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# Assessment of Potential for Ion Driven Fast Ignition*

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**Abstract**

Critical issues and ion beam requirements are explored for fast ignition using ion beams to provide fuel compression using indirect drive and to provide separate short pulse ignition heating using direct drive. Several ion species with different hohlraum geometries are considered for both accelerator-produced and laser-produced ion ignition beams. Ion-driven fast ignition targets are projected to have modestly higher gains than with conventional heavy-ion fusion, and may offer some other advantages for target fabrication and for use of advanced fuels. However, much more analysis and experiments are needed before conclusions can be drawn regarding the feasibility for meeting the ion beam transverse and longitudinal emittances, focal spots, pulse lengths, and target stand-off distances required for ion-driven fast ignition.

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## I. Introduction

This paper explores the potential of ion beams to be used for either or both fuel compression and ignition, which can support by different beams in fast ignition targets. In conventional inertial fusion, ignition and propagating burn occurs when there is a sufficient temperature (5-10 keV) reached within a sufficient mass of DT fuel characterized by a density-radius product greater than an alpha particle range $(\rho r)_\alpha > 0.3$ g/cm$^2$. The necessary conditions for propagating DT burn are achieved by an appropriate balance between the energy gain mechanisms and the energy loss mechanisms. Mechanical work (PdV), alpha particle energy deposition, and, to a smaller extent, neutron energy deposition are the principal energy gain mechanisms in deuterium-tritium fuel. Electron heat conduction and radiation are the principal energy loss mechanisms. When the rate of energy gain exceeds the rate of energy loss for a sufficient period of time, ignition occurs. One adds beam energy deposition as an energy source when one considers fast ignition. In 1975 A. W. Maschke suggested the use of relativistic heavy ion beams to ignite an inertially confined mass of thermonuclear fuel [1]. As in conventional inertial confinement fusion, the fuel was assumed to be precompressed by a factor of the order of 100 in order to minimize the energy needed for ignition. Maschke suggested that lasers might compress the fuel, by high velocity impact, or by ion beams other than the ignition beam. Maschke's "fast ignition" scheme was finally abandoned in favor of the more conventional approach to inertial fusion where the implosion supplies the energy for both compression and ignition. There were at least two reasons favoring the conventional approach: (1) Maschke's scheme was quite inefficient because the ion beams were assumed to have such high kinetic energy that only a small fraction of the total beam energy was deposited in the fuel. (2) The conventional approach had an important programmatic advantage since, for indirect drive, the capsule physics is largely independent of the type of driver. This independence meant that much of the information being obtained in the inertial confinement fusion program using lasers was immediately applicable to ion beam fusion.

In 1994 an important paper by Tabak et al. [2] rekindled interest in fast ignition – this time using short-pulse lasers to provide the ignition temperature. Later, at the 1997

HIF Symposium, Tabak estimated requirements for heavy-ion-driven fast ignition [3]. This approach is now the subject of intense investigation in a number of countries. It promises a number of advantages in terms of target energy gain and reduced requirements on illumination symmetry and target fabrication tolerances or fluid stability. There are, however, important unanswered questions relating to the interaction of intense laser pulses with matter [4] and the feasibility of turning the whole concept into a commercial power plant. In any case, it now appears timely to revisit the question of ion fast ignition. In fact some work on heavy-ion driven fast ignition is already underway in Russia [5], where two pulses of 100 GeV heavy ions from a large synchrotron are envisioned, one of order 5 MJ @ 200 ns for fuel compression, followed by another pulse of 500 kJ @ 200 ps for fast ignition.

If ion beams could be made to deliver the energy density needed for ignition, they would have a number of distinct advantages. The reliability, durability, high repetition rate, and high driver efficiency are expected to be advantages of any accelerator driven inertial fusion system. Likewise, the ability to shield the focusing elements (magnets for heavy ion beams) from neutrons and other fusion products provides a plausible path to a power plant. In particular, for targets that can be illuminated by heavy-ion beams from one or two sides within limited solid angles, there is an additional advantage of being able to use thick-liquid-protected chambers that would greatly reduce or eliminate the need to develop first wall materials that can withstand neutron bombardment for hundreds of displacements per atom.

