A DISTRIBUTED RADIATOR, HEAVY ION DRIVEN INERTIAL CONFINEMENT FUSION TARGET WITH REALISTIC, MULTIBEAM ILLUMINATION GEOMETRY[1]

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Abstract

This paper presents a series of heavy ion driven, inertial confinement fusion targets that all have adequate gain (> 50) for inertial fusion energy. These targets are based on the distributed radiator concept in which much of the hohlraum is filled with low density converter material in approximate pressure balance. This target is driven by heavy ion beams with a Gaussian spatial distribution in a multibeam geometry that is consistent with the number of beams needed by the accelerator and the space needed by the final focusing system. Because the optimal ion species and kinetic energy depend on the integrated system of accelerator, final focusing, chamber transport, and target, we have extended the distributed radiator target to accept ions with range of 0.035 g/cm^2 to 0.08 g/cm^2. In addition, a "close coupled" version of the target, in which the hohlraum wall is brought in closer to the capsule to increase the coupling efficiency, has produced gain > 130 from 3.3 MJ of beam energy.

1. INTRODUCTION

Ion accelerators are well suited to energy production because they have the long lifetimes ($\sim$ 30 years), high repetition rates ($\sim$ 10 Hz), and high efficiencies ($\sim$ 25-35%) needed for a reactor. In addition, focusing is done by magnetic fields so there is no final optic in the beam path. Because accelerators are efficient, relatively low target gains are acceptable. To keep the recirculating power fraction reasonably small, the product of the driver efficiency times the target gain (ηG) must be greater than 8-10. This means that gains as low as 30-40 are acceptable and indirect drive targets can produce more than adequate gain.

Recent work in heavy ion target design has centered around the distributed radiator target[1, 2, 3]. In the distributed radiator target, most of the cylindrical hohlraum is filled with low density converter material. The ions stop in these converters and generate x-rays which implode the capsule. In this type of target, symmetry is obtained by proper placement of the converters inside the hohlraum. In particular, the converters are located near the zeros of the Legendre polynomial, P_4, and the sources are weighted such that P_2 is also zero. The time-dependent symmetry is controlled by choosing the converter materials and densities such that approximate pressure balance is achieved and the converters stay in place. Ion range shortening (which would move the radiating regions even with perfect pressure balance) is minimized by starting with low density materials to avoid range shortening due to changes in density. Range shortening due to changes is temperature is overcome by changing the ion kinetic energy when the target undergoes a large change in temperature.

2. DISTRIBUTED RADIATOR TARGET

The original distributed radiator target assumed that the ion current was carried by two beams (one per side) traveling parallel to the hohlraum axis and that the density profile within each beam was a top-hat distribution. The accelerator cannot carry the 6 MJ of beam energy required in just two beams. If more than two beams are needed, they must be angled to accommodate the final focusing system (magnets, shielding, etc.) upstream. In addition,

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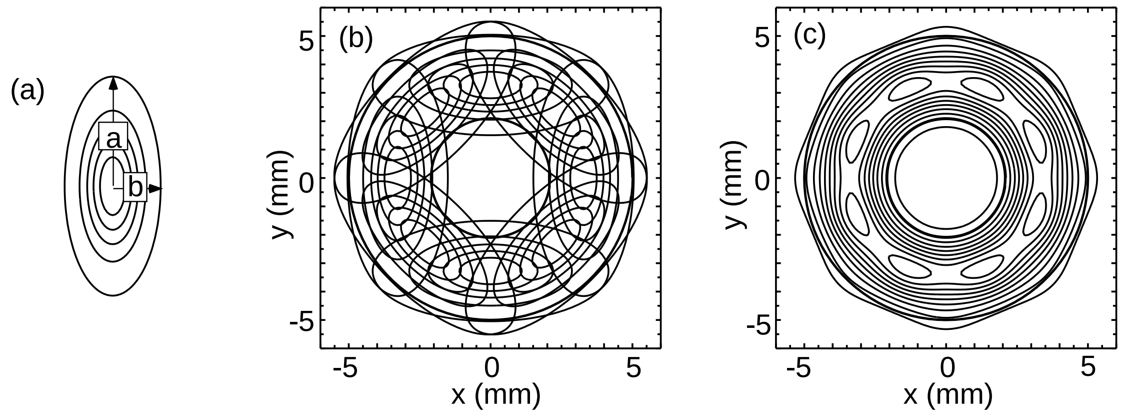

Figure 1: *Elliptically shaped, Gaussian beams are overlayed to form and annulus on the end of the hohlraum. (a) Each beam is an ellipse with a=4.15 mm and b=1.8 mm. (b) In the foot pulse, 8 beams are overlayed to form an annulus. (c) The sum of the 8 beams. When integrated radially, the source has < 2% asymmetry in m=8.*

chamber simulations indicate that a top-hat density distribution is probably not realistic for "conventional" ballistic chamber transport. These simulations show the distribution is more nearly Gaussian [3].

