Experiments to Simulate X-Ray Damage to the First Wall of the Inertial Confinement Fusion Laboratory Microfusion Facility

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EXPERIMENTS TO SIMULATE X-RAY DAMAGE TO THE FIRST WALL OF THE INERTIAL CONFINEMENT FUSION LABORATORY MICROFUSION FACILITY

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Abstract

A critical issue in the design of the inertial confinement fusion Laboratory Microfusion Facility (LMF) is the vaporization of material from the target chamber walls by the target x-rays. One concern is the high pressures on the unvaporized portion of the wall that occur because of the high instantaneous intensity of the x-rays. These high pressures lead to the launching of shock waves into the material, that can cause further damage. In this paper, computational and experimental investigations into this problem are discussed. Experiments on sample first wall materials have been fielded on the SATURN gas pinch x-ray source at Sandia National Laboratories. Some types of graphite and aluminum have been found to survive x-ray pulses that are of similar energy fluence, photon energy, and intensity to those that would be experienced on the first wall of the LMF. Additional experiments and further analysis of the irradiated samples is expected in the near future.

Introduction

The inertial confinement fusion (ICF) Laboratory Microfusion Facility (LMF) would be built in the 1990's to develop high yield targets and use their explosions in a variety of applications [1]. The LMF, presently in a conceptual design and critical issues phase, would explode targets with yields of up to 1000 MJ at a rate of from one per week to two per day. These targets will be driven to explosion by lasers or particle beams, both of which may place limits on the density and type of the gas permitted in the target chamber. It is therefore quite possible that the x-rays generated by the burning target will pass through the target chamber gas and will deposit their energy in the target chamber wall. The pulse width of this burst of x-rays is typically a few ns, much shorter than the thermal diffusion time in the wall. The resultant energy densities are high enough to vaporize the inside layer of the wall, irrespective of the wall material. The vaporized wall material will be at pressures of from tens to hundreds of kbar [2], which is high enough to launch shocks into the unvaporized part of the wall material. These shocks can further damage the wall material or change its properties so that the response is different on subsequent shots.

This paper reports the results of an attempt to experimentally test the response of some proposed target chamber wall materials to intense bursts of x-rays. The approach used in this study has been to use x-rays from a gas pinch source that have about the same photon energies as would x-rays emitted from an ICF target. The SATURN facility at Sandia National Laboratory in Albuquerque was used in this manner to provide x-ray fluences and intensities that are relevant to LMF conceptual designs. I will begin with a discussion of the LMF parameters for a few concepts and will show how experiments on SATURN can indeed be relevant. I will then discuss the experiments themselves and will then present results. I will conclude with a discussion of these results and additional work that is planned for the near future.

Simulation of Experiments

I have used a radiation-hydrodynamics code to simulate the deposition of x-rays in the material. This calculation is then coupled to the CSQ computer code. CSQ is a code written and maintained at SNL, that uses two-dimensional Eulerian hydrodynamics and has sophisticated modeling of phase transitions and crush physics that are probably important to shock attenuation in materials [3]. CSQ has rather limited radiation transport modelling, which makes such coupling to another computer code advisable when doing x-ray vaporization simulations.

I have used CSQ to study how sample first wall materials might behave in experiments that mimic target chamber x-ray conditions. I have done such computer calculations for samples made of aluminum, aluminum coated with a thin layer of alumina, and graphite. The parameters for three experimental environments are shown in Table 1 along with LMF conditions for SNL and LLNL concepts where the wall is assumed to be aluminum. The SNL target chamber designs are of 150 cm in radius while the LLNL design has a radius of 500 cm. PROTO-II is an electron accelerator at SNL that has been used for a number of years to create pulses of x-rays with gas pinches [4]. Specifically, gas puff pinches of neon produce the spectrum shown in Fig. 1 [5]. When one compares this spectrum with the HIBALL target spectrum [6], both have peaks at about 1 keV in photon energy. The experimental arrangement is shown in Fig. 2. The pinch is created in the center of a circle of current return posts and the closest that a sample can be placed to the x-ray source is just outside these posts. SATURN is a similar machine to PROTO-II at SNL except that it is much larger and only fired its first gas pinches in late 1988. Experiments on SATURN have a very similar arrangement to those in PROTO-II. GAMBLE-II is a machine at NRL that can accelerate protons in a beam to simulate x-ray deposition. One should note that the pulse width of the ion beam on GAMBLE-II is more than 40 ns while the gas pinch x-ray

Table 1. X-Ray Driven Stresses in Aluminum.

