Chamber Dynamic Research with Pulsed Power

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Abstract

In Inertial Fusion Energy (IFE), Target Chamber Dynamics (TCD) is an integral part of the target chamber design and performance. TCD includes target output, deposition of target x-rays, ions and neutrons in target chamber gases and structures, melting and vaporization of target chamber materials, radiation-hydrodynamics in target chamber vapors and gases, and chamber conditions at the time of target and beam injections. Pulsed power provides a unique environment for IFE-TCD validation experiments in two important ways: pulsed power devices do not require the very clean conditions that lasers need, and they currently provide large x-ray and ion energy fluences.

1. Introduction

In Inertial Fusion Energy (IFE), Target Chamber Dynamics (TCD) is an integral part of the target chamber design and performance. TCD includes target output, deposition of target x-rays, ions and neutrons in target chamber gases and structures, vaporization and melting of target chamber materials, radiation-hydrodynamics in target chamber vapors and gases, and chamber conditions at the time of target and beam injections. An understanding of TCD is required to design a target chamber that is economically viable and does not pose a threat to safety or the environment. Computer codes have been developed that model TCD phenomena [1]. BUCKY [2], written at the University of Wisconsin, is one example of such a code. BUCKY is a 1-D Lagrangian radiation-hydrodynamics computer code that includes realistic atomic physics, multigroup radiation diffusion, x-ray and ion deposition physics, and vaporization, melting and re-condensation physics. Validation of codes with small but relevant experiments is critical because full-scale experiments will only be possible with ignited targets.

Pulsed power provides a unique environment for IFE-TCD validation experiments in two important ways: pulsed power devices do not require the very clean conditions that lasers need, and they currently provide large x-ray and ion energy fluences. Z-pinch experiments on the Z accelerator at Sandia National Laboratories (SNL) presently can produce approximately 2 MJ of > 100 eV blackbody x-rays in a several ns pulse. The spectrum is colder than what is expected from IFE targets, but the achievable energy fluences and pulse widths are IFE relevant. X-ray vaporization and chamber gas radiation hydrodynamics can be studied with Z as an x-ray source. These x rays could produce high energy density plasmas that mimic phenomena in target explosions that lead to target emissions. In addition, the RHEPP-1 accelerator at SNL can produce up to 15 J/cm^2 of several 100 keV ions of many species with IFE-relevant pulse widths, which could be used to simulate target ion stopping in vapors and gases and the ion melting and vaporization of wall materials.

2. IFE Target Chamber Dynamics

TCD is the integrated study of everything in the IFE target chamber inside the surviving structure. This TCD analysis is an essential part of IFE target chamber design, and it is therefore critical to the development of IFE as an energy source. Target chamber dynamics analysis also leads to chamber designs for which the chamber walls can survive an adequate length of time, the repetition rate is acceptable, the chamber does not pose a threat to safety or the environment, and the driver beams can propagate and the targets can be injected. The TCD analysis includes the following:

- target output characteristics,
- deposition of target emissions in target chamber gases, vapors, liquids and structures,
- impulsive loading and disassembly of liquid jet structures,
- vaporization and re-condensation of liquid and solid target chamber materials,
- radiation-hydrodynamics of target chamber fill gases and vaporized material,
- chamber conditions at time of beam injection, and
- target heating during injection.

The chamber design also has links to other systems, including the target injector, the driver-beam final focusing optics, and the structural wall. Analyses of these systems need input from TCD calculations. This input includes:

- laser or ion beam transport through the target chamber,
- mechanical response of surviving target chamber structures,
- thermal response of surviving target chamber structures,
- tritium retention in surviving target chamber structures, and
- neutron activation in surviving target chamber structures.

