Design Studies of the APEX Light Ion Fusion Experiment

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Abstract

The APEX project is an upgrade of the PBFA-II light ion fusion accelerator at Sandia Laboratories, Albuquerque to allow pulse shaping for driving high gain ICF targets. This upgrade includes: modification of the pulsed power, replacement of the barrel diode with an extraction diode, addition of a z-pinch plasma channel, and addition of a shielded target chamber. In this paper we emphasize the structural response of the target chamber to a 100 MJ light ion driven target microexplosion, shielding and containment of the induced radioactivity, and modification of the PBFA-II facility to accommodate the APEX chamber.

Introduction

The Particle Beam Fusion Accelerator II at Sandia National Laboratory, Albuquerque is designed to achieve significant thermonuclear burn in a DT fusion target, but not high gain. The target performance is limited by the pulse shaping capabilities of the diode-target configuration. In PBFA-II, lithium ions are ballistically focussed from a 15 cm radius barrel-shaped diode surrounding the target at the center of the machine. For high gain the pulse shape must be tailored in a way that is not possible with this configuration. Creating this shaped pulse is the major purpose of the APEX upgrade project. Improvement in the pulse shaping can come through voltage ramping of the ions in an extraction diode and injection into a z-pinch plasma channel with the target at the other end of the channel. This is shown schematically in Fig. 1. With this configuration, time-of-flight compression of the beam can generate the finely tuned temporal power profile that high gain targets require. The inclusion of a long plasma channel for APEX necessitates the modification of the basement of the PBFA-II facility; for now the target will be moved from the center of the machine to the end of the plasma channel. This is shown in Fig. 2. The modification of the pulsed power, design of the extraction diode, and proposed ion beam and plasma channel parameters are discussed by Crow et al. [1] and will not be included here. The following sections are a discussion of the target chamber and shield design, and the structural and neutronic performance of this design.

Target Chamber and Shield Design

Should high gain be achieved, the burning target will generate a blast wave and burst of 14 MeV neutrons. A target chamber to contain the blast and radioactive debris will be required along with biological shielding to protect personnel from the radiation from decaying activation products. A design for this target chamber and shielding that will fit into the existing PBFA-II basement is shown schematically in Fig. 3. This design is based upon a target yield of 100 MJ. The 1 meter diameter spherical target chamber made of aluminum 6061-T6 is submerged in a 4 m diameter tank of borated water. The chamber wall thickness is 5 cm and the inside surface of the chamber is covered with 1 cm thick carbon-carbon composite tiles to serve as a heat shield. The outside of the chamber is covered with 1 cm of boral to reduce activation from the thermal neutron albedo from the water pool. The steel tank is 2 cm thick with 50 cm of concrete around it for shielding.

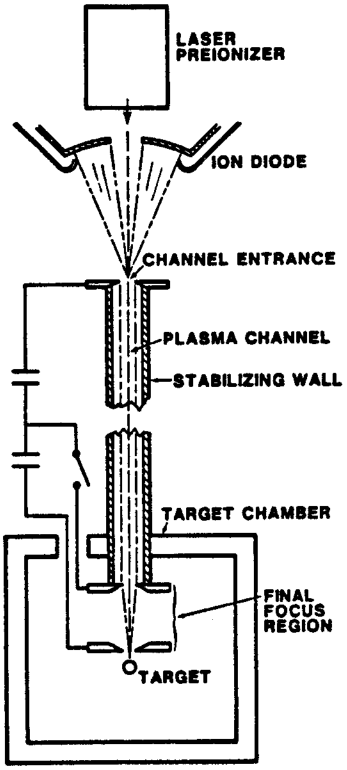

Fig. 1. Schematic of diode-channel-target configuration for APEX.