	PROTO-II (gas pinch)	SATURN (gas pinch)	GAMBLE-II (ions)	LMF/LLNL	LMF/SNL
Range in Al (mg/cm^2)	0.83[1]	0.83[1]	3.9[2]	0.83[1]	0.83[1]
X-Ray Energy (MJ)	0.008	0.100	0.017	220	220
Distance (cm)	3.8	3.8	N.A.	500	150
Energy Fluence (J/cm^2)	42	550	400	68	780
Energy Density (kJ/g)	51	660	108	82	940
Pulse Width (ns)	20	15	43	1	1
Power Intensity (GW/cm^2)	2.6	37	9.3	68	780
Power Density (GW/g)	2.5	44	2.5	82	940
Calculated Stress (@ 0.05 cm) (GPa calculated)	1	7.5	not	7.5	14

(1)Assuming 1 keV photons

(2)Assuming 1 MeV protons and no range shortening

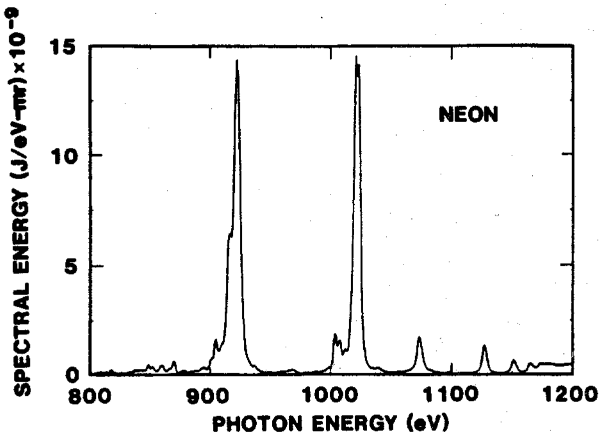

Fig. 1. X-ray spectrum from a neon gas pinch on PROTO-II. Only the component above 900 eV in photon energy is shown. There is another component to the spectrum below a few hundred eV that has about 4 times the energy but more than 5 times the pulse width.

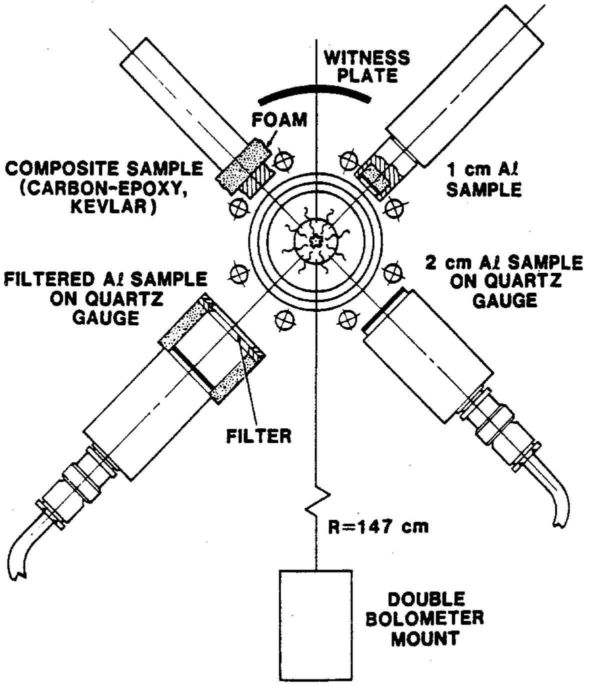

Fig. 2. Schematic picture of experimental arrangement in PROTO-II.

