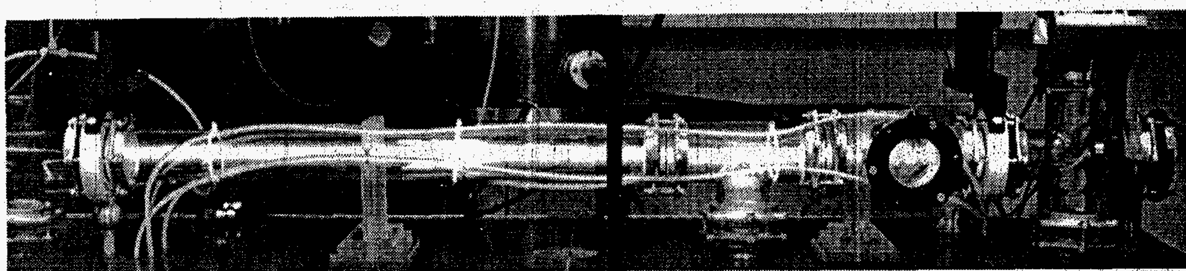
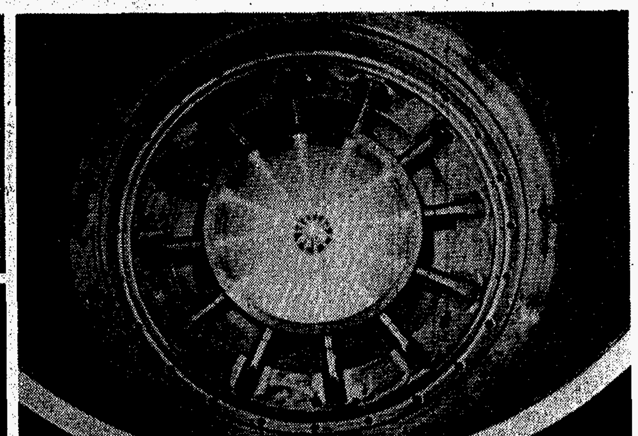
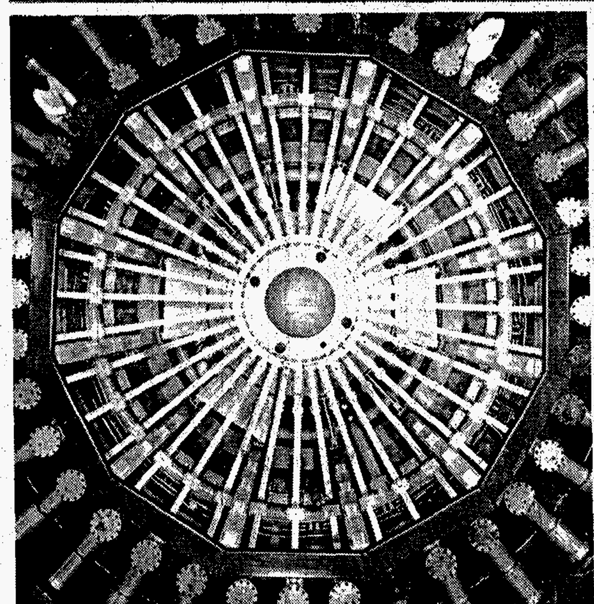
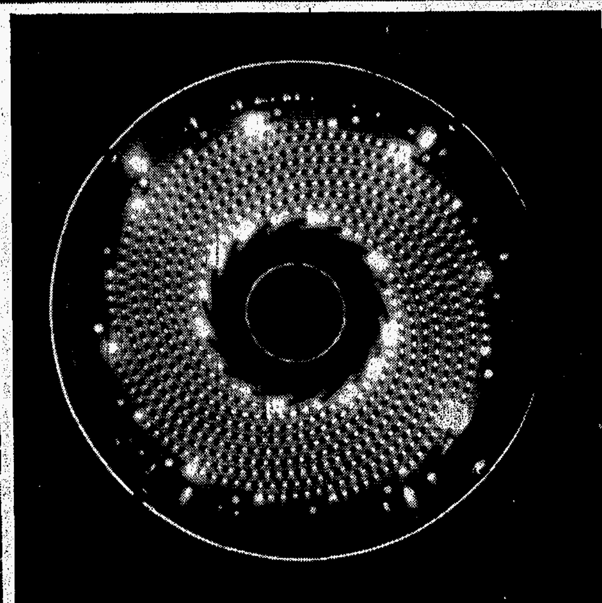
SAND--81-0848

Pulsed Power
Research and Technology
at Sandia National Laboratories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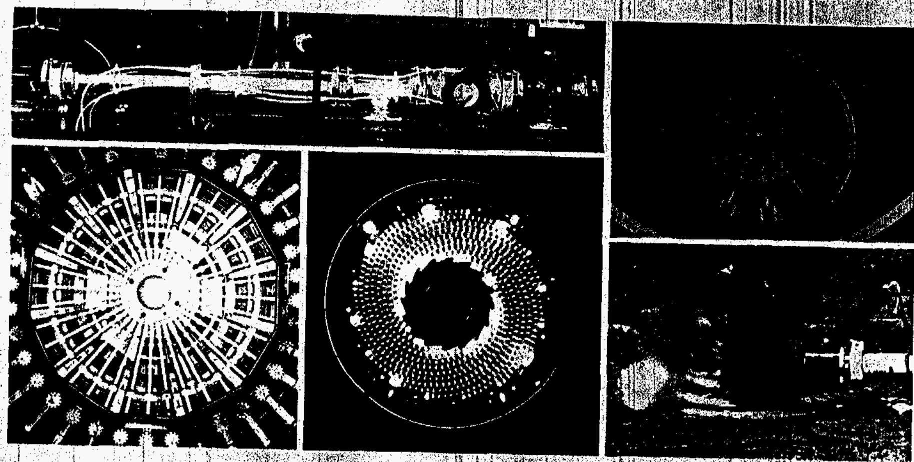

COVER

Highlights of pulsed-power research and technology at Sandia. Clockwise from top left: (1) A laser-triggered discharge for propagation of ions in a channel. (2) A view of the experiment that demonstrated efficient transport of electron beam energy through multiple discharge channels in air. The 12 cylinders around the edge are electron beam sources. (3) The Pulsar generator based on explosive flux compression in a superconducting magnet. (4) The luminous large-area plasma generated for use as an ion source in the Ampfion diode. (5) A view from the top of PBFA-I's magnetically insulated transmission lines.

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Pulsed Power

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Introduction

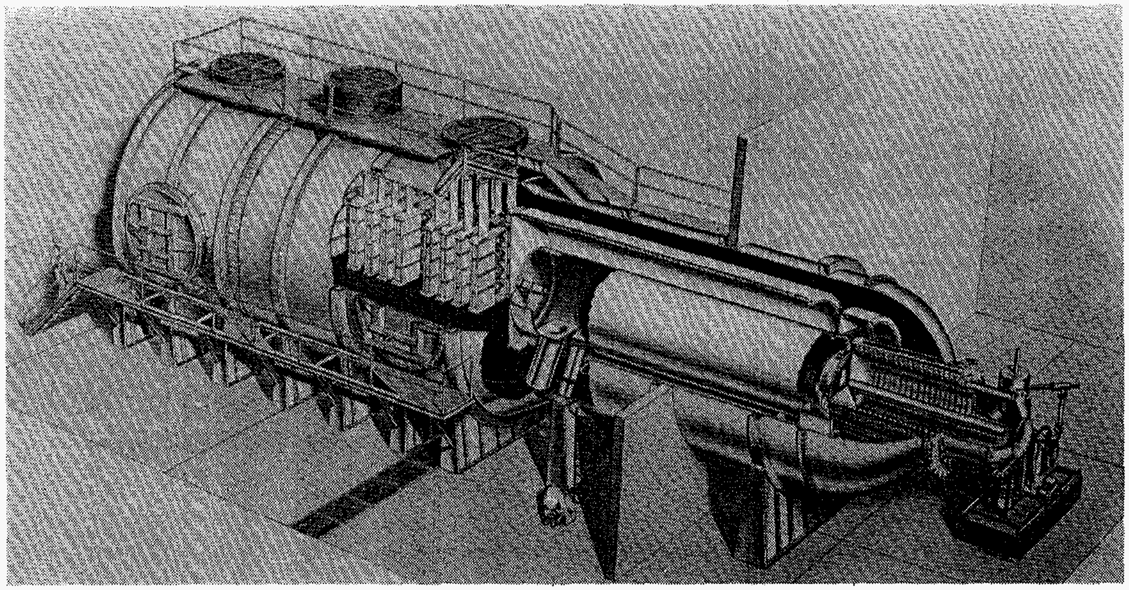
Over the past 15 years, steady and sometimes exciting progress has been made in the hybrid technology called *Pulsed Power*. Based on both electrical engineering and physics, pulsed power involves the generation, modification, and use of electrical pulses up to the multitrillion-watt and multimillion-volt ranges. The final product of these powerful pulses can take diverse forms — hypervelocity projectiles or imploding liners, energetic and intense particle beams, X-ray and gamma-ray pulses, laser light beams that cover the spectrum from ultraviolet to infrared, or powerful microwave bursts.

At first, the needs of specific applications largely shaped research and technology in this field. Now we are beginning to see the reverse — new applications arising from technical capabilities that until recently were thought impossible. Compressing and heating microscopic quantities of matter until they reach ultra-high energy density represents one boundary of our scientific exploration. The other boundary might be a defensive weapon that can project vast amounts of highly directed energy over long distances.

Other applications of the technology may range from the use of electron beams to sterilize sewage, to laboratory simulation of radiation effects on electronics, to electromagnetic launchings

Hermes II as it appeared in 1969

Cutaway drawing of Hermes II showing the new Marx generator



of projectiles into earth or into solar orbits. Eventually we hope to use pulsed power to produce an inexhaustible supply of energy by means of inertial confinement fusion (ICF) — a technique for heating and containing deuterium-tritium fuel through compression.

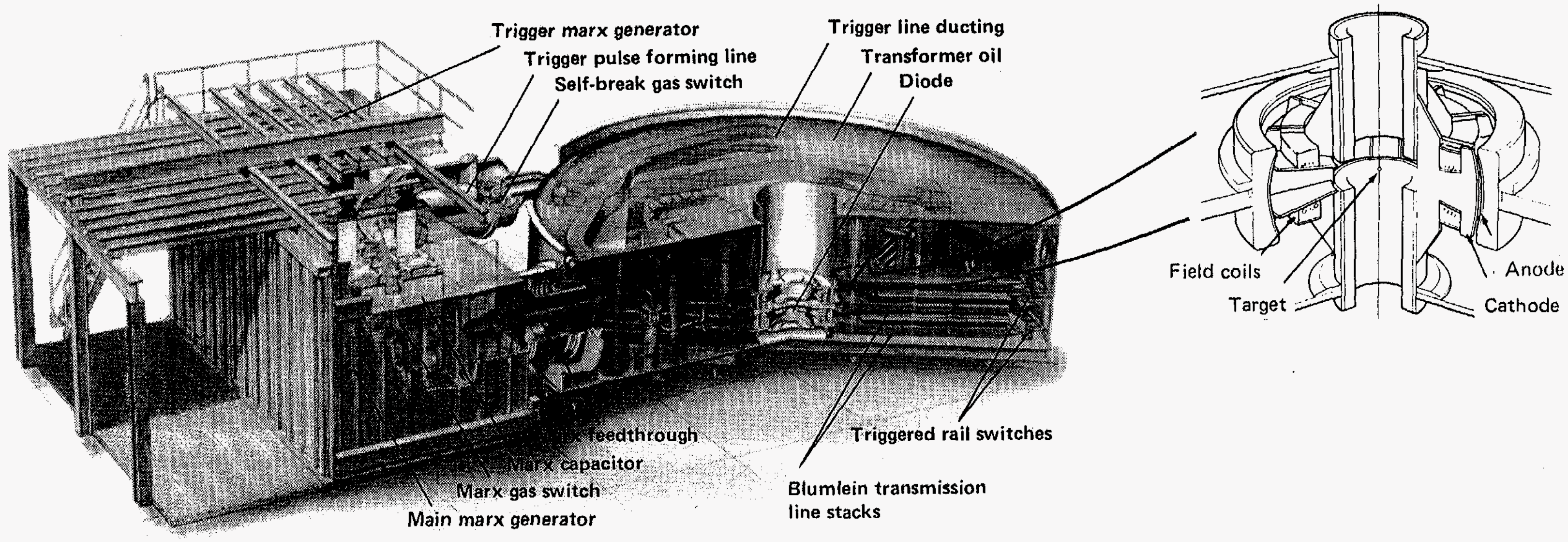
Support for this work has been from two sources: the Department of Defense through the Defense Nuclear Agency to private companies such as Physics International Co. and Maxwell Laboratories; and the Department of Energy, primarily to Sandia National Laboratories. Other laboratories making vital contributions include Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and the Naval Research Laboratory. University contributors include Cornell, Texas Tech, the University of California at Irvine, Massachusetts Institute of Technology, and the University of Illinois.

Sandia's role in pulsed-power research grew out of a 1965 project. We built a pulsed gamma-ray device, an accelerator for laboratory studies of nuclear-weapon effects on electronic subsystems in nuclear warheads. We named that accelerator (developed jointly with the Atomic Weapons Research Establishment in Albermaston, England) Hermes-II. During its development, we learned how to work with high-voltage Marx generators, large oil-filled pulse-forming lines, and 10-million-volt diodes.

Hermes-II, with more than 17,000 test firings to date, has been a productive part of our radiation-effects testing program since 1967, launching Sandia on new ways to explore the control and concentration of pulsed power. This work has led to an ever-wider range of important applications. In 1980 we replaced the original Marx generator, and Hermes II should remain in active use for several more years.

Inertial Confinement Fusion

Proto I

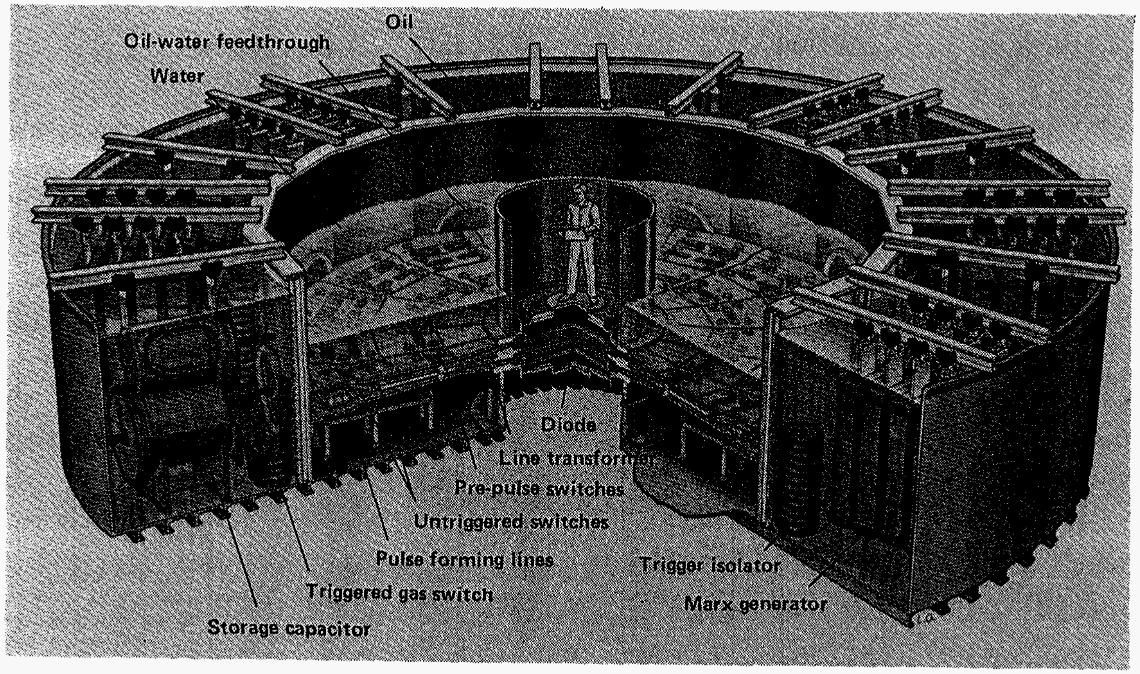


Expanded radiation test requirements in the late 1960s motivated us to develop Hydra and Nereus, water-insulated accelerators that can produce rapidly rising currents of several hundred thousand amperes. By 1973 we were encouraged enough by our progress in this technology to embark on a project to use electron beams for inertial confinement fusion (ICF). We knew then that energy requirements for ignition of a fusion pellet (the deposition of about 1 megajoule of energy onto the fuel pellet during ten billionths of a second) could be more readily achieved with particle beams than with lasers. The problem was to develop ways to efficiently use our energy-intensive technology to implode spherical fuel pellets only a few millimetres in diameter.

