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ABSTRACT

The limits on the cavity gas density required for beam propagation and condensation times for material vaporized by target explosions can determine the maximum repetition rate of Heavy Ion Beam (HIB) driven fusion reactors. If the ions are ballistically focused onto the target, the cavity gas must have a density below roughly 10^{-4} torr (3×10^{12} cm^{-3}) at the time of propagation; other propagation schemes may allow densities as high as 1 torr or more. In some reactor designs, several kilograms of material may be vaporized off of the target chamber walls by the target generated x-rays, raising the average density in the cavity to 100 torr or more. A one-dimensional combined radiation hydrodynamics and vaporization and condensation computer code has been used to simulate the behavior of the vaporized material in the target chambers of HIB fusion reactors.

INTRODUCTION

The economic feasibility of Heavy Ion Beam (HIB) driven fusion reactors as power plants depends on the ability to achieve a high rate of target shots. The required shot rate depends on the cost of the plant, the desired cost of electricity, and the target gain. A high total repetition rate for the plant can occur through a high rate for each target chamber, multiple target chambers, or a combination of the two. The allowable repetition rate for various target chamber designs is the topic of this paper.

The repetition rate for a given target chamber is determined by the required cavity gas conditions at the time of the next shot and the length of time needed to achieve these conditions. If there is no material vaporized off of the chamber walls, which is the case in designs where the target energy density on the walls is low,[1-3] very high repetition rates may be possible. However, this type of design requires very large cavities or small target yields, either of which can bring along certain penalties in the design. Another approach is to allow a thin layer from the first wall of the cavity to be vaporized and recondensed back onto the wall.[4-6] The advantage of this is that the cavities can be smaller and cheaper, or so the designers hope. Also, one could use higher gain targets that improve the economy of power production. On the other hand, one must wait until the vapor density in the cavity has fallen to the point where beam propagation is possible before firing the next shot and there is the chance that the vapor could condense on the wrong spot and damage something.

There is some uncertainty over the limits on the target chamber vapor density imposed by beam transport.[7] If the beam ions are

ballistically focused onto the target by magnets that are several meters away from the target, conventional knowledge says that the density of gas in the cavity should be less than about 3×10^{12} cm^{-3} (10^{-4} torr).[4] There are other possible ways of propagating the ions to the target that allow densities in the 1 to 10 torr range. Some of these schemes involve using electrons from the cavity gas to neutralize the beam ion space-charge, while hoping that the vapor density is high enough to damp out detrimental plasma instabilities. Others use magnetic fields created in z-pinch type plasma channels to keep the ion beams confined to small radii until they reach the target. The methods of propagating beams in higher density gases are generally much less well understood than ballistic focusing, but, as calculations presented in this paper will show, the very low densities required for ballistic focusing may lead to very low repetition rates for some of the target chamber designs.

The vaporization of first wall material and its condensation back onto the walls can be a very complicated process.[8] The target generated x-rays rapidly vaporize the wall material in an as yet poorly understood way: the x-rays raise some of the material to an energy density above that required to raise it to the boiling point but not enough to overcome the latent heat of vaporization and it is unclear what happens to this material. The vaporized material forms a hot and dense layer of plasma near the surface, which is further heated by target generated ions, that may exist long enough for some rather unusual chemistry to take place.[9] The initially very nonuniform pressure profile in the vapor causes a shock wave moving towards the center of the target chamber that eventually collides with other similar shocks, resulting in very complicated hydrodynamic motion on the target chamber gases and vapors. While this motion is occurring, the gas is radiating energy back to the first walls and is condensing. Both of these processes put significant surface heat fluxes onto the wall that can cause evaporation of wall material. Unusual molecular species formed shortly after the vaporization may have a rather low sticking coefficient or may even sputter more material than is condensed. Eventually, the vapor cools enough and enough energy has been conducted away through the walls that condensation proceeds to the point that the ion beam can be propagated through the gas and the next shot is fired.

In this paper, I will present calculations of the time-dependent average gas density in a target chamber. I will do this for three target chamber designs that allow the first wall to partially vaporize: HIBALL,[4] FIRST STEP,[5] and CASCADE.[6] I will begin with a discussion of the physics that goes into the computer code used for these calculations. I will then present and compare the results of the calculations for the three designs. I will conclude with a consideration of what can be done to improve the repetition rates for the designs.