In the case of fast ignition, there are some additional advantages. The coupling of beam energy to the fuel is likely to be relatively simple compared the laser case thus removing one of the principal uncertainties (see section III). Moreover, for ions of the appropriate range, the beam energy can be deposited directly in the fuel, eliminating the inefficiency of converting laser light to electrons or ions that then deposit their energy in the fuel. Finally, because of the reduced requirements on illumination symmetry and stability, it may be possible to devise simple illumination schemes using direct drive or tightly coupled indirect drive, or use of single sided ion illumination for indirect drive fuel compression (see section II b.). This could simplify chamber design and, since direct drive and or tightly coupled indirect drive are efficient implosion methods, it could lead to lower driver energy and, as in the laser case, higher energy gain.

The remainder of this paper discusses this issues and problems associated with ion fast ignition in light of the progress in understanding ion beam fusion and accelerators in the nearly thirty years that have elapsed since Maschke's first proposals. Section II will discuss various target concepts and some requirements for ion-driven fast ignition and fuel assembly. Section III will address the issue of beam-fuel coupling. Section IV will examine some constraints and beam physics limits on various types of advanced accelerators that might be considered for ion-driven fast ignition. Section V discusses the potential for using advanced fuels with fast ignition. Conclusions are presented in Section VI.

**II. Target Requirements**

We consider in this section ion beam requirements for fast ignition in general, where a single short pulse of ions with a range of $2(\rho r)_{\square} = 0.6\ \text{g/cm}^2$ comes in from one direction onto one side of a pre-compressed DT fuel mass, heating a portion of that fuel mass to conditions of ignition and propagating burn in a pulse shorter than the time for the heated region to expand significantly. One example of an ion-driven fast ignition target is shown in Figure 1 below. We assume heavy-ion beams are also used for fuel assembly (see sec. IIc). For fast ignition we will consider both accelerator-produced heavy-ions as well as laser-produced proton beams.

Placement

**Figure 1**: An example of an ion driven fast ignition target using heavy-ion beams to compress the fuel via x-ray conversion in an indirect-drive hohlraum, with direct fast ignition provided separately either by a short intense laser or fast ion pulse.

**II a. Ignition with heavy ion accelerator-produced beams**

The fundamental question for the heavy-ion accelerator approach to fast ignition is: Can one find a combination of accelerator, focusing system, and target parameters such that ignition with a fast ion beam could really makes a difference compared to conventional ignition?

In searching for an acceptable combination one must, in principle, explore a parameter space with a number of dimensions. In fast ignition the parameters of the ignition region are somewhat independent of the parameters of the main fuel and neither the ignition region nor the main fuel need be perfectly spherical.

In the ignition region we can consider various combinations of density, radius, and length. These parameters will be related to the total beam energy, power, focal spot radius, and ion range. The range, in turn, depends on the kinetic energy and mass of the ions. There is an important constraint on the product of fuel density and size. If this product is small compared to the range of an alpha particle produced by the fusion reactions, only a small fraction of the alpha energy will be deposited in the fuel and it will be difficult to achieve ignition. Furthermore, if the ignition region is too small, electron conduction will be excessive. We will now discuss the various parameters and constraints in some detail. Many authors have done this previously. Chapter 3 of Lindl's book [6] provides an excellent summary for conventional targets.

