PRN # 119

SAND--95-2927

PARTICLE BEAM FUSION

Sandia Laboratories

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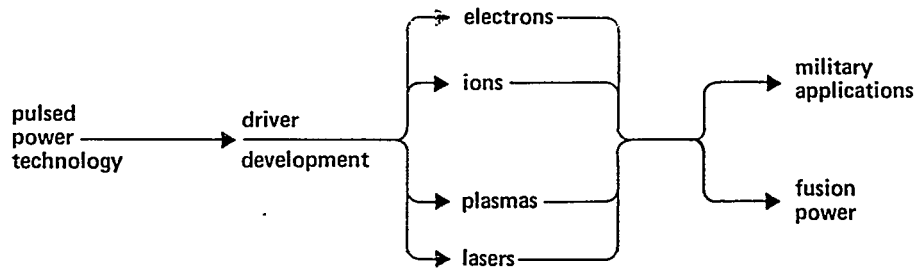
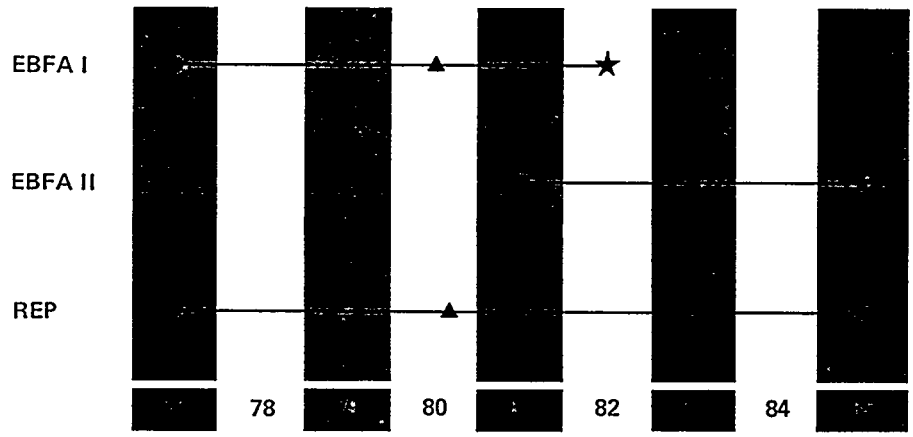
MASTER

driver development



schedule



beams and focused laser beams must include many other factors such as beam transport, and target coupling, as well as target design and fabrication. These issues are being investigated to determine if the perceived practical benefits of particle beam fusion can indeed be realized. The practical considerations are exemplified in a comparison of the leading ICF drivers. The plan being followed by Sandia involves using the Electron Beam Fusion Accelerator (EBFA) to meet three objectives by 1985: significant burn using EBFA I, net energy gain based on an upgrade of EBFA to the 2 megajoule (MJ) level (EBFA II), and demonstration of a single module of EBFA II operated in the repetitive pulse mode. These goals are dependent, of course, on success in solving several key technical problems under investigation. If these technical problems can be solved, then practical applications to fusion power could be considered. The potential for these applications has been studied using economic models that allow one to derive the cost of power based on various assumptions. For instance, our economic analyses have shown that with a pellet gain of 50 to 100, an overall efficiency of 30 percent, a driver cost of $40 per joule, and a pellet fabrication cost of $0.10, power can be generated at costs which are competitive with other advanced energy sources. Less stringent technical requirements (pellet gain of 5-10) would be adequate for hybrid applications to supplement a light water reactor economy. Such a relatively low gain pellet would be simpler to fabricate, would rely on less complex physics issues, and would thus lower the overall risk at an early stage in the evolution of our knowledge.

leading ICF drivers

	SANDIA		LLL		LASL
	EBFA I	EBFA II	SHIVA	NOVA	Antares
peak power TW	30	60	20	250	100
pellet energy, kJ	1000	2000	15	250	100
pulse width, ns	40	40	.1	1	1
cost/joule, $	8	7	1000	300	300
energy efficiency	25%	25%	.06%	.2%	1.8%
operational date	1980	1984	1977	1984	1983

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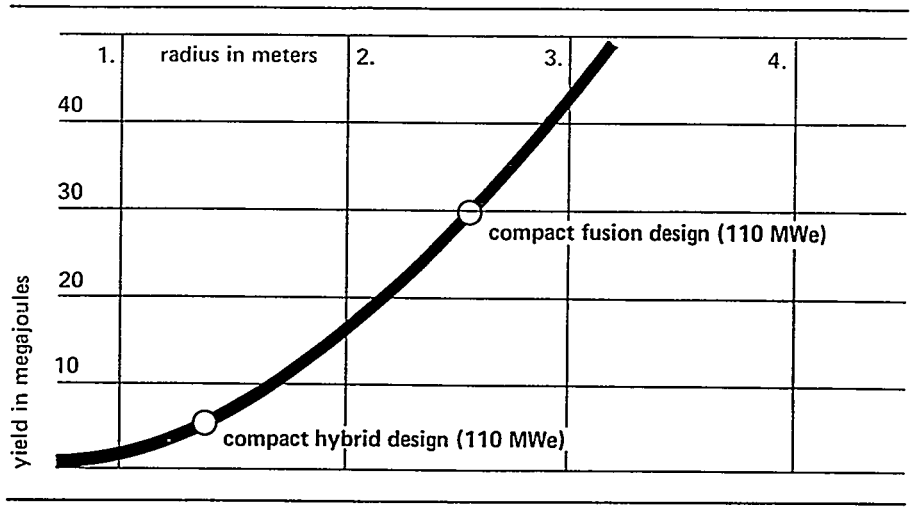
Introduction

Sandia's Particle Beam Fusion Program is investigating several driver options, based on pulsed power technology, with the goal of demonstrating a practical ignitor for Inertial Confinement Fusion (ICF) Reactors. The interrelated aspects of power conditioning and compression, beam-target interaction, and target ignition are being studied. The issues of efficiency, reliability and multiple pulse capability are being integrated into the program to provide a viable approach to an experimental power reactor. On a shorter time scale we expect to derive important military-related benefits from attendant research and facility development. The Sandia pulsed power activity began in the mid-1960's in support of the program to demonstrate the hardness of weapon systems components to nuclear weapons effects. A similar and complementary effort in weapons effects simulation has also been carried out by the Department of Defense. The application of this technology has broadened over the years to include development of ultra-high power electron and ion beam accelerators, techniques for plasma heating, and laser excitation.

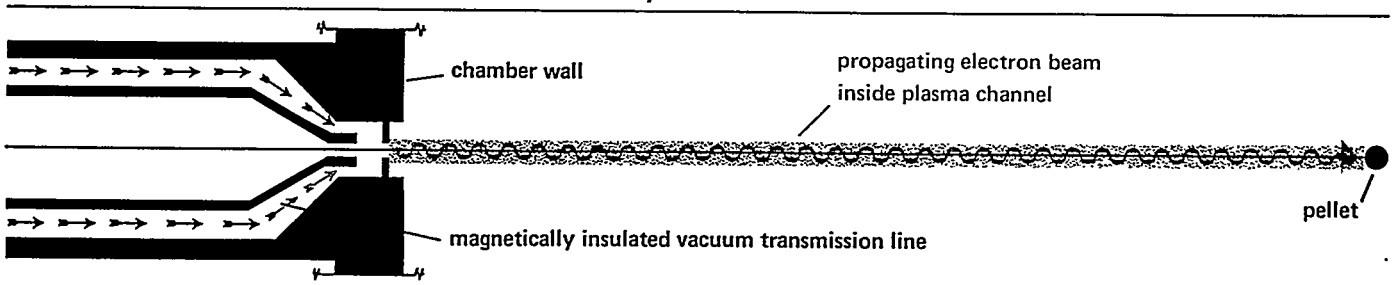
The two most important advantages of pulsed power driven fusion are the inherent low cost and high efficiency of high current particle accelerators. However, comparison of the relative merits of particle