COMPUTER MODELING

To simulate the complex physics of the vaporization and condensation of material in HIB fusion reactor target chambers, a computer

code, CONRAD,[10] has been used. This code attempts to model the behavior of a radiating, moving vapor and a material that is vaporizing or on which vapor is condensing by dividing the problem into two separate regions. The vapor, one of the regions, is modeled with Lagrangian hydrodynamics and multigroup radiative heat transfer. The unvaporized material, the other region, is modeled with a standard finite difference heat transfer method. From this point on, the term "material" will refer to the unvaporized material. Each of these sections is treated with rather standard numerical techniques. There is little experience in how to model the heat and mass transfer between the two regions. For this reason, there have been some options written into the code that allow the user to choose, for example, what model to use for rapid vaporization. Once the initial rapid vaporization is finished, there is no longer any volumetric energy deposition and the additional vaporization is calculated with a standard kinetic expression for the rate that atoms leave a surface at a given temperature.

The vapor section of the problem is modeled as a one-dimensional fluid with multigroup radiation diffusion. The hydrodynamics is modeled with a Lagrangian mesh and a finite difference solution to Newton's first law. The multigroup radiation diffusion is done using a fully implicit finite difference technique, where absorption and emission terms are calculated from opacities provided by the MIXERG[11] code. The energy equation for the vapor is also solved fully implicitly, and the equation-of-state also comes from MIXERG. Heat transfer in the material is also calculated with an implicit finite difference method.

COMPUTATIONAL RESULTS

Condensation calculations have been carried out for three target chamber designs with the CONRAD computer code. The three all allow partial vaporization of the first walls by target generated x-rays. Typical parameters for the three design are listed in Table I. HIBALL uses a coating of liquid lithium-lead eutectic, $Pb_{83}Li_{17}$, on a substrate of silicon-carbide fabric to protect the rest of the structure from the target generated x-rays and ions. The chamber radius is 5 m and the hoped for repetition rate is 5 Hz. FIRST STEP uses liquid lithium that is rapidly flowing so that centrifugal force holds it up against a metal wall. The radius is only 2 m but the target yield is only 25 MJ, compared with 396 MJ for HIBALL. The designers of FIRST STEP hope to run at 10 Hz. CASCADE is 3 m in radius and the first wall is made of flowing graphite pellets that are also held against the walls by centrifugal force. Some versions of the CASCADE design use beryllium-oxide in place of graphite, but it has since been learned that BeO will dissociate and the beryllium will condense, leaving a great deal of oxygen gas in the the cavity that must be pumped out.[9] The target yield is 334 MJ. As one can see from Table I, the x-ray and ion target energy per unit area varies considerably between the three designs and the designs have different wall materials. However, there are similarities as well. For example, all of the calculations have been done using the

Table I

	HIBALL	FIRST STEP	CASCADE
First wall material	Liquid Pb-Li	Liquid Li	Graphite
Target Yield (MJ)	396	25	334
Target Design	"HIBALL"	"HIBALL"	"HIBALL"
Fraction of Yield in X-rays and Ions	0.27	0.27	0.27
Distance from Target to First Wall (m)	5	2	3
X-ray and Ion Energy per Unit Area (MJ/m^2)	0.340	0.134	0.797
Desired Rep Rate per Cavity (Hz)	5	10	5

"HIBALL" target design, scaled to the proper yield. This design is based on a Livermore design that was published several years ago.[12] A burn calculation was done for a variant of this design to provide the required x-ray and ion spectra.[13]

The average gas densities in the HIBALL, FIRST STEP, and CASCADE target chambers, as simulated by CONRAD, are shown in Figs. 1, 2, and 3 respectively. The results for HIBALL show that after 0.2 seconds the density is still 5×10^{14} cm^{-3}, more than 2 orders of magnitude higher than that required for ballistic focusing. This is because the thermal speed of the vapor atoms is very low because most of the energy has been radiated away and the high mass of the lead atoms. One should notice the vapor density is actually increasing very early in the calculation, which is due to the high radiant heat flux. The vapor density in FIRST STEP initially falls very rapidly to below 10^{14} cm^{-3} but then condensation ceases. At this point the evaporation rate is equal to the condensation rate. The evaporation rate is fairly high because the temperature of the surface of the liquid lithium is 540°C at 0.1 second. The condensation could continue if the bulk temperature of the liquid lithium were lowered below 420°C or if some other way of increasing the heat transfer could be found. The thermal conductivity has already been increased over classical values in an attempt to account for convective heat transfer. A set of three calculations have been done for CASCADE, for three values of the sticking coefficient for vapor atoms striking the surface. If all of the atoms striking the surface stick to it, a sticking coefficient of 1, the density of vapor in the cavity falls to the level required for ballistic focusing, 3×10^{12} cm^{-3}, in less than 0.1 second. It has been found,

