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ABSTRACT

Pulsed Power Drivers for ICF and High Energy Density Physics*
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Nanosecond Pulsed Power Science and Technology has its origins in the 1960s and over the past decade has matured into a flexible and robust discipline capable of addressing key physics issues of importance to ICF and High Energy Density Physics. The major leverage provided by pulsed power is its ability to generate and deliver high energy and high power at low cost and high efficiency. A low-cost, high-efficiency driver is important because of the very large capital investment required for multi-megajoule ignition-class systems. High efficiency is of additional importance for a commercially viable inertial fusion energy option. Nanosecond pulsed power has been aggressively and successfully developed at Sandia over the past twenty years. This effort has led to the development of unique multi-purpose facilities supported by highly capable diagnostic, calculational and analytic capabilities.

The Sandia Particle-beam Fusion Program has evolved as part of an integrated national ICF Program. It applies the low-cost, high-efficiency leverage provided by nanosecond pulsed power systems to the longer-term goals of the national program, i.e., the Laboratory Microfusion Facility and Inertial Fusion Energy. A separate effort has led to the application of nanosecond pulsed power to the generation of intense, high-energy laboratory x-ray sources for application to x-ray laser and radiation effects science research. Saturn is the most powerful of these sources to date. It generates ~ 500 kilojoules of x-rays from a magnetically driven implosion (Z-pinch). This paper describes results of x-ray physics experiments performed on Saturn, plans for a new Z-pinch drive capability for PBFA-II, and a design concept for the proposed ~15 MJ Jupiter facility. The opportunities for ICF-relevant research using these facilities will also be discussed.

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Introduction

The near-term goal of the US ICF program is to achieve thermonuclear ignition of deuterium-tritium (D-T) fuel in the laboratory. The long-term goal is to achieve high-yield thermonuclear burn for both defense and energy applications. The National Ignition Facility (NIF) has been adopted as the preferred approach to ignition. It consists of a 1.8 MJ glass laser system designed primarily for indirect drive. Sandia's role in the national ICF Program has emphasized the development of ion beams for the long-term goal of high-yield ICF using light-ions and indirect drive [1-3].

The pulsed-power-based particle beam ICF program at Sandia builds on technologies initially developed during the late Sixties and early Seventies for radiography and for the generation of bremsstrahlung radiation. Rapid advances made in pulsed power technology at Sandia during the mid Seventies to the mid Eighties were mainly driven by the needs of the evolving ICF program. This period led to the development of fast water-dielectric pulse forming lines, the precision synchronization of a large number of pulse forming modules, and the efficient transport of high-power pulses through self-magnetically insulated vacuum transmission lines (MITLs)[4].

The PBFA-I accelerator was built in 1980 [5]. It was originally intended as an electron beam accelerator but was converted to investigate the generation of high power ion (proton) beams once it became clear that electron beams were unsuitable for driving an ICF pellet. PBFA-II was completed in late 1985 [6] as a power source for 24 MeV lithium beams. In this design, currents from 36 pulse-forming modules were added at each of eight layers of a vacuum insulator stack as shown in Figure 1. Each layer adds half of the current from nine separate pulse-forming modules. A set of MITLs within the vacuum insulator stack adds the voltage from the four top and bottom layers to feed power to a common ion diode located at the midplane of the stack. Progress in ion beam power coupling and ion-driven hohlraums on PBFA-II is described in a paper by Filuk et al. in this conference [7].

The long term goal of high-yield ICF requires a configuration where multiple ion beams are generated and extracted from the accelerator and propagated several meters to a pellet located at the center of a target chamber. The evolving ICF driver strategies for LMF and ETF are described in a paper by Olson et al. in this conference [8].

The SABRE accelerator at Sandia is being used to extend the light-ion beam technology developed in PBFA-II to an extraction geometry [9]. This work could be extended to higher voltage and power levels on Hermes III [10] and PBFA-II. Figure 2 shows the original PBFA-II configuration used for the barrel diode experiments as well as how the PBFA-II MITLs could be reconfigured to support extraction ion diode experiments.

Magnetically Driven Implosions

In 1987 PBFA-I was converted into the Saturn accelerator [11]. Saturn is used as a source of ~1 MeV bremsstrahlung radiation. It is also used as a power source for fast magnetically driven implosions and generates ~0.5 MJ of X rays in this mode. Figure 3 depicts the various stages of the plasma implosion process. A pulsed power high voltage generator produces a number of individual output pulses. The current from these individual pulses are added, through a set of MITLs, and delivered to a cylindrical plasma load located at the center of the test chamber. The magnetic forces generated by the drive current cause the plasma to implode thus converting electrical energy into kinetic energy. The kinetic energy is then converted into radiation when the plasma stagnates on axis. Magnetic energy stored near the load region can continue to drive the collapsed plasma producing additional radiation. The implosion system thus represents an additional stage of power compression and the radiation pulse from ~100 ns implosion can be ~ 15 ns in duration. The entire process can also be made to be very efficient [12].