sources have less than half the pulse width. If one is only interested in stresses in the center of the material so that the energy density is important, then experiments on all three machines can be relevant to the LMF. If, however, stresses near the surface are important, the power density (power deposited per unit mass) is the important parameter and only SATURN can do LMF relevant experiments. Even SATURN can only provide a power at one half the LLNL LMF value. The bottom line is the achievable stress in the material, which I have calculated with CSQ for PROTO-II, SATURN, and SNL and LLNL versions of the LMF. In aluminum, PROTO-II can provide stresses of 1 GPa 0.05 cm in back of the first surface and SATURN can provide 7.5 GPa. I have not calculated the stresses that GAMBLE~II could generate in aluminum, though based on the power density one would expect about 1 GPa. I calculated the stresses in a LLNL and SNL LMF aluminum wall to be 7.5 GPa and 14.0 GPa respectively. The calculation of the PROTO-II stresses was rather interesting because here the stresses are only a factor of a few larger than the yield stress and the stresses are non-isotropic. The longitudinal stresses at 0.05 cm peaked at 1.0 GPa while the transverse stresses peaked at 0.7 GPa. These simulations show that experiments on SATURN have the potential to much more closely mimic the conditions in the LMF target chamber than do experiments on GAMBLE-II or PROTO-II.

I have simulated the response of four different materials to x-rays from SATURN with CSQ. The results are summarized in Table 2. In all cases, the samples are assumed to be 3.8 cm from the pinch, which is assumed to generate 100 kJ of x-rays in the lines shown in Fig. 1. There is assumed to be another

Table 2. Stresses in Various Materials Generated with SATURN X-rays.

	Aluminum (unfiltered)	Graphite (unfiltered)	Graphite filtered)	Alumina/Aluminum (unfiltered)
Range of 1 keV X-rays (mg/cm^2)	0.83	0.50(1)	0.50	0.38
Mass Density (g/cm^3)	2.7	1.7	1.7	3.5
Energy Fluence (J/cm^2)	550(2)	2750	550	550(2)
Energy Density (kJ/g)	660	5500	1100	1440
Power Density (GW/g)	44	367	73	96
Calculated Stress @ 0.05 cm (GPa)	7.5	36.0	10.2	3.5
Calculated Stress @ 0.25 cm (GPa)	4.8	12.5	5.0	1.8
Calculated Stress @ 0.25 cm (GPa)	2.7	8.0	N.A.	1.0

(1) The ranges of 1 keV and 300 eV x-rays in carbon are the same. The range of 100 eV x-rays is 0.05 mg/cm^2.

(2) Because of the much shorter range of low energy photons, the part of the spectrum below 900 eV is ignored and is not included in the energy fluence.

400 kJ in x-rays below about 200 eV in photon energy, making a total of 500 kJ in x-rays. I have assumed that the x-rays above 900 eV are emitted in 20 ns in these simulations and that the low energy component is radiated over 100 ns. I have done simulations for aluminum, graphite and aluminum coated with a 100 micron thick layer of alumina.

I have considered the effects of these low energy photons. I have done simulations where these photons are filtered out, perhaps with an aluminum foil, and where they are allowed to irradiate the sample. The ranges of 200 eV x-rays in aluminum and alumina are more than an order of magnitude less than the ranges of 1 keV x-rays and should be mostly absorbed in the blowoff plasma and not contribute to the launching of a shock in the material. Therefore, I only show results for these materials where the low energy photons have not been filtered out; the results with filtering are essentially the same. This is not the case for graphite because the range of 200 eV x-rays is only a little shorter than that for 1 keV x-rays. Both unfiltered and filtered simulations are shown for graphite.

Experiments on SATURN

During May, 1989 I fielded some x-ray vaporization experiments on SATURN like those described in the previous section. All of the samples were donated by LLNL or SNL. The space on the machine was just what remained on experiments that were already planned. The exception to this was shot 669 which only had my samples on it and was donated by SNL. I did not have any active diagnostics to measure the stress levels. The sample holders were loaned to me by other experimenters at SNL. The samples were held in stainless steel 316 Swaglok fittings that held the samples in place with an annular lip. The back of the samples were supported with carbon foam that was, in turn, supported with a thin aluminum disk. I am still in the process of analyzing these experiments, but results as I know them are shown in Table 3. One can see in Table 4 that all samples except 2 and 5 were utterly destroyed. Sample 5, a two-directionally woven graphite in a carbon matrix called K-Karb, was not damaged in the plane of the graphite fibers but these planes became delaminated. Sample 2, aluminum 6061 with a layer of alumina blasted on its surface, survived well except that the alumina was removed. All of the other samples were fine grained graphites or graphites with short fibers. Sample 3, Graphnol, was a fine grained graphite that survived the best of these as it was broken into about 6 pieces. The others were turned into powder. I could not even find any pieces of sample 4.