The targets described here use beams with a Gaussian distribution. In addition, the number of beams and the angles that the beams make with the axis are consistent with an accelerator designed by a systems code [4]. To minimize the amount of wasted energy, each Gaussian beam was focused to an ellipse, as is shown in figure (1), and the ellipses were then overlayed to form an annulus on the end of the hohlraum. The beams had major and minor semi-axes of 4.15 mm and 1.8 mm for an "effective" radius ($\sqrt{ab}$) of 2.7 mm. An elliptical beam spot is a natural choice since the accelerator uses alternating gradient focusing. In an alternating gradient focusing system, the beam is focusing in one direction and de-focused in the other by each quadrupole magnet. By alternating the polarity of the magnets, the beam is confined and tends toward an elliptical shape. Two cones of beams were used to illuminate the target. 16 beams (8 per side) of 3 GeV Pb^+ ions were used during the low power "foot" of the pulse and 32 beams (16 per side) of 4 GeV Pb^+ ions were used during the main pulse. Figure (2) shows the side view of the target including the ion beams, while figure (3) shows the ion current per beam and the resulting hohlraum temperature as functions of time. The target was driven by a total of 5.9 MJ of beam energy and produced 390 MJ of yield in an integrated (beam deposition to fusion burn in the same computer calculation) Lasnex [5] calculation for a gain of 66.

Some types of accelerators are better suited to longer range (higher kinetic energy) ions. Because only about 1 MJ out of the 5.9 MJ of beam energy ends up in the heat capacity of the converters, it is possible to double the amount of converter material (and hence, the ion range) for about 1 MJ more beam energy. Since almost 3 MJ ends up in the hohlraum wall, we kept the target geometry fixed and increased the converter density. Using this technique, we produced two successful integrated designs using increased ion range. In the first case, we increased the range from 0.035 g/cm^2 (4 GeV lead ions) to 0.05 g/cm^2 (5.5 GeV lead ions); this target produced 370 MJ of yield from 6.35 MJ of ion energy for a gain of 58. In the second case, we increased the range to 0.08 g/cm^2 (8 GeV lead ions); this target produced 413 MJ of yield from 7.4 MJ of beam energy for a gain of 55. All of these cases have adequate gain for an inertial fusion power plant.

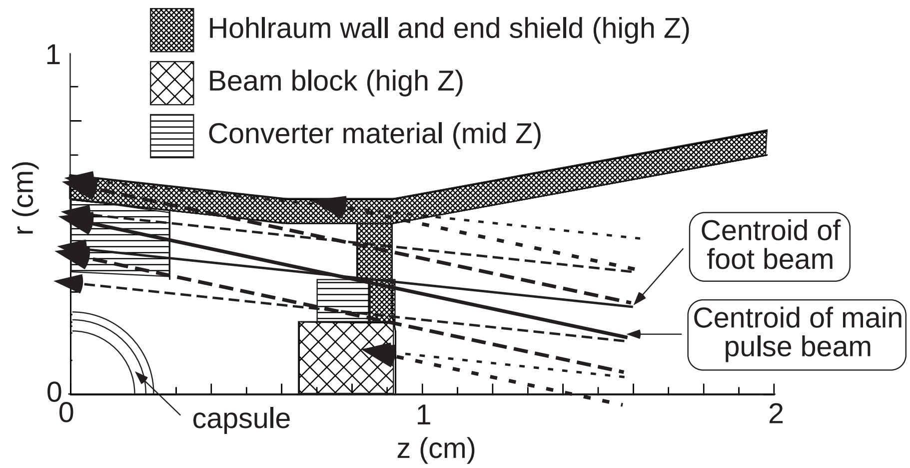

Figure 2: *A schematic of one quarter of the distributed radiator target. The complete target is a reflection about z = 0 and a rotation about the z axis. The arrows represent the Gaussian ion beams entering the target.*

3. CLOSE COUPLED TARGET

A preliminary cost of electricity (COE) for power plant based on the distributed radiator target is reasonable: 5.6 cents per kWh for a 1 GWe plant and 4 cents per kWh for a 2 GWe plant [6]. These same codes predict a 17% decrease in COE if we could drive the same capsule with about 3 MJ of beam energy. A simple scaling suggests that we might be able to do this if we reduce all the hohlraum dimensions by 27%. In doing so, more of the beam energy would be coupled to the capsule (hence, "close coupled"). Reducing the hohlraum size means a much smaller case-to-capsule ratio and less radiation smoothing than in the full size target so that maintaining time-dependent symmetry is critical.