The work on magnetically driven plasma implosions has been motivated by applications to radiation effects science research, X-ray lasers and high-energy-density physics. Work on Z-pinch physics dates back several decades. Progress has been arguably limited by problems associated with control of instabilities in the imploding system. The advent of fast pulsed power drivers in the Eighties resulted in fundamental changes. An analysis of the scaling of MHD instabilities in imploding plasma liners by Hussey et al. [13] shows that the Rayleigh-Taylor instability dominates in the worst, most unstable implosions. The result is that short high-temperature radiation pulses can be more readily obtained with shorter implosion times. The use of high-power, short-pulse generators such as Saturn to drive plasma implosions shifts the problem emphasis from plasma dynamics towards high-efficiency, fast pulsed power systems. This line of research thus benefits greatly by using systems that take maximum advantage of the substantial progress in fast pulsed power science and engineering made over the past 15-20 years.

The Saturn Experiments

The experiments on Saturn were preceded by x-ray laser experiments on Proto-II [14] which themselves built on the results of the SCORPIO Z-pinch program [15]. The configuration used for the X-ray laser experiments is shown in Figure 4. In this scheme an annular shell surrounds an X-ray laser rod which sits on the cylindrical axis of symmetry of the Z-pinch implosion. The annular shell serves both to stagnate the imploding plasma, converting plasma kinetic energy into radiation (the flashlamp), and to hydrodynamically isolate the laser rod from the imploding plasma. With this geometry the lasant can remain homogeneous for a time before being destroyed by the imploding plasma. These experiments on Saturn were successful in demonstrating a population inversion in helium-like neon [16].

The X-ray physics research on Saturn has continued over the past few years with emphasis on radiation effects science and high energy density physics studies. This effort first evolved into a tri-laboratory effort involving participation from Los Alamos National Laboratory and Lawrence Livermore National Laboratory. It has since expanded into an international collaboration which to date includes the Commonwealth of Independent States and the United Kingdom. The basic goals of this effort has been to generate and characterize macroscopic laboratory plasmas (~1 cm^3) over long time scales (15-30 ns) and to use these results to benchmark our computational modeling.

Magnetically driven implosion experiments have been performed by this international, multi-laboratory team using ~ 10 MA drive current on Saturn at Sandia and ~ 3 MA on Angara V at Trinity in Russia. These experiments have been heavily diagnosed to develop a better understanding of the pinch dynamics as well as to characterize the resulting radiation environment. The experiments include simple vacuum hohlraums as well as foam filled hohlraums; with and without high-Z doped material. Figure 5 shows that comparable hohlraum temperatures have been achieved using ion beams on PBFA II and magnetic implosions on Saturn.

PBFAII-Z and Jupiter

A team of pulsed power and Z-pinch physics experts (Jupiter Design Options Study Team - JDOST) was chartered by Sandia and the Defense Nuclear Agency to evaluate technology options and assess the feasibility of a ~15 MJ laboratory X-ray source for radiation effects science and testing. The team included participants from DOE and DoD laboratories, universities, and private industry. The eight-month study concluded that the most promising approach for the near term was using a ~100 MJ (energy stored), 450-500 TW, 8-10 MV, ~100 ns pulsed power generator. The relatively short implosion time was chosen to minimize problems with implosion instabilities. As stated earlier, this approach tends to shift the area of difficulties from plasma dynamics towards more stringent requirements on the pulsed power generator.

Figure 6 shows a design concept for Jupiter. It consists of ~30 high voltage generator modules based on the inductive voltage adder technology that has proven to be very reproducible and reliable on Hermes III. The output pulses from the individual modules are added in parallel within the test chamber and fed to a single cylindrical plasma load located at the chamber axis. A module consists of a four-stage inductive voltage adder. Each of the four submodules is fed by four individual pulse forming lines (PFLs). Each PFL delivers the same power as each of the PBFA II pulse forming modules. Our plans are to complete construction of a testbed module and demonstrate the requisite integrated performance by the end of FY96.

The largest technical risk associated with the construction of Jupiter pertains to the performance of the Z-pinch implosion with ~ 55 MA drive current. The highest current experiments to date have been performed on Saturn at ~ 10 MA drive current. We are developing a Z-pinch drive capability for PBFA II. This capability will be obtained by redirecting the output from the 36 individual PFLs through a short vacuum insulator stack and using a set of MITLs, similar to those used on Saturn, to deliver the summed current pulse to a single Z-pinch load. A sketch of the PBFAII-Z configuration is shown in Figure 7. Calculations indicate that PBFAII-Z should be capable of driving 20-25 MA implosions with ~ 100 ns implosion times. PBFAII-Z should be completed during FY96 and will enable ~ 2 MJ implosion experiments. These experiments will validate our understanding of power flow and implosion dynamics and will provide the necessary confidence for scaling to Jupiter level parameters.

Applications to ICF

The pulsed power R&D, ICF, and Radiation Science programs at Sandia are highly interdependent. The individual programs have benefited greatly from the strong linkage between them. Sandia is a leader in developing laboratory X-ray sources using fast magnetically driven implosions and has initiated a comprehensive assessment of how the rapid progress being made with these systems can be leveraged for the benefit of the ICF program.