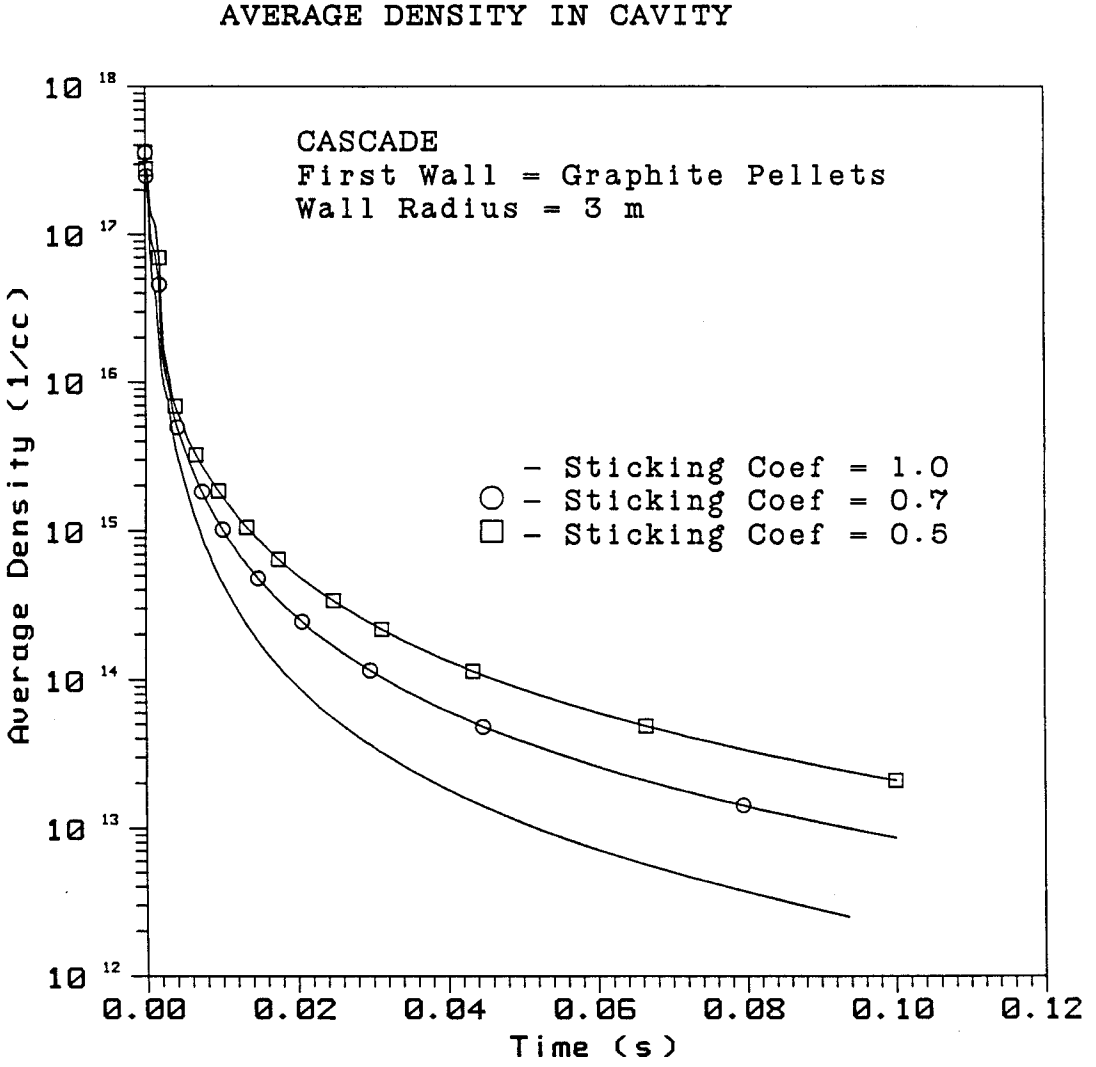

Fig. 1. Average Vapor Density in HIBALL Target Chamber versus Time.

however, that because of the chemistry of vaporized carbon the sticking coefficient may be about 0.7.[9] This leads to a density of 1×10^{13} cm^{-3} at 0.1 second and should lead to a level acceptable for ballistic focusing by 0.2 second. If the correct value is actually 0.5, condensation occurs too slowly to allow a 5 Hz repetition rate and ballistic focusing.