Experiments on focusing electron beams and energy deposition in matter began in 1973, as well as extensive target design calculations. In 1977 our attention began to shift from electron beams to ions, because of their more favorable deposition characteristics. Rapid progress in ion-beam focusing took place at Sandia, Cornell, and the Naval Research Laboratory. By 1979, as the result of a successful series of ion-beam generation and focusing experiments on our Proto-I accelerator, we were committed to the light-ion approach to inertial fusion.

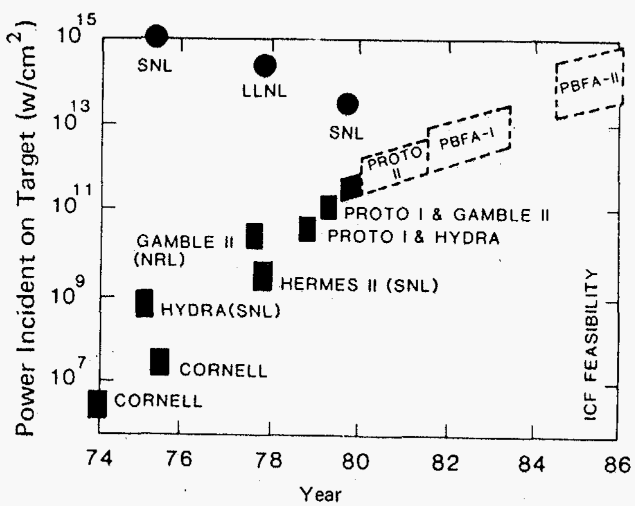
In 1981 we will investigate scaling on the 10-terawatt generator Proto-II before extending to the megajoule, 30-terawatt level on the Particle Beam Fusion Accelerator, PBFA-1, in 1982. We expect to upgrade PBFA to the 3.5-megajoule, 100-terawatt level by 1985.

Advances in ion-beam generation and transport will be required before beam concentration can be improved. New ion sources, diodes, plasma channels, and diagnostic methods are under ac-



Proto II

tive development. Current research is oriented toward creating and diagnosing the conditions needed to demonstrate ICF feasibility. The section that follows discusses examples of methods and developmental activities in Sandia's ICF program.



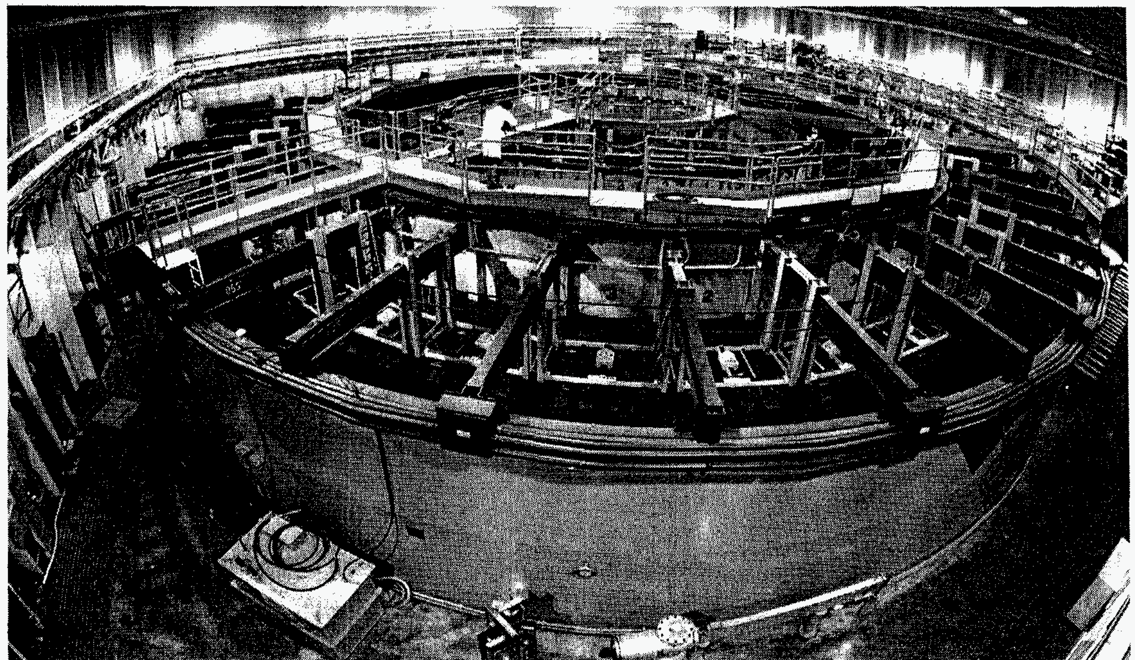
Significant milestones for the demonstration of ICF feasibility

Pulsed-Power Generators

A new type of pulsed-power generator has been developed to provide electromagnetic pulses for laboratory experiments requiring very large power and energy pulses. The technology was demonstrated in the 30-terawatt, 1-megajoule PBFA-I, which became operational in 1980. This modular system efficiently produces terawatt power pulses by multistaged energy transfer, storage, and switching. Tens of modules are synchronized with low-jitter gas switching, and the short pulse duration of 20 to 40 nanoseconds is achieved with self-breaking water-dielectric switching. To achieve the desired voltage and pulse polarity, the output pulse is conditioned with several water and/or vacuum-insulated devices. Power is transported through long, magnetically self-insulated, vacuum transmission lines to the central experimental area. From there power is channeled to the experiments by means of magnetically self-insulated power feeds.

New technologies—laser-triggered gas switching, magnetic switching, and magnetic flashover inhibition—are being developed to extend capabilities to future accelerators like the 100-terawatt PBFA-II. These new experimental capabilities will greatly advance our knowledge of inertial confinement fusion, weapons physics , and weapons-effects simulation.

PBFA I

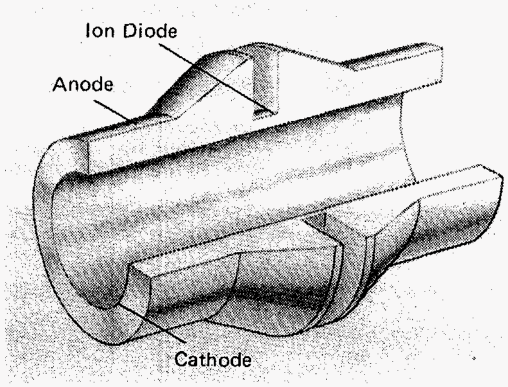


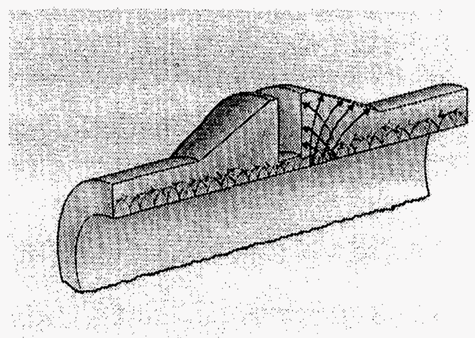
Computer Simulation

Computer modeling of the combined electromagnetic fields and beam dynamics saves time and money in pulsed-power technology and applications. With computer modeling we can vary parameters over a wide range, selecting the best circuit parameters and geometries before commitment to a final design. Our codes use simulation particles to represent electron and ion motion in transmission lines and accelerating gaps. Fields are obtained by the numerical solution of two-dimensional equations that relate internal field distributions to input boundary voltages.

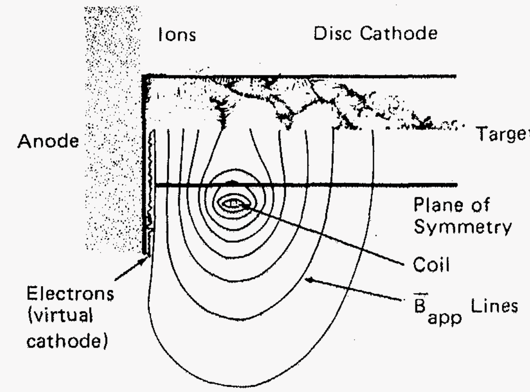
In a typical numerical simulation, the voltage pulse length is divided into many small time segments. During each segment, simulation particles emitted from the electrodes are advanced slightly by electromagnetic forces. Effects of these particles on the electromagnetic fields are included by computing a new field distribution. This process is repeated until particle and field dynamics reach a quasi-steady state. The resulting data can be used to direct new experiments and also to compare with measured parameters.

An example of transmission-line simulation is shown in these two figures. The results are part of a study for PBFA-I of the effects of switch nonsimultaneity on insulating properties of the power-transmission lines. The first figure shows a model of two coaxial lines feeding a common, symmetrically located, ion-generating diode. The right transmission line was delayed to represent switching jitter. The second figure shows typical electron trajectories when the pulse begins to deliver power to the load. The two wave fronts interact just at the right of the load, resulting in greater leakage of electrons. The simulations have helped define the allowable limits for switch nonsimultaneity.



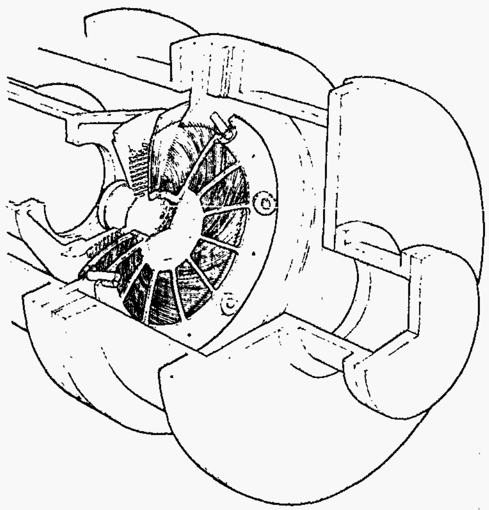


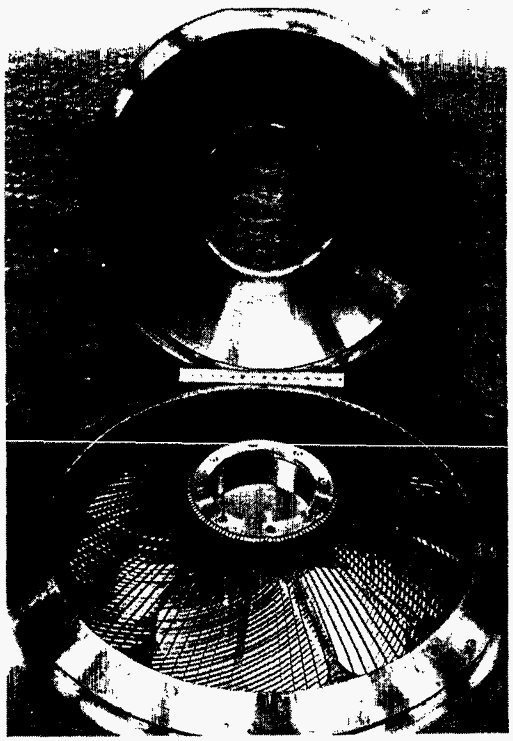
Particle simulation—Proto I ion diode

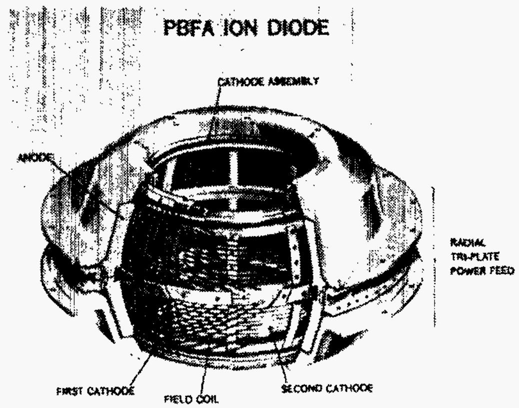


Simulations have also proved useful elsewhere. For example, they helped guide the development of ion diodes for Proto-I and Proto-II. This figure shows the position of the electron cloud that accelerates the ions. We can follow their trajectories to the target mounted on the diode axis of symmetry.

Ampfion multigrid ion diode
(cutaway shows details of the assembled device)



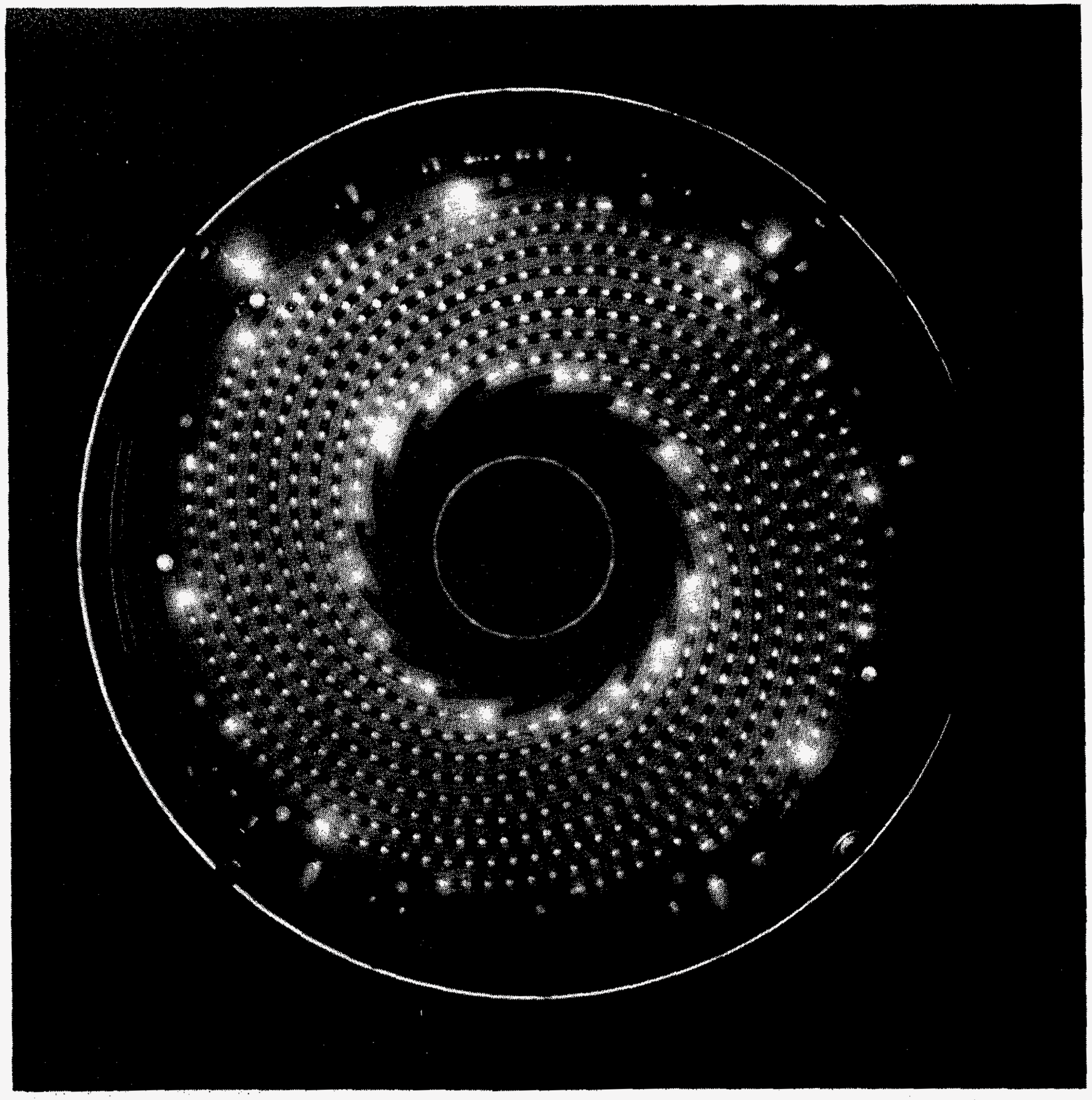




Ion Diodes

In the diode shown in the previous figure, a pair of current-carrying field coils produces the transverse magnetic fields which shut off the electron flow that would otherwise dissipate most of the diode power. Unfortunately, these fields extend over a large region, causing additional unwanted deflection of the ion trajectory and preventing self-neutralization of the ion beam's magnetic field. A complex, multigrid ion diode approach called Ampfion (Auto-Magnetic Plasma Filled Ion) alleviates this problem. Ampfion was designed to accelerate carbon ions, provide its own electron-insulating magnetic field, eliminate undesired magnetic fields from the ion drift region, and focus ions in both the transverse and axial directions. Axial focusing (often called bunching) is achieved by the temporally rising impedance of the diode. This rising impedance causes a rising diode voltage that allows the later, more energetic ions to catch up with the earlier ones at the focal point.

The first series of diode tests has been encouraging. All design features were met except for transverse focusing of the beam. Because inadequate initial uniformity of the plasma that fills the diode causes greater beam divergence, we are developing several ways to improve plasma homogeneity.