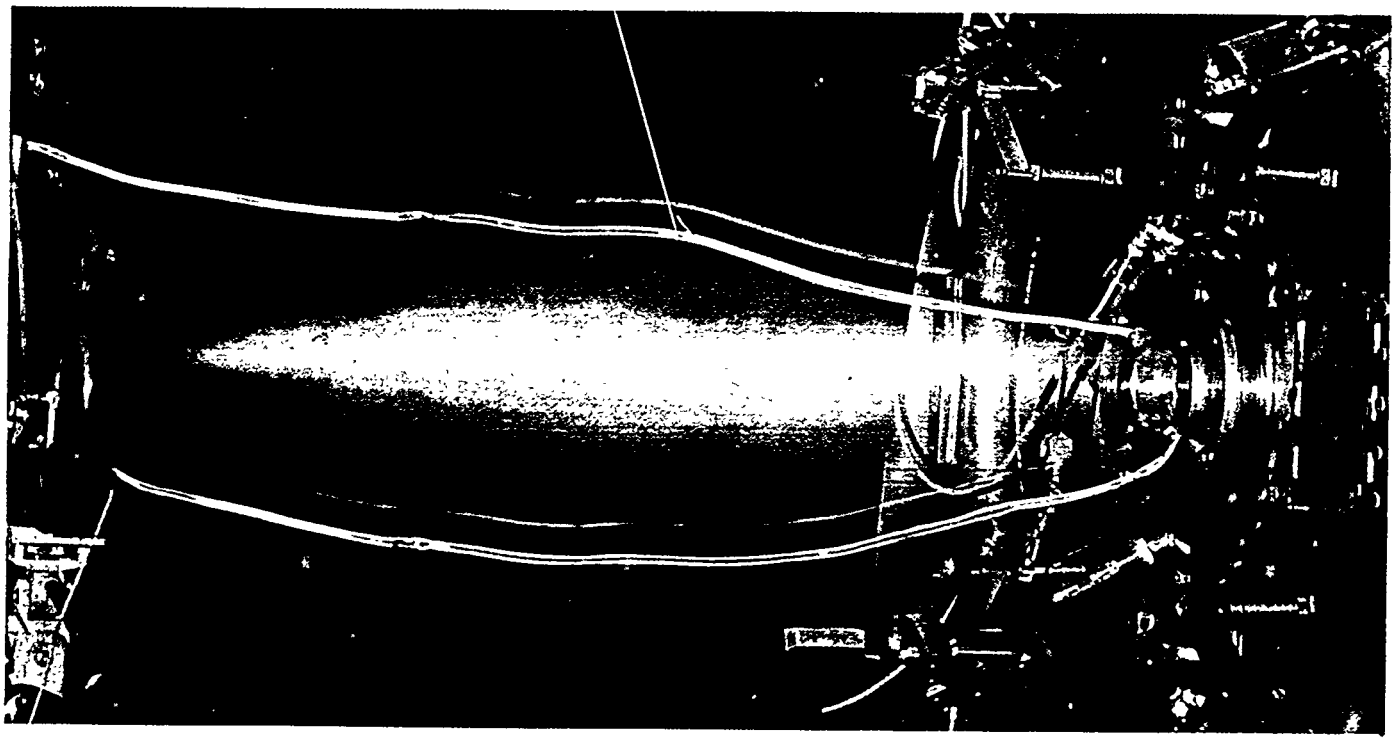
chamber radius as a function of pellet yield



With either a pure fusion or a hybrid approach, it is necessary to have sufficient "standoff" between the injector and the explosion for reliable long life operation of reactor components. Significant advances have been made in energy transport using plasma channels to guide a focused particle beam to the target. Here we see a plasma channel formed by a pulsed 10 μsec discharge in air. In this experiment the discharge is initiated and thus directed by a fine wire; in a reactor, a laser or other means will be needed to initiate the discharge on a repetitive basis.

Contrary to the laser reactor approaches which cannot use a dense buffer gas in the reaction chamber, we are not faced with the typical problems of first wall erosion due to x-rays and debris. On the other hand, these explosion by-products (~ 20% of the pellet yield) are stopped by the buffer gas and their energy is converted into a "fireball" near the pellet, which expands and applies an over pressure to the first wall. Fortunately, this overpressure decays rapidly with radius so that reasonably sized chambers can accommodate this loading.

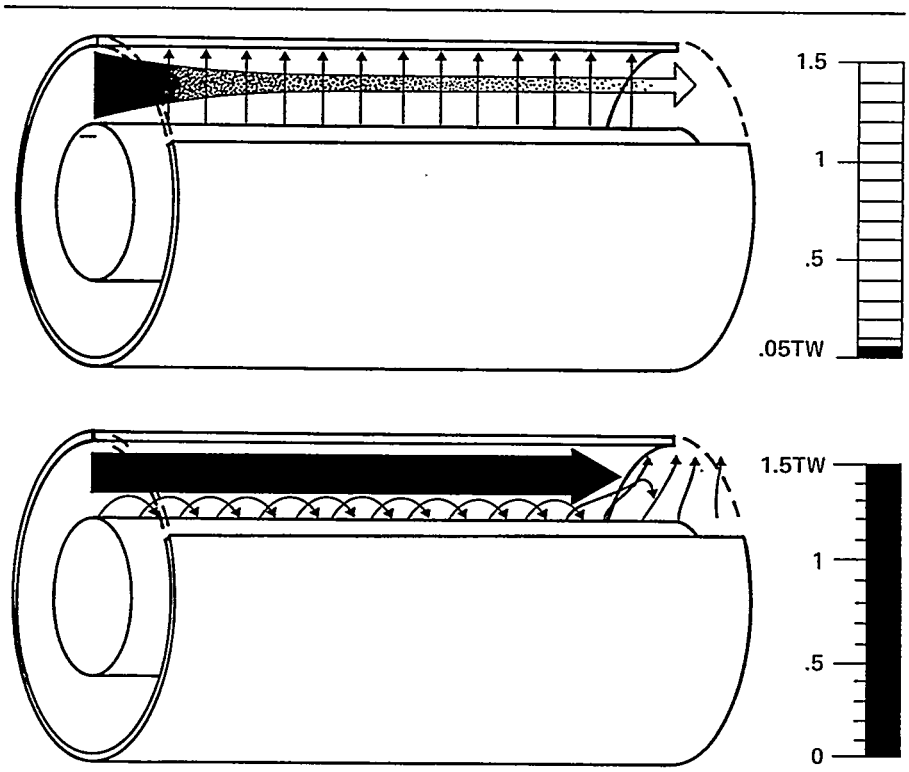




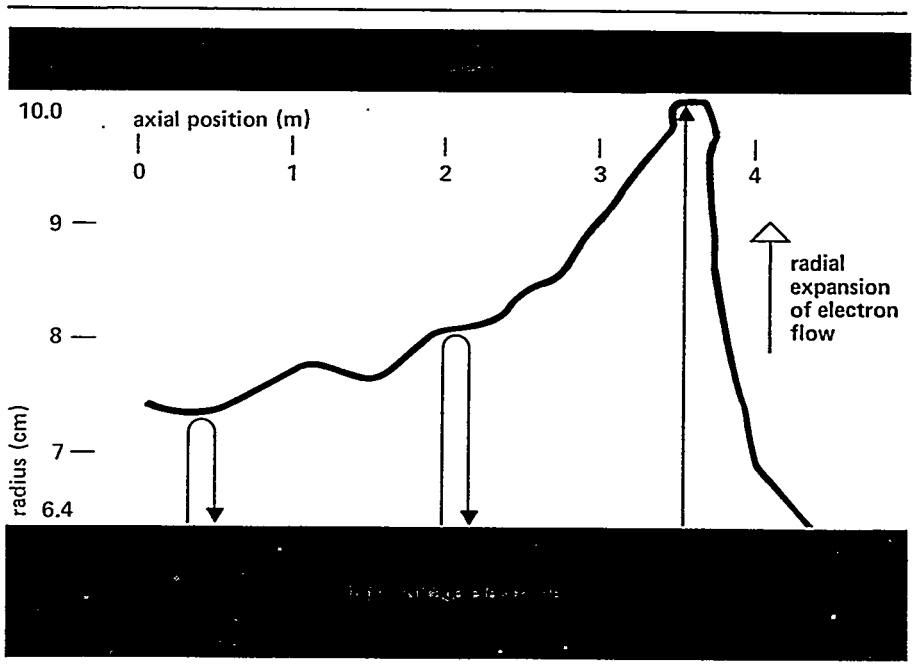
Self Magnetically Insulated Transmission Lines (MITL)

Although we are considering systems tradeoffs and technology requirements for reactors, our immediate problem is to demonstrate feasibility of target ignition. This entails several physics questions which have yet to be answered. The matter of reliably delivering an energy of 1 MJ and a power level of ~ 10^{14} watts (W) to the target has been of primary concern because of the electrical breakdown of materials. This problem has been largely circumvented by use of magnetically insulated transmission lines and by beam transport in plasma channels. (The development of the MITL concept has involved contributions from the Kurchatov Institute, Physics International as well as Sandia Labs.) The concept of using the self-magnetic field of a powerful electromagnetic pulse to inhibit breakdown is central to our approach of power concentration. Without this self-field approach, the power which could be transmitted in a reasonably sized transmission line would be less than .1 terawatt (TW). On the other hand, at high power levels the self-magnetic field

