X-Ray and Debris Ion Spectra Emanating from NIF Targets

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UWFDM-949

Prepared for the Eleventh Topical Meeting on the Technology of Fusion Energy, June 19–23, 1994, New Orleans LA.

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ABSTRACT

Simulations of the breakup of the NIF targets have been performed. The x-ray and debris emission are predicted and compared with generic results that were commonly used before the recent declassification. These simulations are one-dimensional, while the target is two-dimensional. The computational models are discussed in some detail, and the problems of one-dimensional simulations are acknowledged.

I. INTRODUCTION

The National Ignition Facility will use a large solid state laser to drive inertial fusion targets to ignition. The laser light will be converted to a wavelength of 0.35 μm. The laser will direct 1.8 MJ of this light onto Hohlraum targets. The NIF target design is shown in Fig. 1. After absorbing the laser energy in a gold case where x rays are created, the target directs the x rays onto a fuel capsule, driving it to ignition. The burning capsule will generate up to a few tens of MJ of fusion energy per shot. The resulting total energy will, after the target microexplosion is complete, consist mostly of x rays, neutrons and hot debris material (ions). In the NIF, the x rays and debris ions can cause significant damage to the target chamber and laser optics. In this paper, we will show the results of one-dimensional simulations of the break up of the NIF target. From these simulations, we will obtain the time-dependent x-ray spectra and the characteristics of the ion debris after the microexplosion.

This work allows target chamber analysis to consider specific spectra from actual target designs, which is an improvement over the generic spectra[1] used in the past. The generic spectra were obtained from a computer simulation of thermonuclear burn and radiation-hydrodynamics of an unclassified target concept that looked remotely like the Hohlraum target in Fig. 1. This was a heavy ion target concept developed by Bangerter and others[2] which led to the time-integrated spectrum shown in Fig. 2.

For the work presented in this paper, we assume that the NIF target shown in Fig. 1 consists of a fuel capsule with an inner shell of 0.18 mg of deuterium-tritium fuel and a 2.35 mg plastic outer ablator 0.016 cm thick. The total capsule is initially 0.111 cm in outer radius and is suspended in the center of a gold Hohlraum. The 30 μm thick gold case has the dimensions shown in the figure and has 128 mg of gold. The Hohlraum is filled with 500 torr of He gas and the inside of the case has 1 μm of plastic. The two laser entrance holes are covered with 100 Å thick plastic windows.

II. COMPUTER CODES

Simulations have been performed with the CONRAD[3] computer code, which is a one-dimensional Lagrangian radiation-hydrodynamics code with x-ray and ion energy sources. CONRAD has been developed at the University of Wisconsin and used in several fusion plasma applications. Radiation transport is calculated with a one-dimensional multigroup flux-limited diffusion method. Equations of state and opacities are interpolated from tables that are either supplied by the IONMIX[4] computer code, by the EOSOPC[5] computer code, or from the SESAME[6] tables. CONRAD also can calculate equations-of-state internally with models that are valid at solid and higher densities using a method used in the ANEOS[7] subroutines used in several codes at Sandia National Laboratories. The EOSOPC code can produce

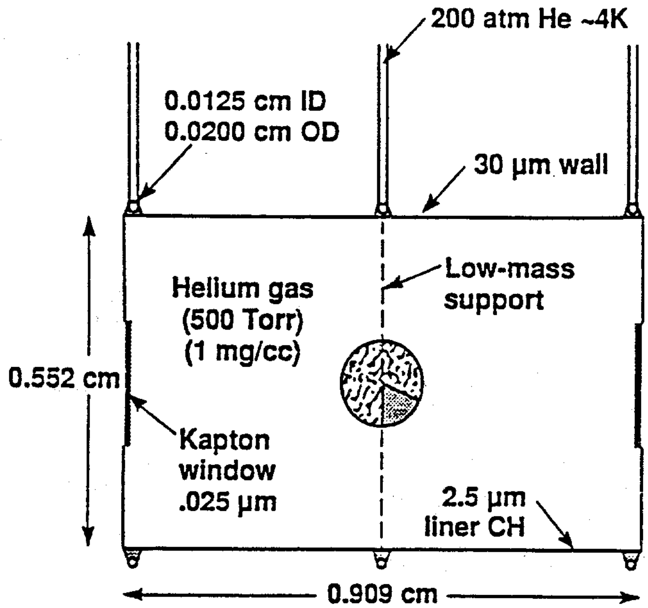

Fig. 1. NIF target design.

opacities that are valid for high density and high atomic numbers and is used in calculation of gold opacities for the simulations discussed in this paper. The equation-of-state of gold is calculated with the ANEOS methods that include lattice separation energies and electron degeneracy effects, and where the material pressure is zero when the material is cold and exactly at solid density. CONRAD has a single plasma temperature, and therefore assumes that the electrons and ions are at the same temperature.