The analysis of the TCD is strongly driven by the target output and is sensitive to energy partitioning among the photons, neutrons and ions and to their spectra. When an IFE target ignites and burns, about 80% of its fusion energy is released as 14 MeV neutrons. The density-radius product of the fuel is about 3 g/cm^2, so the fuel itself re-absorbs about 15% of the neutron energy and softens the neutron spectrum. The ionic fusion products, mostly ^{4}He but some ^{3}He, ^{3}H, and ^{1}H and other minor contributors, are almost entirely stopped in the dense fuel, the so-called bootstrap heating effect. About 30% of the DT fuel typically burns during a target explosion. The fuel reaches 50 keV or more during burn, becoming fully ionized so it produces bremsstrahlung photons, but very few bound-bound or bound-free photons. Because bremsstrahlung emission from hydrogen isotopes is relatively weak, only a few percent of the fuel capsule yield is in photons. The remaining 20 – 25% of the capsule yield is an expanding flow of the energetic ions that comprise the capsule. The whole capsule, including the ablator, is accelerated outward in the target explosion. For direct-drive laser fusion targets, the capsule is the entire target. For current indirect-drive heavy and light ion targets and for z-pinch IFE, the fuel capsule is enclosed in a massive high-atomic-number hohlraum. The neutrons are unaffected by the hohlraum, but the very-high-velocity expanding capsule plasma collides with and imparts its energy and momentum to the hohlraum. The much more massive hohlraum is raised to temperatures of hundreds of eV, thus converting the highly directed kinetic energy of the capsule ions to thermal x-rays that are radiated by the more slowly expanding hohlraum plasma.

Radiation-hydrodynamics modeling in IFE target chambers is important to the analysis of gas-protected, thin-liquid-film and thick-liquid-wall target chamber designs. For any reasonably sized target chamber, the intense non-neutronic emission released from both direct- and indirect-drive targets heats the material, absorbing that energy and raising the temperature to a point such that radiative heat transfer is important. In liquid designs with a low-density vapor in the chamber, the vapor generated by the absorption of target energy will radiate and cause additional vaporization. Self-shielding of the liquid by its vapor is important in determining the total mass of liquid vaporized and the mechanical loading on the surface due to ablation. In gas-protected concepts the gas will radiate to the first wall, which must avoid erosion through vaporization, melting and fracture.

Typical IFE target chamber x-ray parameters are shown in Table 1 for HIBALL [3], CASCADE [4], HYLIFE-II [5], LIBRA-SP [6] and OSIRIS [7]. These are all indirect-drive power plant concepts for which the x-ray output is dominant. With the exception of HYLIFE-II, for which the first surface is very close to the target, the x-ray fluence per shot is in the range of 25 to 85 J/cm^2. Alternatively, the SOMBRERO [8] direct-drive laser fusion target chamber would have 4.5 J/cm^2 of x-rays on its graphite first wall if the xenon fill gas were not present. However, SOMBRERO would experience ion fluences on its graphite wall of 15.8 J/cm^2 and lower, which would still be worrisome fluences on the final optics. The ion fluences from indirect-drive targets are typically about 25 to 35% of the x-ray fluence.

Table 1. X-ray Environment for Some IFE Target Chambers

Parameter	**HIBALL**	**CASCADE**	**HYLIFE-II**	**LIBRA-SP**	**OSIRIS**
X-ray Energy per Shot (MJ)	89.5	75	56	168.1	71.9
Distance from X-ray Source (cm)	500	400	50	400	350
X-ray Fluence per Shot (J/cm^2)	28.5	37.3	1800	83.6	46.7
T_{BB} (eV)	450	450	100-400	450	450
Material	$Pb_{83}Li_{17}$	Graphite	Flibe	$Pb_{83}Li_{17}$	Flibe