The motivation for this study is best seen in Figure 8 which shows the measured hohlraum temperatures achieved to date on existing facilities and an extrapolation of these data to PBFAII-Z and Jupiter. Although this approach does not allow for stand-off, and thus is not a candidate for the long-term goals of high-yield ICF, it is possible to conceive of a number of important radiation transport and internal pulse shaping experiments using this technology. The ultimate promise is the potential to drive a pellet. Achieving this promise however will require developing concepts that transform the radiation from the cylindrical converter into a spatially uniform, temporally programmed pulse to drive the imploding capsule.

Conclusions

Magnetically driven implosions using fast pulsed power generators form the basis for a growing international collaboration on X-ray physics. This technology has proven capable of converting electrical energy into X-ray energy with an overall efficiency of 15-20 percent. The Saturn and Angara V experiments will be extended to include ≥ 20 MA, ~2 MJ implosion experiments on PBFAII-Z during FY96. A design concept for Jupiter that makes use of inductive voltage adder technology has been developed and would enable ~ 55 MA, ~ 15 MJ implosion experiments. Sandia has initiated an assessment of how success with hohlraums generated on PBFAII-Z and Jupiter could best be used for the study of ICF implosion physics.

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References

1. J. P. VanDevender and D. L. Cook, Science, **232**, 831 (1986)

2. J. P. Quintenz, et al. "Progress in Light Ion Fusion," Proc. IAEA Technical Committee Meeting on Drivers for Inertial Confinement Fusion, Osaka, Japan, April 15-19, 1991.

3. M. K. Matzen, et al. "Progress in Ion Beam Target Design and Experiments," in *Proceedings of the 15th International Conference on Plasma Physics and Controlled Nuclear Fusion Research*, Seville, Spain, Sept. 26-Oct. 1, 1994.

4 J. J. Ramirez, et al., "Very High Pulse-Energy Accelerators," Proc. 1989 Particle Accelerator Conf., Chicago, IL, March 20-23, 1989, 1446.

5. T. H. Martin, et al., "Particle Beam Fusion Accelerator I," IEEE Trans. on Nucl. Sci. NS-28, No. 3, 3368 (1981).

6. B. N. Turman, et al., "PBFA II - A 100 TW Pulsed Power Driver for the Inertial Confinement Fusion Program," Proc. 5th IEEE Pulsed Power Conf., Arlington, VA, June 10-12, 1985, pp. 155-161.

7. A. B. Filuk, et al., "Progress in Ion Beam Coupling and Ion-Driven Hohlraums on PBFAII," in Proceedings of this Conference.

8. C. L. Olson et al., "ICF Driver Strategies for IFE," in Proceedings of this Conference.

9. D. L. Hanson, et al., "Improved Field Geometries for SABRE Extraction Ion Diode Operation With Passive Ion Sources," Beams 94 10th International Conference on High Power Particle Beams, San Diego, CA, June 20-24, 1994.

10. J. J. Ramirez, et al., "Hermes III - A 16 TW, Short Pulse, Gamma Ray Simulator," Proc. 7th International Conference on High Power Particle Beams, Karlsruhe, West Germany, July 4-8, 1988, pp. 148-157.

11. D. D. Bloomquist, et al., "Saturn, A Large Area X-Ray Simulation Accelerator," Proc. 6th IEEE Pulsed Power Conf., Arlington, VA, June 29-July 1, 1987, pp. 310-317.

12. P. J. Turchi and W. L. Baker, J. Appl. Phys. 44, 4936 (1973).

13. T. W. Hussey et al., J. Appl. Phys. 51, 1452 (1980).

14. M. K. Matzen, et al., J. Phys. Colloq. (Paris) 47, C6-135 (1986).
15. M. J. Clauser, L. Baker, D. H. McDaniel, R. W. Stinnett, and A. J. Toepfer, "Magnetic Implosion of Plasmas with Short Pulse, High Power Generators," Sandia Report, SAND78-1387C.

