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Dennis Slaughter

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MASTER

OVERVIEW OF THE ICF 1000 MJ EXPERIMENT CHAMBER DESIGN*

Dennis Slaughter
Lawrence Livermore National Laboratory
P. O. Box 5508, Livermore, California 94550
(415) 422-6425

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ABSTRACT

A conceptual design of an experiment chamber for a high gain ICF facility (1000 MJ) is being developed. Performance goals have been established. Several design approaches are being evaluated through computer simulations, engineering analysis, and experimental testing of candidate first wall components.

INTRODUCTION

A conceptual design is being developed for the ICF Megajoule Experiment Area (MEA) which is the containment chamber and target support portion of the Laboratory Microfusion Facility (LMF). The objective is a concept which meets all of the performance goals at an acceptable cost and which minimizes technical and safety risks.

Performance goals for the MEA are very stringent. Anticipating 10 MJ of laser light at nominally 353 nm and fusion gain of 100, the nominal fusion yield is 1000 MJ. Variations in target compression (pR) of a factor of two from predicted values could result in maximum fusion yield of 1400 MJ including 5×10^{20} neutrons. Similarly, soft x-ray yield is assumed to be as high as 250 MJ and target debris is assumed to carry as much as 250 MJ, though nominal full yield values are smaller. These products generate unprecedented loads on the MEA. The 10 ns soft x-ray pulse and the target debris contain the energy equivalent of about 100 kg of high explosive.

Anticipating one full yield shot per week over a 10 year lifetime, the MEA is to be designed for 500 full yield shots. In addition, we anticipate 2000 shots at yields less than 100 MJ and at a rate one per day. Neutron generation during the life of the facility is expected to be about 0.1-0.5 grams.

Structurally, the MEA should withstand the shock generated when the soft x-ray pulse produces ablation of the inner wall surface and consequent hydrodynamic loading. In addition there is impulsive loading from target debris and the ablation it produces as well as pressure loading due to the residual hot gas. Finally, the generation of high velocity shrapnel from the target environment and masses associated with military applications experiments poses a serious threat to any first wall design.

The MEA must also resist buckling stresses due to possible hydrostatic and atmospheric loads as well as seismic loads. Driver propagation requires vacuum pressures lower than 10^{-2} Torr and diagnostics needed for low yield shots would be difficult at vacuum pressures above 10^{-4} Torr. In addition, the MEA should provide for 60-80 driver penetrations (depending on driver design) up to 60 cm diameter and up to 100 diagnostic penetrations.

The MEA must support neutron and gamma ray shielding. Design goals are to reduce prompt radiation dose to personnel outside the chamber during a shot, and radiation dose following a shot due to activation to levels which do not exceed 100 mrem per working week. Personnel access to the interior of the MEA is desired within one day after a low yield shot (less than 10 MJ) and within one week after a full yield shot. Access will be complicated due to residual tritium (up to 50 mg per shot) and by the need to maintain acceptably low radiation dose rates (100 mrem/hr for brief servicing requirements and 2.5 mR/hr for major repairs or installation of new equipment).

Finally, provision will be made for simulations of weapons radiation fields for the evaluation of military components. Exposure volumes nominally 100 cm x 100 cm in exposure area and 50 cm thick are desired in the immediate vicinity of the target.

DESIGN APPROACH

For the baseline design, we assume targets which emit x-rays in the neighborhood of 1 KeV. Figure 1 shows the photon mean free path¹ (solid lines) for carbon, aluminum, and water frost at density 0.1 gm/cm³. It is clear from the figure that the x-ray pulse penetrates only the first few microns of the first wall even if it is constructed of low-Z materials.

The x-ray fluence at which a short pulse of 1 keV photons begins to cause permanent damage in many materials of interest for optic and the first wall is² 0.5-1.0 J/m². Figure 2 shows a plot of x-ray fluence at the first wall due to a 250 MJ pulse vs. the wall radius.

Unprotected first walls of common construction materials such as aluminum or steel must be placed at nearly 60 m radius to avoid vaporization entirely. Even carbon, which is most resistant to vaporization, must be located 30 m from the target.