Table 2. Features of the BUCKY Radiation-Hydrodynamics Code

1-D Lagrangian MHD (spherical, cylindrical or slab)
Thermal conduction with diffusion
Applied electrical current with magnetic field and pressure calculation
Radiation transport with multigroup flux-limited diffusion, method of short characteristics, and variable Eddington factor
Non-LTE CRE line transport
Opacities and equations of state from EOSOPA or SESAME
Equilibrium electrical conductivities
Thermonuclear burn (DT, DD, D^3He) with in-flight reactions
Fusion product transport: time-dependent charged particle tracking, neutron energy deposition
Applied energy sources: time- and energy-dependent ions, electrons, and x-rays
Moderate energy density physics: melting, vaporization, and thermal conduction in solids and liquids
Benchmarking: x-ray burnthrough and shock experiments on Nova and Omega, x-ray vaporization, RHEPP-1 melting and vaporization, PBFA-II K_α emission, …
Platforms: UNIX, PC, MAC

3. Computer Simulation Methods

A few codes exist to model TCD, one being BUCKY. The BUCKY 1-D radiation-hydrodynamics code models many aspects of TCD. BUCKY, whose features are listed in Table 2, has been developed at the University of Wisconsin over the past 25 years. It has been benchmarked in comparison with many experiments on lasers, shock-tubes and pulsed power machines. BUCKY has been used to do ICF target design and to calculate the target output, wire-array implosions, and target chamber dynamics. Most importantly for this discussion, BUCKY calculates the response of materials to intense x-rays, including vaporization and melting, vapor motion and shocks in the remaining solid material.

One purpose of all TCD experiments is the validation of such computer codes, which model many complex physics issues. The radiation transport methods used have finite ranges of validity. Most of the codes are fluid codes, however, and sometimes the materials will either fall below a pressure of a few Mbar at which the strength of materials becomes an issue, or they will reach a low enough density that gas particles are no longer in equilibrium with each other. The experiments suggested below will be useful in addressing these issues and in benchmarking the codes.

Table 3. X-ray Environment for Z

Parameter	**Z (z-pinch only)**			
X-ray Energy per Shot (MJ)	2			
Distance from X-ray Source (cm)	399	72.8	39.9	7.28
X-ray Fluence per Shot (J/cm^2)	1.0	30	100	3000
T_{BB} (eV)	200			

Table 4. X-ray Damage Parameters for NIF

Parameter	**NIF (20 MJ Target)**				**NIF (1.4 MJ laser only)**			
X-ray Energy per shot (MJ)	4				1			
Distance from X-ray Source (cm)	564	103	56.4	10.3	282	51.5	28.2	5.15
X-ray Fluence per shot (J/cm^2)	1.0	30	100	3000	1.0	30	100	3000
T_{BB} (eV)	300				100-300			

4. Pulsed Power Facilities

The Z and Saturn z-pinch facilities can supply x-ray fluences, pulse widths and spectra [9] that are relevant to IFE target chambers, while RHEPP-1 can do the same for ions. Many of the issues discussed above can be studied experimentally on these pulsed-power facilities. Achievable x-ray fluences are shown in Table 3 for Z. Saturn, which produces about 0.5 MJ in soft x-rays, would require a sample to be closer to the x-ray source than Z would, but high fluences may still be reached. The distance between the x-ray source and the sample is important because the z-pinch assembly is a source of debris as well as x-rays. The debris consists of ions and larger chunks of material that can damage the sample and complicate the interpretation of the experiments. With distance, the debris becomes separated in time from the x-rays and allows for mitigation.

In comparison, the National Ignition Facility (NIF) will also produce relevant x-ray fluences, spectra and pulse widths. Parameters expected for the NIF are shown in Table 4. For the non-ignited NIF, it is assumed that 1.4 MJ of absorbed laser energy will produce 1.0 MJ in x-rays. As the NIF laser beams are successively activated, the radiated x-ray value will start much smaller but will rise approximately to this level when the NIF is fully constructed. If a fusion target is used on the NIF, the laser-generated x-rays will implode and ignite an ICF capsule, which is assumed here to create 20 MJ of fusion yield. About 20%, or 4 MJ, of this yield would be released as x-rays. So, the NIF could generate close to the same x-ray fluences as Z produces now, although the spectra may be different.