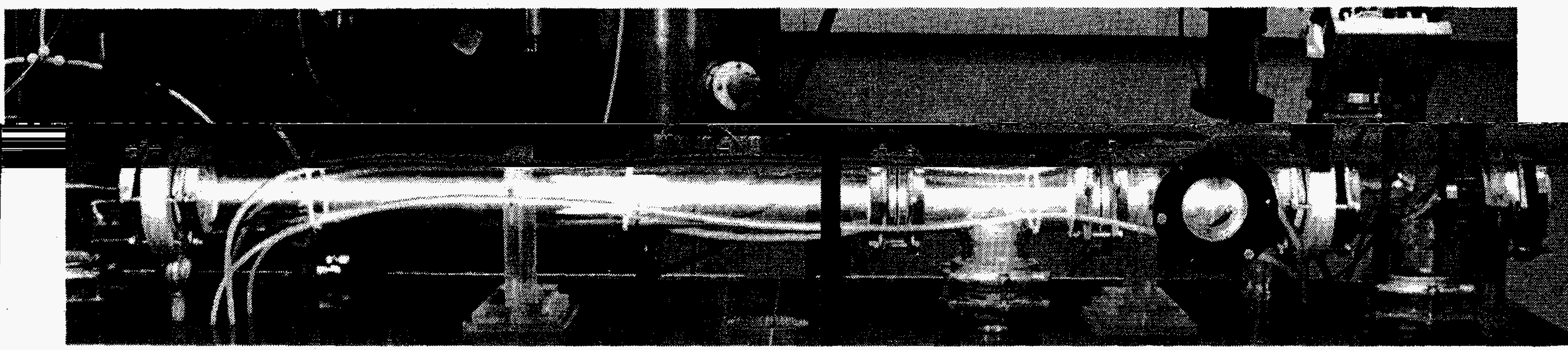


Plasma Sources for Ion Diodes

Efficient high-emittance sources of dense but uniform plasma over large surface areas are needed in ion-beam diodes. Typically a plasma should have a density of about 10^{15} cm^{-3} and should fill the accelerating gap. For a large accelerator like PBFA-I, a plasma volume is needed that covers more than half the surface of a 1-metre-diameter sphere to a depth of about 10 centimetres.

The figure shows the luminous part of a plasma generated by a recently developed source for the Ampfion diode. This plasma is formed over a source that is 30 centimetres in diameter by a series-parallel array of graphite-coated spark gaps, which are discharged by a low-inductance capacitor and switch assembly. The low-inductance circuit supplies a 7-kiloampere current pulse with a pulse width of about 200 nanoseconds. Deposition of nearly 40 joules of energy in the spark gaps within such a short time results in a carbon plasma of the desired density over the area spanned by the spark-gap array. This plasma is more than 75 percent, four-times-ionized carbon. With most of the plasma in a single charge state, the efficient multiplication of power is possible during propagation of beams from the diode to the target. Using printed-circuit materials and techniques

A 142-cm discharge initiated by a pulsed CO_2 laser in 20 Torr (2600 Pa) of ammonia gas



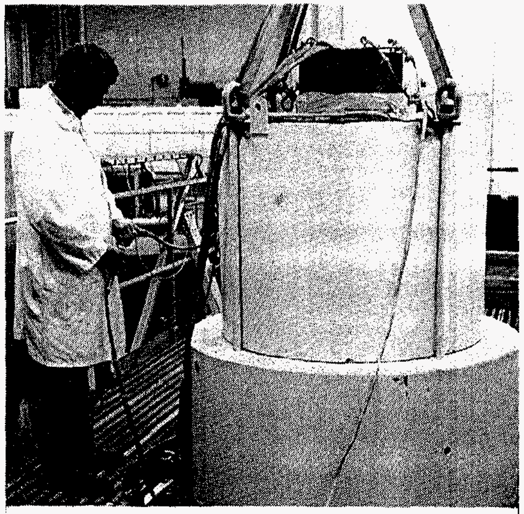
to fabricate the spiral arrays and improved capacitors permits low-cost, accurate replication of these sources and expansion to the large areas required for PBFA-I.

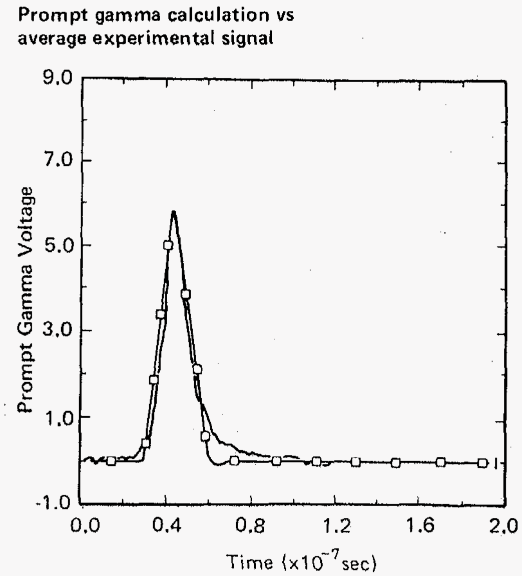
Ion Transport in Laser-Initiated Channels

Efficient concentration of intense ion beams onto a single thermonuclear target in a reactor application requires the creation of guiding plasma channels several metres long. In each channel, an externally driven discharge will confine the ions in the discharge magnetic field as they travel toward the target. We have already shown that ions propagate in wire-guided discharge channels; for repetitive pulsing, however, laser initiation of these channels is needed.

The laser initiates the discharge by heating the background gas so that both axial mass reduction and weak preionization occur. In these experiments a pulsed CO_2 laser is tuned to a vibrational mode of the NH_3 molecule. As little as 1.8 joules of laser energy initiates a 1.4-metre discharge. A particular advantage of this scheme is that the laser absorption mechanism is saturable, leading to an axially uniform preionization and a straight, well-behaved discharge.

Experiments with ion-beam propagation in laser-initiated channels are under way with both time-resolved and total-dose activation techniques. Further work centers on understanding what is needed to properly match the transport channel with the ion diode.





Ion Beam Diagnostics

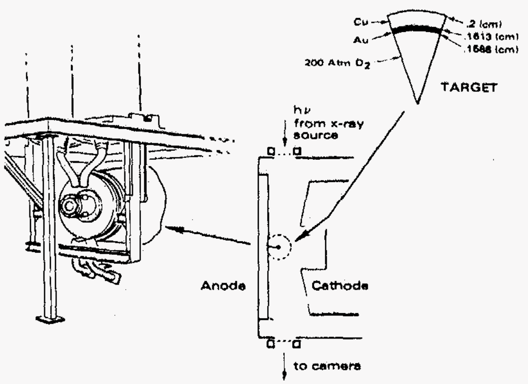
One of the most important and fundamental measurements in particle beam fusion is the measurement of the ion current (and its density) upon an ICF pellet. To measure these quantities for a proton beam, we have developed a prompt gamma-ray diagnostic capability that allows a proton beam to strike a thick Teflon or lithium metal target. Prompt gamma ray from nuclear reactions are then emitted in a quantity that is related to the proton current on target and the nuclear reaction cross section. The proton current density can then be inferred from target size.

The time history of the gamma-ray production is measured with the detector shown here, made up of six heavily shielded scintillator-photomultiplier combinations with a time resolution of 4 nanoseconds. Shielding preferentially allows transmission of the gamma rays produced in the reactions and attenuation of the lower energy X-ray bremsstrahlung background from the accelerator. Typical data obtained from a Teflon target shot on the Proto-I accelerator are shown. The smooth curve is actual experimental data. The curve labeled with open squares is the predicted prompt gamma-ray signal based upon the diode voltage, total diode current corrected for electron loss, and the nuclear-reaction cross section.

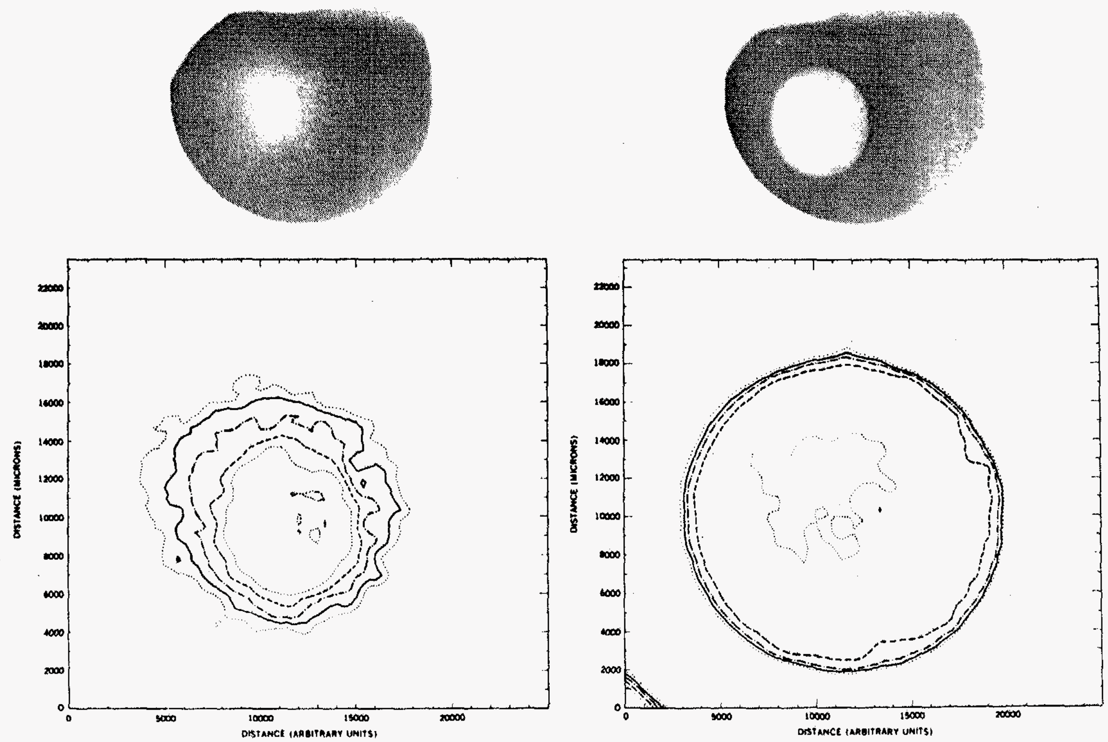
X-Radiographics for Targets

In the ICF approach to controlled thermonuclear fusion, ignition is achieved through compressional heating and confinement of the fuel by an imploding shell of dense pusher material. A major problem is the instability of the pusher during its ablative acceleration and later deceleration by the compressed fuel, which can lead to reduced fuel compression and confinement as well

Experimental setup of
radiographic system and spherical ICF target



X radiographs of deuterium-filled gold lined copper targets. On the right is the target before implosion; on the left the imploded target. The graphs are computer-corrected isodensity contour representations of the target implosion.

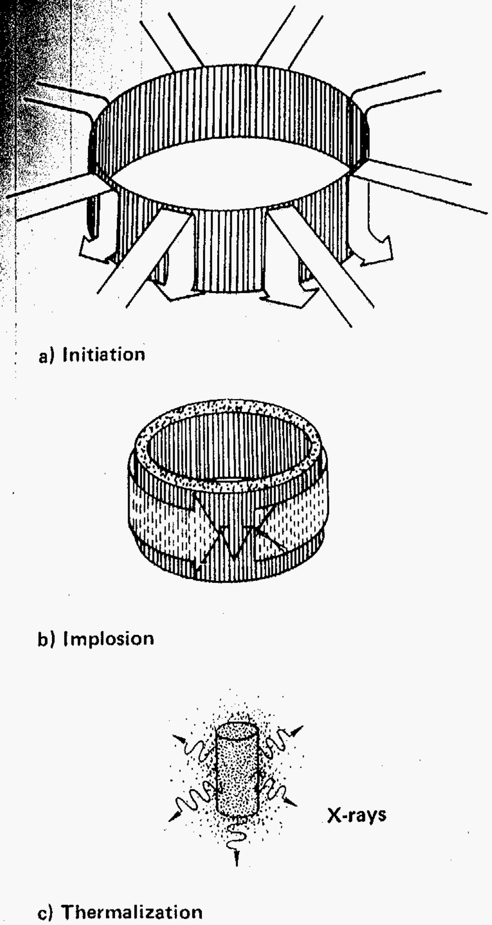


as mixing of pusher material with the fuel. A study of the problem requires an X-ray backlighting technique to observe the target's hydrodynamic behavior through the imploded pusher material. Critical regions of interest are the interfaces between the target ablator and the pusher, and between the pusher and the fuel.

Previous radiographic studies of target implosions used either targets with a low mass pusher or a system of low resolving power; both failed to fully address the important question of pusher integrity during implosion. We have now demonstrated on the Hydra accelerator a high-resolution radiographic device that allows us to investigate target behavior. Our experiments used an electron beam to irradiate a target mounted on a thin fiber.

In these experiments the ablatively driven, spherical targets were filled with 200 atmospheres of deuterium and had a copper shell ablator with a thickness greater than the electron range. The shell was lined with a thin gold layer to permit direct observations of the pusher fuel boundary. This gold liner imploded at a radial velocity of 2 x 10^5 centimetres/second. From the measured convergence ratio we have inferred a maximum fuel density in the compressed state of greater than several times solid density. Similar experiments with ion-beam driven targets will be carried out soon.

Stages in a foil implosion
a) current flows through foil into a plasma
b) plasma implodes
c) X-rays are emitted at very high intensities

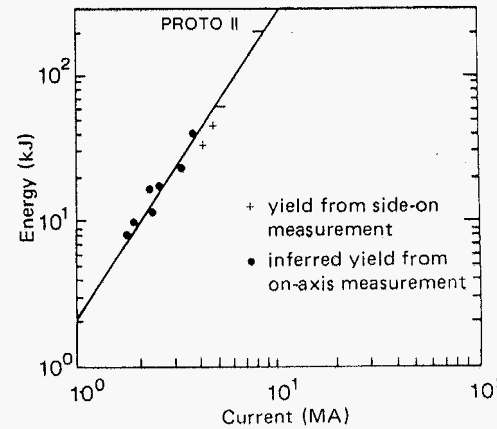


Magnetically Imploded Foils

Two recently developed techniques—magnetic insulation and magnetic flash-over inhibition—have made it possible to build high-power, low-impedance machines capable of delivering the high currents (~MA) and short pulses (<50 ns) needed to magnetically implode foils at interesting energy levels. Experiments have demonstrated that thin (6000 Å) cylindrical foils can be imploded stably by short high-power pulses (5×10^{12} W). The cylindrical implosion produces a dense, hot plasma on axis that will radiate X-rays efficiently at very high intensities. This figure shows the sequence of events by which a magnetically imploded cylindrical foil can be used to produce radiation. These X-rays are suitable for driving ICF targets, and experiments have already achieved 10-nanosecond pulses. The radiated energy has been shown to scale as the square of the driving current over more than an order of magnitude in driving energy.