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reduces residual gas pressure.

Experimental verification of shock attenuation in frost is not yet complete. The ability to grow a uniform layer in a reasonably short time on a large wall and for that layer to be self supporting in the presence of mechanical shocks or vibration remains to be established. Finally, the stability of the layer over long periods has yet to be demonstrated.

First walls of carbon are attractive due to their relative freedom from neutron activation and resistance to vaporization. Carbon-carbon walls consisting of strong carbon fibers weaved into a matrix in two or three dimensions are being studied by Sandia National Laboratory (K. Wilson, J. Whitley), General Atomics (R. Bourque, K. Schultz), Kaman Sciences (L. Webster), and LLNL (K. Sinz, D. Schauer). These materials are strong when densified by diffusing and pyrolyzing carbon into the matrix. A carbon wall erodes when a few microns of the surface vaporizes on each full yield shot. However, recondensation replaces much of the material and residual porosity attenuates propagation of shock pressures and reduces the likelihood of spall due to the initial ablative shock.

These materials are very expensive in 3-D format and cost considerations may limit their use. The 2-D weaves are much less expensive but are vulnerable to delamination during shock loading. In all cases some means of post-shot decontamination of the wall must be demonstrated and recondensation on optics must be evaluated.

Alternatively, shock loading of the permanent first wall may be reduced by introducing high aspect ratio textured surfaces into the wall so that shock waves are generated at large angles with respect to the surface normal of the substrate. A fiber structure resembling a carpet has been studied by W. J. Shafer Associates⁴ (M. Monsler, W. Meier) and a surface of steep pyramids has been studied by General Atomics (R. Bourque, K. Schultz). They present a large area, oblique to the x-ray flux, so that the areal loading is reduced and the amount of ablated material is less. In addition, the ablation generates a shock directed toward the local surface normal which has a small component directed into the substrate. Consequently, shocks propagating into the permanent first wall are believed to be substantially reduced in peak pressure.

The protective concepts based on highly structured surfaces are difficult to study through computer simulations. Viability of these concepts will be determined experimentally. Adequate protection of the permanent substrate against damaging tensile shock waves must be demonstrated. It must also be shown that these concepts are economical either through inexpensive replacement of the wall or very long useful lifetime with minimal servicing. A method of decontamination of the surface must also be demonstrated.

Our final design may incorporate a staged defense including two or more of these protection concepts.

COMPUTER SIMULATIONS

Computer simulations have been used to predict shock loading of the first wall for most of the design approaches above. In most cases the calculations indicate no permanent damage to the MEA^{3,5,7}.

Computer predictions of shrapnel generation in the area near the target are just beginning at Kaman Sciences and the Stanford Research Institute (SRI). Conclusions are not yet available. Results of these calculations and studies directed toward mitigating the effects of shrapnel generation in both full yield and low yield shots will be critical to the feasibility of our design approach.

Studies directed toward protection of the driver final optics are also continuing and are presented elsewhere⁸. Material and design choices for the MEA may impact substantially on the feasibility and design choice for protecting the optics. Those interactions are part of our ongoing design effort.

Finally, detailed analysis of the structural design to support the wall, driver beam lines, and neutron shielding is ongoing with computer calculations. Instability due to buckling, bursting due to residual hot gas pressure after a shot, seismic loads, and resonant excitation of chamber fundamental modes by the relatively low frequency loads imposed by target debris and gas pressure loading are areas of particular concern. Results of these calculations will be important in determination of the material thicknesses and the amount of metal to be included within the neutron/gamma ray shield. There is a continuing interaction between the need for strength in the chamber and the need to reduce the mass of materials which will undergo neutron activation and restrict personnel access. Hydrocarbons and carbon-carbon composites must be seriously considered for structural components not protected by neutron shielding.

EXPERIMENTS

Experiments are beginning to determine the shock mitigating properties of several of the first wall design approaches described above and for which computer simulations have shown favorable results.