self magnetically insulated transmission lines



time dependent-2-D simulation of magnetically insulated coax



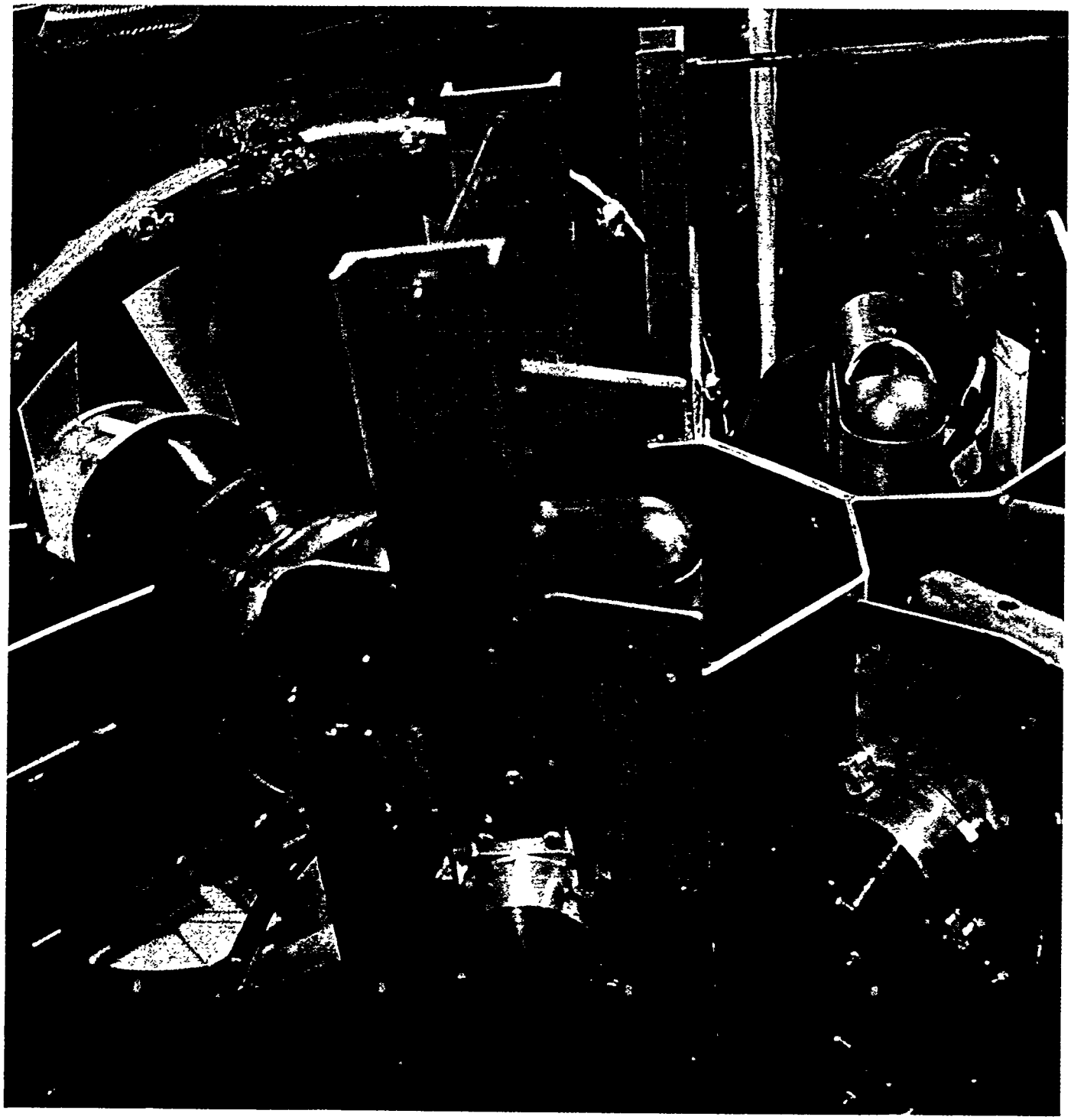
of the traveling wave causes the emitted electrons to return to the high voltage electrode, and power levels of 1 TW or greater can be transmitted.

A two dimensional computer simulation of a magnetically insulated coaxial line demonstrates this effect. At the head of the pulse, the electrons reach the ground electrode, but within a short distance into the pulse, they are turned back and the power is transmitted efficiently.

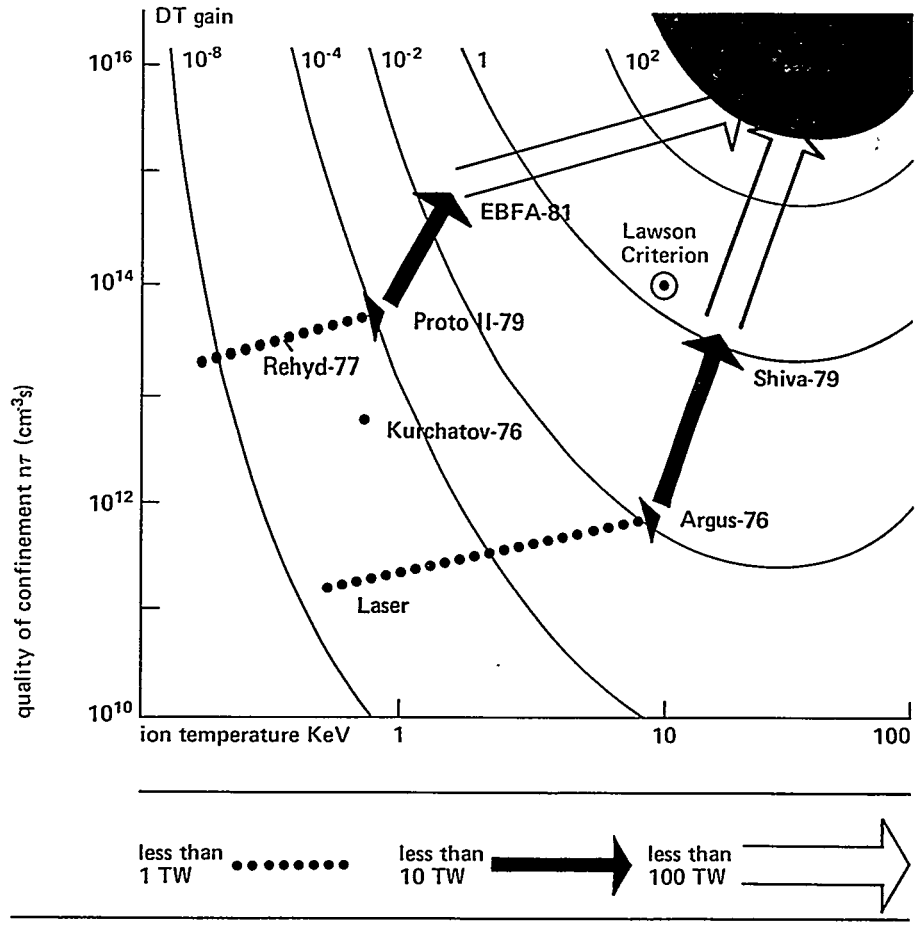
This principle has been demonstrated on our Magnetic Insulation Test Experiment (MITE), one module of the 36 module EBFA. A 7-meter (M), long, magnetically insulated line was tested at the 1 TW level showing ~ 90% efficiency of energy transport. We are using a tri-plate line inside a cylindrical vacuum chamber, rather than a coaxial line. This permits tighter packaging of the output beams near the target. In addition, by tapering the MITL, the power density can be enhanced to greater than 10^{11} W/cm^2 before the beam is formed in each diode. The multiple beams would then be transported from the exit point of the vacuum line via a plasma channel to the target as previously described.

Both relativistic electrons and nonrelativistic light ions are being considered for this approach to power concentration and beam transport.

MITE



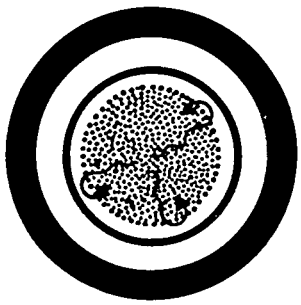
ICF program power goals



Targets

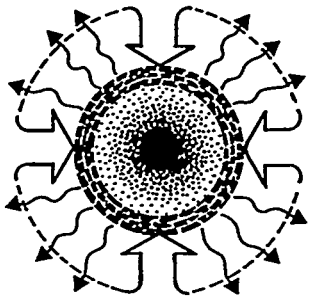
The targets designed for particle beam applications are of necessity larger and thus more massive than laser targets because of the longer pulse durations of the source and more limited focusing capabilities of energetic particles. This means that our targets can reach higher levels of confinement more easily with the greater levels of energy available, but must be optimized to reach high temperature. Here we see the familiar path being pursued in the ICF laser program in comparison with the electron and ion approaches. We are closer to the required values of $n\tau$ (ignition condition) and our experiments are emphasizing ways to achieve the necessary high temperatures. The data point representing the 1976 Kurchatov result was achieved using a comparatively modest power level but employed a method for enhancement of the compressional heating of the fuel.

magnetic confinement fusion



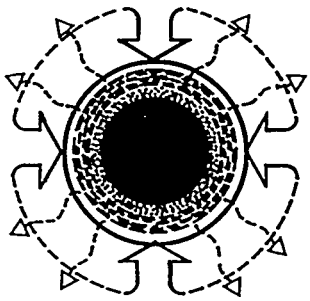
Magnetic field holds heat.