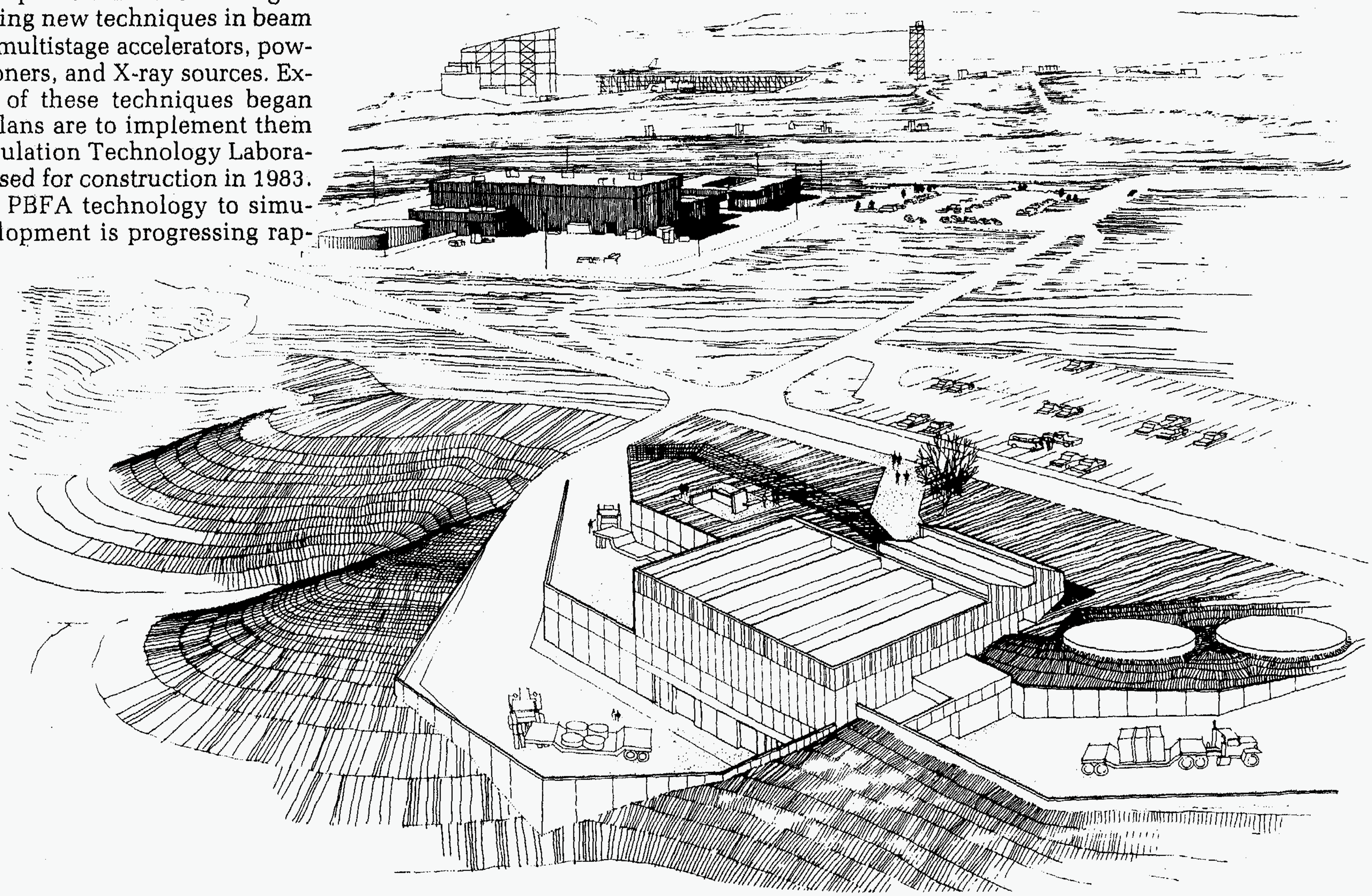
This ICF approach is especially attractive because of the simplicity and efficiency of X-ray production. Experiments to be conducted soon at the 200-kilojoule level will provide a data base for fielding breakeven experiments on PBFA-II.

The scaling of foil kinetic energy with peak driving current

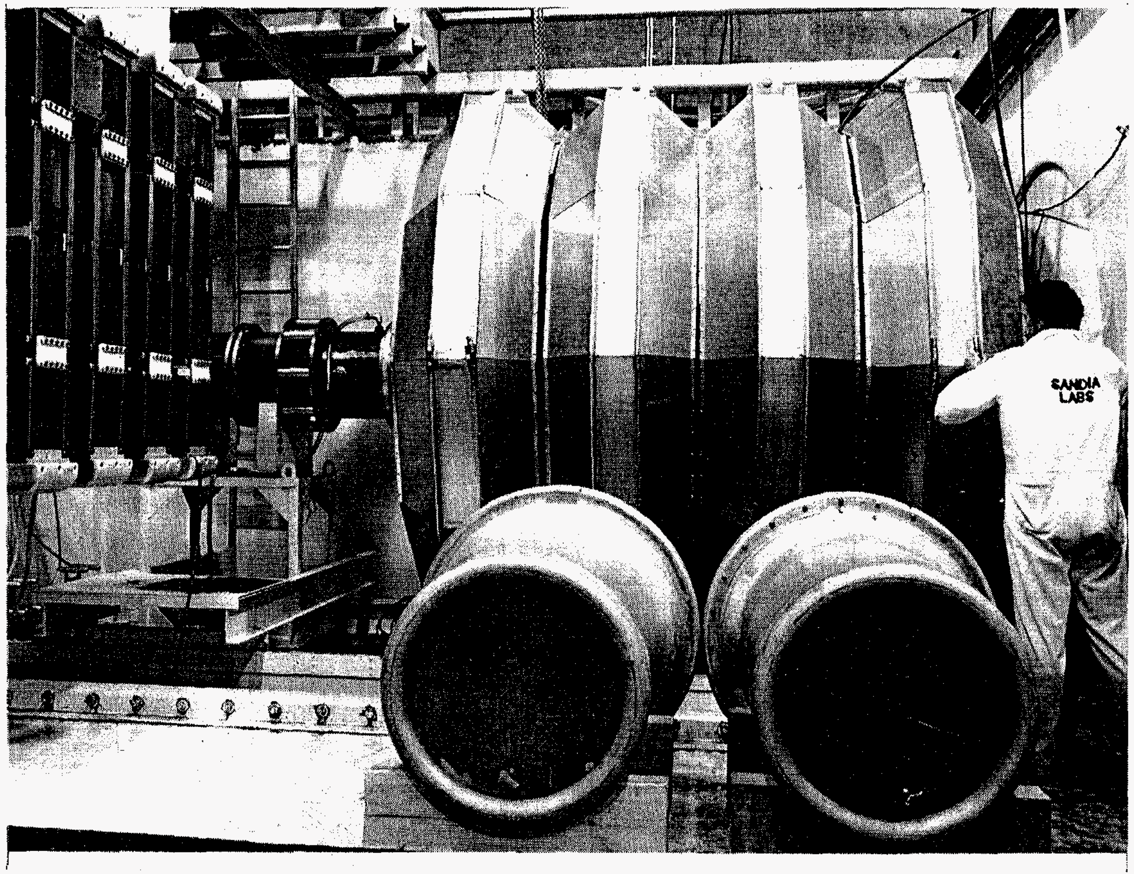


Simulation Technology

With the evolution of pulsed-power technology for PBFA-I, it became clear that radiation simulation capabilities could be improved an order of magnitude by using new techniques in beam handling, multistage accelerators, power conditioners, and X-ray sources. Exploitation of these techniques began in 1980; plans are to implement them in the Simulation Technology Laboratory proposed for construction in 1983. Spinoff of PBFA technology to simulator development is progressing rapidly.



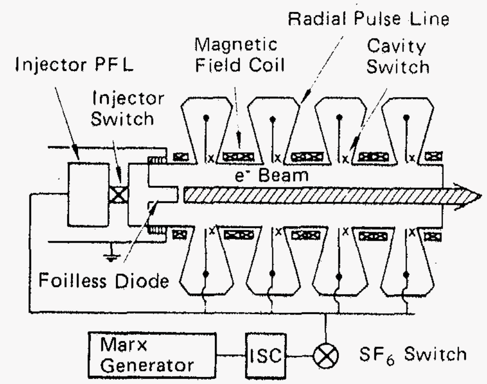
RADLAC I



The RADLAC Linear Accelerator

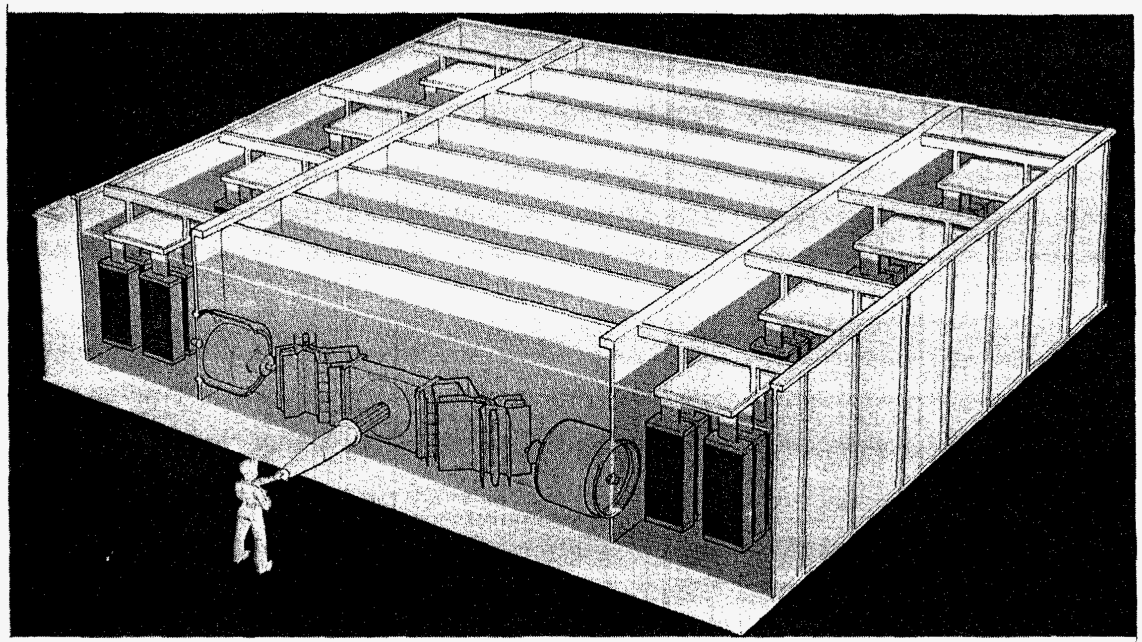
In our multistage accelerator approach, a relatively small, low-voltage diode produces a fast-rising, high-current pulse. The kinetic energy of the beam is then increased as desired by using multiple inductively driven accelerating gaps. Our pulsed-transmission line approach can be compared with the more conventional linear induction accelerators that use ferrite- or iron-loaded accelerating modules. We can achieve higher accelerating gradients (~5 MV/m), higher voltage per accelerating unit (~2 MV/stage), and the capability to accelerate very high beam currents (~100 kA) as a result of low line impedance.

Schematic of RADLAC I. The Marx generator charges an intermediate storage capacitor, which rapidly energizes the injector as well as the four radial pulse lines through a self-breaking SF_6 spark gap. The injector switch and the four RPL switches, all self-break, oil dielectric, are adjusted to give synchronous timing of the current pulse and the application of accelerating voltage in the gaps.



RADLAC-I (Radial Line Accelerator) is our first device based on this concept. It consists of a Marx generator, an intermediate-storage capacitor, a high-current injector, and four radial pulse-line accelerating cavities. An annular electron beam produced by a foilless diode is transported through the accelerator by a strong axial magnetic field.

The artist's conception of Hermes III shows the PBFA Marx generators, intermediate storage capacitors and pulse forming lines which provide the pulsed power. Voltage doubling convolutes drive the vacuum diodes, which contain the accelerating gaps, from both sides. This provides a symmetric power feed. Each beam is injected at 4 MeV and then accelerated through six gaps to reach the final 15 MeV. After final acceleration the beams are guided to a γ ray converter target to provide a uniform, short pulse of high intensity radiation.



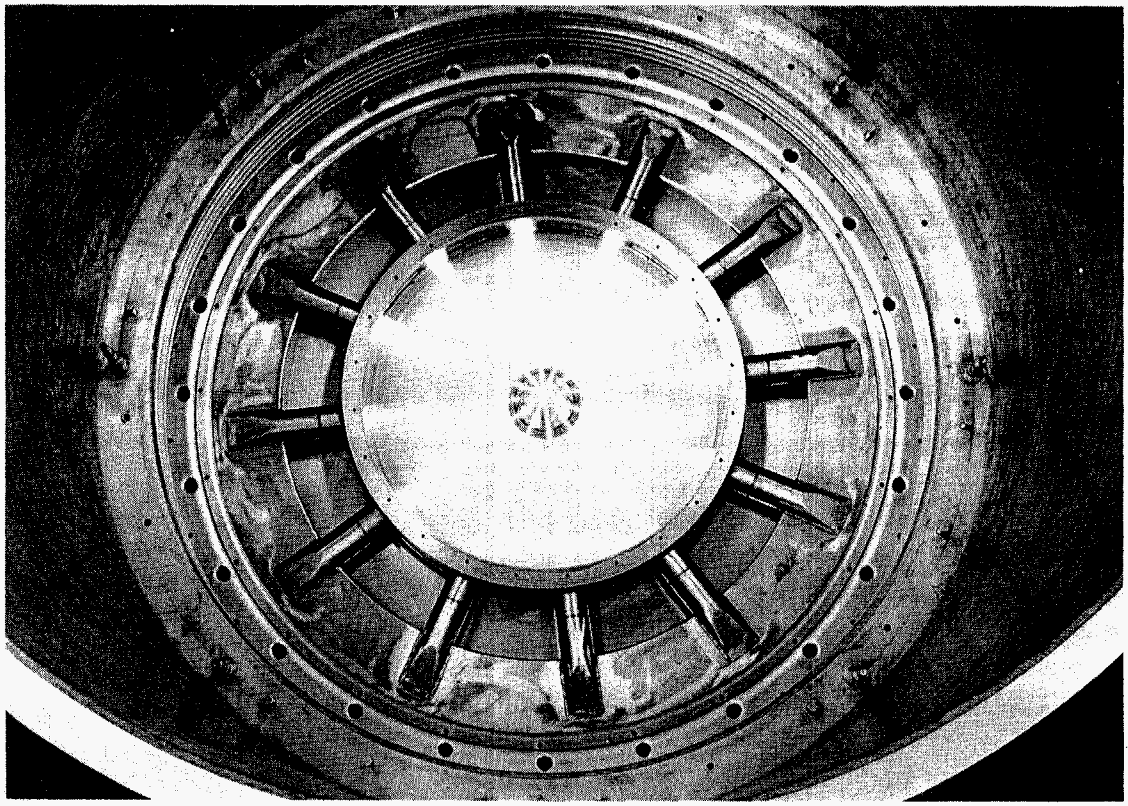
The device has accelerated-beam currents of 25 kiloamperes to kinetic energies of 9 megavolts, with 90 percent current-transport efficiency through the accelerating structure. Experience gained with RADLAC has permitted the design of much higher voltage, higher current linear accelerators.

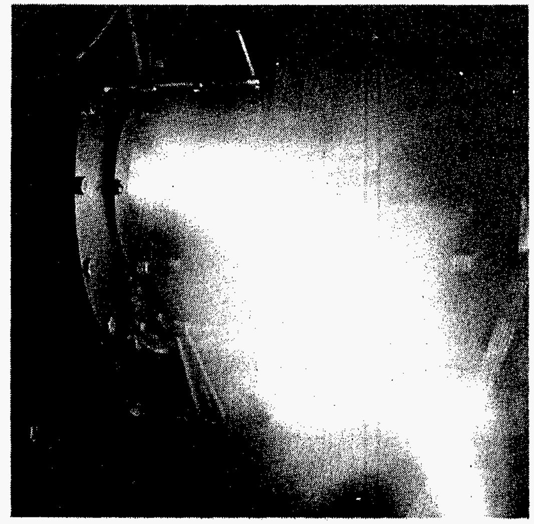
The Hermes III Advanced γ-Ray Effects Simulator

Hermes-III, an advanced simulator to be constructed as part of the Simulation Technology Laboratory project, will satisfy our γ-ray vulnerability testing requirements for dose, dose rate, and the time-derivative of dose rate over an exposure area. It will allow testing weapons systems electronics packages up to subsystem size. Simulators now in use deliver their dose in a relatively long pulse (~100 ns). This means that important time-dependent effects cannot be simulated. The 20-nanosecond radiation pulse width of Hermes-III will eliminate this deficiency.

Hermes-III will combine the multiterawatt, short-pulse, modular pulsed-power technology from PBFA with the high-current, high-voltage electron-beam handling capability from RADLAC to deliver multiple electron beams totaling 1.1 megamperes at 15 megavolts onto a γ-ray converter target. A multiple-beam approach will minimize the inductance associated with each beam injector diode and accelerating gaps, allowing use of the short, fast-rising pulse from the PBFA modules.

Experiments are under way to develop multiple-beam handling methods for Hermes-III. The Megamp Accelerator and Beam Experiment (MABE) is the primary test bed for Hermes-III development.