Gas gun experiments are planned at LLNL and Kaman Sciences to measure attenuation of shocks in aluminum, teflon, and porous alumina over aluminum. In addition, x-ray flux simulations are scheduled at the Gamble II facility (NRL) using a proton beam (with some carbon). Figure 1 shows the proton range⁹ (dashed curves). (Note that the energy scale is in units of 100 keV for protons). At energies below 1 MeV the energy is deposited at depths comparable to that of soft x-ray deposition in the MEA. Proton beams at energies of 600-800 keV are expected to simulate the x-ray ablation and consequent shock loading in MEA first wall components at energy densities up to 300 J/cm². Samples of aluminum, teflon on aluminum, alumina on aluminum, water frost on aluminum, 2-D carbon fiber weave, 3-D carbon fiber weave, carbon fiber carpet and carbon pyramids will be exposed to these beams. Shock propagation measurements will be made and exposures repeated to assess multiple shot life expectancy.

PERSONNEL ACCESS

Choice of materials for those components which are placed inside of the neutron shielding is critical in order to meet the goals for personnel access. This issue has been explored in considerable detail at LLNL¹⁰ and will be reviewed only briefly here. Steel construction must be ruled out of the interior because of the long lived ⁵⁴Mn and ⁵¹Cr activity produced by neutron irradiation of iron. This is shown in Fig. 3 where the radiation

Figure 1. Photon mean free path (solid) where energy is units of keV and proton range (dashed) where energy is in units of 100 keV. Curves are for: a) Water frost at density 0.1 gm/cm³, b) carbon, and c) aluminum.

Figure 2. Maximum single shot x-ray energy fluence on MEA first wall.

We consider the MEA containment design viable if the construction cost is less than 80M\$, the annual operating cost less than 20M\$, and these goals can be reached without unacceptable safety or technology risks. Cost considerations force the design to incorporate a first wall which is feasible at a radius approximately 5 m. However, Fig. 2 shows the energy fluence on the wall to be about 100 J/cm² for full yield shots. About 0.1 MJ/gm is deposited in the first few microns of the wall, giving an energy density 25 times larger than that of detonating TNT.

FIRST WALL

Protection of the MEA permanent first wall may be approached using sacrificial/replacable shields. Alternatively,

the first wall may be of a robust design where ablation of the surface is tolerated and occasional repair or resurfacing is feasible. Several of these approaches are discussed in detail in other papers in these proceedings^{3,5} and elsewhere⁶. Consequently, they will only be discussed qualitatively here.

Target shrouds consisting of .25 cm polyethylene or 7 cm of frozen nitrogen are currently being studied at LLNL^{3,7} and at the University of Wisconsin⁸ as a means of reducing or eliminating soft x-ray illumination of the permanent first wall. The shroud absorbs the soft x-rays as well as target debris and is vaporized in the process. It may be located any distance from the target but, in order to minimize its mass and minimize the probability of shrapnel generation due to incomplete vaporization of the shroud, it is likely to be placed immediately around the target. The shroud provides helpful collimation for diagnostics and, in the case of a frozen nitrogen shroud, it reduces the heat load on cryogenic targets due to thermal radiation from the wall. It also may be used in combination with other protection approaches described below.

Experimental verification of the computer simulations and a demonstration of the fabrication technology have not yet been completed. In particular, the ability of the shroud to expand the time over which energy is delivered to the MEA first wall and reduce the corresponding flux to a level at which conduction cooling of the wall prevents vaporization has yet to be shown under MEA conditions.

Sacrificial inner layers may be used to protect the permanent first wall. Three such materials are currently being considered. Kaman Sciences Inc. (L. Webster) is studying plasma spraying of porous alumina over an aluminum wall at room temperature. The alumina, which is made porous by inclusion of small microballoons, attenuates the shock wave produced from ablation of the alumina surface. As a result the tensile stresses in the aluminum substrate are greatly reduced and failure of the wall is avoided. Teflon may be used instead of alumina. Both materials have been studied as protection mechanisms for re-entry vehicle nose cones subjected to nuclear weapons radiation and extensive experimental testing demonstrates their shock mitigating effects.