inertial confinement fusion



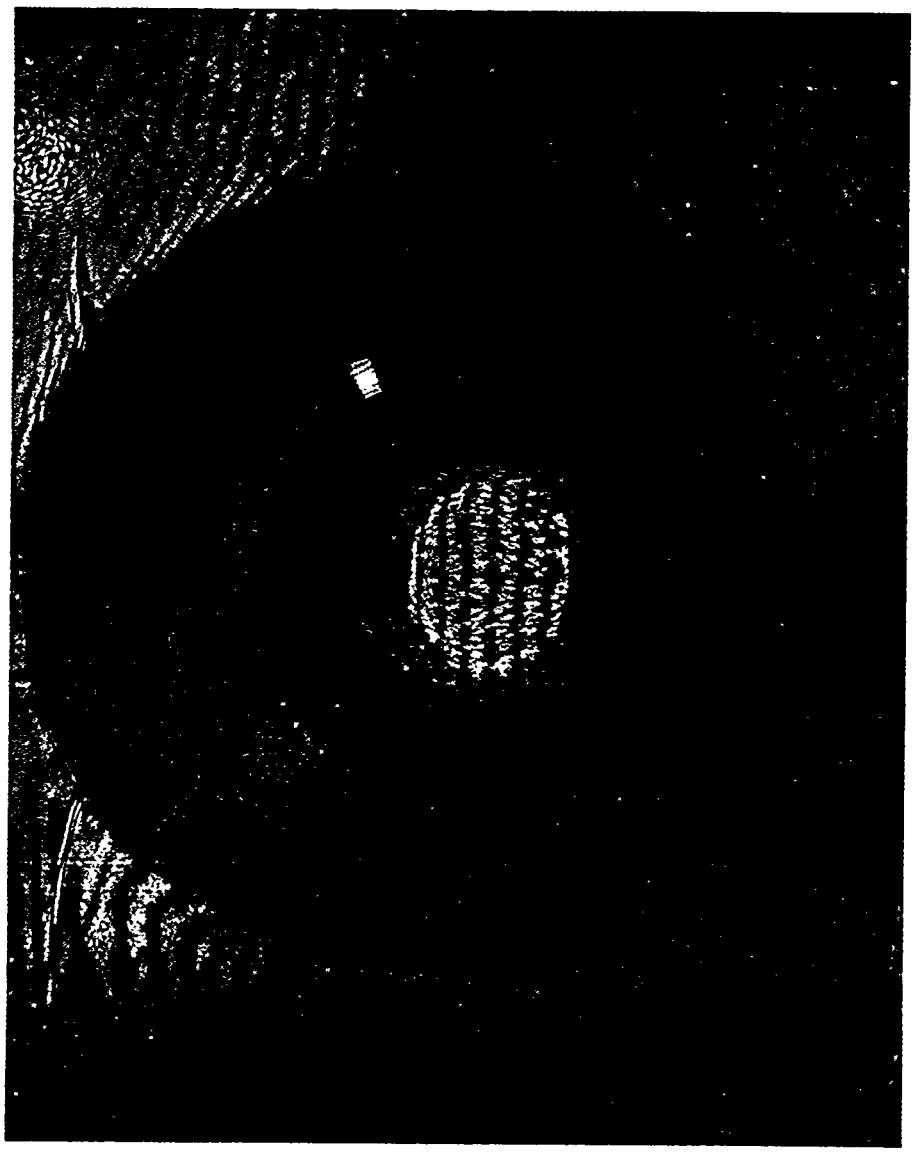
Collapsing shell confines and heats fuel. Energy is lost to wall by electron thermal conduction.

inertial confinement fusion with magnetic thermal insulation



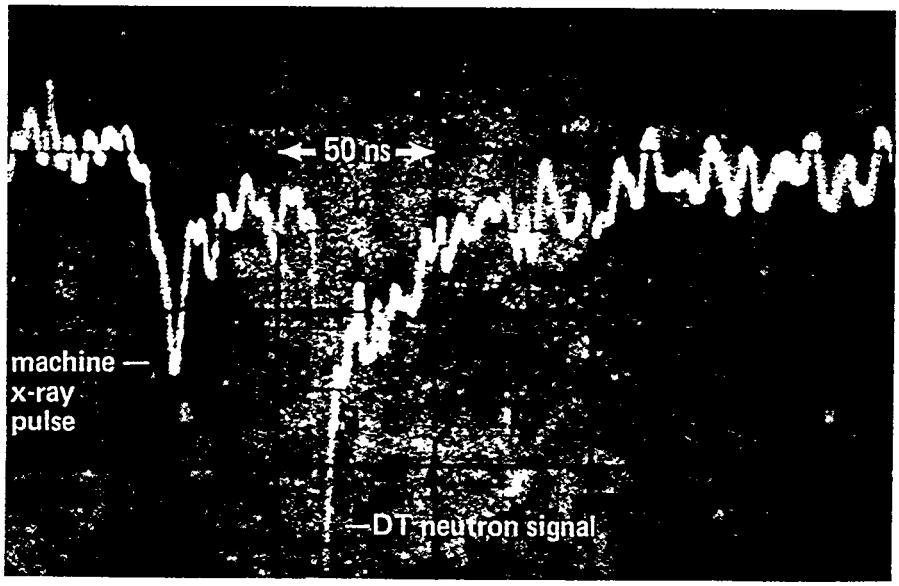
Magnetic field reduces loss giving higher fuel temperature.

imploding target hologram

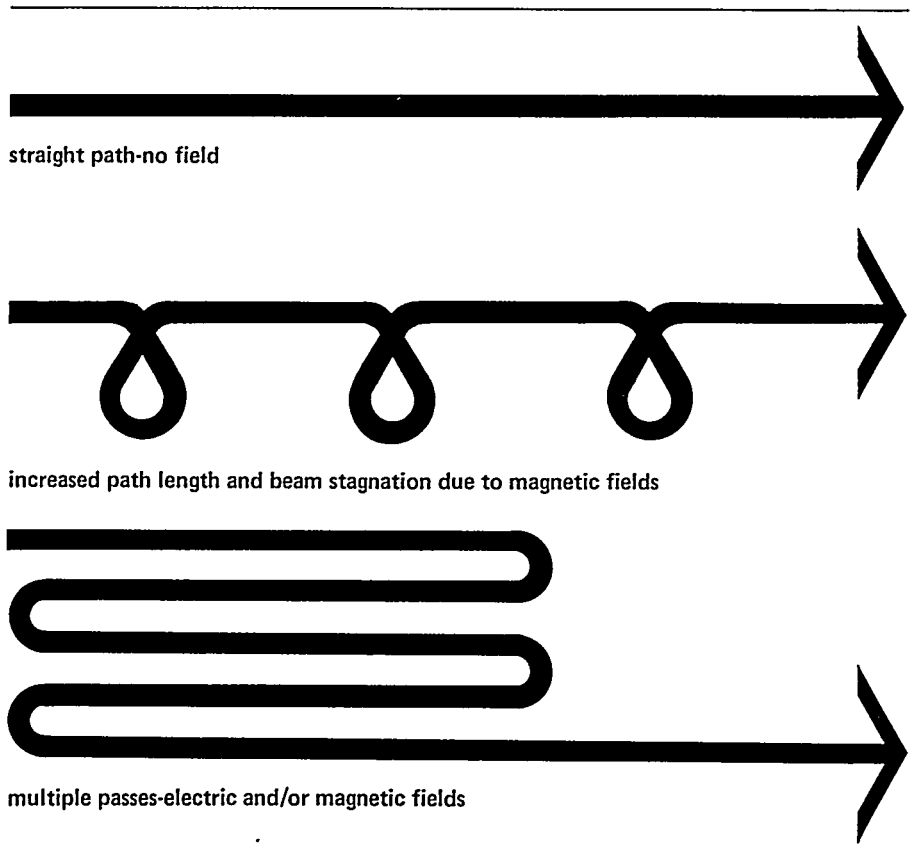


In other target work we are studying the dynamic behavior of imploding cylinders to determine the required symmetry of irradiation and material properties. We have observed (using holographic interferometry) that exploding pusher targets implode in a stable manner even with large initial perturbations, but that ablatively driven targets have much more stringent symmetry requirements. In other experiments we have seen evidence of particles of matter ejected from the inner surface of an imploding shell, and such studies are assisting us in defining the required beam uniformity and target quality.