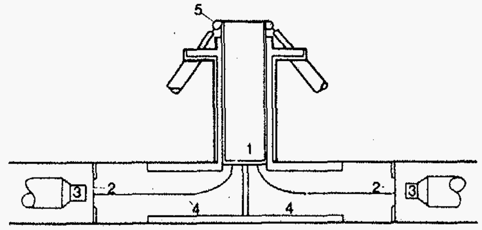


Beam transport technique within a curved channel

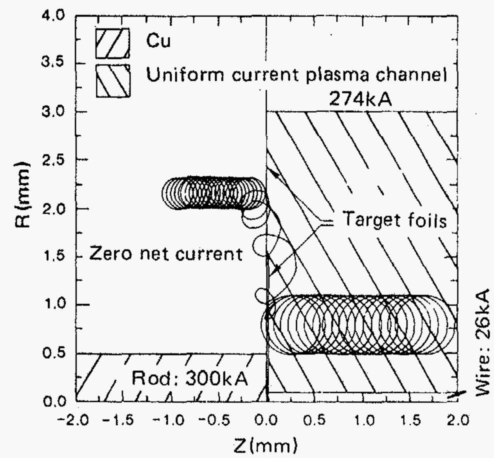
MultiBeam Transport Use for Bremsstrahlung Sources

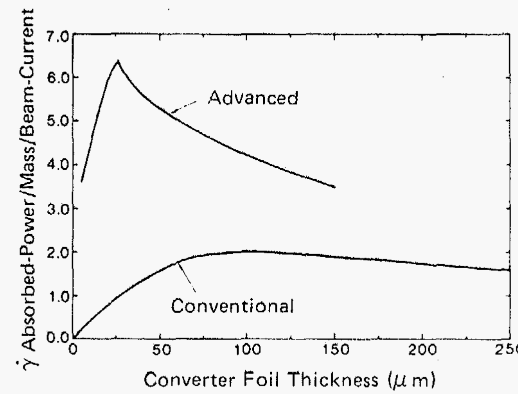
For eventual fusion applications, multiple ion beams will be transported in current-carrying plasma channels. The magnetic field from the discharge-driven current, supplied from a separate capacitor bank, will confine the ion beam in the channel. This concept has already been tested with an array of electron beams focusing like the spokes of a wheel onto a central target. Measurements of electron-beam transport efficiency have been correlated with theory, permitting a normalized method for predicting ion-beam concentration. We have also concluded that electron beams can be delivered efficiently to targets as small as 1 centimetre in radius.

Application of this beam-transport technique to radiation-effects experiments now opens a new degree of flexibility in bremsstrahlung source development. We have found that beams can be transported equally well in either curved or straight channels. A curved channel requires that the discharge follow a fine wire curved along a prescribed path.



Schematic of advanced Bremsstrahlung source concept





As shown in this figure, electron beams generated in accelerators like Proto-II can be redirected so that they strike a single bremsstrahlung radiation converter from about the same direction.

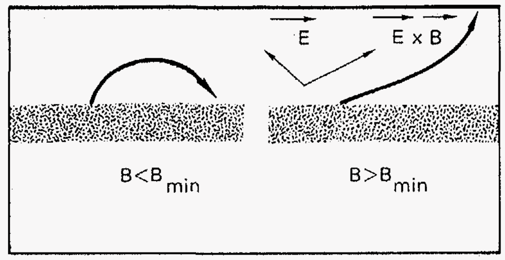
Advanced Bremsstrahlung Radiation Sources

Advanced techniques to improve the efficiency and spectral control of bremsstrahlung sources are under development. Our goal is to simulate radiation effects in subsystems at higher levels than before.

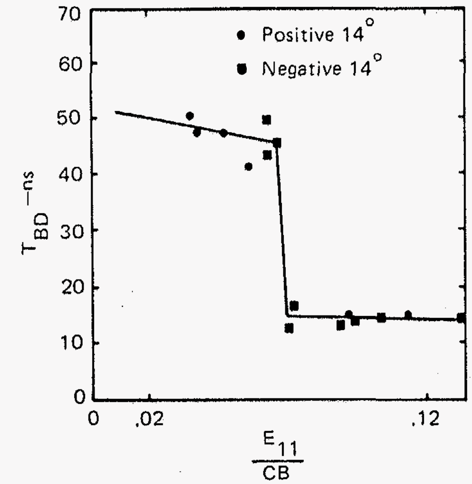
One method under study involves propagation of a beam in the magnetic field created by a current-carrying rod. The beam drifts cycloidally in a region where its own forces are neutralized by a background plasma, as shown in this computer simulation of electron behavior. The beam then interacts with a target foil located at the end of the rod, where the current is split with the current from a much smaller wire and a plasma channel in such a way that the beam tends to stagnate at the foil. The abrupt change in the azimuthal magnetic field focuses the beam, causing the electrons to make multiple passes through the foil. An advanced source is obtained by replacing the copper target with a thin tantalum converter foil.

In this figure the power deposition in the surface layer of a gold foil, when exposed to the bremsstrahlung environment of this advanced converter, is compared with the more conventional situation where the same beam interacts with the foil without reflexing. Realizing this concept will depend—among other things—on our success in achieving efficient injection, minimizing collisional losses in the transport stage, obtaining proper field variation at at the converter, and dealing with any collective or hydrodynamic effects.

Magnetic flashover inhibition



Cathode Field



Although the basic elements of pulsed power have changed relatively slowly since 1965, there are many new opportunities for advances in power generation and conditioning. The first terawatt accelerators permitted us to investigate methods of "magnetic" insulation that allow the transfer of power at enormous levels of intensity. New, more efficient methods will soon be available for transferring power between pulse-conditioning stages in a precise, repetitive, long-lived, and reliable manner. We are also seeking ways to use chemical energy for delivering the ultra-short pulses needed with high-power accelerators.

Magnetic Flashover Inhibition

With magnetic flashover inhibition (MFI), magnetic fields associated with the large currents in low-impedance, high-power accelerators inhibit electrical breakdown at the vacuum insulator interface. This interface divides the liquid-dielectric pulse-forming line from the vacuum magnetically insulated transmission lines in the accelerator's power flow sequence (see figure for the basic concept). In the first phase of breakdown, an electron avalanche begins on the insulator surface. If the avalanche is unchecked, eventually a plasma forms a low-impedance path across the insulator surface and shunts all current from the magnetically insulated transmission line. Theory indicates (see figure) that there is a critical value of magnetic field at which electrons are pulled out of the avalanche, interrupting breakdown.

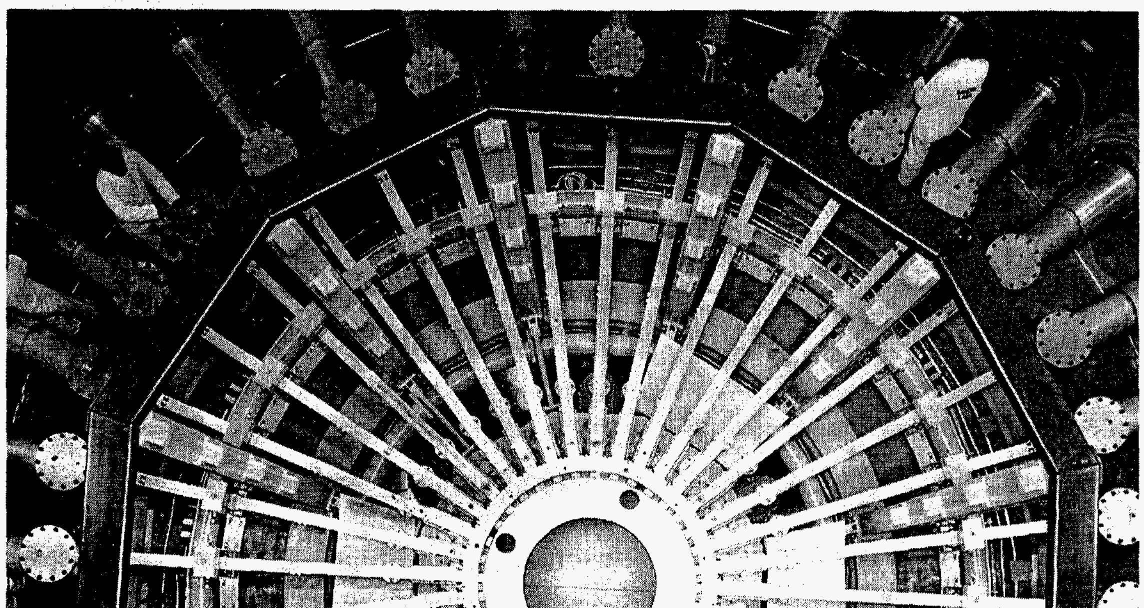
For Proto-II operated without MFI, the breakdown strength of the insulator interface is 14 megavolts per metre. Recent experiments with Proto-II in the MFI mode have reached breakdown strengths of 24 megavolts per metre. This is equivalent to a threefold increase in the power flowing through the insulator interface. This experiment is significant because it verifies MFI for a large insulator surface area.

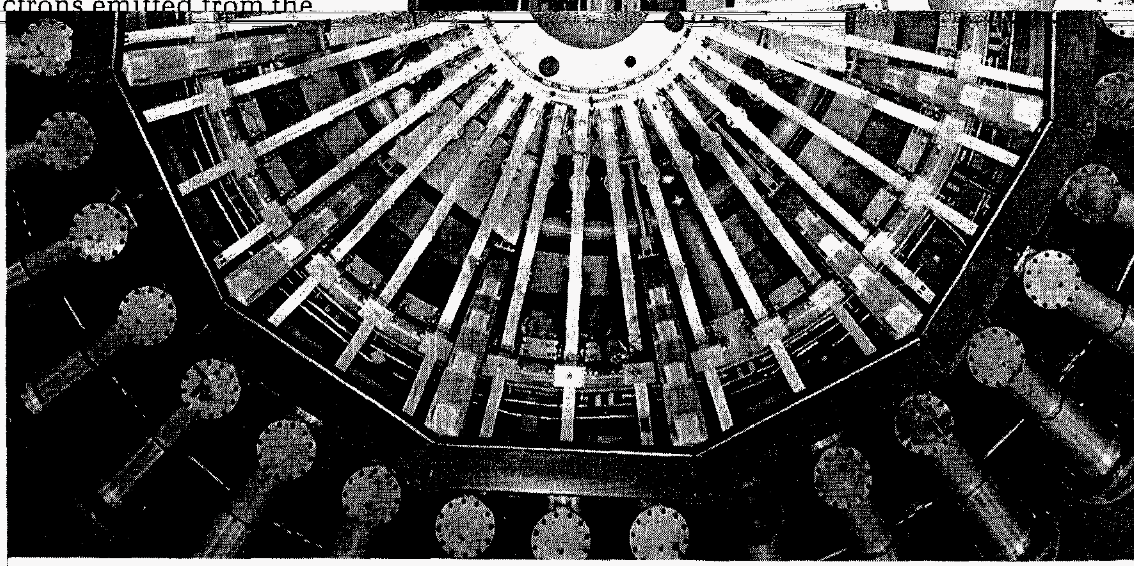
Transport of Terawatt–Level Power Pulses

Magnetically self-insulated vacuum transmission lines (MITLs can efficiently transport short (several tens of nanoseconds), very intense power pulses with far higher electric-field stress and power density than can conventional power-transport systems. Thus, energy generated in relatively large capacitors and pulse-forming lines can be compressed and delivered to ion- or electron-beam diodes closely grouped around a target, as they are in fusion or radiation simulation.

High field stresses (~10 MV/cm) and power densities (1 TW/cm²) are possible because electrons emitted from the

Top view of PBFA I's MITLs





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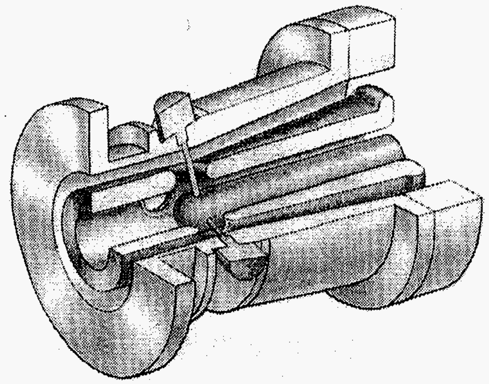
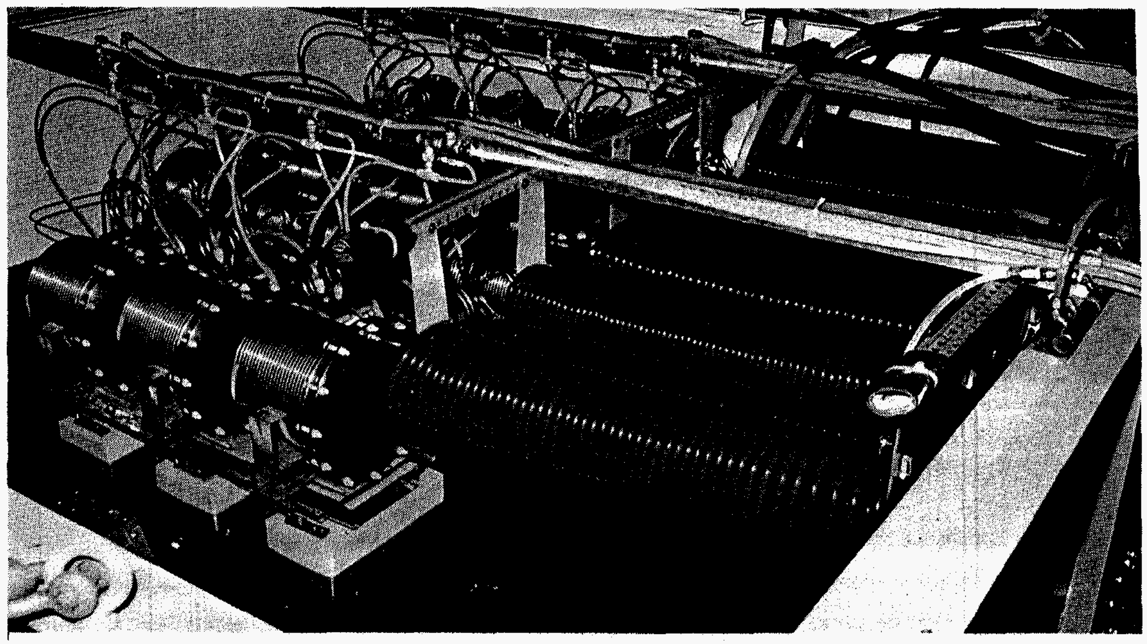
Cutaway of convolute



"convolute" has also successfully transformed a coaxial line to a triaxial line by passing half the incident power of 1 terawatt through four 1.6-centimetre-diameter holes with 3-millimetre center pins. A similar convolute combines two radial disk lines into a single parallel disk feed at a level of 8 terawatts.

Tests are under way on a convolute to connect the 36 individual PBFA-I MITLs into a radial disk feed. One exciting prospect is a convolute designed to combine the 36 PBFA-I lines (operated half positive and half negative) to obtain doubled output voltage.

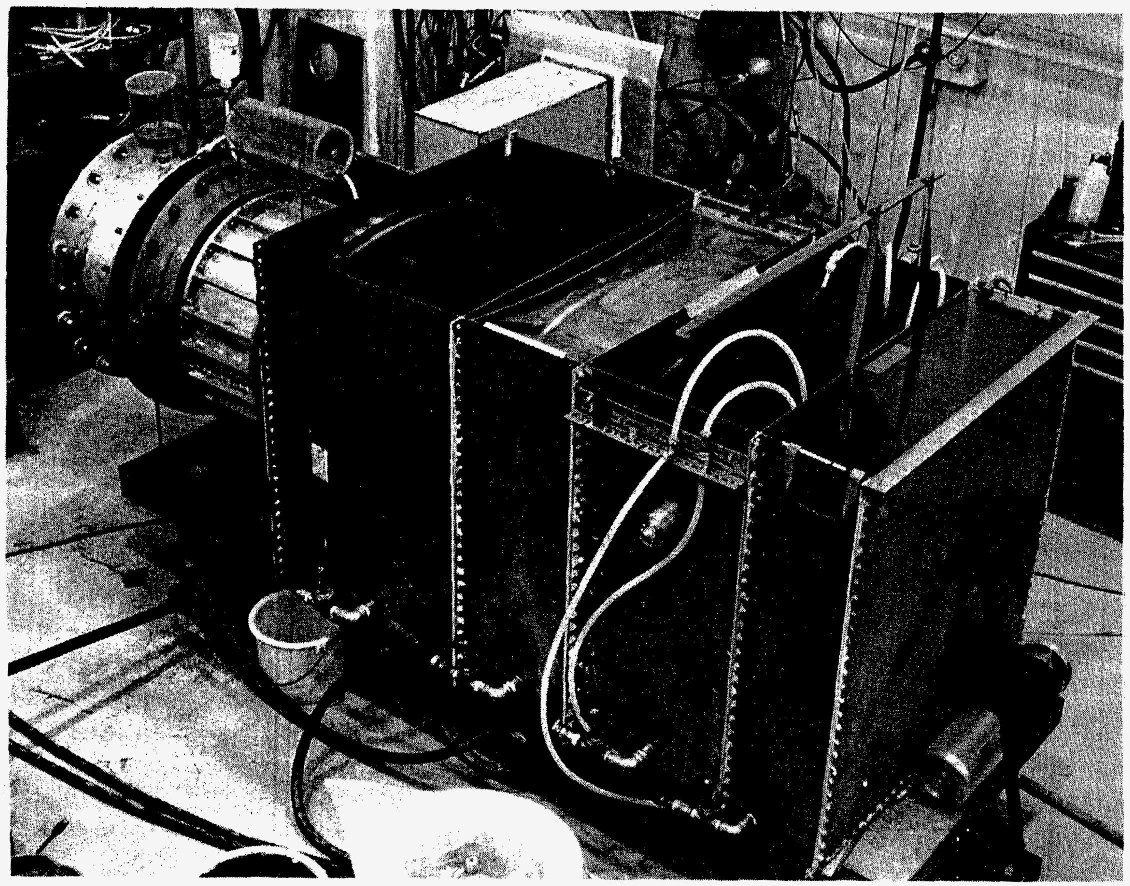
Inductively isolated Marx generator



Repetitive Pulsed Power

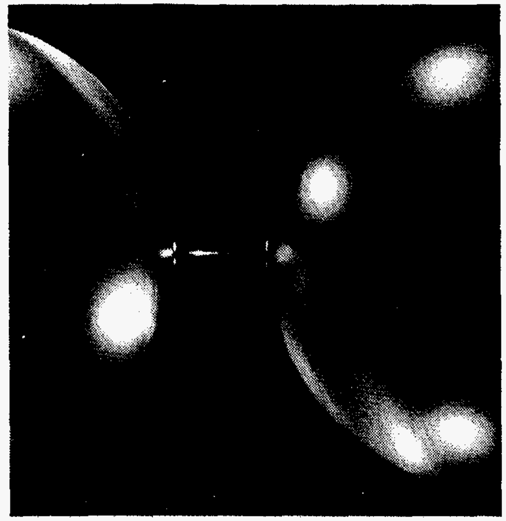
High-average-power accelerators will be needed to transform ICF systems into economical energy sources based on the light-ion-beam approach. These same components can be used in the electron-beam accelerators required for most gas laser systems. Significant progress has been made in developing both transformer and Marx-generator systems for these applications.