For ion fast ignition we assume a cylindrical ignition region with a length equal to the ion range equal to twice the alpha range in hot DT, which is 0.6 g/cm$^2$ for 2 $(\rho r)_\alpha$.. We will take the main independent parameter to be the fuel density $\rho$ at peak compression, controlled by the hohlraum radiation temperature Tr for driving implosion of the fuel capsule. Table I shows ignition requirements for two fuel densities achieved for similar capsules driven with two radiation temperatures Tr = 150 and 120 eV. In both cases the electron conduction power, the alpha deposition power, and the bremsstrahlung power are smaller that the required beam power. At this level of approximation we ignore them leading to the following table:

Placement

**TABLE I** Requirements for ion-driven fast ignition for two hohlraum temperatures used for fuel compression discussed in section IIc

It is noteworthy that there may be ways to relax the requirements on power, energy, and focal spot size. For example, one could consider a hybrid between fast ignition and conventional inertial fusion where part of the ignition power is provided by the implosion. The igniter beam (or beams) would be arranged to penetrate the target in such a way that the Bragg peak occurs at the usual target hot spot. Or one might increase the expansion time by tamping the ignition region. In fact Magelssen published a paper in 1984 [7] in which he presented calculations of a target driven by ion beams having two very different energies. The lower energy ions arrived first and imploded the target to a spherical configuration with a rather dense pusher or tamper surrounding the fuel. The higher energy beams were then focused onto the entire assembly, heating both the fuel and the pusher. The combination of the exploding pusher and the direct ion energy deposition heated the fuel to ignition. Another target scheme proposed by Murakami [8], which might be called "impact ignition" or "fast impact ignition", seeks similar advantages as with fast ignition, but with lower intermediate peak drive power for ignition, by separating a fuel capsule into two spherical segments with a metal cone, one segment containing only a few % of $4\pi$ solid angle. "Slow" implosion of the larger segment is initiated first for main fuel compression, followed by a delayed beam of intermediate intensity to drive the smaller segment to higher velocities $> 10^8$ cm/s for fast impact ignition at the convergent arrival of the two imploding segments. We will discuss a bit more about this option later on. It appears that there might be a very large number of possible variations and geometries between pure fast ignition and those methods that use tamping, fast impact and/or exploding pushers.

**II b. Ignition with laser–produced proton beams**

An interesting alternate route to fast ignition with ion beams was triggered by the discovery of intense, short, energetic, directed beams of protons off the rear surface of solid targets irradiated by ultra intense lasers [9]. In addition to producing short ion beam pulses for fast ignition, laser generated ion beams also offer the option to make a much smaller front end ( a compact ion injector) for a heavy ion driver. The initial idea of fast ignition already dealt with the problem that laser light is stopped and absorbed at a point along the rising slope of the density, orders of magnitude below the region where the compressed fuel has to be ignited. So for fast ignition there is the need for energy deposition in a small volume in a short time, by particles that can are not likely the subject of instabilities or other uncontrollable phenomena. With the discovery of those intense, short, energetic bursts of ions with excellent beam quality, the idea of using those beams for fast ignition was introduced [10, 11]. Protons have several advantages for fast ignition compared to heavier ion species [12] and to electrons for this application. First, because of their highest charge to mass ratio for ions, protons are accelerated most efficiently up to the highest energies in laser-produced electrostatic sheaths. For a given energy, protons can penetrate deeper into a target to reach the high-density region, where the hot spot is to be formed, because of the quadratic dependence of ion stopping power on the charge state. And finally, compared to electrons, protons, like all ions, exhibit a characteristic maximum of energy deposition rates at the end of their range (the so-called Bragg-Peak), which is desirable in order to heat a localized volume efficiently. As sketched in Figure 2, the basic idea is to use multiple, short pulse lasers irradiating a thin foil. The protons were accelerated off the rear surface of the foils and, because of the parabolic geometry, are focused into the compressed fuel. The higher mass and the neutralized space charge make them less likely to be subject of instabilities compared to fast ignition with electron beams. As has been shown in [9, 10], the ion beams have an excellent beam quality, e.g. emittance, which allows for the focusing into a small volume, the pulse duration is short, and the particle numbers are high. So after some years of research, what is the current experimental and theoretical status of the prospects for proton fast ignition (PFI)? To summarize: there has been no insurmountable problems identified so far, and the experimental results are encouraging.