Table 3. Samples of LMF First Wall Materials Irradiated with SATURN X-Rays in May 1989.

Sample No.	Shot No.	Material	Result
1	658	Graphite H-451 fine grained	Destroyed powder
2	658	Alumina coated aluminum 6061	Survived
3	664	Graphnol fine grained graphite	Destroyed six pieces
4	665	Graphite AO5 short random fibers in a carbon matrix	Destroyed nothing left
5	669	K-Karb 2-D woven graphite in a carbon matrix	Survived delaminated
6	669	Graphite CGW fine grained	Destroyed powder
7	669	Graphite AJT fine grained	Destroyed powder
8	669	Dunlop breakpad graphite fibers in a carbon matrix	Destroyed shredded

In August of 1989, I fielded another set of experiments on SATURN. These used argon gas pinches as an x-ray source. The spectra from these pinches differ from those for neon in the photon energy of the dominant lines; neon has lines at about 0.9 and 1.0 keV, while argon emits lines in the 3 to 4 keV range. Also, argon has about 40 kJ in these lines, while neon can have as much as 100 kJ in its lines. The pulse widths of the x-rays can be as low as 10 ns for argon gas pinches. For these experiments, I used 3 and 4 directionally woven graphites in a solid carbon matrix, bare aluminum 6061 and aluminum 6061 coated with a layer of carbon, a loose carpet material made of graphite, and two samples of 2-directionally woven graphite, where the x-rays were unfiltered and then filtered with a thin aluminum foil. The 3 and 4 directional graphites were an attempt to stop the delamination seen in K-Karb. The aluminum experiments are an extension of the previous experiments with alumina on aluminum in that they use a sacrificial layer to protect the aluminum, while carbon would be much easier to spray onto the wall of an LMF before each shot. The carbon carpet is a relatively new idea for LMF target chamber wall protection [7], which uses the looseness of a long fibered carpet to prevent the generation of a shock. The filtering of x-rays is an experimental test of the low energy photon effects examined computationally.

The results of these experiments are given in Table 4. One can see that the aluminum survived both with and without the carbon protection. The 4-directional weave was successful in combating delamination, though the 3-directional random weave was not. The graphite carpet was almost totally undamaged by x-rays. The unfiltered 2-directional weave was destroyed, while the filtered sample survived. I have no quantitative results yet as to the performance of the gas pinches, but preliminary indications are that there were in excess of 350 kJ of x-rays on all shots.

Table 4. Samples of LMF First Wall Materials Irradiated with SATURN X-rays in August 1989.

Sample No.	Shot No.	Material	Result
1	736	Bare Aluminum 6061	Survived
2	736	Carbon Coated Aluminum 6061	Survived
3	736	Stapleknit graphite	Destroyed Delaminated
4	737	4-D Woven Graphite (FMI)	Survived
5	739	3-D Random Fiber Graphite	Destroyed
6	737	AO5 Graphite Fine Grained	Survived
7A	739	2-D Woven Graphite (Unfiltered)	Destroyed
7B	739	2-D Woven Graphite (Filtered)	Survived
8	737	Graphite Carpet	Survived

Summary and Future Work

The experiments reported here show that woven graphites and aluminum with a protective layer of alumina survived LMF relevant x-ray pulses. I have irradiated three types of graphite that have fibers in 3 or 4 directions and have found that 4-D woven survives x-rays from an argon pinch. I have tested bare aluminum and aluminum coated with a thin layer of graphite in a beam of argon pinch x-rays and found that both survived. I have also tested carbon carpet and have found that it survives. I have computationally and experimentally shown that filtering of the low energy photons in the pinch spectrum makes a great difference to the response of graphites.

We plan to do additional analysis of the experiments. Once we have all of the data resolved, we plan to simulate with CSQ the response of the sample materials for the spectrum observed in the experiment. We plan to examine samples under a scanning electron microscope to look for changes in the microstrucure induced by the x-ray driven shocks. I also plan to measure changes in the bulk properties of the irradiated materials.

I plan additional experiments on SATURN. I plan to repeat the experiments in Table 4 for neon pinch spectra to test the effects of spectrum. I plan to repetitively test some samples, because that is what they will experience in the LMF. I also plan to test other materials, some that may be more relevant to ICF power reactors.

Acknowledgement

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