Pulsed power accelerators traditionally use Marx generators for primary energy storage and voltage multiplication. We are looking at techniques for replacing charging resistors with inductors that will increase the energy-transfer efficiency of these generators to more than 90 percent. The photo shows an inductively charged Marx generator (3 MV, single pulse, 1.5 MV repetitive pulse, 20 hz, 1.25 — 5 kJ) developed at Sandia and now used to test capacitors and to develop high- and low-voltage spark gaps that will allow operation for more than 10^7 pulses. Measurements are under way to determine the ultimate efficiency of energy transfer.

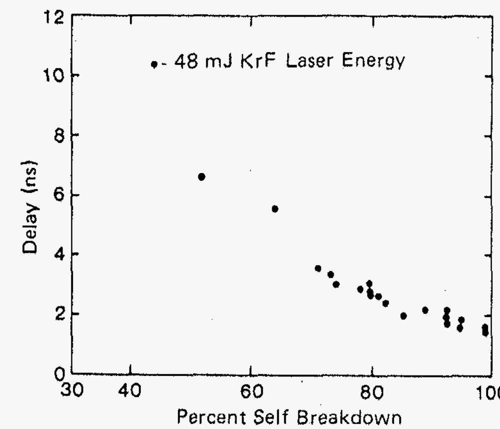


Transformer system

Resonantly charged, air-core transformers offer an attractive alternative for energy storage and voltage multiplication in repetitive systems. This photo shows a transformer system (1.5 MV, 1.25 kJ, 20 pps) developed and operated for $>10^6$ pulses in a continuous run without failures. The energy-transfer efficiency from the capacitor bank to the pulse-forming transmission line is more than 91 percent. The transformer steps up the voltage from 22 kilovolts on the primary capacitor bank to 1.5 megavolts on the pulse-forming line. Unique electrostatic grading structures in the secondary allow high-voltage operation without degradation of the magnetic coupling. This experiment is being upgraded to the 5-kilojoule level, and the design of a 50-kilojoule experiment is nearly complete. Demonstration of operation at this level would be a critical step toward a megawatt, average-power, light-ion-beam system.



Delay vs self-breakdown voltage, KrF laser into 10% SF_6/90% N_2



Laser Triggered Gas Switches

Laser triggering may provide a way to obtain subnanosecond timing of multi-megavolt gas switches in large pulsed-power systems like PBFA. The gas switch under study uses two rounded metal electrodes, each with a small hole in the center to allow injection of a laser beam, and a high-pressure gas as a dielectric. Unlike previous triggering experiments where a laser was used to generate a point plasma at one electrode, we use an ultraviolet laser to ionize a channel of the dielectric gas between the electrodes.

Two different triggering schemes have been studied. In the first, we used dopant molecules that are ionized in the intense laser fields. The dopant concentration is only ~10 parts per million, but provides an adequate laser-induced source of electrons. In the second triggering method we induced the breakdown of SF_6 by means of a tightly focused, KrF laser beam. We have observed breakdown arcs 10 centimetres long in multiatmosphere mixtures with as little as 70 millijoules of laser energy.

Using ultraviolet lasers with both of these laser-ionization schemes, we achieved low-jitter triggering of a sub-megavolt switch. This photo shows a KrF laser-induced ionization channel between the electrodes of the switch. Data obtained for these conditions are shown in this figure. Between the laser pulse and the switch breakdown, the

t-to-shot jitter in delay time is sub-
osecond for voltages above 70 per-
t of self-break. The curve of delay
percent of self-break is very flat in
region; the delay changes, for ex-
ple, by only 1 nanosecond for volt-
s between 70 and 90 percent of
-break. This would be beneficial in
rge pulsed-power system with many
tches because the voltages on the
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ger pulse arrives.

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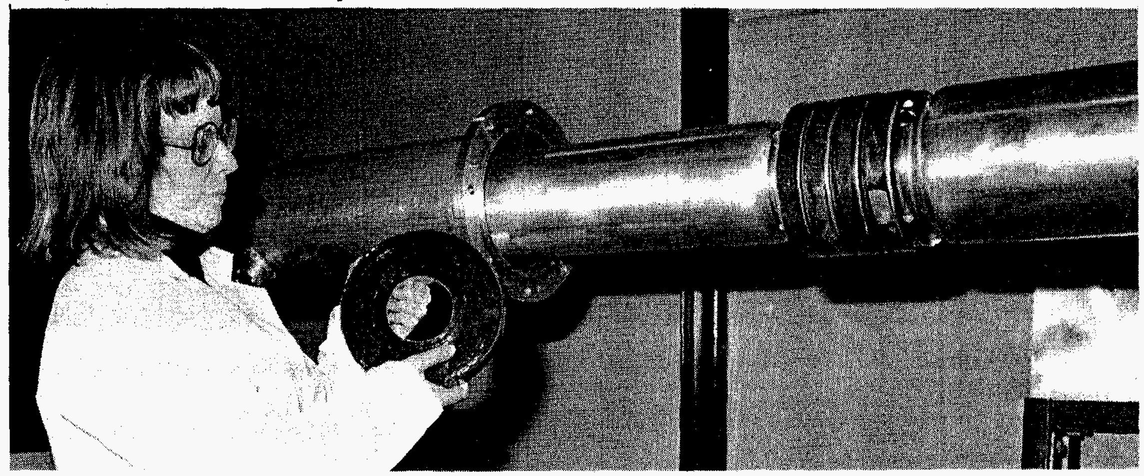
A magnetic switch with a metallic glass core (a toroidal inductor in its simplest configuration)



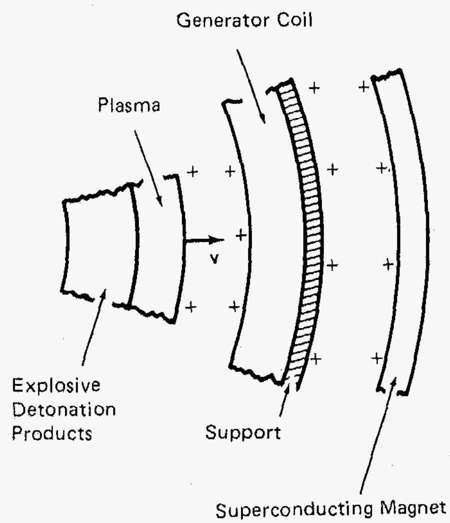
Magnetic Switching

An inductor with a magnetically saturable core can be used as a switch in the following sense. When the relative permeability of the unsaturated core is high, the inductance of the element is also high. This high inductance effectively blocks the voltage-current pulse in a pulse-forming line, and when the voltage across the inductor reaches a certain point, the core saturates. Its relative permeability approaches 1, and the inductance of the element drops suddenly by a factor of several hundred, allowing the pulse to pass. If this switching effect occurs at close to maximum voltage, the result is a strongly time-compressed pulse of high peak power.

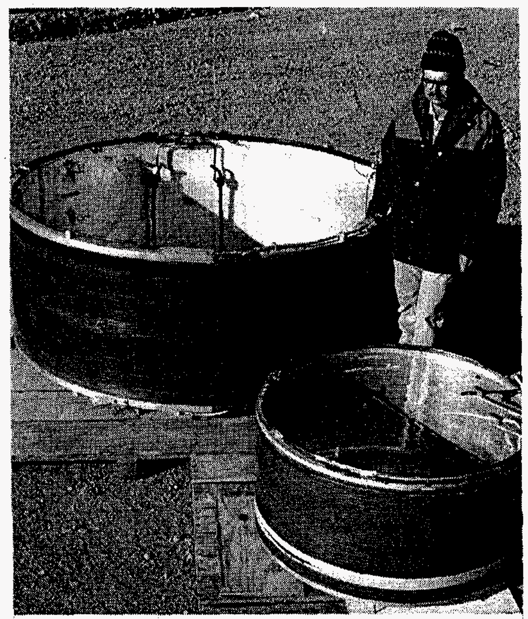
At the power levels used for magnetic switching several years ago, this technique was less attractive than solid-state and thyratron technology. Only recently, with the need to dependably and repetitively switch very high power in very short times, has magnetic switching resurfaced as a possible solution. Gas spark gaps degrade rapidly at these power levels, and water gaps have impossible repetition rate characteristics. At the same time, advances in magnetic materials have lessened some of the early problems with response time and energy loss. These is good reason to believe that a saturable inductor can provide the fast, dependable, repetitive switch needed in many pulsed-power applications.

Sandia's magnetic-switching experiment (see photo) uses a Marx generator to produce a 160-kilovolt, 200-nanosecond pulse. This pulse drives a water-transmission line with two back-to-back metallic glass cores placed in the system to form a single-turn inductor midway down the line. Our data have demonstrated magnetic switching on a useful time scale in a typical pulsed-power configuration. Future experiments will investigate the power-handling and repetition-rate characteristics of this technique.

PULSAR generator elements



Superconducting coils of the 1- and 2-m magnets will store 300 kJ and 2 MJ, respectively



Electric-Pulse Generation by PULSAR

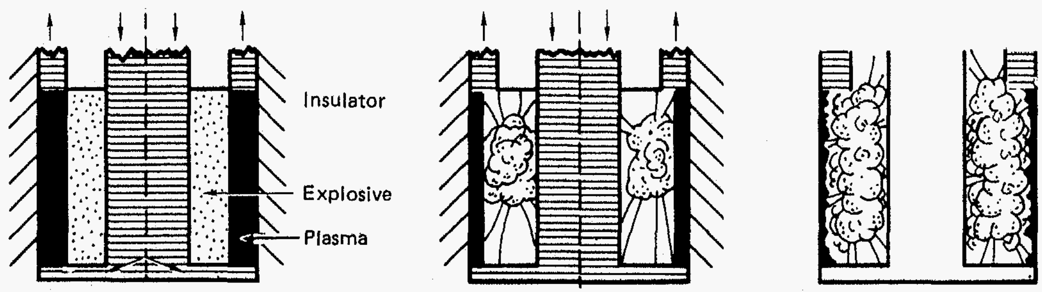
The traditional method of producing high-power electric pulses is to generate electric energy at lower power, accumulate it in storage capacitors, then suddenly release it by fast switching. For future applications calling for pulses of unprecedented energy, however, this method may require facilities that are too large, complex, and expensive to be practical. To provide a better primary power source for very high energy applications, a pulse generator called PULSAR is being developed that could produce electric pulses at high enough power to eliminate the need for initial storage and switching. This type of generator could furnish relatively convenient, inexpensive access to an energy regime that is not now available.

Pulses are generated by using high explosive to drive a highly conductive plasma into a generator coil nested within a superconducting magnet. The velocity and electrical conductivity of the plasma are high enough to trap and compress magnetic flux of the magnet within the coil. A power pulse in the generator circuit is then produced without damage to the system and without loss of current in the superconducting magnet.

Limitations in the chemical power of the explosive mean that the plasma's conductivity and velocity cannot be made high enough for efficient operation at small scale. The thrust of the experimental/theoretical program is to determine the scaling laws. Experiments began with generators of about 0.3-metre diameter and will continue with larger ones (1- and 2-metre diameter). The power level produced at the 0.3-metre scale was 2×10^8 watts.

The most difficult task is to understand, model, and control the mixing that takes place between the highly conducting plasma and the poorly conducting products of explosive detonation. This mixing, apparently driven by the Rayleigh-Taylor instability, is an important factor limiting performance at small scale. At large scale its importance should diminish.

Switch mechanism



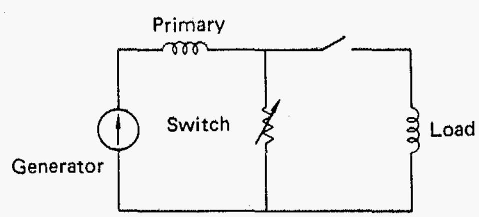
Step 1. A cylindrical plasma is formed as current flows through the system.

Step 2. The centrally located explosive is detonated, and the plasma channel is compressed.

Step 3. An instability develops between the plasma and explosive products. This instability mixes the non-conductive explosive products into the plasma, and current flow is terminated.

Explosively Activated, Fast-Opening Switch

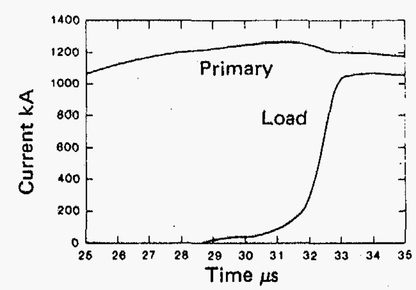
Inductive energy-storage devices such as explosively-compressed magnetic-flux generators and homopolar generators can deliver energies up to 100 megajoules, but these devices typically operate much more slowly than the submicrosecond range needed for most pulsed-power applications. If we use



an opening switch, as shown in this circuit diagram, the stored energy from the inductive generator can be diverted from the primary circuit over to the load on a time scale governed by the operating time of the switch. We are developing such a fast-opening switch for use with magnetic-flux compression generators. Its operational element is a conducting plasma that carries the total primary current until the channel is compressed and interrupted by an explosive charge. The figure explains operation of the switch.

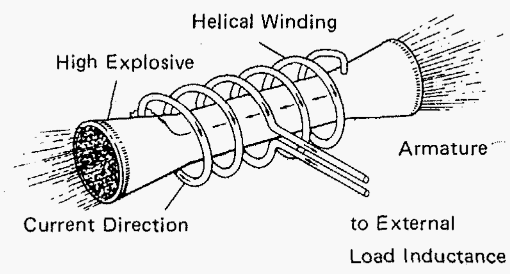
When current flows through the aluminum film, an aluminum-air plasma is formed at the outer surface of the explosive. The explosive is detonated at its axis, and the plasma switch is opened when the nonconducting explosive products compress the plasma and mix into it. Typical current traces are shown on the graph.

Primary and load currents in a small-scale INTREPID experiment

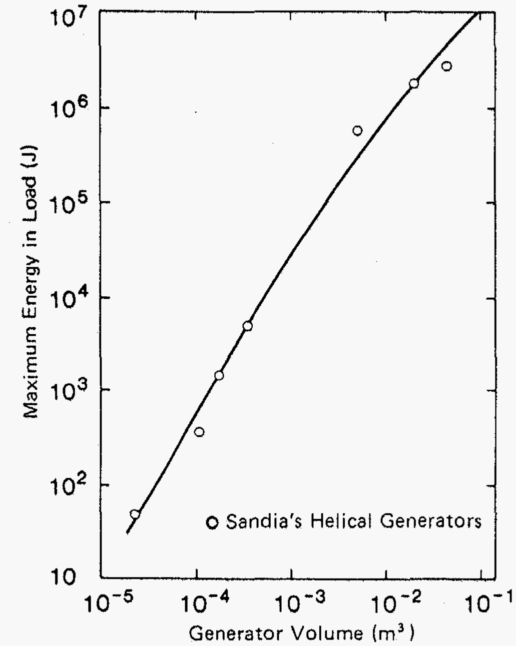


Small-scale experiments have demonstrated submicrosecond switching time at 1 megampere, and scaling data indicate that a large-scale device can be designed for much faster switching time at even higher current levels. This capability, when used with a high-energy inductive storage device, will furnish the pulsed power for experiments in ICF, particle beams, and other advanced concepts.

Schematic of helical generator showing double-ended detonation that increases output power in large designs.



Maximum energy vs volume for seven established helical generator designs. Explosive-to-electric energy conversion efficiency improves as generator volume increases. Conversion efficiency is ~ 5% for the largest generators.