16. J. L. Porter et al., Phys. Rev. Lett. 68, 796 (1992).

Figure Captions

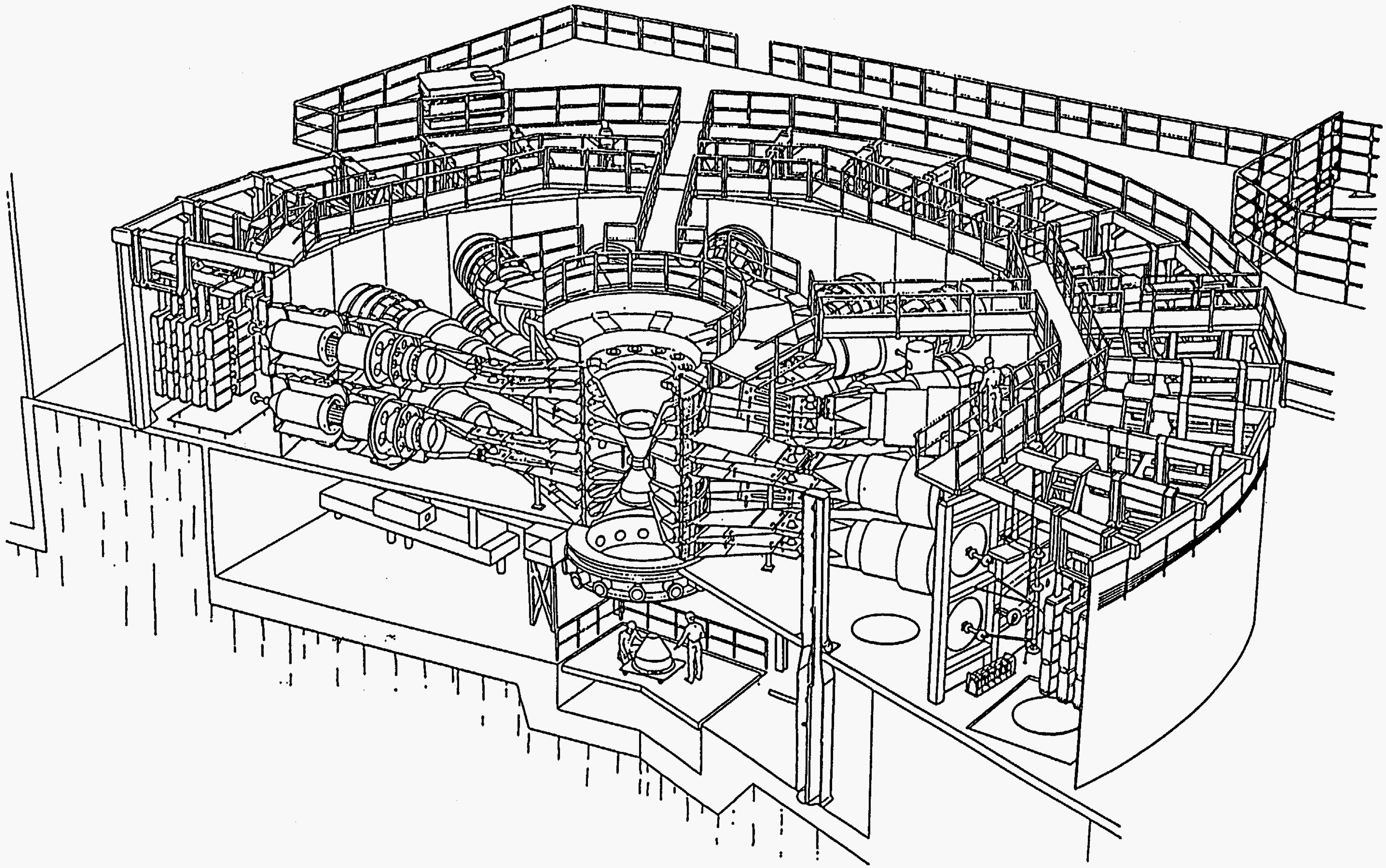
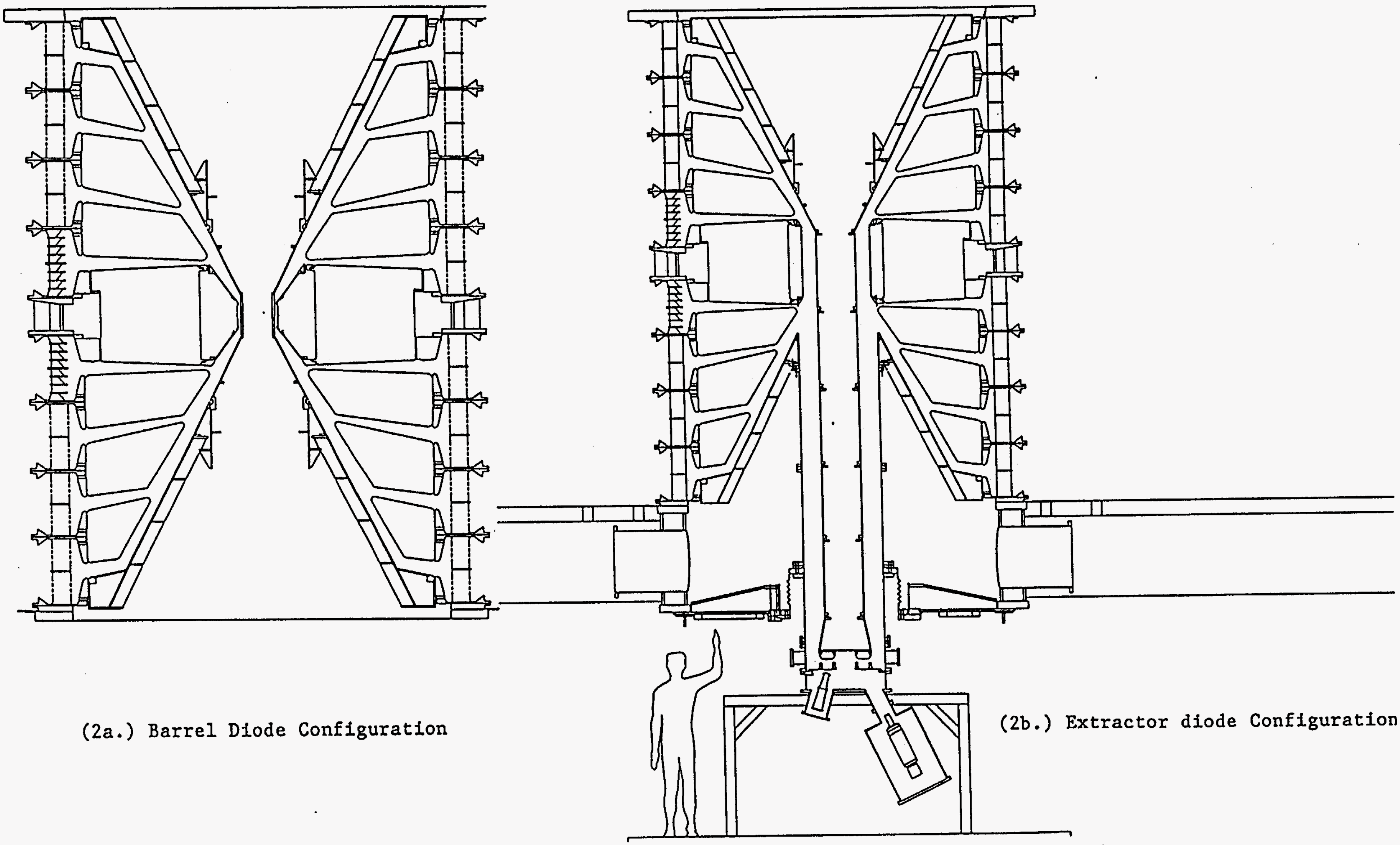