The target approach which was first tested at Sandia in late 1976 with success, is to adapt an idea from magnetic fusion, i.e., use of a magnetic field to thermally insulate the fuel from the surrounding high density wall (electron conduction is inhibited). If the fuel is preheated with a high current discharge prior to implosion, the resulting embedded magnetic field allows higher final fuel temperatures. Using such a target, we have produced 10^6 deuteruim-deuterium (DD) neutrons, and deuterium-tritium (DT) experiments are now underway. The DT neutron pulse from an imploded target using preheat and magnetic thermo-insulation has an easily characterized fast neutron pulse which arises at the time of target implosion. This clearly defined pulse shape can be easily distinguished from background



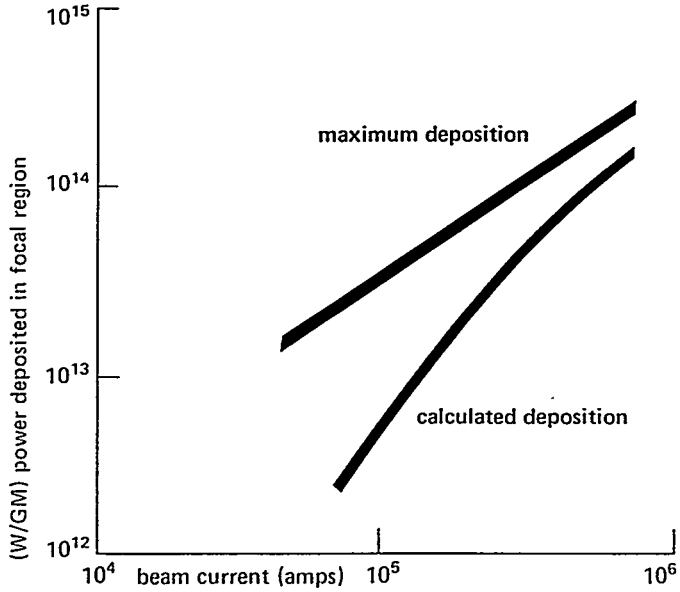
D-T neutron signal

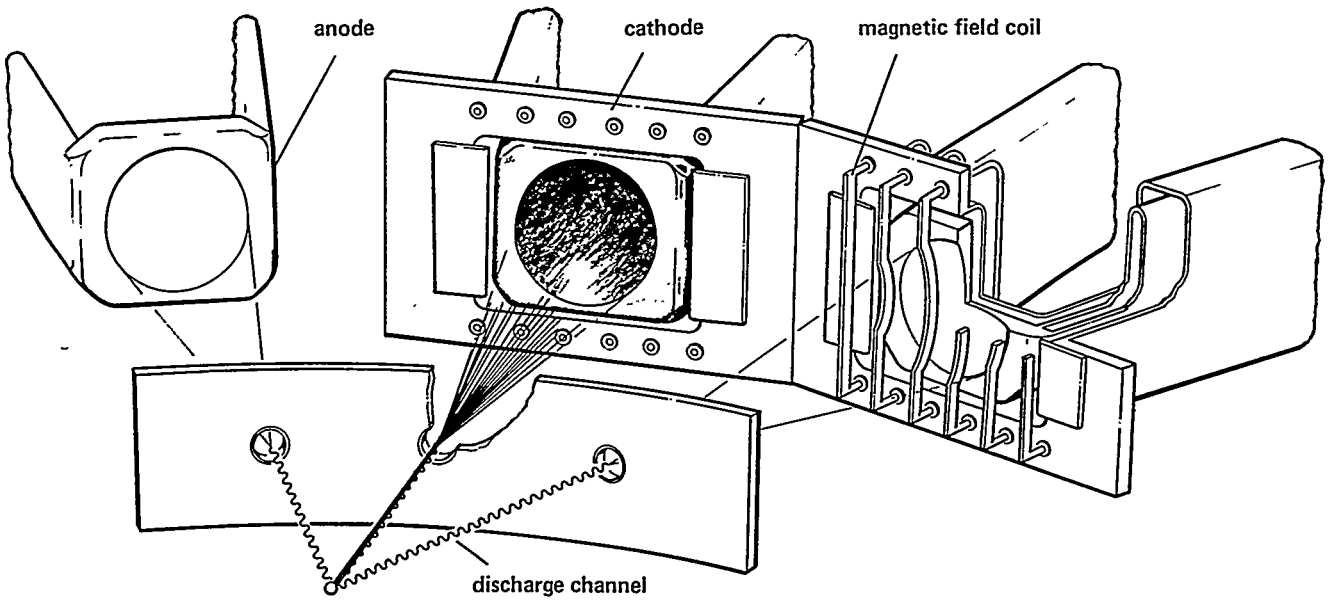


enhanced deposition

neutrons which might be a source of spurious results. This type of target is continuing to be evaluated because of its promise in reducing the beam power needed for ignition. Another aspect of our target related research involves the question of beam deposition in the outer layer of the target. In order to reduce the amount of mass needed to effectively stop the electrons and thus the necessary beam energy, it is important to rely on beam self-field effects for range shortening. If self-electrostatic and magnetic effects are ignored, a 1 MeV electron would deposit only 10% of its energy in a 10 μm thick gold foil. On the other hand, according to deposition calculations, the self-field of a 1 MA beam should reduce the electron penetration length and increase the absorption efficiency to 90%. In a simplified sense, this effect can be explained by stagnation of the beam electrons thus giving each electron more opportunities to interact with the thin foil via classical collisions. Evidence for enhanced deposition has been observed in our lab as well as in labs in Japan, Israel and the Soviet Union.

calculated deposition
for an 800 KeV
2 mm beam radius
10 μm thick Au foil

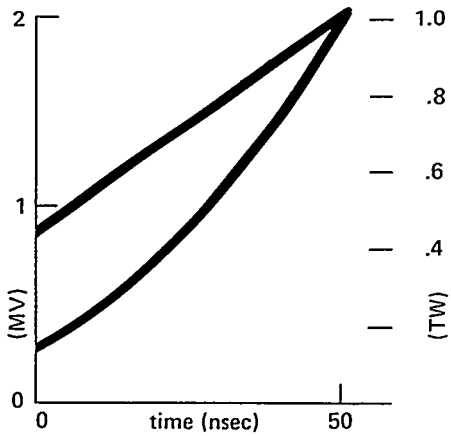




Ion Beam

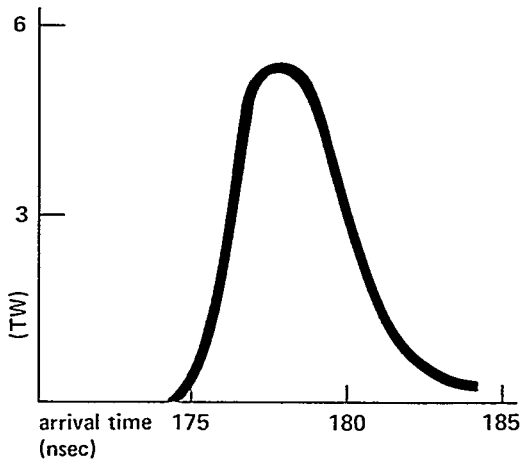
The other particle beam approach receiving increased emphasis in the U.S. is the use of light ion beams generated with the same pulsed power technology as that used for electrons. Here the goal is to efficiently suppress the electron flow and to extract from the diode a converging light ion beam. We, together with a group at Cornell University, are investigating use of electron suppressing magnetic fields applied by pulsed coils; a similar ion beam effort at the Naval Research Laboratory is emphasizing the suppression of the electron flow by self-magnetic fields in the high current diodes. In one diode configuration being considered for EBFA, multiple ion beams are geometrically focused over a distance of less than 1 M and then transported in plasma discharge channels to the target. By increasing the voltage during the power pulse, the ion beam can be bunched longitudinally as it propagates to the target, thus increasing the power by more than a factor of 5.