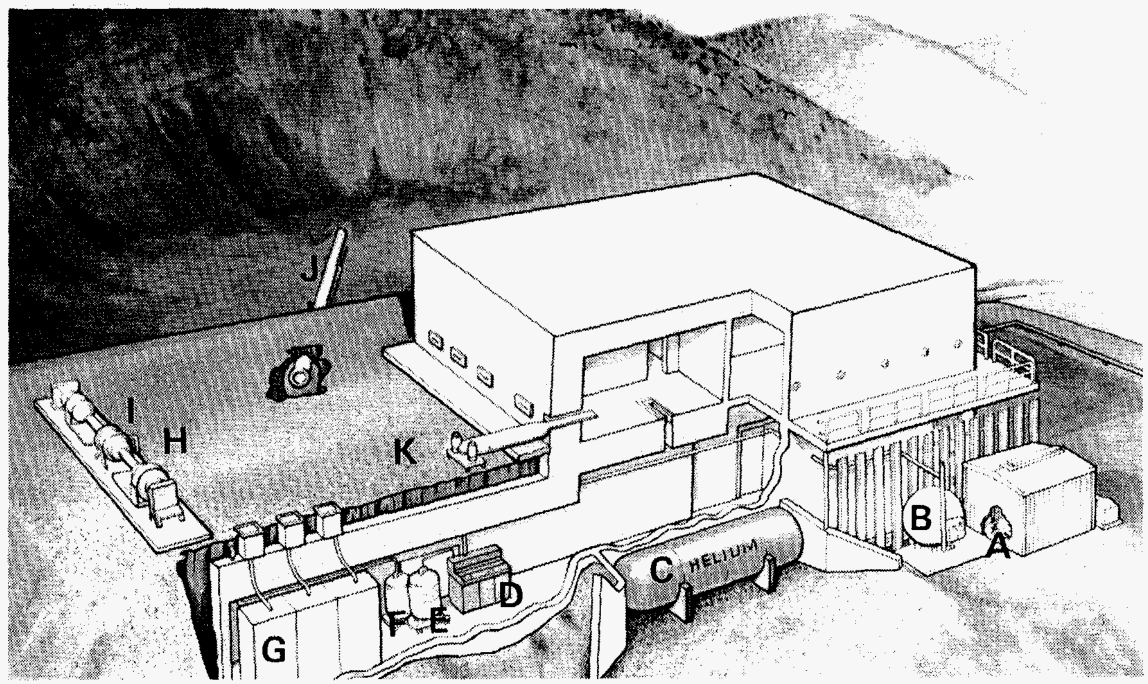
Helical Explosive Generators, and The Electroexplosive Facility

The moving part of an electric generator (the armature) approaches the limit of areal power density when it convects and accumulates the magnetic flux through which it moves. Relatively small, explosively powered, self-destructive generators (explosive generators) made of ordinary copper or aluminum can achieve this, making them useful as compact, one-shot sources of pulse power.

Sandia has spent much effort over several years to develop the helical-type explosive generator, which is the most useful and versatile because of its relatively high impedance. Designs have been developed that produced pulse energies of from 50 joules to 2.6×10^6 joules. Successful computer codes have been written—including the finite-difference, two-dimensional magnetohydrodynamics COMAG codes to investigate basic physics questions, and fast-running equivalent-circuit codes for generator design development and for anticipating performance with various loads (inductive, resistive, and capacitive).

The Electroexplosive Facility was built in 1969 to accommodate large explosive-generator development and application. Recent addition of a helium liquefier and a closed cryogenic system makes this facility unique in its ability to combine high-explosive and large superconducting magnets in the same experiment.

Electroexplosive facility



Features of the cyrogenic system:
A. Helium compressors
B. Liquid nitrogen
C. Gaseous helium
D. Helium liquifier
E. Helium storage dewar
F. Control dewar
H. Helium transfer line

Other features:
G. Three 200 kJ - 20 kV capacitor banks
I. 1-m magnet
J. Recoilless cannon
K. Two explosive generators operating in parallel into protected load

Application to Directed Energy Technologies

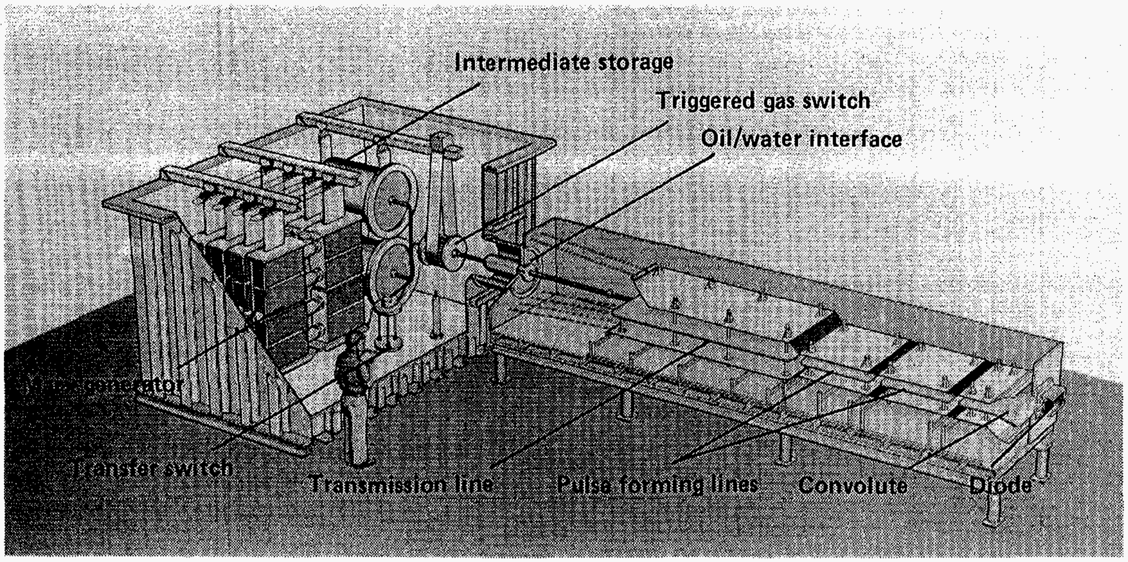
As we explore various ways of accelerating projectiles or producing directed intense beams of light, electrons or ions, we are finding a synergistic interplay among the common pulsed-power technologies. We have shown that electron beams are indispensable for excitation of high-gain gas lasers, and that laser triggering of switches may lead to the low-jitter operation needed for many applications. Now we are learning that the combination of a laser with a powerful electron beam may provide the route to a very compact ion accelerator. We have also shown that controlled injection of electrons into a multistage ion accelerator can greatly enhance the allowable beam intensity in an accelerator that produces an ion beam of low divergence.

RAYITO – Laser Excitation Through the Use of Electron Beams

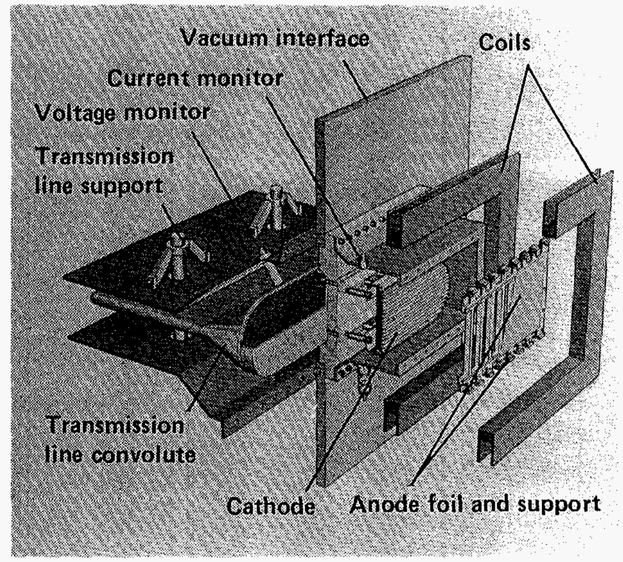
High-power electron beams are generally used to excite several classes of high-power lasers. A few examples are rare-gas-halide (RGH) exciplex lasers, rare-gas excimer lasers, and the hydrogen-fluoride laser. In other gas lasers, electron beams are used to stabilize an electric discharge. The electron-beam system shown here was built to develop advanced power-conditioning technology for RGH lasers, the primary candidates for future-generation drivers for laser fusion.

A diode driver produces an electron beam by megavolt pulse-forming lines that feed energy from the Marx generator. A plasma is formed on the cathode by the electric-field-induced flashover of the cathode surface, and the intense electric field accelerates the electrons toward the anode. The high-energy electrons passing through the thin foil that separates the high-pressure laser cell from the vacuum diode are stopped in the cell by multiple collisions with gas molecules. Excitation

RAYITO electron-beam system



RAYITO diode

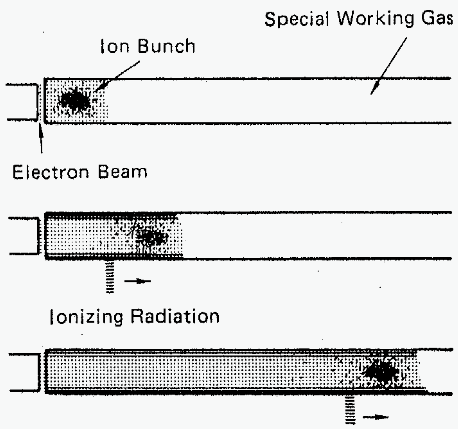


pathways in the laser are complex and laser-specific, but in many different lasers a high efficiency is realized through converting electron-beam energy to laser energy.

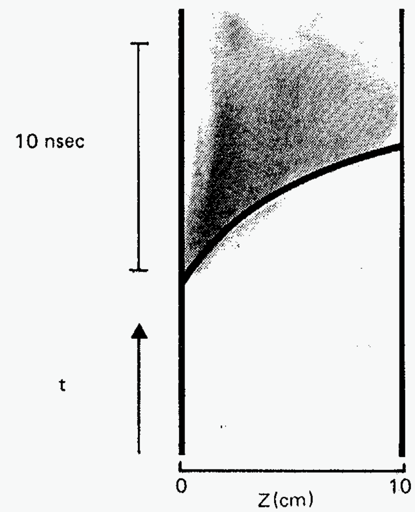
The RAYITO facility functions as a test bed of advanced power-conditioning technology for laser-fusion RGH lasers. System specifications require a large increase in the efficiency of the pulsed-power system, and improved methods of managing the intense electron beam in both the diode and the laser cell. Electron beams can be managed through the use of intense magnetic fields to control electron trajectories. But advanced technology is needed to reduce the magnetic-field requirement in order to realize an energy-efficient, affordable system.

Other areas of technology development include methods of increasing transfer efficiencies of the pulsed-power system and the ribbed structure that supports the thin anode foil. This foil separates the high-pressure laser cell from the vacuum diode.

The IFA Concept



Demonstration of IFA beam-front control. The beam enters from the left and follows the programmed sweep of the curved line. Here protons are accelerated from rest to 5 MeV in 10 cm.



The Ionization-Front Accelerator (IFA)

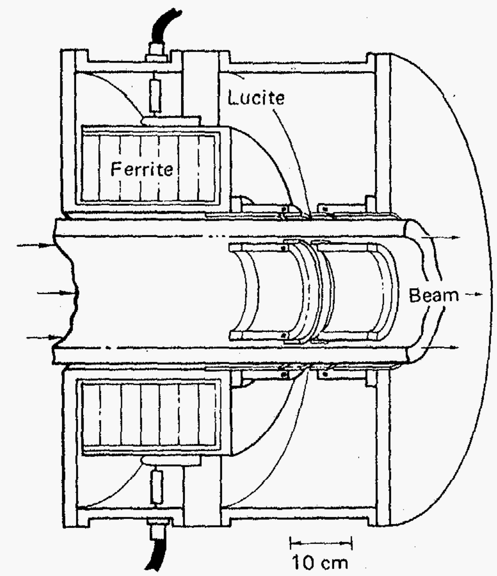
In the IFA—a high-gradient, collective-effort accelerator—ions are accelerated in a deep potential well at the head of an intense relativistic electron beam (IREB). The potential well is made to move with the desired phase velocity by actively controlling the ionization of a suitable working gas. Laser photoionization is used to ionize the gas, and the laser light is accurately swept to produce a moving ionization front. The potential well at the IREB head follows this front synchronously. Ions are trapped and accelerated in the potential well up to high energies.

Conventional ion linacs have accelerating fields of only about 1 megavolt per metre, whereas the IFA provides a direct way to control accelerating fields of about 100 megavolts per metre and higher. This IFA concept promises a new generation of compact, high-energy, high-power, low-cost accelerators for all types of ions. Besides military applications, applications should be found in nuclear physics, intense neutron generation, spallation breeding, cancer therapy, and heavy ion fusion.

IFA proof-of-principle experiments are complete. For these experiments Cs was the working gas. In a two-step photoionization process, a dye laser excited the Cs and a frequency-doubled ruby laser ionized the excited Cs. The key results are the demonstration of the IFA-controlled beam-front motion (the streak-camera picture shows an example of this control), and the collection of ion data which suggest that controlled accelerating fields of 50 megavolts per metre have been achieved over an acceleration length of 10 centimetres.

A larger, improved IFA is now being designed to produce controlled accelerating fields of 100 megavolts per metre over an acceleration length of 1 metre. This system will use a new working gas that requires only one laser for photoionization. The ion data base will investigate scaling of the acceleration length up to 1 metre, as well as power amplification (i.e., an instantaneous ion power higher than the instantaneous IREB power) with an ion beam at the terawatt power level.

Cutaway of Pulselac Acceleration Gap

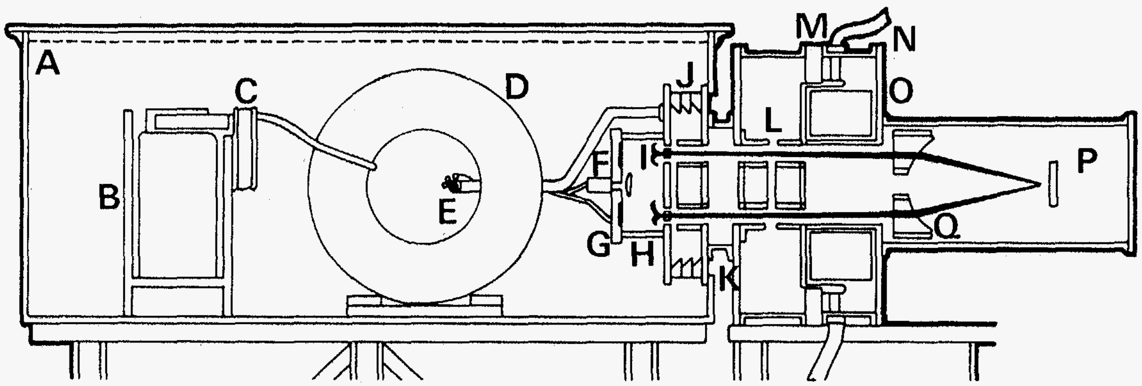


Pulselac, A MultiStage Ion Accelerator

Pulselac grew out of studies of the alleviation of space charge effects in ion beams (neutralization), and application of this phenomenon to high-current transport in accelerators. We seek to use the natural tendency of electrons to flow quickly into an unneutralized distribution of ions, greatly reducing the space charge fields. This is straightforward in regions with no applied electric fields—theoretical studies have shown that neutralization can occur within nanoseconds. But in the presence of electric fields, as in an acceleration gap, the electrons must be controlled so that they do not cross the potential. The figure shows how this is done with transverse magnetic fields that turn the electrons while allowing the ions to pass unimpeded. Focusing components can be added to the acceleration field by influencing the electron distribution through magnetic-field shaping.

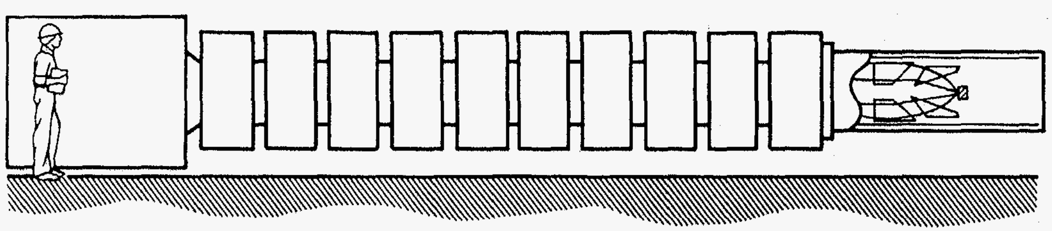
Several experiments have been carried out to investigate neutralization physics and demonstrate the feasibility of high-current ion accelerator technology. A 3-kiloampere injector of carbon ions was developed that used active plasma suns to introduce ions at the anode. The resulting beams were space-charge-neutralized and transported to a second, independent gap where the ions were postaccelerated. Electrostatic ion--beam focusing by magnetic-field shaping was also demonstrated. Recent experiments have concentrated on developing large-area electron sources and studying a gas-injection plasma gun to enable investigations with a wide variety of ions.