As x-ray generators Z and Saturn have some advantages and disadvantages compared with the NIF. First of all, Z and Saturn exist now, while the NIF will not begin operation for a few years and will not reach its full laser energy or the ignition of ICF targets for several years after that. The largest currently available laser facility, Omega, might now create about 15 kJ in x-rays. Another advantage of Z and Saturn is that they do not need to limit the production of large amounts of debris in an experiment, since the z-pinch assembly itself is already a larger source of debris than would be produced by the TCD experiments. The NIF will have to limit the amount of debris produced during a shot to prevent excessive damage to or coating of the laser debris shields. However, the debris produced on Z and Saturn make experiments more complicated; hence, the low debris mass on the NIF could be seen as an advantage as long as the TCD experiment does not generate much debris itself. The NIF laser will be able to divert several of its beams to drive x-ray backlighters for diagnosing experiments, while Z will soon (in 2001) have a single backlighter laser and Saturn has none.

The RHEPP-1 facility produces high rep-rate pulses of intense ion beams. The only constraint on experiments (aside from the usual toxicity and radioactivity limits) is that the ion diode needs to be in a vacuum. Diagnostics for ion beam parameters are currently available on the facility. Diagnostics to evaluate experimental samples, such as velocity interferometers (VISARs), laser reflectometry for melt duration, and lasers for vapor plume diagnostics are not currently available but can be implemented. X-ray diagnostics would have to be developed for some of the experiments.

5. Experimental Studies of IFE Chamber Dynamics

A number of experiments are under consideration for pulsed power machines to study IFE target phenomena. These include studies of the target output, the response of materials to intense x-rays, target chamber blast waves, and response of materials to intense ion debris. Investigations of these issues are critical to TCD. All of these phenomena can be modeled with codes like BUCKY.

The non-neutronic output emitted by direct-drive targets is primarily in ionic debris. In the SOMBRERO direct-drive study, the target chamber size and the fill gas species and density are dictated by the output ion spectra. Experiments are planned on Z or Saturn to simulate the breakup of the target ablator into ion debris. In a direct-drive IFE target, the ablator is accelerated to a very high (~3000 km/s) velocity by the explosion of the capsule. Carbon atoms in a plastic ablator at this velocity would have a particle kinetic energy of 560 keV. Some direct-drive target designs have gold added to the ablator; gold atoms would have a particle energy of 9.2 MeV. But, in fact, the heavier particles may be moving more slowly than the hydrogen atoms. To evaluate such an effect, in experiments a foil of ablator material would be irradiated with intense z-pinch x-rays and rapidly accelerated to as high a velocity as possible. A mass spectrometer or CR39 emulsion would then record the ion energy, for comparison with code predictions. In a second type of target output experiment, the ions from the foil would collide with a wall of a simulated hohlraum (a gold or lead foil) and create a stagnant plasma similar to that which would occur inside the hohlraum of an ignited IFE indirect-drive target. The x-ray spectrum emitted from this plasma would then be recorded and compared with code calculations.

The response of materials to intense x-rays can be assessed by a class of experiments on Z and Saturn. All of the materials and fluences given in Table 1 are of interest. One question that needs to be resolved, however, is the fidelity of Z and Saturn in simulating the response of materials to IFE direct- and indirect-drive target x-rays. Figures 1 and 2 are an attempt to address this issue. Figure 1 shows, from a BUCKY calculation, the expected mass-density-profile response of a piece of stainless steel to 100 J/cm^2 in x-rays from a titanium wire-array pinch. Using the expected spectrum and pulse width (~13 ns FWHM), a shock of about 1 Mbar is launched into the steel. Figure 2 shows the results of a BUCKY calculation for a piece of steel irradiated by 100 J/cm^2 in x-rays, with the spectrum and pulse width (~ 3 ns FWHM) calculated for the LIBRA-SP target. We see that the compression and speed of