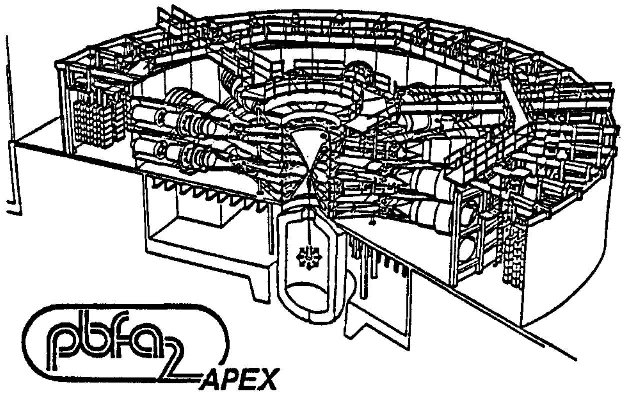

Fig. 2. Modification of PBFA-II to accommodate target chamber in basement.

The APEX experimental campaign consists of only 30 high yield shots and this has led to a "throw-away" chamber design. A chamber is used for only one high

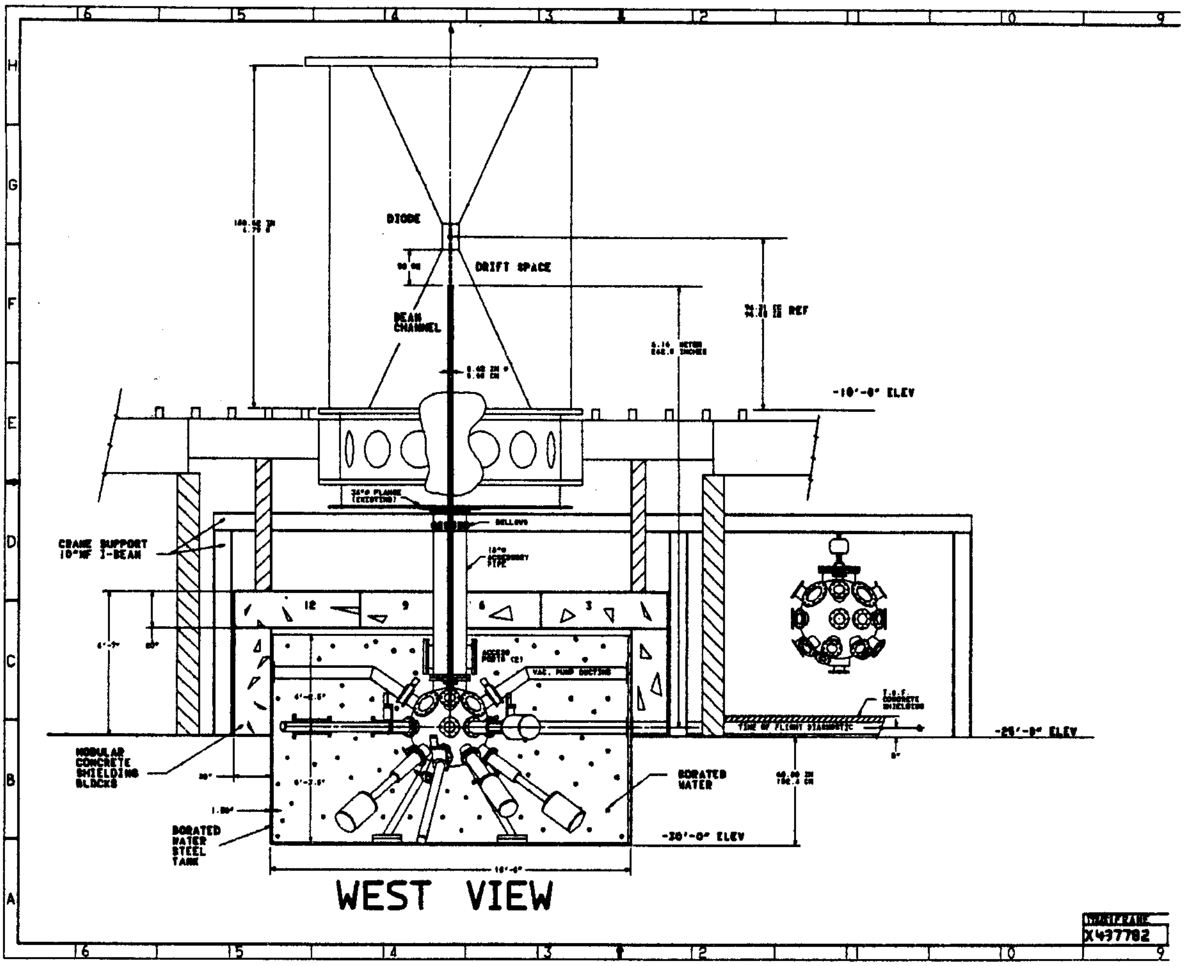

Fig. 3. APEX target chamber and shield.