Figure 1.



(2a.) Barrel Diode Configuration

(2b.) Extractor diode Configuration

Figure 2.

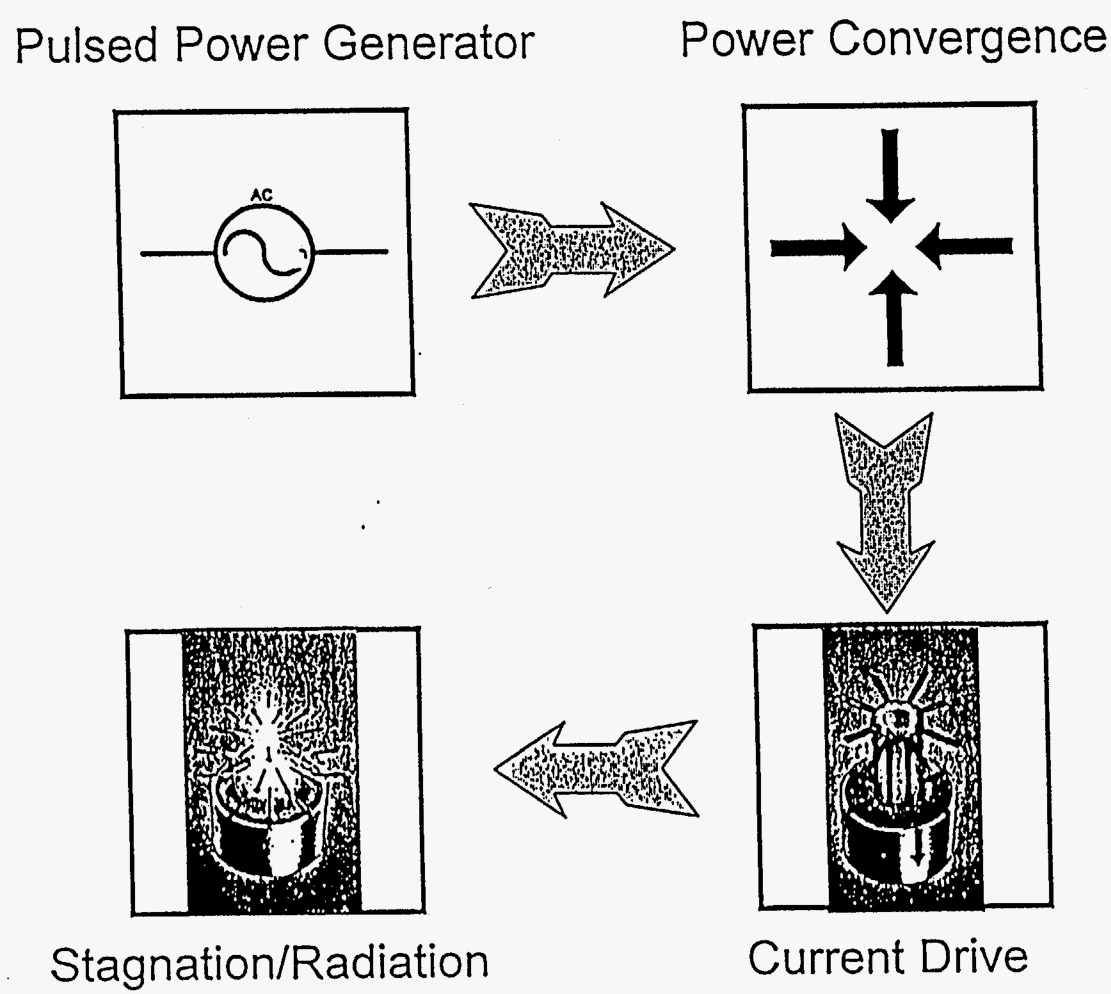

Pulsed Power Generator
Power Convergence
AC
Current Drive
Stagnation/Radiation

Figure 3.