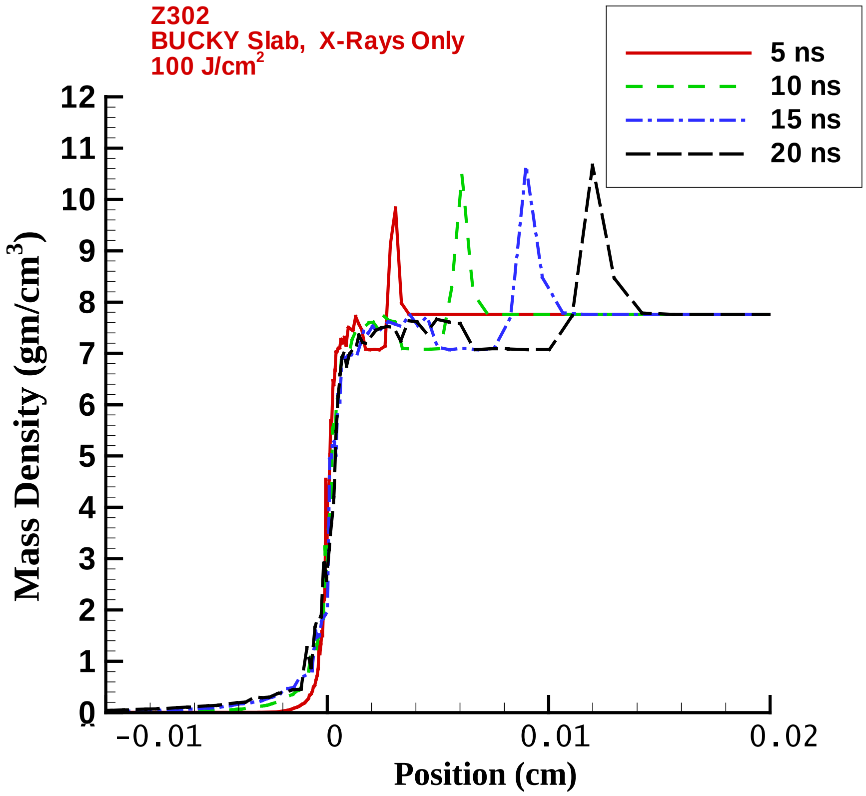

Figure 1. Mass density profiles at various times calculated in stainless steel with BUCKY. 100 J/cm^2 of x-rays with the spectrum and pulse width from Z shot 302.

the shock in the solid material is very close in the two cases. It is interesting to note that the ~1 Mbar pressure of the propagating shock is roughly the point at which the fluid approximation in BUCKY needs to be corrected for the effects of material strength. There are some differences in the blowoff plasmas in the two example calculations, perhaps because of the different pulse widths. For these experiments on Z and Saturn, masking part of a sample from the x-rays and then performing post-shot profilometry would allow us to study vaporization and melting. Post-shot electron microscopy of the samples would allow us to identify the melt layers and the changes in the material microstructure. The recoil shock and the impulse on the sample would be measured with diagnostics such as the active shock breakout diagnostic on the back of the sample. The dynamics of the vapor could be probed with x-ray radiography or laser shadowgraphy. After sufficient experimentation on material samples, larger-scale IFE chamber components could be tested. In particular, these larger-scale components could be easily accommodated on Saturn, which already contains a 13.4 m wide, 10.1 m long, 4.6 m tall concrete- and earth-shielded exposure cell beneath the accelerator. A similar feature would be required on Z to test large IFE chamber objects.

Blast waves are another important aspect of TCD that can be studied on Z and Saturn. When a gas or vapor is heated to a temperature high enough that radiation transport is important, the opacity of the gas is important to the TCD. This occurs in gas-protected target chambers such as SOMBRERO, where the target ions and the x-rays are deposited in the gas and the re-radiation rate to the target chamber walls determines the target chamber design. Liquid-wall target chambers also have similar phenomena when the target x-rays vaporize material and the vapor is further heated by the ions. In