There has been some indication that ballistic focusing may indeed be possible at densities of more than 1×10^{14} cm^{-3}.[14] If this is true, there is no problem for FIRST STEP and CASCADE in running at 10 Hz. HIBALL may marginally be able to run at 5 Hz.

CONCLUSIONS

Computer simulations of the condensation of target explosion created vapor in three designs of HIB target chambers have been carried out. If the relatively hard vacuum of 10^{-4} torr is required

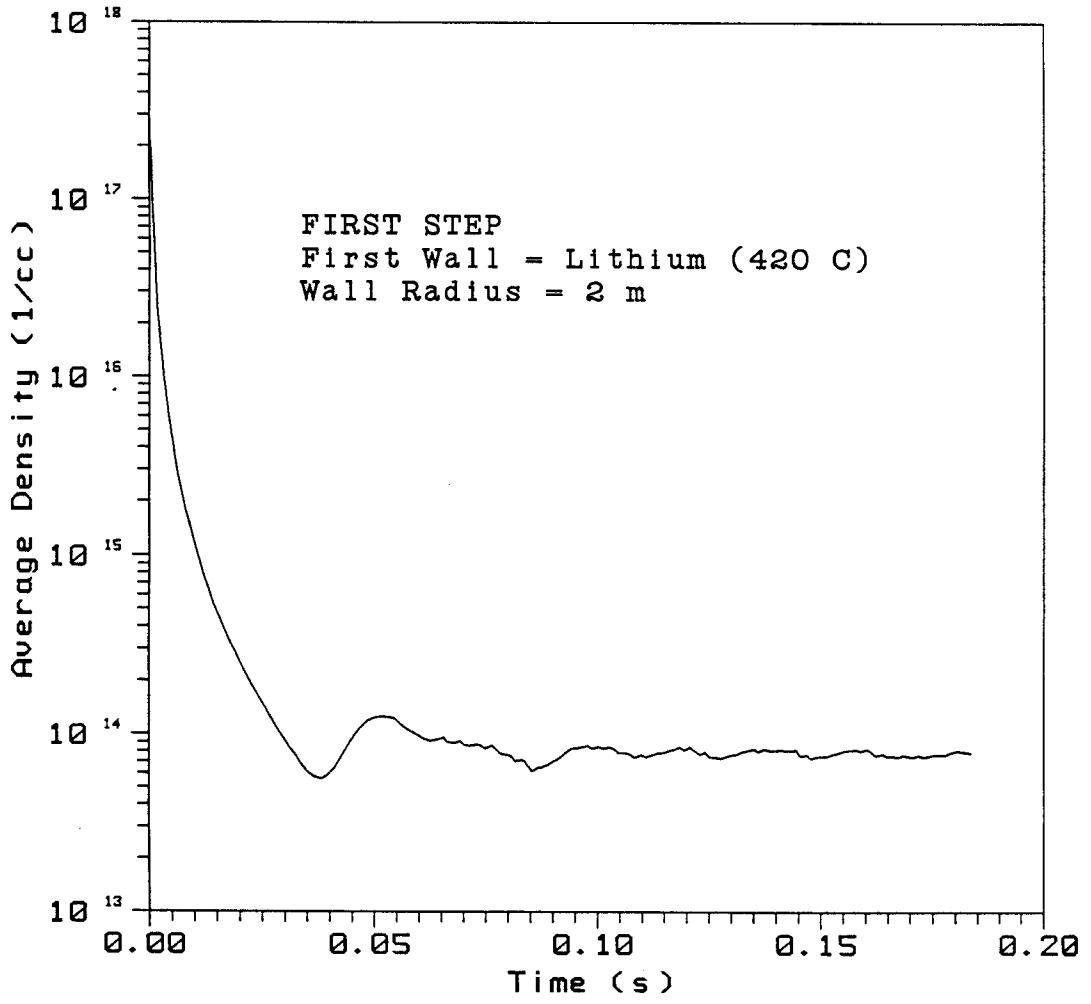

Fig. 2. Average Vapor Density in FIRST STEP Target Chamber versus Time.

for ballistic ion beam focusing, one has three different concerns for the three designs, each of which could make the repetition rate unacceptably high. In the case of HIBALL, the vapor can cool rapidly due to radiation so that the thermal speed can become very low and the cavity is so large that it takes too long for the vapor atoms to reach the surface. In FIRST STEP, the vapor pressure of the liquid lithium is high at fairly low temperatures so that the condensation can be greatly slowed if the surface temperature of the lithium is even as high as 540°C. In CASCADE, the chemistry of the vapor causes the sticking coefficient of the vapor on the surface to be significantly below 1.