yield shot and is then discarded and replaced with a new one. In this way, the activated chamber need not be handled, except to remove it, and the surrounding structure has a sufficiently low activation to allow hands on access to the experimental area once the chamber is removed. The cost tradeoff between replacement and reuse of activated chamber is in favor of the "throw-away" approach due to the costs of remote handling. We estimate the replacement cost of the target chamber and other replacement equipment to be $236,000 per shot.

The total installed cost of the APEX project is estimated to be $1.8 million. This does not include the costs of: a tritium control system, research and development to determine exact specifications, diagnostic development, equipment, and installation, and recurring operational costs. About $1.4 million is for facility modification. The two major facility modifications are (1) the rework of the elevator pit to accommodate the shielding tank, installation of the modular concrete cover for the tank and (2) excavation for and building of a below grade two story laboratory building intended to house experiment diagnostic equipment. Other major cost items include the time-of-flight tunnel and support, the borated water shield handling system, the TOF diagnostic room, the waste disposal area, and the experiment staging area. The remaining $400,000 is for the initial target chamber and vacuum system. It is expected that the development costs will greatly exceed the modification, manufacture and installation costs of the facility.

Radiation Hazard Analysis

The radiation hazard from a single 100 MJ target shot comes in two forms: (1) the prompt neutrons and photons from the shot itself, and (2) the decay gamma rays from activation products created by the prompt neutrons. Prompt neutron and gamma fluxes were computed using the MCNP Monte Carlo program, taking into account the softening of the neutron spectrum through collisions in the compressed target. The activation product inventory was estimated using the REAC2 program and the dose rates resulting from both prompt and decay radiation were estimated with the ISOSHIELD program.

The prompt radiation affects both personnel and electronics. Personnel can be protected by exclusion from the target chamber area during a shot. The prompt dose behind the 50 cm thick concrete shield tank is 34,000 Rem. Electronics should be placed behind an additional 2 m of concrete to reduce the dose to acceptable levels.

The greatest operational hazard is from the decay gamma rays resulting from the activation products induced by the fusion neutrons. The majority of this activation is in the target debris and beam tube debris created during a microexplosion and in the target chamber structure. Unburned tritium also presents a significant hazard. A full pellet burn will leave 4 curies of unburned tritium in the chamber. Immediately following the shot there is over

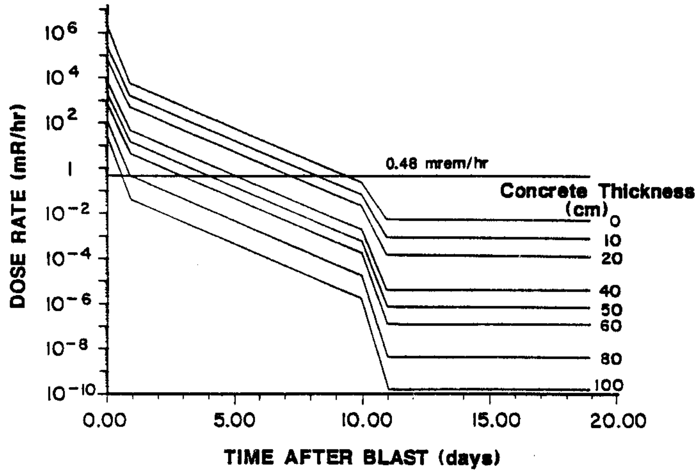

Fig. 4. Dose rate behind concrete shielding following 100 MJ target shot.

1 megacurie of activity in these components, but this decays to about 0.1 curies in 10 days (not including the tritium) and thereafter remains at this level. This activation will be completely removed from the target experiment area by isolation and removal of the target chamber after each shot.