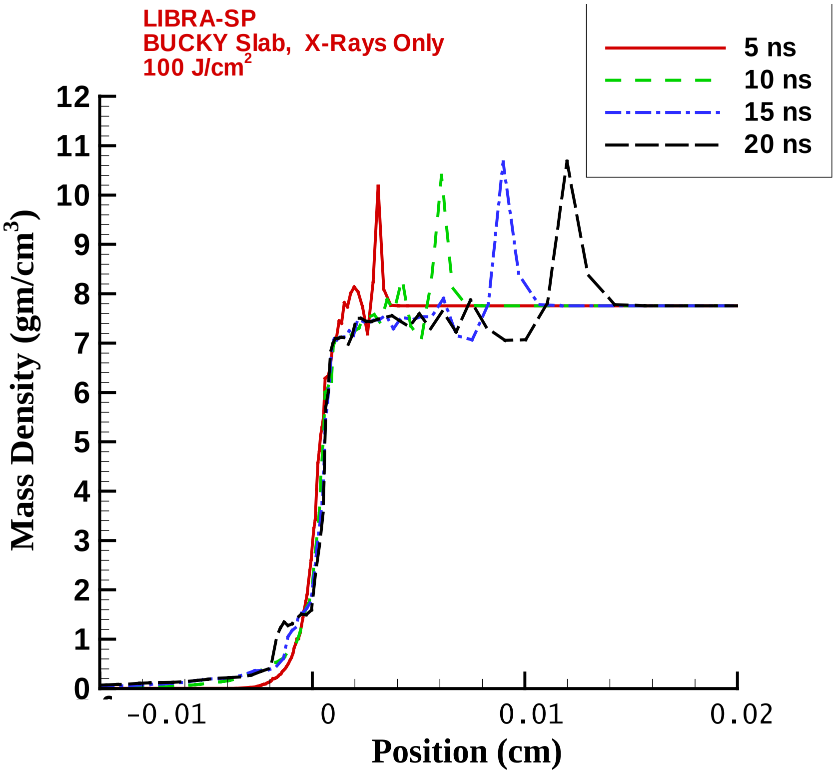

Figure 2. Mass density profiles at various times calculated in stainless steel with BUCKY. 100 J/cm^2 of x-rays with the spectrum and pulse width calculated for the LIBRA-SP target.

both cases, the gas or vapor is heated to temperatures of 5 to 100 eV. It is very difficult to know the opacity of gases below about 10 eV [10]. These opacities are calculated but the validity of these calculations needs to be tested. Figure 3 shows how sensitive the radiation reaching the SOMBRERO wall is to the opacity. Here BUCKY calculations have been performed using various multipliers on the Planck opacity. In this case, the fill gas is optically thin, so the rate at which radiation reaches the chamber walls is dominated by the emission of the radiation, which is governed by the Planck opacity. The greater the opacity, the better the gas emits and the higher the radiant power. There are two types of experiments on Z and Saturn that could address this issue. By creating plasma with x-rays at the desired temperature and density, we could measure the opacity through spectral absorption. Another method would be to create a blast wave in a gas or foam and measure its properties for comparison with code calculations using calculated opacities. Both types of experiments are required to understand this issue fully.

The response of materials to intense ions is the final type of experiment we will mention here. The deposition of ions in target-chamber fill gases drives the formation of blast waves. Also, ion heating of x-ray-produced vapor is important to blast waves in liquid-wall target chambers. Ion-driven blast wave experiments could be done on RHEPP-1, by replacing the gas with a foam or a vapor that was created on a preceding shot. Ion damage to solids and liquids is also an issue. For example, ion damage to the final optics in laser-fusion power plant concepts might be an issue. Figure 4 shows a set of melt-duration experiments done on RHEPP-1, with comparisons to BUCKY simulations. Here a piece of pure silicon was irradiated with a beam of nitrogen and hydrogen ions with energies of several hundred to more than 1000 keV and at fluences up to 3 J/cm^2. The calculated melt depth is also shown. Silicon