Placement

**Figure 2:** Schematic view of Proton Fast Ignition of fuel compressed in indirectly driven hohlraums. (Figure not to scale). The rear surface of the laser target is shaped to focus the proton beam into the spark volume.

Let's have a look into the details: One of the requirements for PFI is the possibility of focusing the proton beams into a small volume. It has recently been demonstrated, that proton beam focusing is indeed possible and spot sizes of about 50$\mu$m have been achieved. This is still larger than required by PFI, but it also depends on the geometry of the experiment, which was set-up in order to do isochoric heating, and on the electron sheath geometry. The pulse length was in the right order of magnitude for PFI, which was indicated already in first experiments on ion acceleration [13]. The protons are not monochromatic, but rather have an exponential energy distribution. This seemed to be a concern at the beginning for two reasons. First, because of the different energies, the dispersion of the proton pulse from the source to the target lengthens the pulse and therefore a maximum distance less than a few millimeters is required to keep the energy deposition of the PFI beam within the disassembly time for the hot spot region. The close distance to the pellet, on the other hand, raises the concern if the thin metallic foil, that is to be the source of the protons, can be kept cold enough so as not to develop a density gradient at the rear surface, which would diminish the accelerating field. A second concern was related to the stopping power. Because of the difference in initial velocity, the energy deposition of protons with different kinetic energy is spread over a larger volume. Slower protons are stopped earlier and do not contribute to the creation of the igniter spark. Fortunately, recent numerical simulations have relieved those concerns. Simulations by Basko, et al. (presented at the Fast Ignition-Workshop 2002, Tampa, Florida) have shown that the protective shield placed in front of the source can withstand the x-ray flux of the pellet compression and keep the rear surface of the source foil cold enough for the acceleration via the mechanism described in this article. The distance between the source and the ignition spot can be a few millimetres. If this distance is too short for the compression geometry (e.g. not using a closely coupled hohlraum) the distance can be adjusted using a similar cone target [14, 15] as for conventional Fast Ignition.

Since the first time the concept of PFI has been brought to public a deeper understanding of the underlying physics has been achieved. Detailed numerical simulations have been carried out taking advantage of more and more sophisticated and realistic computer modelling. A big surprise was the fact that a monochromatic proton beam is actually not the optimum to heat a hot spot in a fusion target. Numerical simulations [16] have shown that one has to take into account the decrease of the stopping power of the nuclear fuel with increasing plasma temperature. So an exponential energy spectrum, like the one that is generated by this mechanism, is the most favourable one. The first protons with the highest energies penetrate deep into the fuel. By the time the proton number increases and the target temperature rises, the stopping power is reduced, thereby compensating for the lower initial energy of the incoming protons. Thus the majority of the protons deposit their energy within the same volume.

In contrast to conventional FI, the proton fast ignition can easily be implemented into indirectly driven scenarios [6, 17], for example, in heavy ion driven hohlraums such as depicted in Figures 1 and 2. A detailed numerical study addressed a consistent scenario of a proton beam triggered fast ignition target compressed by heavy ion beams [18].

There are other practical advantages of PFI. Because final focusing of the ion beam is provided by the geometry of the source foil in PFI, the pointing and focusing requirements for the high energy short pulse laser beams are significantly relaxed. In fact the laser beam foci can be as large as a few hundred $\mu$m, which will flatten the shape of the electron sheath that is driving the protons, and which will enhance their focusability. As a consequence, the final optics of the short pulse lasers can be mounted farther away from the reactor center, which might increase their lifetime.

Existing short pulse lasers already have demonstrated intensities sufficient for generating the proton energy spectra required for PFI. Regardless of the nature of the igniter beam, calculations show a minimum deposited energy required for fast ignition of at least 10 kJ or more depending on the ion focal spot size [19]. There have been many experiments at different laser systems accelerating proton beams. Measured and published efficiencies for converting the primary laser energy into ion beams seem to be favourable for PFI. While experiments at low-energy short pulse lasers have conversion efficiencies below one percent, the conversion efficiency increases to a few percent for systems of a few joules of energy and further increases to more than 10 % for systems having hundreds of joules at comparable focused intensities. Extrapolating conversion efficiencies with increasing laser energy to multi-kilojoule laser systems indicates that conversion efficiencies of more than 10 % can be expected, which would result in the need for a few hundred kilojoules of short pulse laser energy for PFI, assuming a few 10's of kilojoules of proton beam energies would suffice for fast ignition.