The borated water shield must be sized to limit significant activation of structure to the removable target chamber. The concrete shield thickness is sized to limit dose levels behind it to acceptable levels for personnel access after a shot. Calculations indicate that 75 cm of borated water is required to reduce the activation of the steel tank to negligible levels. Figure 4 shows the dose rate at the surface of the concrete shield as a function of time following a shot for different shield thicknesses. A shield thickness of 50 cm gives a surface dose of 0.48 mrem/hr at about 4 days after a shot. This is assumed to be an acceptable waiting time for a reduction to the design average dose level. At one day after the shot the dose is only 10 mrem/hr, which is acceptable for limited access. If the water is removed, the dose at the shield surface increases by about two orders of magnitude.

Post shot access and removal of the target chamber will require that at least part of the concrete shielding on the top be removed. Figure 5 shows the dose at the pool surface for different water shield thicknesses. The occupational dose design standard of 0.48 mrem/hr is reached at 10 days following a shot for a thickness of 75 cm. To remove the chamber with the least exposure to personnel it should be surrounded by a temporary shield. Calculations show that 2 cm of lead are enough to reduce the contact dose to 0.48 mrem/hr at 11 days after a shot. This is consistent with the 10 day waiting period for removing the concrete shielding blocks. These results are summarized in Table 1.

Table 1. Dose Following 100 MJ Target Shot.

	0 day	1 day	5 day	10 day	19 day
75 cm H_2O/50 cm Concrete	2823.	14.8	0.174	6.1-4	6.7-7
75 cm H_2O only	1.05+7	1.12+4	132.	0.48	0.014
Bare Chamber	9.32+9	1.10+6	1.31+4	78.0	11.1

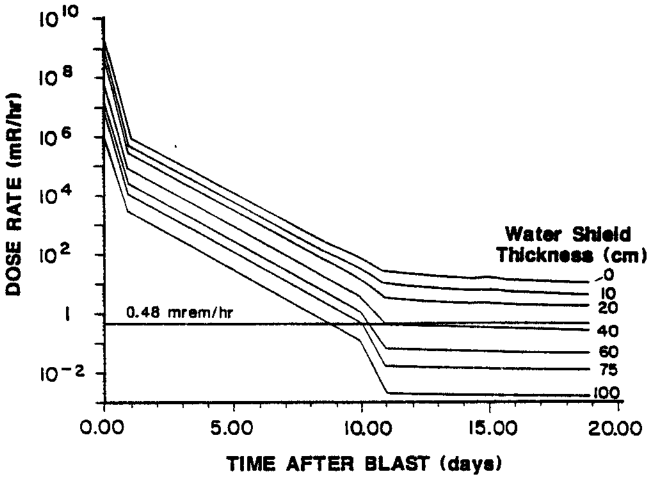

Fig. 5. Dose rate at water pool surface following 100 MJ target shot.

Target Chamber Structural Response to Blast Wave

The "throw-away" nature of the target chamber directs its design toward the smallest size consistent with an acceptable structural response to the target blast. Since each chamber will experience only one shot, the design criteria is to avoid rupturing. There are no fatigue considerations of importance.

At diameters of 1 meter or less there is significant ablation of surface material due to energy deposition by target x-rays. This ablated plasma creates a recoil impulse on the chamber and the hot plasma contributes to a quasi-static pressure as it fills the chamber. The chamber is assumed to be initially filled with 100 torr of helium gas. The ionic debris from the target microexplosion stops in this gas and creates an outward propagating blast wave. This blast wave intercepts the ablating material from the wall as shown in the R-T diagram in Fig. 6. Following this interaction, a blast wave is partially transmitted to the wall and collides at about 48 microseconds. For the base case of 1 meter diameter, the CONRAD radiation-hydrodynamics program