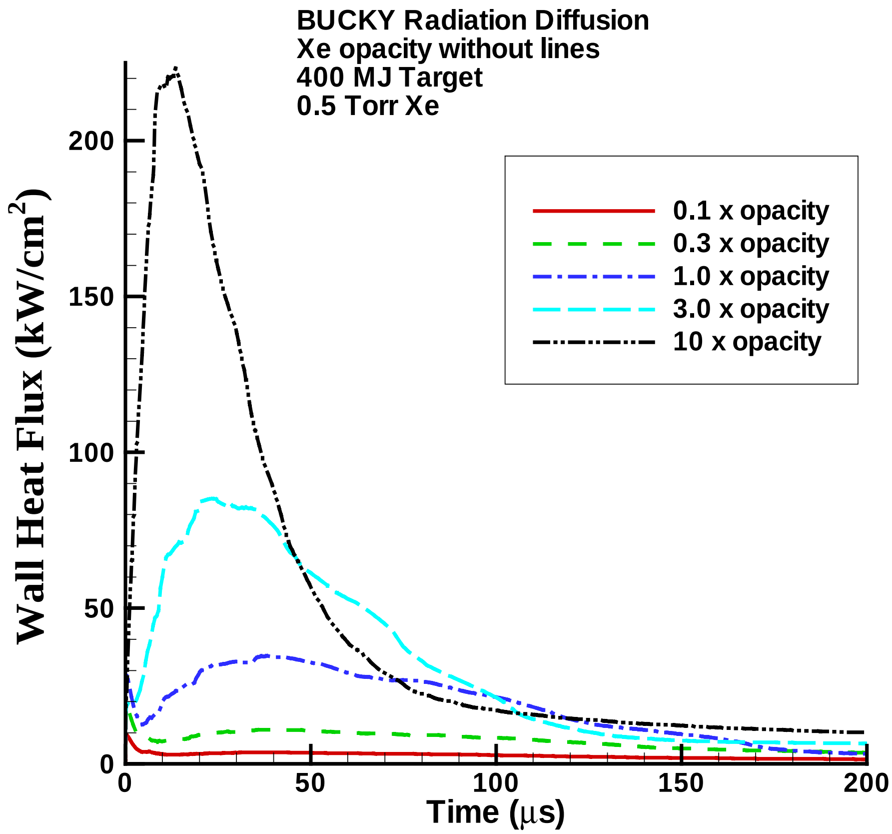

Figure 3. Radiant heat flux on SOMBRERO first wall versus time for a variety of multipliers on the Planck opacity of xenon gas. Calculations with BUCKY for a 400 MJ direct-drive target and a 650 cm radius chamber filled with 0.5 torr of xenon.

has the property that the laser reflectivity is very different for the solid and liquid, so the duration of the melt layer can be measured and compared with calculations. The agreement with the calculation is not perfect but is encouraging.

6. Conclusions

Several types of experiments that are important to IFE TCD could be done on pulsed-power facilities. These include 1) target ion and x-ray output experiments, 2) the response of materials to intense x rays, 3) x-ray-driven blast wave experiments, and 4) the response of materials to intense ion beams. Z and Saturn are robust facilities that exist today and that include an extensive suite of diagnostics that already must operate in a harsh radiation environment. When it becomes available, the NIF laser will also be useful for doing some of these experiments. The RHEPP-1 facility is useful for experiments with rep-rated ion beams. All of these experiments are critical to validating TCD computer codes and to understanding target chamber dynamics. For IFE to progress as an energy option, these issues must be faced.

