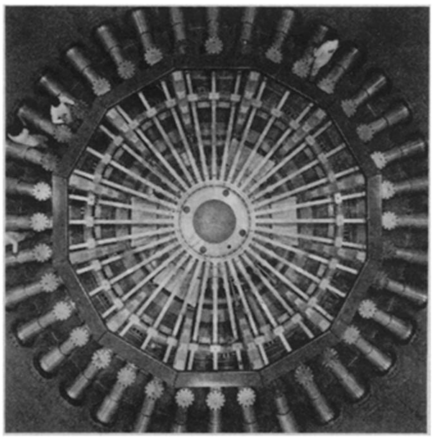
It's a long and difficult road to a power plant for the 21st century

By DIETRICK E. THOMSEN

Inertial confinement fusion is great if you have the right driver. The driver delivers energy to a small pellet of fuel from all sides at once. The energy ought to cause implosion of the fuel pellet, and so increase the density and temperature of the fuel so that useful numbers of nuclear fusions occur.

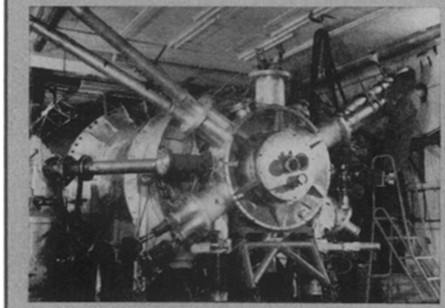
Inertial confinement fusion works — in bombs. The goal of much current striving is to make it work in fuel pellets small enough that their energy release can be contained in some kind of vessel and put to practical use. That means amounts of fuel that release the energy of about 1,000 sticks of dynamite. Some inertial confinement experiments have actually produced a few fusions, but researchers are still decades away from their practical goal.

From what the public has been allowed to learn in open reports, the driver in a fusion bomb is gamma rays produced in the explosion of a fission bomb. Controlled fusion laboratory experiments in the United States, the Soviet Union, Western Europe and Japan are trying laser light, gamma rays and beams of several kinds of particles: electrons, protons or ions.


Illustrations: Sandia National Laboratories

PBFA-I's 36 transmission lines supply 30 trillion watts to a diode located in the center circle.

The making of high power pulses


Illustrations: Physics International

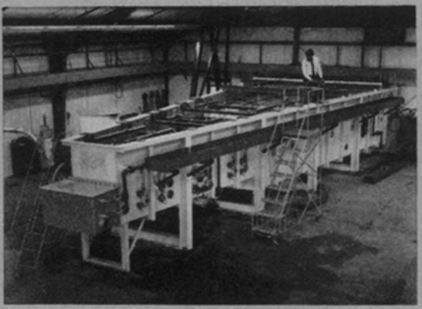
Pithon

High power accelerators were designed to simulate the effects of nuclear explosions. They produce various forms of radiation characteristic of the explosions so that its effects on materials and electronic components can be studied in the laboratory. Physics International (PI) of San Leandro, Calif., which makes high power accelerators, was founded by people from the Lawrence Livermore National Laboratory, an organization long concerned with bombs and their effects.

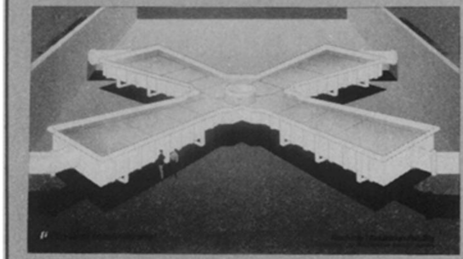
The relationship is still close. Physics International builds pulsed power generators, as the machines are also called, for Livermore and the closely related Sandia National Laboratories as well as for other U.S. government laboratories. Other customers include universities in the United States and abroad, foreign government laboratories and private corporations. In addition to building and selling the apparatus, PI maintains a basic research program of its own. Although it has supplied components for the interial confinement thermonuclear fusion program at Sandia, PI's own research concentrates on bomb simulation and other radiation effects, including a program looking toward a laser in the extreme ultraviolet or soft X-ray range of the spectrum (SN: 9/24/83, p. 197).