In addition to these encouraging results, it should be noted that currently there are plans for building multi-kilojoule short pulse laser systems in the US, Japan, UK and France. So, finally, the chances are high to further explore this fascinating field of research and to evaluate the potential of PFI as an alternative way to achieve ignition.

**II c. Heavy-ion driven hohlraums for fuel assembly**

We have looked at the possibility of reducing the beam power requirements for a heavy ion driver using fast ignition, for two hohlraum geometries at two different temperatures and using 2 mm and 4 mm radius compression beam focal spot sizes. We consider here the ion beam requirements for fuel compression, assuming either a short pulse laser or ion beam (as described in Table I) for the igniter. We also assume the igniter beam has access to the compressed core via a cone focus geometry, like the one being designed by Steve Hatchett and tested on Gekko and Omega [13, 15]. We started with two similar capsules (designed by Mark Herrmann), which are driven at two temperatures [20]. The first is driven at 150 e V and has an outer ablator radius of 3.05 mm, outer fuel radius of 2.93 mm, and inner fuel radius of 2.78 mm. The capsule has 3.84 mg of DT. The second capsule is driven at 120 eV and has an outer ablator radius of 3.05 mm, outer fuel radius of 2.95 mm, and inner fuel radius of 2.8 mm. This capsule contains 3.89 mg of DT. Both capsules have a plastic (CH) ablator (undoped) and have a central DT gas fill of 1.00666e-4 g/cc with 1.27e-4 atomic fraction Xe in the gas. It should be noted that these capsules have thin shells-the initial aspect ratio (radius divided by thickness) is greater than 10 in both cases.

We considered two hohlraum geometries using indirect drive with heavy ion beams for fuel compression: a hohlraum for compressing fuel with ion beam illumination from two ends, with an igniter (either short pulse ion or laser beam) coming in from the side (Figure 1), and a hohlraum geometry using single-ended illumination for compression (Figure 3) with heavy ion beams of 2 mm radius (Fig.3a) and 4 mm radius (Fig. 3b), and with a high Z cone for a short pulse laser or fast ion igniter beam from the other end. The geometry for single-sided illumination was chosen so that the converters (shown as blocks in Fig 3a, b) are at the zeros of the third Legendre polynomial. Steve Hatchett's symmetry calculations with the cone focus geometry show the best results when a 10% $P_1$ flux asymmetry is applied (i.e. higher flux opposite the cone). This is a fairly small asymmetry so for the purposes of the scaling law analysis, we designed the hohlraums for nearly symmetric conditions. Effects like range shortening, and hydrodynamic motion of the converters, which are not included here, will have to be taken into account in some future final design.

<u>Axisymmetric single sided hohlraums</u>

One difficulty in designing the hohlraum with the converters near the zeros of $P_3$ is that the converter is very close to the cone. Steve Hatchett [13] typically uses cones with half angle of 35 degrees while the zero of $P_3$ is at 39.23 degrees. The design shown in Fig 1 assumes the ion beams have a minimum radius of 2 mm. The beam diameter plus the capsule radius then sets the hohlraum radius of about 7 mm.