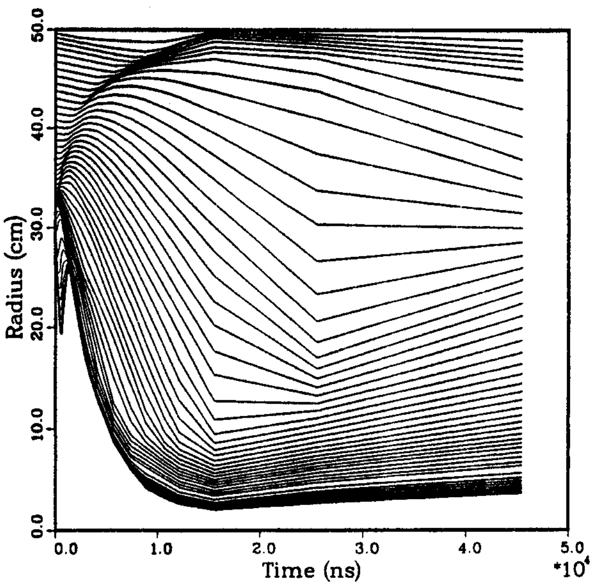

Fig. 6. R-T diagram of blast wave interaction with ablating surface.

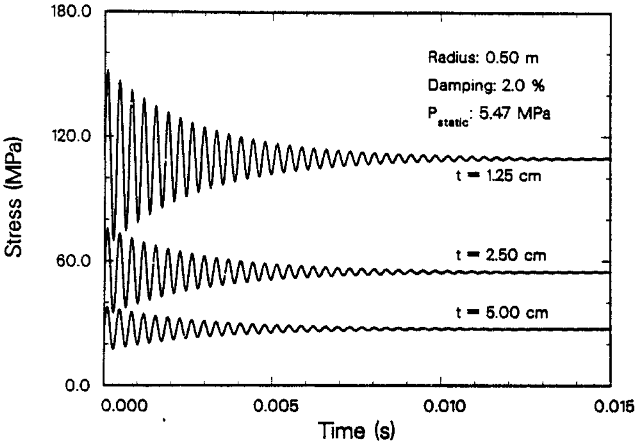

Fig. 7. Transient stress in APEX target chamber.

predicts that 80 grams of carbon is ablated from the wall, while there is only about 10 grams of helium in the chamber. This results in a recoil impulse of 50 Pa-s and a blast wave impulse of 75 Pa-s. The quasi-static pressure of the combined helium and carbon plasma in the chamber following the shot is 5.5 MPa.

For the mechanical analysis we assume a spherical chamber and completely symmetric motion. The shell remains spherical and simply expands and contracts with the same radial displacement component everywhere on the sphere. The equations of motion of the sphere are solved with a Runge-Kutta algorithm using the results of the CONRAD simulations as the loading. Results of the stress analysis calculations are displayed in Fig. 7 for different chamber wall thicknesses and for a diameter of 1 meter. The yield stress of aluminum, 270 MPa, is never exceeded. This larg safety factor between computed stress level and the yield stress gives us confidence that such a chamber concept is feasible.

Scoping calculations are done for differing chamber radii, keeping the helium gas pressure and target yield fixed at 100 torr and 100 MJ respectively. As the radius is reduced, the impulse from ablated surface material increases while the impulse from the blast wave is reduced. At 35 cm radius, the impulse from the blast wave is lowered to a negligible value by shielding from the more massive ablating material, while at 1 meter radius, there is negligible recoil impulse because little material is ablated from the surface. Thus there is a tradeoff. However, as the radius is reduced the quasi-static pressure of the material filling the chamber varies in inverse proportion to the volume change. While these parametric calculations are incomplete, they indicate that there is a change of scaling of wall loading from standard strong shock theory once the chamber radius is below 1 meter for 100 MJ explosions. Ablating surface material dominates the loading as the radius is reduced. This transition point will of course depend upon the target yield.

Summary and Conclusions

The APEX upgrade of the PBFA-II accelerator is designed to provide the pulse shaping required to implode high gain targets. The preliminary analysis and design presented in this paper confirms that a target chamber and radiation shielding consistent with a 100 MJ target microexplosion can be fabricated and installed in the basement of the PBFA-II facility after appropriate modifications. Analysis shows that a replaceable target chamber with a lifetime of one high yield shot may be the best option to minimize radiation exposure and cost.

Acknowledgement

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References

[1] J.T. Crow, G.O. Allshouse, E.L. Neau, C.L. Olson, and S.A. Slutz, 1987 IEEE Pulsed Power Conference.