A high power accelerator stores electrical energy, building it up and then releasing it suddenly in very short, high power pulses. In most American designs, says Alan J. Toepfer, vice president of PI, an array of capacitors called a Marx generator or Marx bank does the storing. Marx banks can fill large rooms. The energy is stored in the tension in the dielectric (usually oil) in which the capacitor plates are immersed.

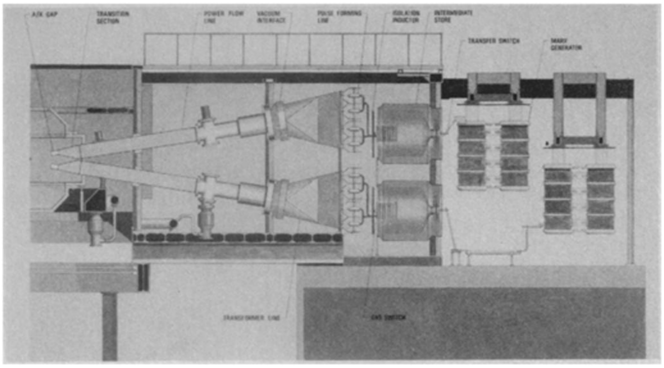
The Marx bank discharges its energy through a sequence of capacitors (with water as a dielectric) and switches. Each stage of this procedure compresses the pulse in time. It begins as an energy discharge of a few microseconds and gets down to something like 60 to 100 nanoseconds at the final stage—that is, a compression to about 1/100 of its original duration. Power ratings in the terawatts (trillions of watts) can result. The most powerful machine on the PI property at the moment is PITHON, which delivers a maximum power of 5 terawatts.


Eagle

Soviet designers, Toepfer says, prefer to use induction coils for energy storage and coils and switches for discharge. Here the energy is stored in the magnetic fields generated by the coils rather than in the tension of a polarized dielectric. Toepfer says this kind of a design has some advantages in cost and efficiency as the coils can operate in vacuum. That does away with the need for oil and water and systems to handle them


Roulette

At the end of the process of pulse compression, the power is delivered to a load, usually a diode, which can generate high power beams of electrons or ions, or which can implode a plasma to make ultraviolet or X-rays. These radiations are made at the strength that bombs would make them and so inflict comparable damage, but in a controlled way, on whatever materials scientists may wish to study. For many studies this procedure gets around the need for explosions, which are always messy and in some cases forbidden by the test ban treaty. In a somewhat ironic closing of



The power pulses for PBFA-II will begin in the Marx generators at left and end in the anode cathode gap at extreme right.

It is not clear yet whether lasers or particle beams will prevail. Particle beams are cheaper, and their energy couples more easily to the target, allowing larger targets. Lasers, however, pack much higher power.

Physicists working on the particle beam side — at least the American ones — are convinced that the heavier the particles the better. The American program began with electrons and then switched to protons. The next step in a soon-to-be-completed apparatus called PBFA-II ("Pibfa-two," or Particle Beam Fusion Apparatus II) will be lithium ions. This news — after years of discussing use of light ions, this will be the first attempt — was reported in San Francisco at the recent Beams '83, the Fifth International Conference on High Power Particle Beams, by J. Pace van Devender, department manager for inertial confinement fusion at Sandia National Laboratories in Albuquerque, N.M., where the American particle beam program is concentrated.

The Soviet counterpart program at the Kurchatov Institute in Moscow, which employs the machine called Angara, continues to use electrons. The electrons implode a foil, which produces gamma rays to serve as the fusion driver. American physicists, progressing toward the ions they think more efficient, profess not to know why the Soviets continue to use this arrangement. Leonid I. Rudakov, the leader of the Soviet effort, had been scheduled to discuss Angara at Beams '83, and American colleagues were hoping he would tell the reasons. Due, presumably, to travel disruptions, the Soviet delegation never arrived at the meeting (SN: 9/17/83, p. 181).