CONRAD does not include thermonuclear burn, so we began the calculations by assuming that the fuel capsule has the yield energy plus some fraction of the laser energy. The rest of the laser energy is distributed around the inside surface of the Hohlraum. The fuel capsule consists of a deuterium-tritium interior surrounded by a plastic ablator. The initial conditions of the capsule come from a simulation performed by Jon Larsen[8] with the HYADES code. This was a one-dimensional simulation of the target burn including the effects of radiation transport and has both electron and ion temperatures. The simulation provides initial temperature, density and velocity profiles for the CONRAD runs for a 20 MJ target yield (4 MJ of non-neutronic yield).

The NIF target is two-dimensional and CONRAD is one-dimensional. We have performed two 1-D spherically symmetric calculations, as shown in Fig. 3. The materials in the shells are also shown in Fig. 3. The gold is initially at solid density and cold, except for the few microns facing the capsule,

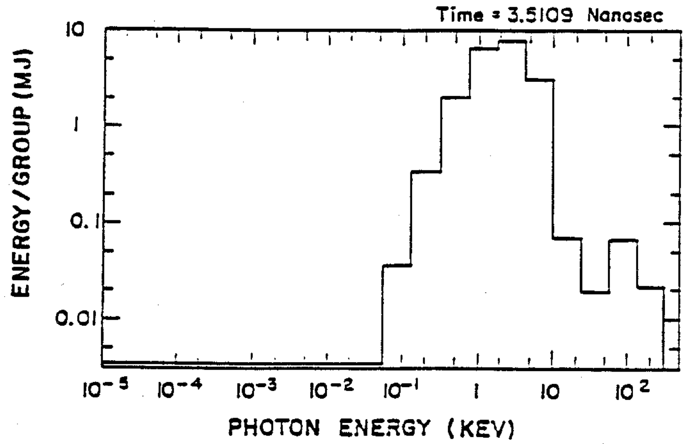

Fig. 2. Time-integrated x-ray spectrum emitted by the Bangerter heavy ion target.

which is at about 1 keV. One calculation attempts to model the behavior in the direction perpendicular to the Hohlraum axis of symmetry (from the center of the capsule out through the Hohlraum case) and the other behavior in the direction down the axis of symmetry (from the capsule out through the laser entrance hole). These calculations are in error because the hydrodynamic flow is 2-D. The target will see cylindrical blow-off from the inside of the Hohlraum and other 2-D behavior after the collision between the capsule and Hohlraum will make these 1-D simulations invalid after a certain time. However, they are useful in determining the general features of the target breakup. For example, these calculations clearly show the importance of the interaction between the expanding capsule and the Hohlraum case and the filtering effect of the Hohlraum case on the emitted x rays.

III. ONE-DIMENSIONAL RESULTS

The results of the one-dimensional CONRAD simulations of the breakup of the NIF target are summarized in Fig. 4 and Fig. 5 and in Table I. In Table I, the two runs are labeled “Hole” and “Case”. The non-neutronic energy is 7.2 MJ and 7.4 MJ in the two runs. The “Case” calculation includes a gold shell that has some laser energy remaining, so there should be more non-neutronic energy in this calculation. In both runs, 4 MJ is due to thermonuclear yield. The non-neutronic energy is higher than it should be by perhaps 50%. Since the capsule initial conditions come from a different code with a different equation-of-state and a different way of calculating the total energy (electron and ion temperature versus plasma temperature), it is not surprising that