In order for this protection strategy to be viable it must be possible to economically spray the surface layer on a wall at room temperature and, at a later time, be able to economically remove it together with embedded debris for decontamination purposes. These technologies remain to be verified experimentally.

Low density water frost may also be used as a sacrificial inner layer. Energy Technology Engineering Center (ETEC) has shown that water frost may be grown at low density on a first wall then cooled to cryogenic temperatures where it is stable and has low vapor pressure (10⁻⁹ Torr). This concept is being studied jointly by ETEC (N. Hoffman) and LLNL³ (C. Orth, K. Sinz). A 2 cm thick layer of frost at density 0.1 gm/cm³ absorbs the soft x-ray pulse and partially evaporates. It attenuates the shock pulse to pressures of a few bars at the permanent first wall. After the shot the wall is allowed to warm so that the frost melts and is drained away together with the radioactive debris and tritium. The cold first wall required for frost maintenance also reduces thermal radiation heat load on cryogenic targets by a factor of ten and the post-shot recondensation

dose rate in the center of the MEA is shown as a function of time after a full yield shot (3.5×10^{20} neutrons). The calculation assumes a chamber constructed of a 4 cm thick SS304 steel at 5 m radius. Calculations for identical chambers constructed of 5083 aluminum and low activation aluminum (with iron, copper, and manganese reduced to less than .001%) are also shown. Several curves are included to indicate the accumulation of radioactivity from a series of nominal full yield shots at the rate one per week. The figure shows dose rate following the first (dots), 25th (dashes) and 500th (solid) shots.

Figure 3. Radiation dose rate inside MEA following a nominal full yield shot for 4 cm thick first walls at $R=5m$. Curves are for: a) steel (SS304), b) aluminum (5083), and c) low activation aluminum. Results shown are dose rate following first (dotted), 25th (dashed) and 500th (solid) shots.

In an aluminum chamber the radiation dose is dominated for more than a week by ^{24}Na decay due to the ^{27}Al (n, α) reaction. At longer times the radiation dose is dominated by manganese, iron and copper impurities present in the aluminum.

Accumulation of long lived activities over the facility lifetime further limits access. Only in the case of an experiment chamber constructed of low activation aluminum does the dose rate decay below 100 mrem/hr within 8 days after the 500th full yield shot. In a chamber of 5083 aluminum the post shot dose rate does not reach 2.5 mrem/hr during any reasonable cooling time. Of course the dose rates scale almost linearly with aluminum mass so that a thinner wall would reduce the dose. But even a wall of low activation aluminum and only 4 mm thick has dose rates greater than 100 mrem/hr until six days after any full yield shot.

It is important to point out that even low yield shots require long cooling times when the chamber is constructed of aluminum. Early dose rate scales linearly with yield; the figure may be used to show that a shot generating only 1% of full yield (gain=1) produces post shot dose rates greater than 100 mrem/hr for approximately four days (even if low activation aluminum is used). It appears our goal of one day cooling time after

low yield shots can be met only with a design based on low activation aluminum with thickness no greater than 4 mm, i.e., the aluminum cannot be used as a load bearing component.

Inclusion of aluminum in chamber components incurs a substantial price. The latter may be accommodated with substantial gamma-ray shielding of the aluminum components. Restrictions of access may only be reduced by a substantial reduction in the amount of metal incorporated into the MEA design. Maximum use of carbon or hydrocarbons, free of metallic impurities, will reduce the required waiting times for servicing MEA components.

CONCLUSION

Components of the MEA design have been developed. Computer simulations are nearly complete and experiments beginning. Structural and radiological calculations are currently underway in order to establish necessary dimensions of the components and their cost. Probable distributions of shrapnel mass and velocity are being studied in order to design shrapnel mitigating defenses into the MEA design.

At the present time there appear to be no technological barriers to the construction of a suitable chamber for a 1000 MJ ICF facility, although there are several difficult problems for which solutions are being developed. We have every reason to believe that the performance goals can be met and that the cost will be acceptable.

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