hypothetical ion beam voltage and power



proton beam from one 34 cm diameter ion diode

calculated power of bunched ion beam



channel length = 2.5m — maximum injection angle-16°

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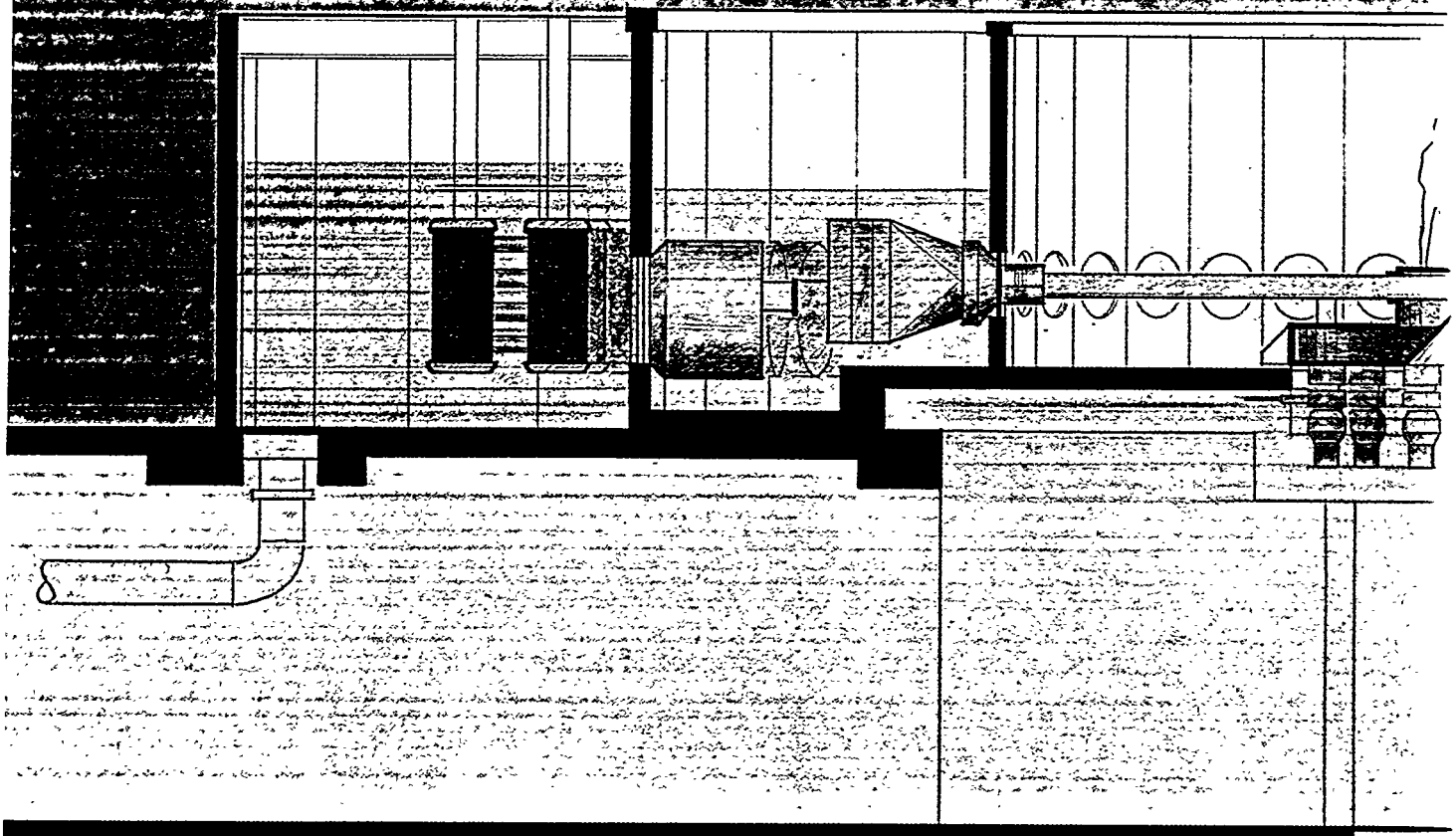
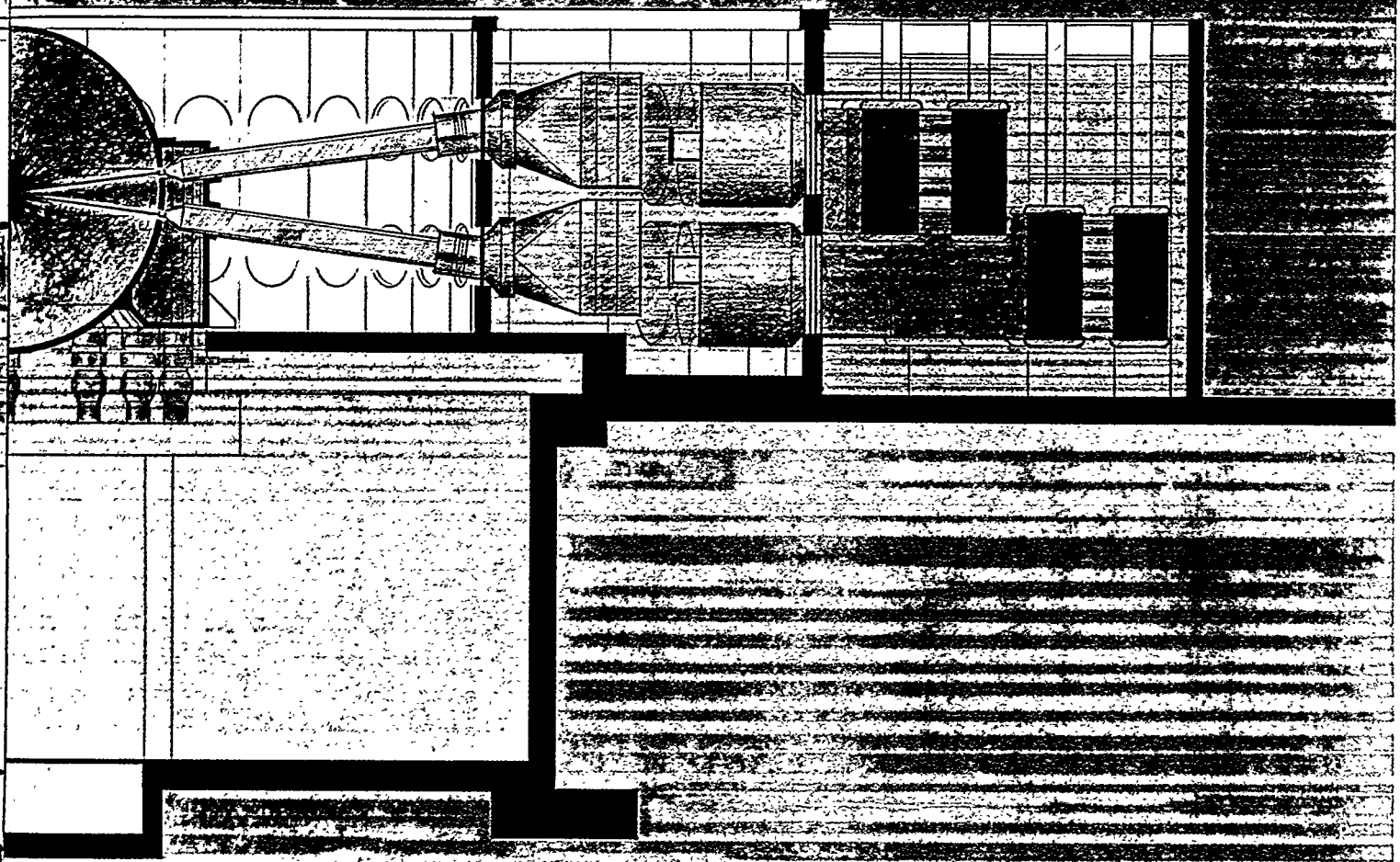
EBFA-I