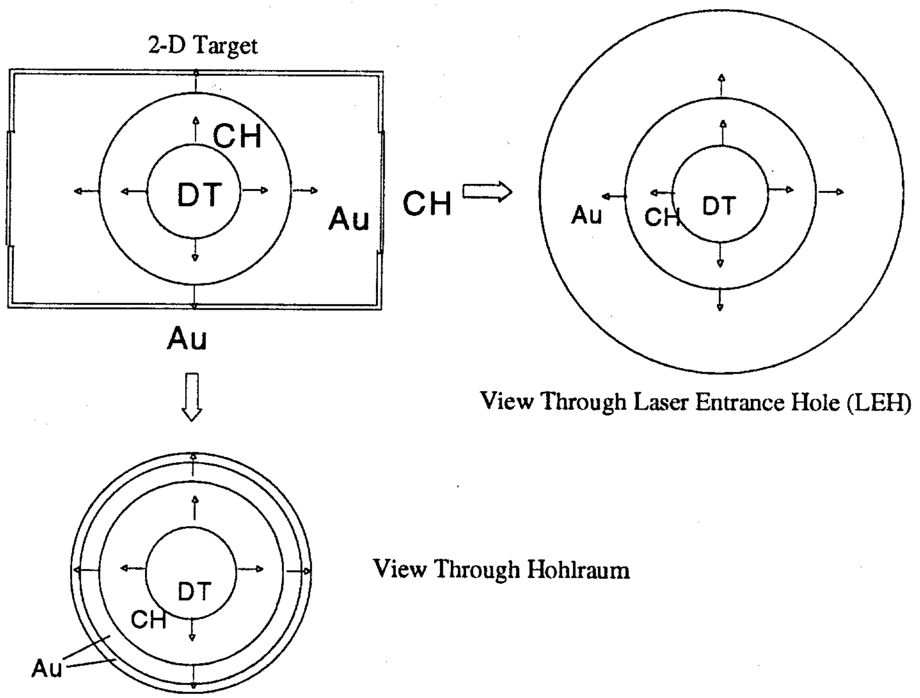

Fig. 3. Two one-dimensional CONRAD computer code runs simulate the breakup of the two-dimensional NIF target.

the energy is not exactly equal to the expected value. The "Hole" simulation predicts that most of the non-neutronic energy is in kinetic and internal energy of the capsule debris, with about half as much going into radiation of x rays. In the "Case" run, the situation is reversed; most of the non-neutronic energy at the end of the run has been radiated away, with about half as much remaining in kinetic and internal energy of the debris. The difference is due to the collision between the capsule and the gold case in the "Case" run, which converts the kinetic energy into thermal energy. The increased internal thermal energy leads to high temperatures in the outer capsule and inner edge of the gold case. The inner case reaches temperatures above 1 keV, which lead to substantial radiation emission. This process does not occur in the "Hole" calculation.

Differences also can be seen in the time-integrated emitted spectra, shown in Fig. 4. The "Hole" results look approximately like a blackbody spectrum, with the peak occuring at about 2 keV photon energy. There is a high energy tail extending out to about 100 keV, which is probably from the very hot D-T fuel in the capsule at the start of the calculation. The "Case" spectrum is very different; consisting of a low temperature part peaking at about 500 eV, a gap with very few photons between 8 keV and 70 keV, and a high energy part between 70 and 100 keV. The low energy part is due to the radiation that burns through the case. The time-dependent radiated power leaving the target also contrasts the differences. Figure 5 shows that before 1 ns after the end of the burn, the power has the same temporal shape in both runs, but the power leaving through the case is reduced by a factor of 100. This temporal shape is what one would expect from rapid radiation diffusion from a hot cen-

TABLE I

Results of CONRAD Simulations for the Breakup of a 20 MJ NIF Target

	Hole	Case
Total non-neutronic energy (MJ)	7.2	7.41
X-ray energy (MJ)	2.58	4.54
Debris energy (MJ)	4.60	2.87
Max. outer shell velocity (cm/μs)	179	35.1
Min. outer shell velocity (cm/μs)	101	16.2
Specific energy in debris (MJ/gm)	1700	47.0
"Average" velocity of debris (cm/μs)	184	30.7
Elapsed time (ns)	3.0	30.