The American program began with the intention of using electrons. Construction of a machine called EBFA-I (Electron Beam Fusion Apparatus I) began in 1977. Meanwhile, success in producing protons with another device called PROTO-I, persuaded the experimenters to switch to protons, and in 1979 EBFA became PBFA-I (SN: 12/1/79, p. 375). At the Beams '83 meeting, van Devender described the proton experiments that have been done with PBFA-I over the last couple of years. Meanwhile, PBFA-II is under construction — it is expected to begin experimentation in 1986 — and the decision was recently taken on the strength of success with PBFA-I to start PBFA-II with lithium ions.

The ion beams — protons can be regarded as hydrogen ions, the lightest of all ions — are produced in diodes energized by high power accelerators. High power accelerators store up large amounts of energy and release it in short, high power, high current pulses (see box). The diode in PBFA-I consists of a piece of plastic as the anode and a cloud of electrons confined by a magnetic field as the cathode. The diode is wrapped around in a circle, actually a slice of a sphere, with the fuel pellet target at its center.

A high voltage difference is maintained between the anode and the cathode. The tension causes a plasma of protons and electrons to form on the surface of the anode. The cathode attracts the protons, and they gain momentum as they fly toward it. The cathode is mostly empty space, and so the momentum carries the protons right through it, and they go on to hit the target. PBFA-II will be similar, but the anode will carry strips of lithium nitrate, which will form a plasma of lithium ions and nitrate radicals.

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the circle, the ion beams may also be powerful enough to ignite thermonuclear fusion in fuel pellets in a controlled way.

In addition to capacitors or coils, the switches are crucial elements of the design and the subject of much current research and development. It is the switches that control the duration and shape of the pulses. The precise shape of the pulse is extremely important in many applications. In controlled fusion experiments, says J. Pace van Devender of Sandia, "[Ion] beam quality is a function of pulse power quality." One of the advantages of the machine PBFA-II that van Devender and co-workers are now building is that it will enable them to shape the pulses better.

The switches are opening switches. Unlike ordinary electrical switches, whose decisive act is closing the circuit, these pass current until a certain saturation point is reached and then open the circuit. The switches are basically diodes themselves and pass current in the form of electrons flowing between their electrodes. There are two general varieties, plasma erosion switches and reflex switches. The one controls current saturation by the gradual erosion of an electrode plasma that supplies the current; the other does it by using an auxiliary cathode to reflect electrons in a complicated way that effectively cancels the current when the saturation point is reached. In their open position the switches may function as high power diodes themselves, or the act of opening may shunt the energy to another load connected in parallel.

Although PITHON is the most powerful machine now at PI, the nearly complete Double Eagle is called the "flagship of the fleet." It will produce 7 terawatts of power in 75-nanosecond pulses, 1.7 megavolts at 5.4 megamperes current. Double Eagle consists of two components, each called Eagle, diametrically opposite each other and delivering power to a common load. The first Eagle, built and functioning, delivers 4.5 terawatts alone. The Eagle design is a pilot for a circular arrangement called ROULETTE, which could have up to 20 such modules around a circle, delivering up to 70 terawatts to a common load. PI physicists are not certain they will ever build that much of ROULETTE—they could stop at configurations less than 20—but Double Eagle is on the ground and should fire its first shot sometime in November.

In addition to the well tested capacitors and induction coils, some more exotic methods of energy storage are under study, Toepfer says. The Naval Research Laboratory in Washington, D.C., is trying homopolar generators, essentially large magnetic induction wheels. In the Soviet Union the versatile physicist Andrei D. Sakharov has suggested using magnetic implosion devices. In these arrangements, a magnetic field is trapped in an electrically conducting box, and the box is imploded by detonating charges fastened to its sides. This compresses the trapped energy spatially. Such devices have been used in the U.S. to provide power pulses for railguns (SN: 4/4/81, p. 218), and for injecting test materials into the atmosphere from rockets, but what Sakharov proposes is a much larger application.