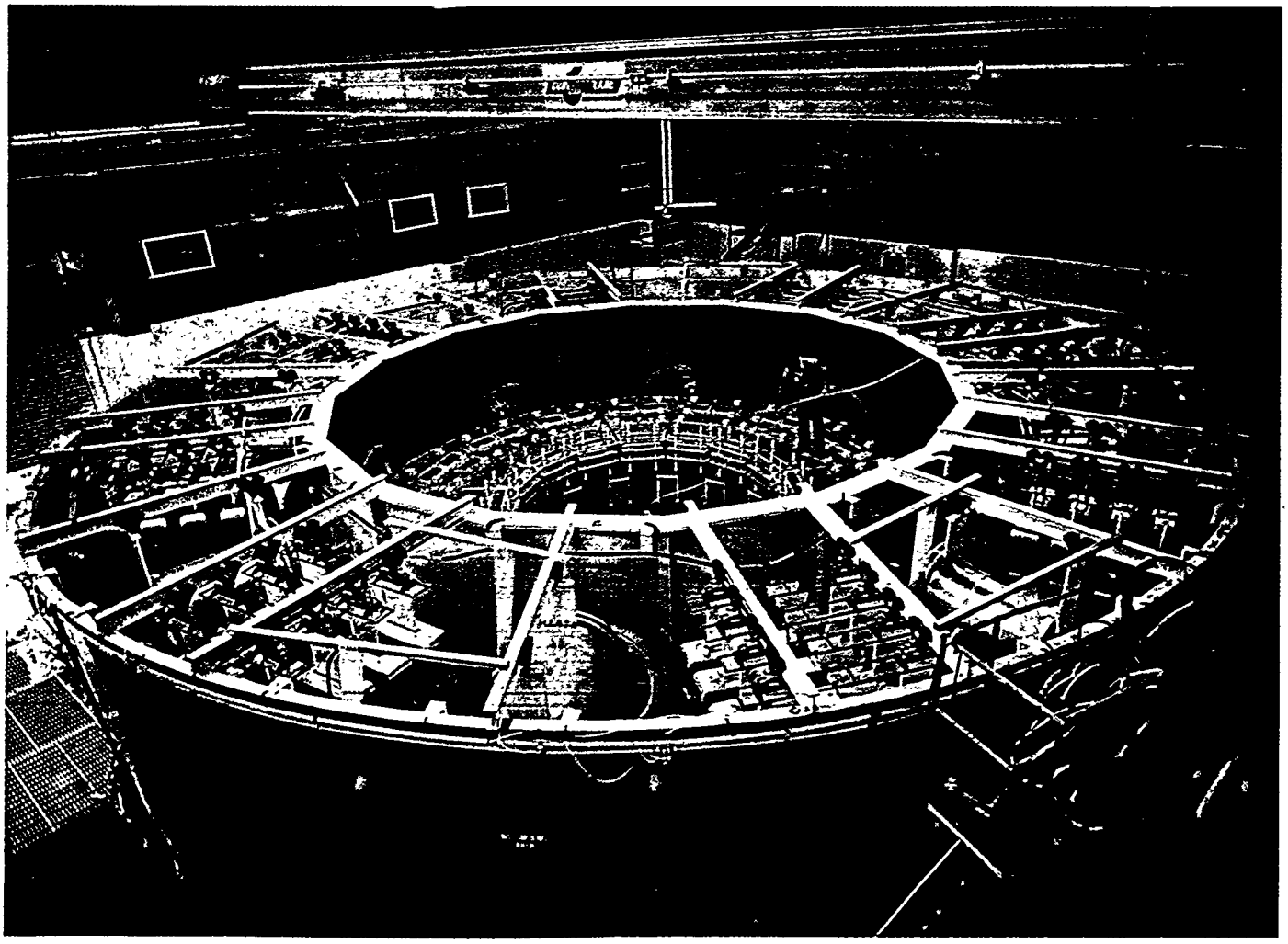
EBFA·II

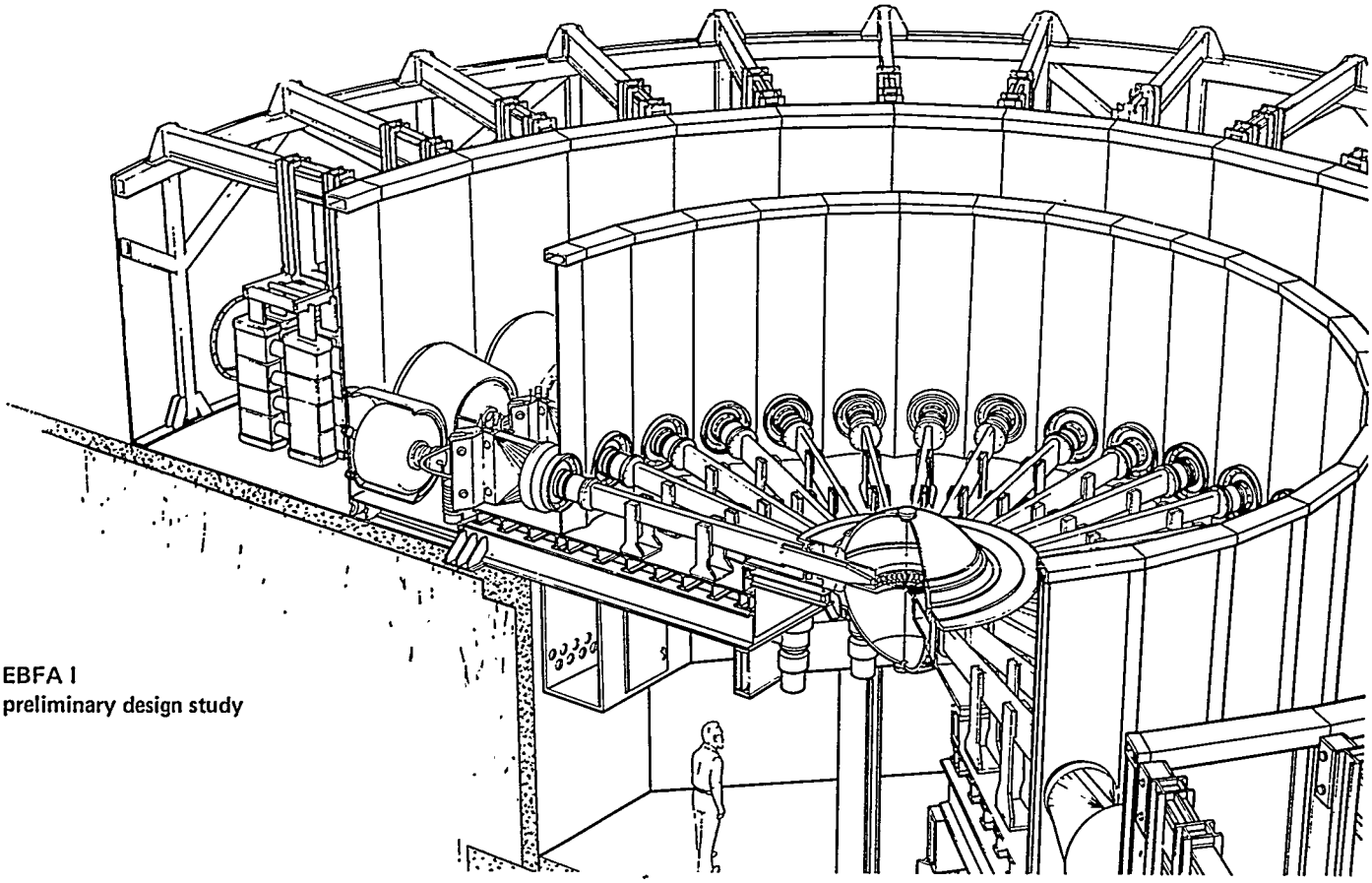


The Electron Beam Fusion Accelerator (EBFA) is to be constructed in a new facility which is to be ready for occupancy in the fall of 1978. The accelerator will initially consist of 36 modules delivering 1 MJ total, and is being constructed to permit a later upgrade to more than 2 MJ.
The entire facility, which will not be completed until 1983 at the soonest, will also include a systems integration experiment whose objective is to demonstrate the necessary repetitive pulse capability for future reactor related experiments, which could follow in the 1990's.

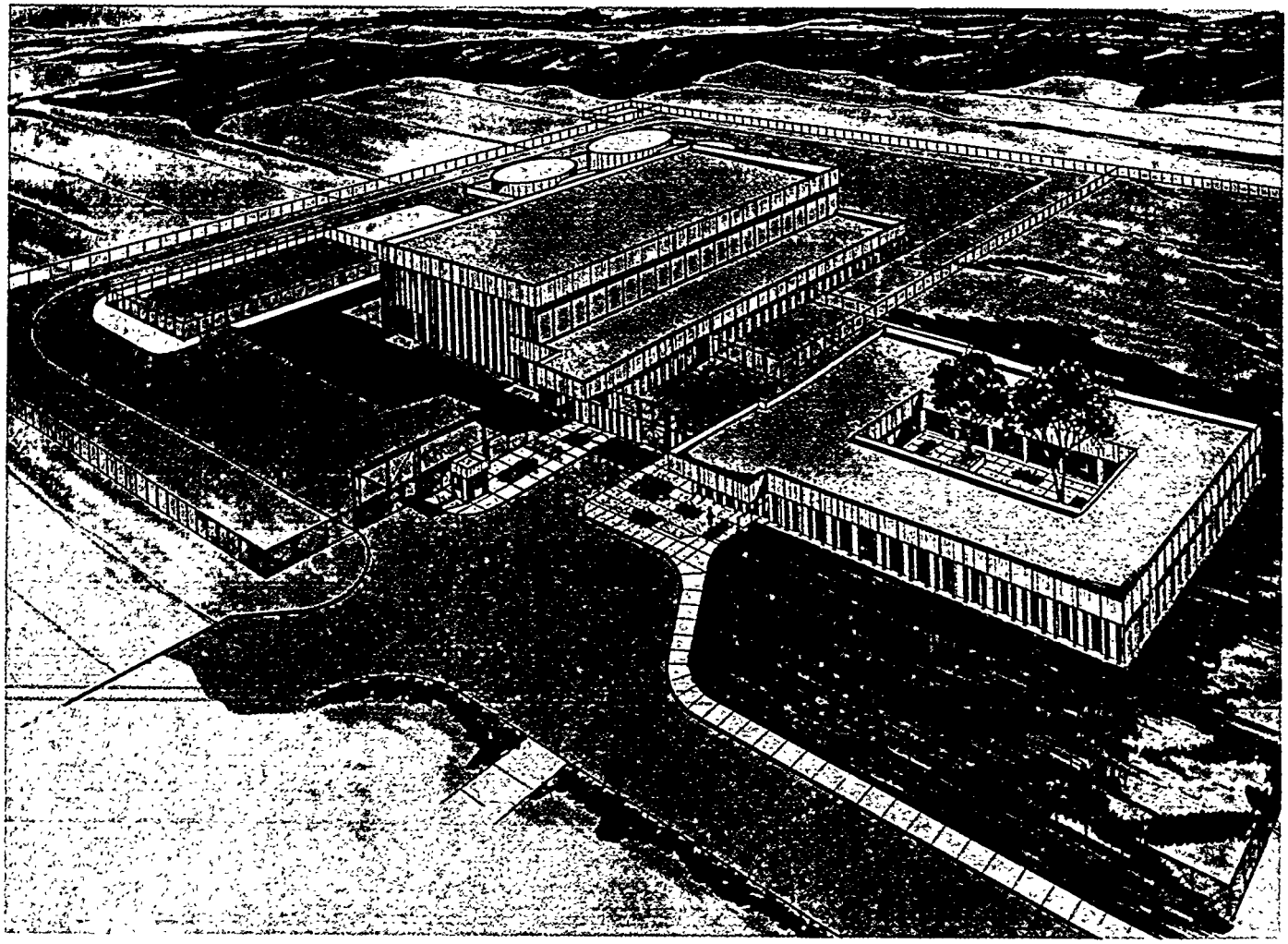
Many of the energy storage, switching and pulse focusing elements of EBFA have been tested on our Proto II accelerator, which has operated at the 8 TW level. Multiple electron beam and ion beam development experiments are planned for the near future on this machine.