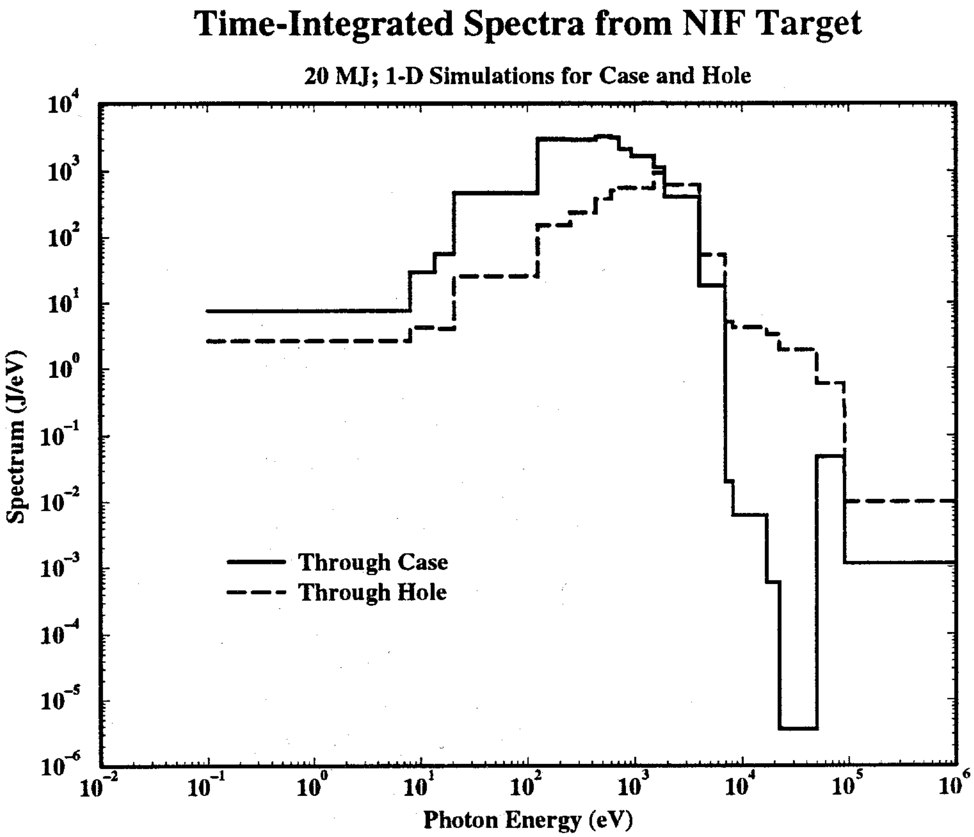

Fig. 4. Time-integrated x-ray spectra from one-dimensional simulations of the breakup of the NIF target.

tral source. Clearly the gold in the case is acting as a filter of the x rays emitted by the capsule, which just stream out the hole. At about 1 ns after the end of the burn, the capsule strikes the inside of the case, leading to a rapid rise in the radiated power as the produced radiation burns through the case. The radiation continues for tens of ns, with the power showing some structure as the debris from the capsule continues to collide with the remains of the case as it begins to move outward.

The debris spectra can be estimated from the CONRAD runs by considering the velocities of the various parts of the target at the end of the runs. In the "Hole" calculation, most of the mass is in the plastic ablator. The velocity of the inner edge of the ablator is 101 cm/μs and is 179 cm/μs for the outer edge. If one estimates the "average" velocity by calculating the debris energy per atom,

$$V_{ave} = \sqrt{\frac{2\,E_{debris}}{M_{debris}}} \qquad (1)$$

one obtains 184 cm/μs, which is higher than the maximum seen in the simulation because internal energy is included in the debris energy. The internal energy should in fact lead to a spread in the debris ion velocities. The difference between the velocity at the inner and outer edges of the ablator will lead to a time-of-flight spreading of the pulse width seen on the NIF target chamber wall. In the "Case" run, the debris velocities are much lower because the total energy in debris is lower and the mass of debris is much higher. Most of the debris in this direction will be gold. The "average" velocity, as defined in Eqn. 1, is 30.7 cm/μs and the velocities at the inner and outer edges of the case are 16.2 and 35.1 cm/μs.

IV. CONCLUSIONS

The results presented here are somewhat different from the generic Hohlraum target results shown in Fig. 2. The "Case" spectrum has the same general features, but has a lower peak photon energy. The "Hole" spectrum is totally different. The generic spectrum is emitted over 1.5 ns and has the same gen-

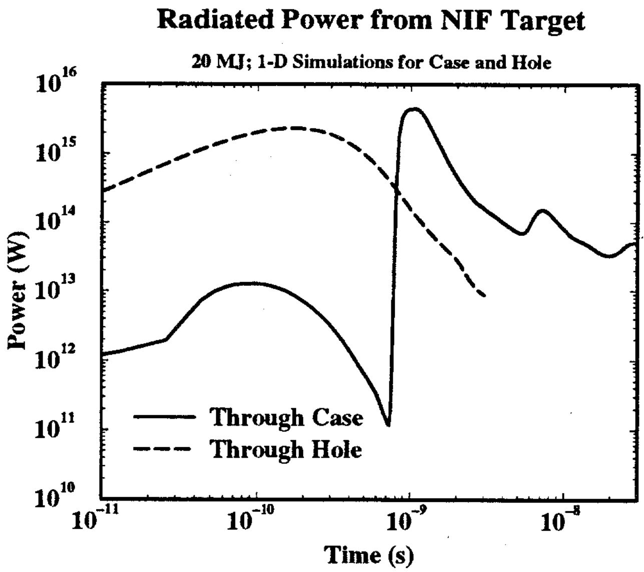

Fig. 5. Time-dependent x-ray power from one-dimensional simulations of the breakup of the NIF target.

eral temporal shape as the "Case" power in Fig. 5, but once again is very different from the "Hole" results. The generic debris spectrum is calculated as in Eqn. 1, which the simulation has shown will lead to some error. It will also not provide the proper time-of-flight spreading in the pulse width. So, now that target designs are available for the NIF, these types of simulations are necessary to provide the correct wall loading.

The simulations presented here represent our first attempt to study the breakup of NIF targets. We have also performed two-dimensional simulations without radiation transport and are considering integrating target burn dynamics into the simulations. We also hope to perform simulations for the NIF target as the design evolves, for NOVA experiments, and for ion beam fusion targets.

ACKNOWLEDGEMENT

This work is supported by Sandia National Laboratories.

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