—D.E. Thomsen

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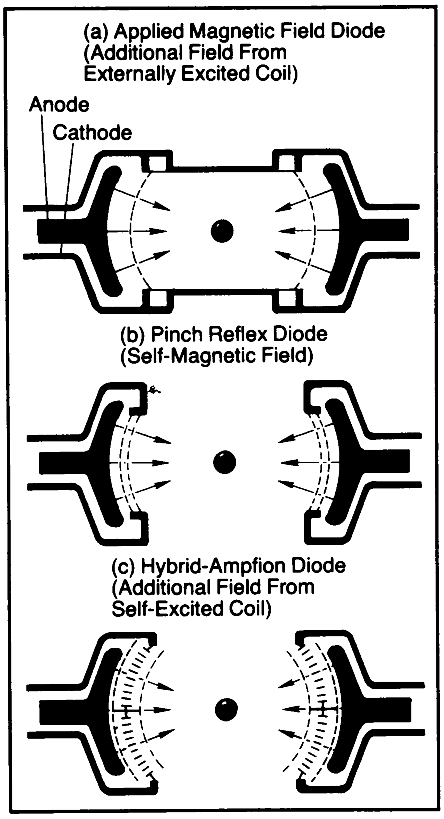
Experimentation addresses such questions as how best to configure the diode and whether or not to use auxiliary magnetic fields so as to focus the proton beam most efficiently on the target. Serious problems crop up from time to time. One that particularly concerns van Devender and his co-workers at the moment is that the electrons in the anode plasma, which were expected to behave regularly and form part of the return current of the diode (compensating for the movement of the protons), have a tendency instead to drive themselves back into the solid material of the anode. There they cause damage that produces irregularities in the distribution of the anode plasma and so inhomogeneities in the beam that goes to the target. Future experimentation will seek ways of supressing this damaging feedback.

"Inertial confinement fusion is a very, very difficult thing to do," van Devender says. Still progress goes steadily on. Speaking of target size, van Devender says, "A year ago we could hit a golf ball; now we can hit a marble." A pea-sized target is what they're aiming for. PBFA-II should be able to hit a 3-millimeter target. PBFA-I produces pulses with 33 megawatts of power. PBFA-II should be able to produce 100 megawatts for a peak potential difference of 6 megavolts.

Still there is a long way to go. "We are in the stage of developing the tools to develop the tools to do experiments to show us whether implosion hydrodynamics will let us do it," van Devender says. The implosion, he says, would have to compress a liquid (the target) to 1,000 times liquid density and heat it to 100 million kelvins. That would require a power concentration of at least 100 terawatts (100 trillion watts) per square centimeter of target surface. If that implosion can be triggered, the physicists then have to determine whether it proceeds in the optimum way or even in a possible way to produce a significant number of fusions. For now they can't even reach that question.

A power reactor would have to be much bigger than these experiments, which are a few tens of centimeters across at most. A reactor would have to be several meters across. That raises questions of long-distance beam transport. The beam is extremely dense, and so the mutual repulsion of all these positively charged ions would blow the beam apart if physicists tried to propagate it through a vacuum. The pressure of an inert background gas holds the beam together. But the beam will not penetrate meters through such a gas unaided. A path has to be made for it by pre-ionizing the background gas along its route. Laser beams could do this, but that's a whole other set of experiments. Even the most optimistic don't expect success at blitzkrieg speed. Van Devender told the meeting, "Everyone in this room will either have retired or died by the time we have power on the grid." ☐



The three varieties of diode being tested for use in PBFA-II. The pinch reflex diode uses the ion beam's own magnetic field to focus the beam. The others use auxiliary magnets.