Adjustments to the designs may improve the repetition rates. In HIBALL, the rate may be increased by making the cavity smaller, and in FIRST STEP, increasing the flow rate of the lithium may lower the vapor pressure by lowering the bulk temperature of the lithium

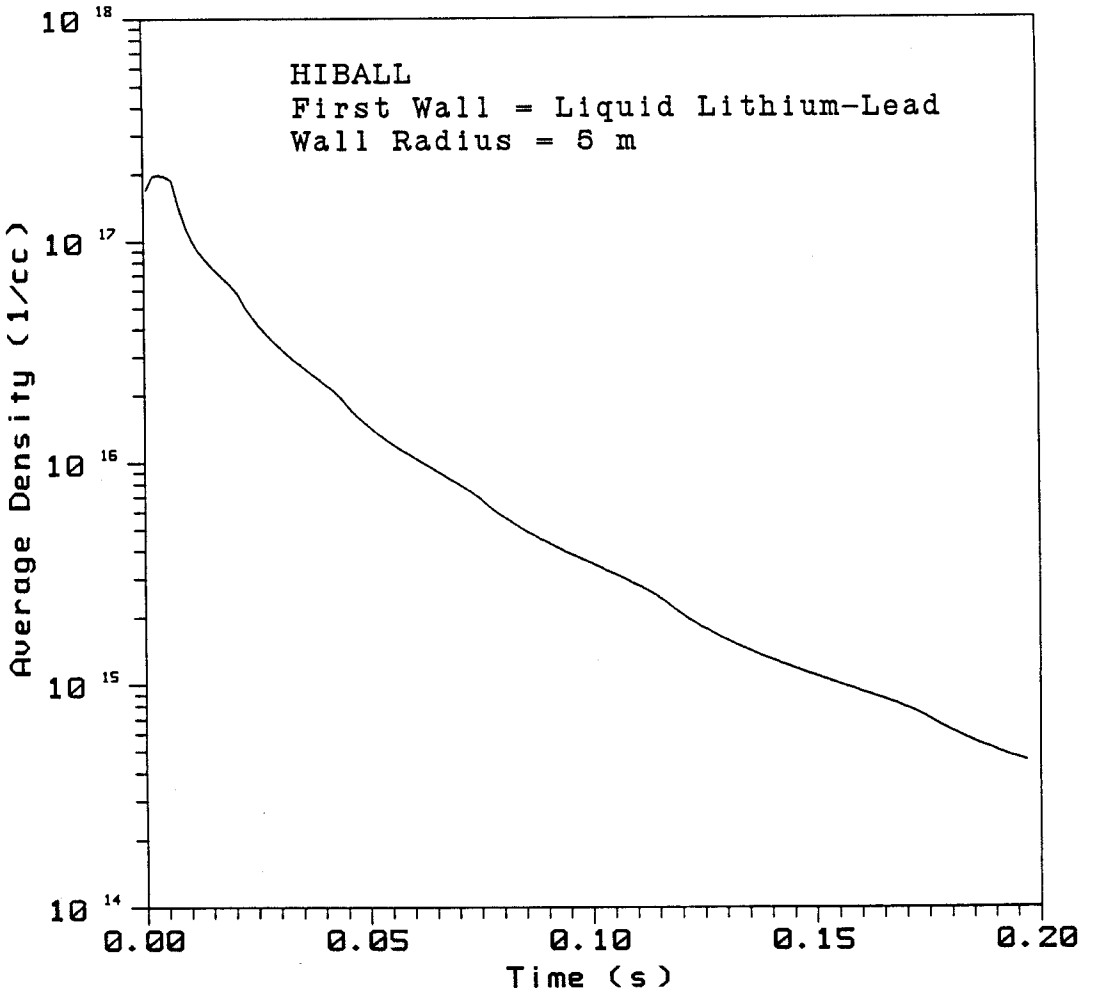

Fig. 3. Average Vapor Density in CASCADE Target Chamber versus Time.

and increasing convective heat transfer. It is harder to say what can be done to CASCADE to change the chemistry of the vapor, but the search for improvement must begin by gaining understanding of the physics of such hot and dense vapors. If it is indeed possible to focus the ion beams through denser gases, all three designs show promise of allowing reasonable repetition rates.

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