Two-dimensional integrated Lasnex calculations predict that it is possible, however. We reduced the hohlraum dimensions of the target shown in figure (2) by 27%. The size of the beam block, which is set by the capsule size, remained the same. This meant that the effective beam radius was reduced by more than 27%. The beams used in these calculations had major and minor semi-axes of 2.78 mm and 1.0 mm for an effective radius of 1.67 mm. The ion range was also reduced: the foot was driven by 0.49 MJ of 2.2 GeV Pb ions while the main pulse was driven by 2.78 MJ of 3.5 GeV Pb ions. This target produced 436 MJ of yield from 3.3 MJ of beam energy for a gain of 132.

The impact of the close coupled target on the integrated system of accelerator, final focus, and chamber transport needs to be evaluated. While the close coupled target reduces the beam energy needed to drive the capsule, it puts more stringent requirements on beam focusing and beam pointing/target positioning. Future work will address these issues.

4. CONCLUSIONS

We now have several variations on the distributed radiator, heavy ion target that produce enough gain for inertial fusion energy. These targets are driven by ion beams with a Gaussian distribution that are arranged in a geometry that is consistent with the reactor chamber and final focusing system. These targets can also accept ion ranges from 0.035 g/cm^2 (4 GeV Pb was used in the Lasnex calculation) up to 0.08 g/cm^2 (8 GeV Pb) with a penalty of 1.5 MJ of additional energy. In addition to expanding the parameter space for this type target, these calculations show the flexibility of the target.

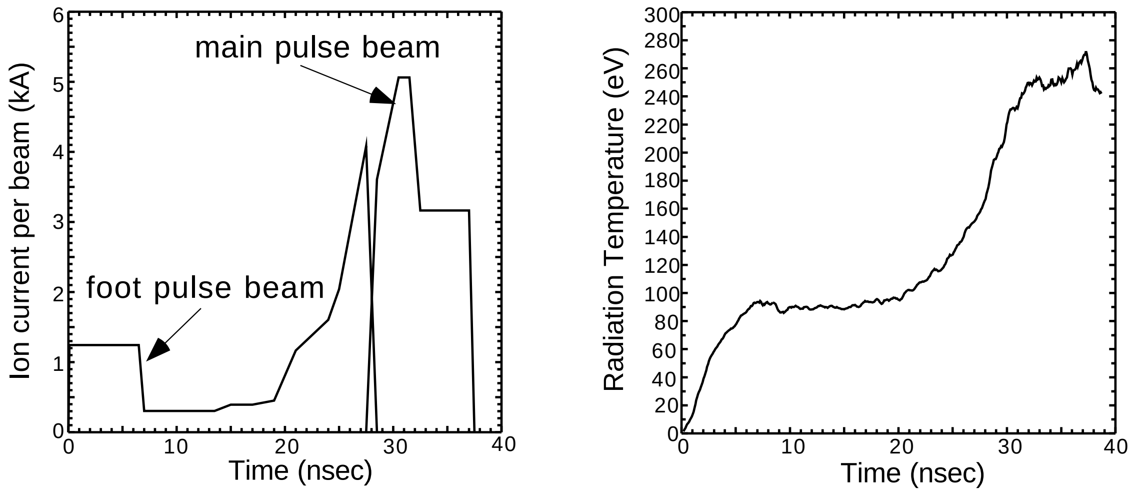

Figure 3: *Left: Ion current per beam as a function of time assuming 16 beams of 3 GeV Pb^{+} ion in the foot and 32 beams of 4 GeV Pb^{+} ions in the main pulse. Right: Radiation temperature inside the hohlraum as a function of time.*

Because accelerators are efficient, target gains as low as 30 may be acceptable for a heavy ion fusion power plant. Getting higher gain by decreasing the beam energy required may be desirable, however, because the cost of the driver increases with the beam energy. We have designed a close coupled version of the distributed radiator target that uses a smaller hohlraum while driving the same capsule. This target has produced gain 132 from 3.3 MJ of beam energy in two-dimensional, integrated Lasnex calculations. The impact of the close coupled target on the integrated system of accelerator, final focus, and chamber transport will be evaluated in the future.

One of the goals of the inertial fusion energy program is to construct an Engineering Test Facility (ETF) that demonstrates all the physics and technology needed for an inertial fusion energy power plant. The ETF would be a high repetition rate, high gain facility that would be used for testing chamber concepts, materials, and advanced targets. Since the ETF would not be a power plant, it would not need the full yield required for 1 GWe operation. A scaled-down version of the close coupled target is an attractive route toward an affordable ETF. Scalings predict that a close coupled ETF target driven by 1.5-2 MJ could produce $>$ 100 MJ of yield. Two-dimensional, integrated Lasnex calculations of such a target are in progress.

References

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