Proto II

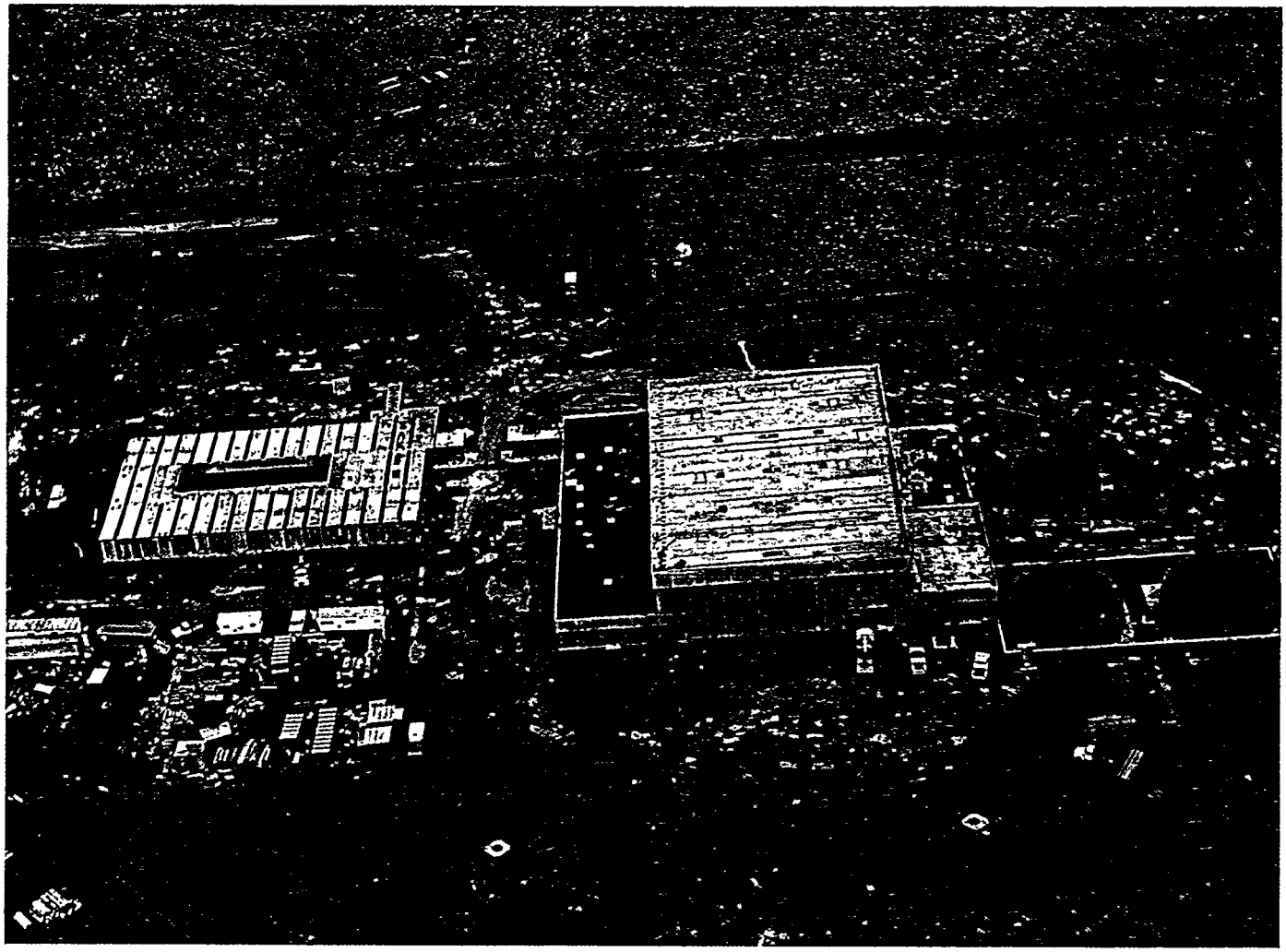




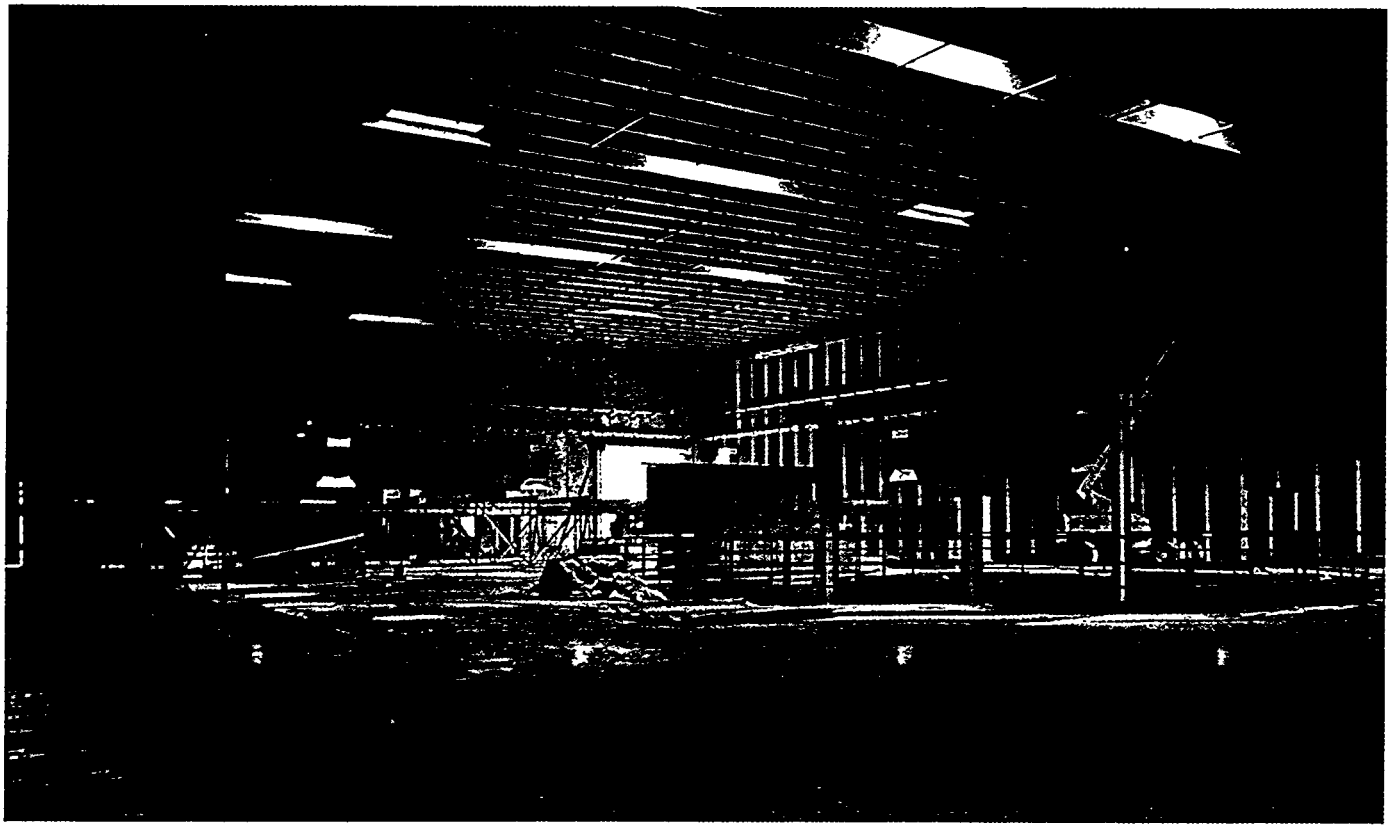
EBFA I
preliminary design study



Electron Beam Fusion Facility-aerial view

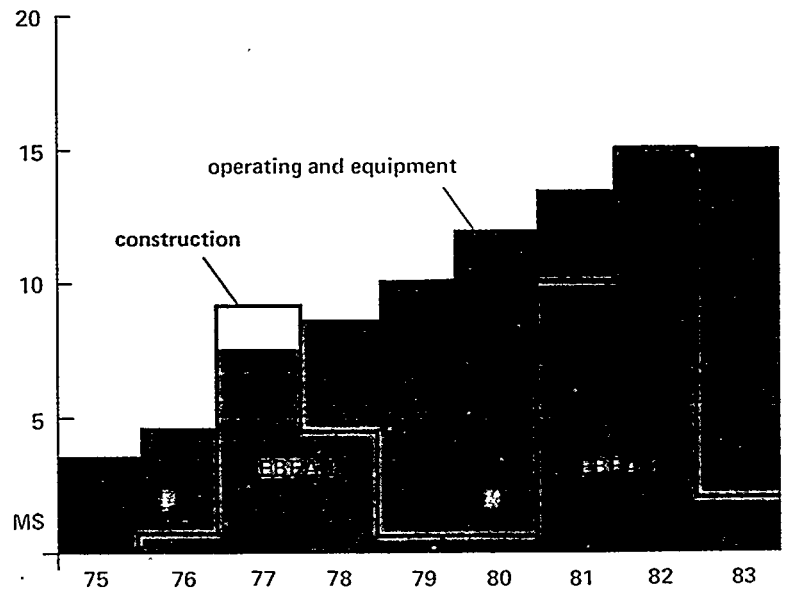


Electron Beam Fusion Facility-interior view



Budget

Sandia's Particle Beam Program budget has grown substantially since its inception in 1973; slower growth is expected through the net energy gain experiments in 1985. The EBFA upgrade and systems integration facility costs are estimated to be ~ $30M, and this expansion is being requested for first substantial funding in FY '81. This schedule will permit us to obtain sufficient experience with Proto II, MITE and EBFA to define the upgrade components with minimal risks.



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