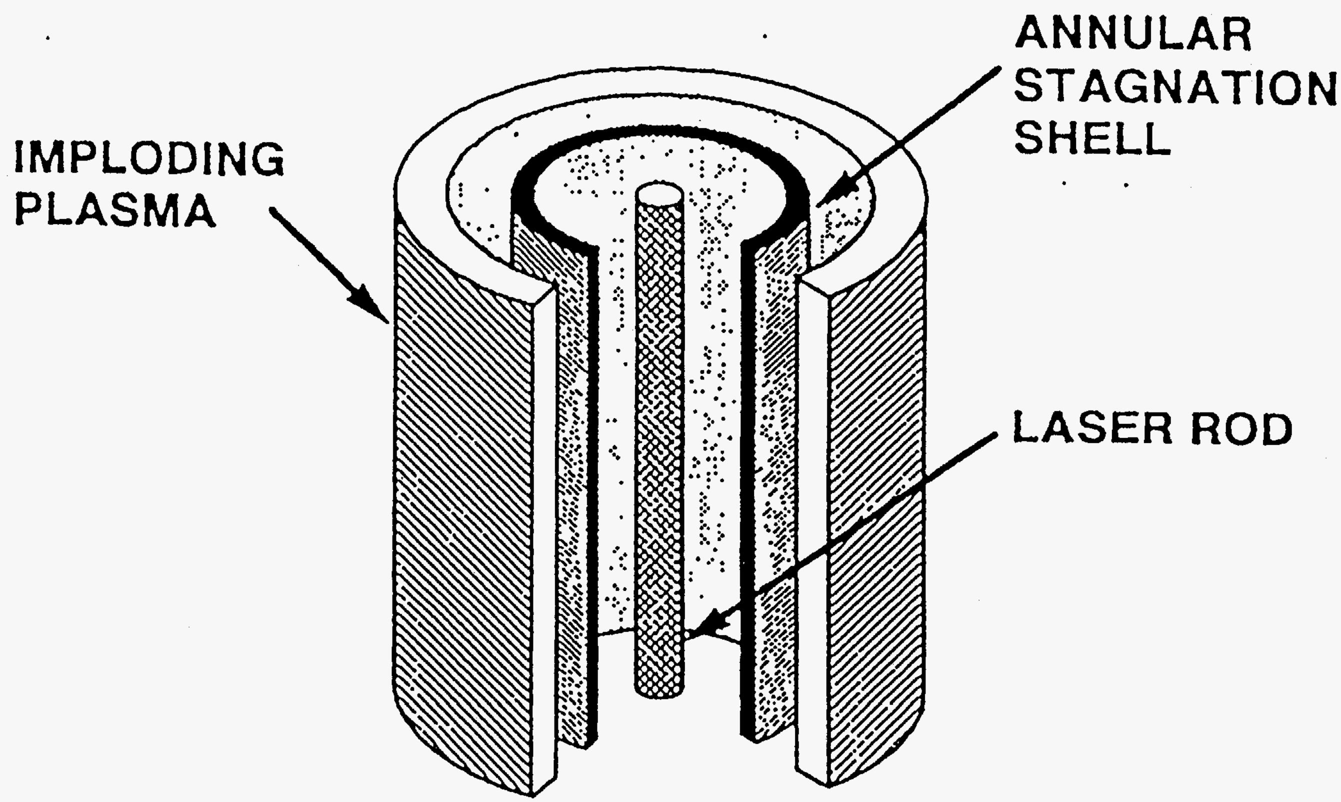
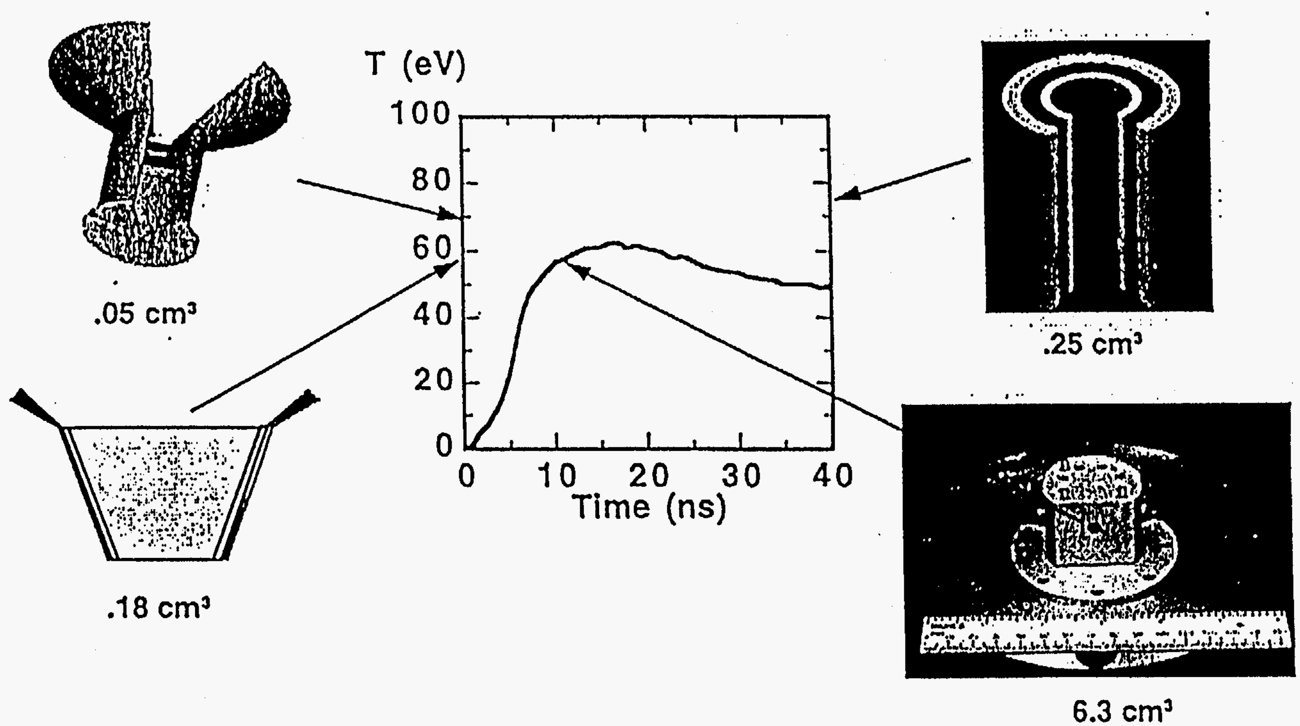