Pulselac C Multistage Ion Accelerator



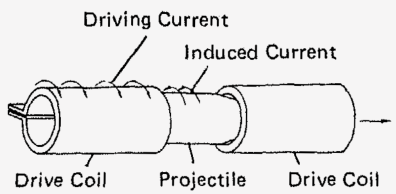
A. Oil housing for injector voltage source
B. Pulse-forming network for injector
C. Triggered switch
D. 4:1 iron core transformer
E. Transformer secondary with power lines for plasma gun
F. Pulsed gas valve
G. Pulsed coils to magnetically accelerate plasma
H. Plasma expansion chamber
I. Injector gap anode with extraction slots
J. Insulator stack
K. Chamber for magnet power feeds and beam diagnostics
L. Acceleration gap with magnet coil sets
M. Insulator
N. Power feeds from pulse modulators
O. Ferrite cores
P. Beam diagnostic chamber
Q. Toroidal sector magnetic lens

Pulselac D

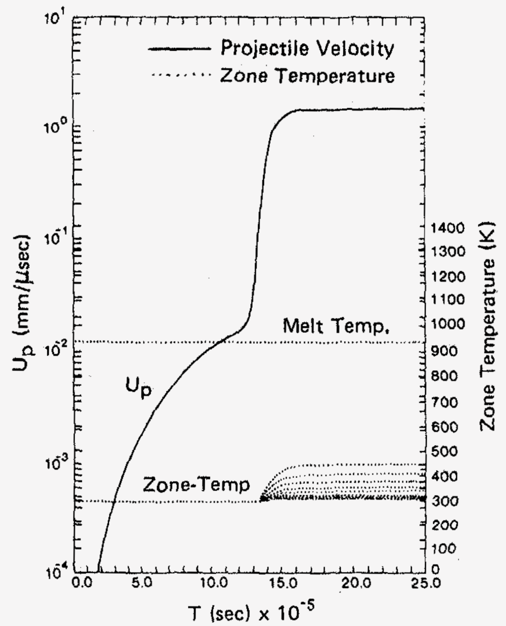


An inductive linear accelerator called Pulselac C is under development. Shown here are the injector, first stage, and a preliminary focusing experiment with a toroidal sector lens. A beam current of 3 kiloamperes of N^+ is expected. A conceptual design of a 50-megavolt, 10-kiloampere Pulselac D is shown.

Schematic of θ gun, two stages. Driving currents in the θ direction are synchronized with projectile position and delayed until mutual inductance between the projectile and the drive coil begins to decrease.



Computer calculation of the performance of a single-stage θ gun. The projectile is a 50-mm-dia, 0.2-kg aluminum cylinder. An explosive generator drives the 4-turn drive coil.

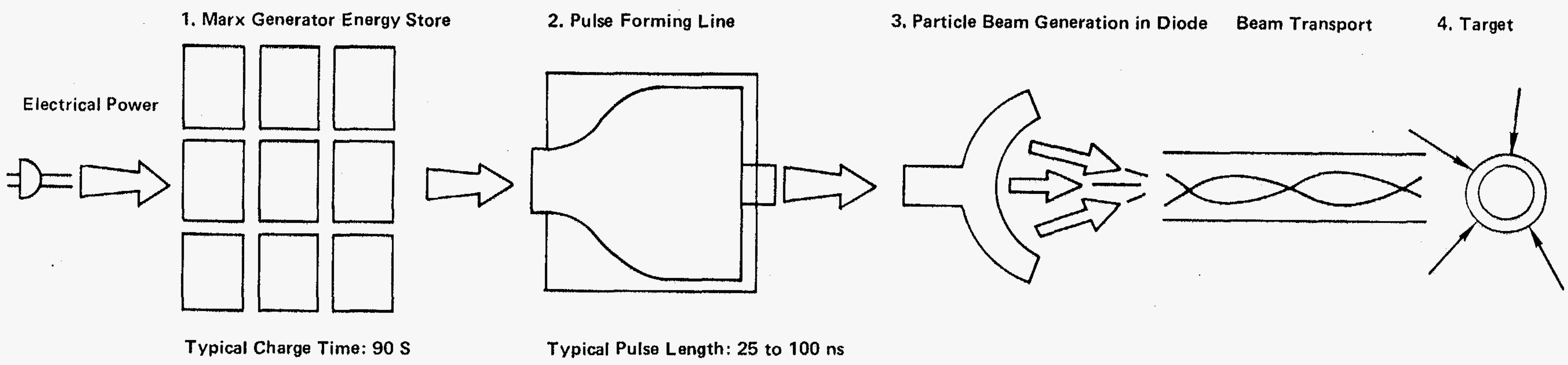


Electromagnetic Launching

Launching projectiles by means of strong electromagnetic fields instead of chemical-gun propellant or rocket fuel promises benefits that have been pursued sporadically for more than a century. If this Jules Vernean dream of launching vehicles from earth into space could be realized, the impact on modern space activities would be profound. Advances in pulsed-power technology, along with modern defense and space requirements, have led to new efforts at several laboratories to look at the possibilities.

At Sandia, emphasis has been in evaluating an electromagnetic gun with potential for both military and space uses. This "theta" gun differs from the rail gun under study elsewhere in that its accelerating forces are distributed along the length of the projectile, not concentrated at the end. This allows greater acceleration (from shorter guns) of the long, thin projectiles needed for earth-to-space launching and most military applications. Computer codes have been developed to calculate the performance of the theta gun and to predict optimum arrangements for its use with various pulsed-power sources.

In addition, an experimental program has begun. Its technical challenge lies in achieving electomagnetically driven projectiles that combine high acceleration, acceptable ohmic and aerodynamic heating, high ballistic coefficient, and stable flight through the atmosphere.



Pulsed-Power Accelerator Operation

A pulsed-power particle-beam accelerator generates and focuses intense beams of energetic particles. Because the power requirements for fusion are many times greater than the world's present power production capability, energy in these accelerators is taken slowly from the local power grid and then compressed temporally through a series of stages. This temporal compression bridges the gap between accelerator power consumption at 40 kilowatts and the production of power at a rate approaching 100 terawatts.

Four stages characterize the operation of such accelerators:

1. Electrical energy is slowly stored in a bank of high-voltage capacitors (often called a Marx generator).

2. Through the use of high-speed switches to multiply voltage, the energy is transferred rapidly into a pulse-forming line. This line then shapes the energy into a pulse of large amplitude and short duration.

3. The power pulse is delivered to a high-voltage diode in vacuum for conversion into a beam of energetic electrons or light ions.

4. Under forces produced by electric and magnetic fields within the diode, the beam acquires energy and can then be focused to almost 1/100 its original area.

A single beam may irradiate a target within a diode—or several beams may be propagated outside the diode along a narrow preionized channel toward the target.

sed-Power Historical Milestones

TE	DESCRIPTION	FACILITY/ DEVICES	SPECIFIC RESULTS	SIGNIFICANCE
4	Atomic Weapons Research Establishment accelerator inception	SMOG (AWRE)	Initial operation of first pulsed-power accelerator at AWRE, ~3 MV, 50 kA	Start of pulsed-power technology transfer to Sandia.
5	Accelerator operation	SPASTIC	First US pulsed-power accelerator operation, 3 MV, 50 kA	Collaboration with AWRE; Sandia commitment to pulse power.
65	Formation of Sandia pulsed-power group	Area V	Pulsed-power division established to build facility for simulation	Sandia commitment to large pulsed-power apparatus and research
66	Accelerator operation	Hermes-I	Oil-filled Blumlein accelerator operation at 3 MV, ~50 kA	Extendable technology for high-voltage accelerator and simulation facility.
68	Accelerator operation	Hermes-II	Operation at 1.3 TW-100 kJ output at 13 MV, 100 kA	Largest simulator accelerator and simulation facility.
970	Accelerator operation	Nereus	350-kV, 100-kA, 2Ω output accelerator	Our first low-impedance, water-insulated line, solid dielectric-switched unit.
972	Accelerator operation	Hydra	Modular 1-MV, 1-MA, 50-kJ output	Pinching and fusion experiments started.

1972	Accelerator operation	Slim	400-kV, 0.7-MA, 70-ns output	Our first mylar-insulated, low-impedance accelerator with multiple beams. The beam pinch experiment led to the present fusion program.
1974	Accelerator operation	Proto-I	2 MV, 500 kA, 1 TW, 20 ns	First double-sided multichannel switched accelerator specifically designed for fusion experiments. Also large-scale test of triggered and untriggered multichannel oil switch.
1976	Water switching test bed	Ripple	Researched present water pulse line technology	Provided untriggered multichannel water switching, staged switching for short-pulse, high-power output. Later the MFI and water convolutes were developed.
1977	Accelerator operation	Proto-II	8 TW, 1.5 MV, 6 MA, 20 ns, 100 kJ	Provided first multi-module water-insulated accelerator for fusion experiments.
1977	Start accelerator construction	PBFA-I	Place contracts for facility construction and initial procurement	Initiate PBFA project.
1978	Test bed operation	RTF-I	First repetitively pulsed experiments	Provided 350 kV, 300 J/pulse at 100 pps (or 30 kW). 10^6 shot switch,

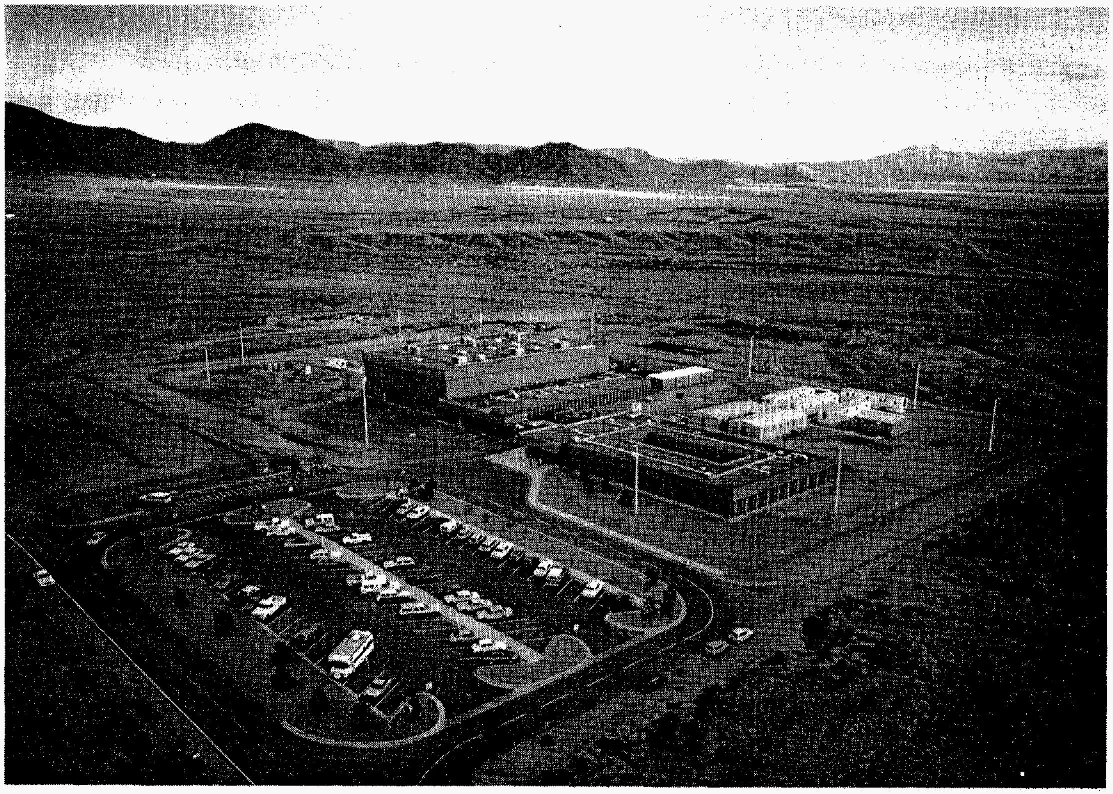
				10^5 shot diode operation at 100 kA/cm^2.
1978	Test bed operation	MITE/MITL	Test of PBFA-I technology utilizing Magnetically Insulated Transmission Line	Developed prepulse shields, convoluted lines, magnetic insulation, 208 kJ Marx, pulse inversion,dual polarity, power flow, and 90% efficient magnetically insulated power flow for 7 m at 10^{11} W/cm^2.
1978	First multiple-stage ion acceleration demonstration with pulsed-power drive	Pulselac	Magnetic insulation of multiple gaps and space charged-neutralized transport demonstrated	First experiment verification of new low cost means that may be extendable to generate intense ion beams at 100 MeV or more.
1979	Test bed — cavity design and beam stability studies	RADLAC	9 MV, 25 kA, ns operation	First modular multistage high-current accelerator with cavities employing radial transmission lines.
1979	Test bed — accelerator operation	HydraMITE	Full power test of PBFA-I module	Provided 0.8-TW, 2-MV, 400-kA, 35-ns pulse for PBFA-type experiments. Permitted the final design to be released for PBFA-I fabrication.
1979	Adoption of ion baseline approach for PBFA-I and II	MITE, Hydra-MITE	Pulse inversion and stacking demonstrated	Allow higher voltage modules with either polarity to be used in PBFA.

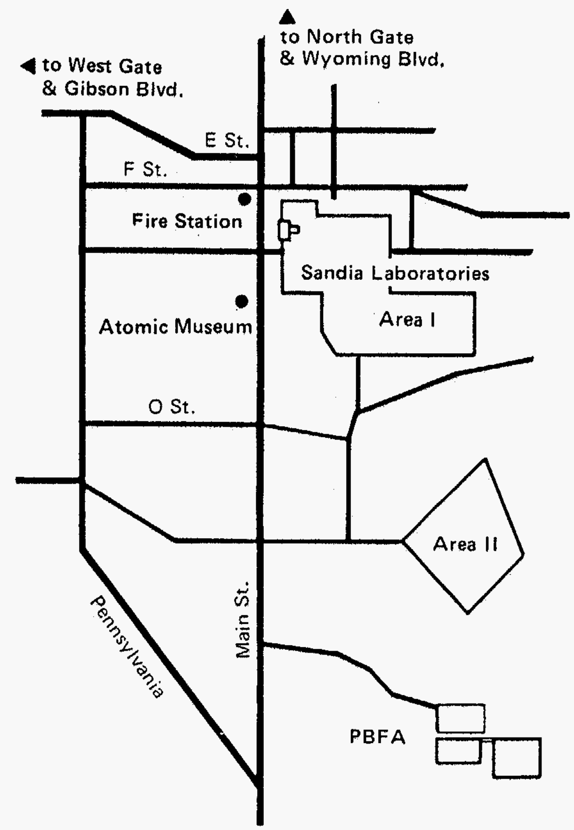
1979	Start construction module PBFA-II	SuperMITE	200-kJ Marx generator installed; tank completed	Will allow full-scale module testing of PBFA-II concepts.
1980	Accelerator operation	PBFA-I	30-TW, 1-MJ design parameters demonstrated	Completion of PFBA-I on schedule and on cost permits program to proceed with beam and target experiments.
1981	Start PBFA-II project	PBFA-II	Initiate final design.	Will allow breakeven experiment to take place in mid 1980s.

Sandia National Laboratories

Sandia is one of the multiprogram laboratories of the Department of Energy (DOE). Since 1949 it has been operated by the Bell System under a contract with Western Electric. It is an engineering laboratory with a broad scientific base and a diverse capability in many areas. At its two major facilities at Albuquerque, New Mexico, and Livermore, California, Sandia employs 7900 people, 2500 of whom are professional/technical staff. During its 30-year history, Sandia has become known as a laboratory that can take projects from problem definition through research and development to hardware production. Its engineering and scientific capabilities are now being applied to meet urgent national needs for nuclear safety and safeguards, fuel cycle protection, and energy development as well as weapons. Sandia's expertise spans the range from basic research in a number of physical and engineering sciences, through development and design stages, into manufacturing liaison, and finally into stockpile management and field engineering.

Sandia's major role is that of a systems engineering laboratory with responsibility for the nonnuclear portions of nuclear weapons systems. However, Sandia's experience in the safety, security, and control of nuclear weapons, weapon effects, and with surface and satellite sensor systems is now being applied to such areas as controlled fusion, reactor safety, nuclear waste management, and fuel-cycle and materials safeguards. The extensive engineering and scientific capabilities of the Laboratories are also being directed toward the execution of a broad spectrum of nonnuclear energy problems, such as solar energy, drilling technology, and fossil-fuel extraction, conversion, and combustion.

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