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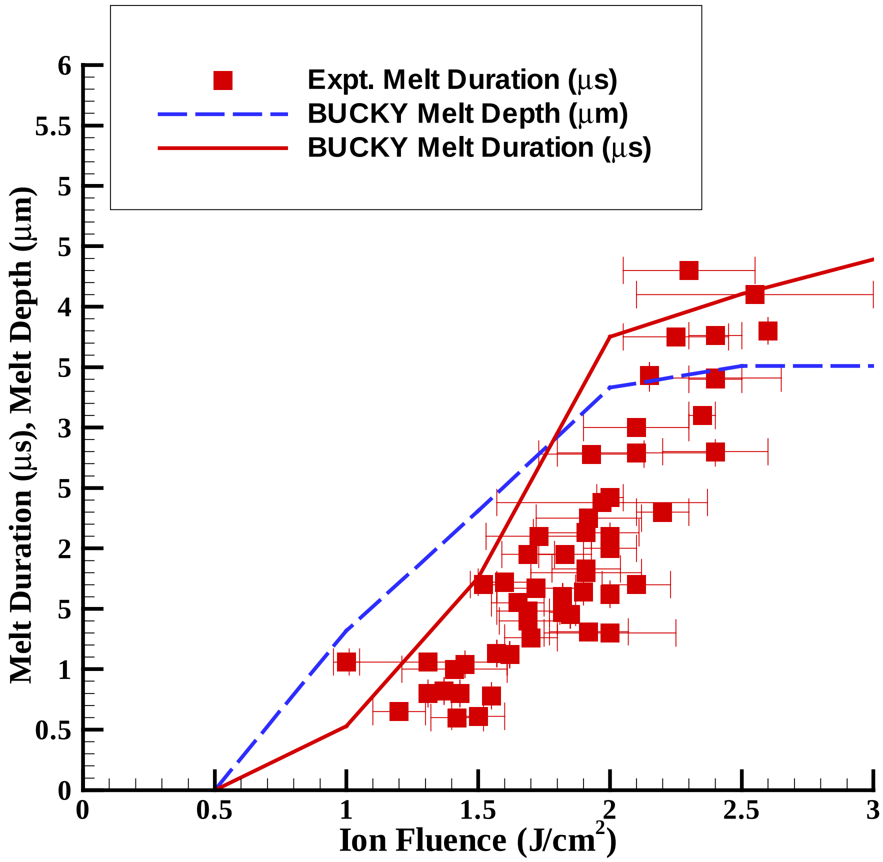

Figure 4. Ion melting of silicon. RHEPP-1 experiments and BUCKY simulations.

References

1. G.A. Moses, R.R. Peterson, and J.J. MacFarlane, "Analysis and Experiments in Support of ICF Reactor Concepts," *Physics of Fluids B* **3,** 2324 (1991).
2. R.R. Peterson, et al., "The BUCKY and ZEUS-2D Computer Codes for Simulating High Energy Density ICF Plasmas," *Fusion Technology* **30**, 783 (1996).
3. B. Badger, et al., "HIBALL - A Conceptual Heavy Ion Beam Driven Fusion Reactor Study," University of Wisconsin Fusion Technology Institute Report UWFDM-450 (September 1981).
4. G. Kessler, G.L. Kulcinski, and R.R. Peterson, "ICF Reactors – Conceptual Designs," in *Nuclear Fusion by Inertial Confinement, A Comprehensive Treatise*, edited by G. Velarde (CRC Press, 1992) p. 673.
5. R.W. Moir, et al., "HYLIFE-II Progress Report," Lawrence Livermore National Laboratory Report UCID-21816 (December 1991).
6. G.L. Kulcinski, et al., "LIBRA-SP, A Commercial Fusion Reactor Based on Near Term Technology," *Fusion Technology* **30**, 1641 (1996).
7. W.R. Meier, et al., "OSIRIS and SOMBRERO Inertial Fusion Power Plant Designs," W.J. Schafer and Associates Report WJSA-91-01 (March 1992).
8. I.N. Sviatoslavsky, "A KrF Laser Driven Inertial Fusion Reactor 'SOMBRERO'," *Fusion Technology* **21**, 1470 (1992).
9. D.D. Ryutov, M.S. Derzon, and M.K. Matzen, "The Physics of Fast Z Pinches," *Rev. Mod. Phys.* **72**, 167 (2000).
10. W. Huebner, Los Alamos National Laboratory, private communication (1977).