Figure 4.



T (eV)
100
80
60
40
20
0
0
10
20
30
40
Time (ns)
.05 cm³
.18 cm³
.25 cm³
6.3 cm³

Figure 5.

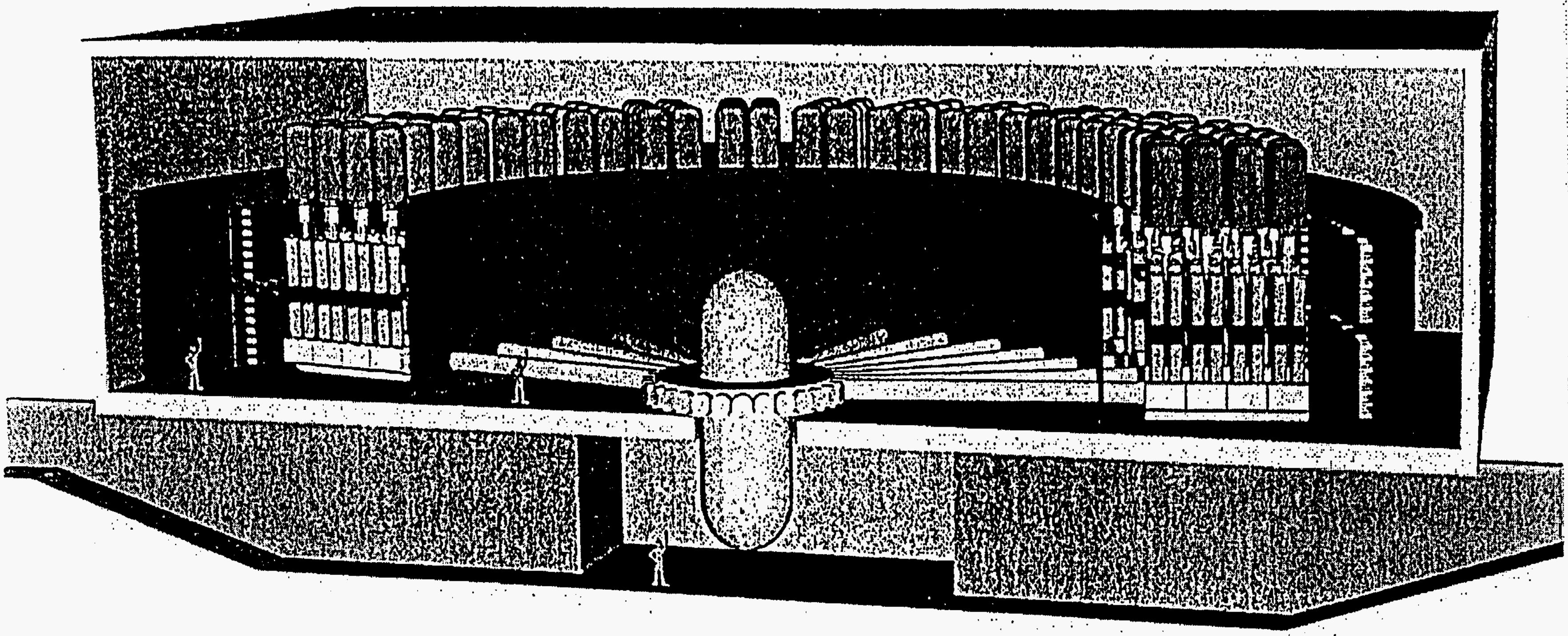


Figure 6.

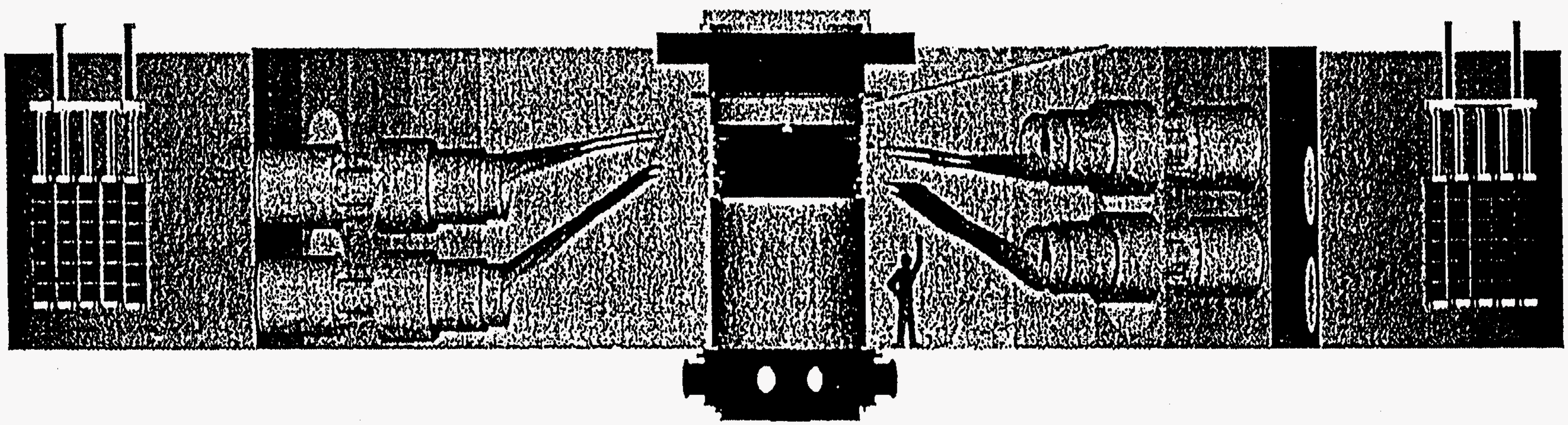


Figure 7.

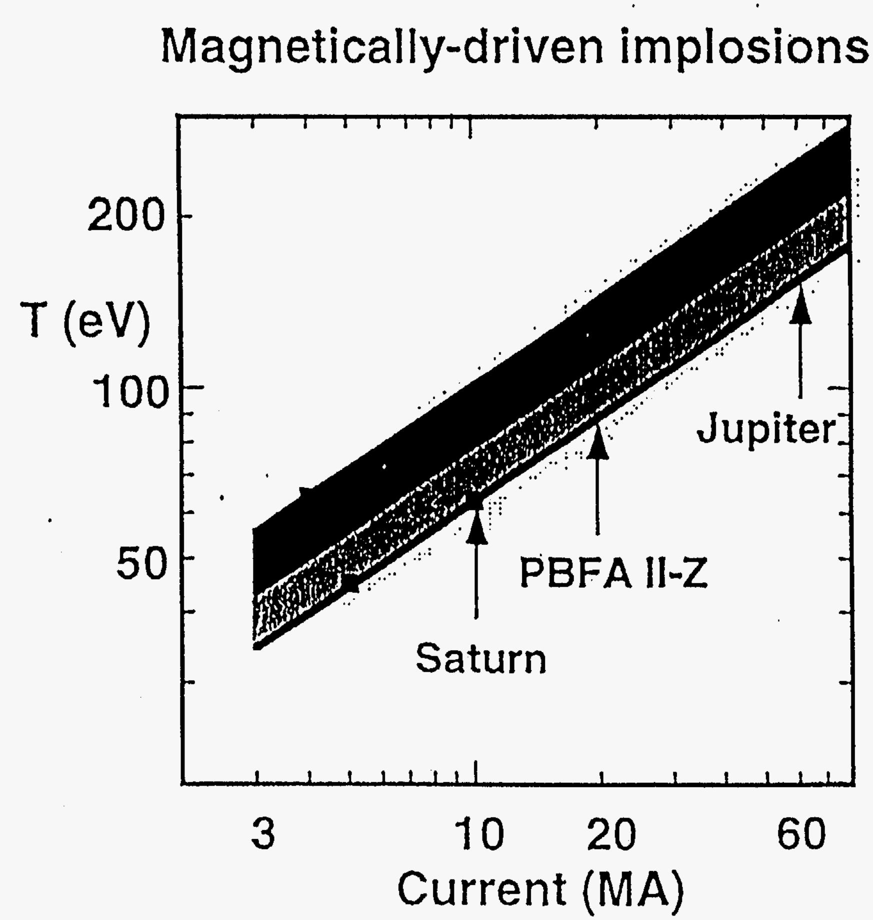

Magnetically-driven implosions
T (eV)
200
100
50
Jupiter
PBFA II-Z
Saturn
3
10
20
60
Current (MA)

Figure 8.