*Energetics for 150 eV, one-sided target*: If we scale the wall loss from the distributed radiator targets, we find

$$E_{wall} = (3\ MJ)(A_{wall}/6.22)(T_r/0.25)^{3.3}(\tau/8)^{0.6},$$

Placement

**Figure 3:** Hohlraums for fuel compression with single-ended illumination by heavy ion beams of 2 mm radius (a) and 4 mm radius (b).

scaling from a previous design where the distributed radiator target [21] had a wall loss of about 3 MJ, a wall area $(A_{wall})$ of 6.22 cm$^2$, a temperature $(T_r)$ of 0.25 keV, and a pulse duration ($\tau$) of 8 ns. For the one sided, 150 eV target, $A_{wall} = 10.1$ cm$^2$ (including the cone), $T_r = .15$, and the pulse duration 17 ns. From this we find $E_{wall} = 1.4$ MJ. The converter heat capacity is approximately,

$$E_{conv} = 0.115 \times 10^3 (r_{hohl}^2) RT$$

where $r_{hohl}$ is the hohlraum radius, $R$ is the ion range (g/cm$^2$), and $T$ is the converter temperature in keV. For this estimate, we have used the heat capacity of DT, as given by Lindl's book [6]. For a $r_{hohl}$= 0.7 cm, $R = .03$ g/cm$^2$, and $T=0.15$ keV, we find $E_{conv} = 0.8$ MJ This capsule absorbs 430 kJ, so $E_{cap} = 0.43$ MJ. We approximate the radiation escaped through the beam entrance window by scaling from the distributed radiator target as

$$E_{esc} = (0.67\ MJ) 0.5 \pi (r_{end}/5\ mm)^2 (T_r/0.25)^4 (\tau/8).$$

This is a rough approximation, which assumes the temperature on the outside surface of entrance window scales with the hohlraum temperature. Darwin Ho derived a formula that is a better estimate for the escaped energy-in this case, the amount of energy escaped will be small, and so we just use the above approximation. Note the factor of 0.5 comes from the fact that we have only one entrance window for the one sided target, so we get $E_{esc} = 0.1$ MJ. Thus, for the 150 eV one –sided drive hohlraum, we get total ion beam energy for compression of

$E_{beam}$ = 1.4 + 0.8 + 0.43 + 0.1 = 2.7 MJ and *Power* = 2.7 MJ/(17 ns) = 160 TW. From I-D calculations, the $\rho r$ of the imploded capsule is about 3.3, which would mean a yield of about 460 MJ assuming *(pr / (pr+6)* ) burn efficiency. The average fuel density is 175 g/cm$^3$. Using Atzeni's formula [19] for the required fast ignition energy deposited, we find that we would need to deposit 50 kJ of energy for ignition for fast heavy ions, if they could be focused to the required 30 micron radius spots, or, the same ignition energy in electrons would require about 150 kJ of short- pulse laser energy, assuming 30 % efficiency of laser energy to usefully deposited electron energy.

*Energetics for a 120 eV, one sided target, 2 mm spot size:* We now re-do the above calculation replacing $T_r$ = 0.12 keV and $T$ = 28 ns: $E_{wall}$ = 0.9 MJ, $E_{conv}$ = 0.64 MJ, $E_{cap}$ = 0.26 MJ, $E_{esc}$ = 0.08 MJ, and $E_{beam}$ = 1.9 MJ, leading to a heavy ion beam power for fuel compression *Power* = 1.9 MJ/(28 ns) = 68 TW. In 1-d calculations, this capsule reached a $\rho r$ of 2.25 for a predicted yield of 350 MJ. The average fuel density is 80 g/cm$^3$, which means we need to deposit 200 kJ of fast ignition energy, assuming heavy ions in a 60 micron radius spot. Alternatively, ignition with electrons would require about an estimated 600 kJ of short pulse laser energy. This results in a target gain 350/ (1.9+0.6) = 140 with a laser igniter, or 167 with a heavy ion igniter.

*Energetics for a 120 e V, one sided target with a larger 4 mm radius spot:* The hohlraum radius for this one sided geometry is set by the capsule radius plus the beam diameter, now 2 x 4 = 8 mm (Figure (3). The wall area for this geometry is increased considerably. The wall area is now $A_{wall}$ = 19.6 cm2. For a 120 eV drive with a pulse duration of 28 ns, this results in 1.7 MJ of energy into the wall. The converter energy is also larger due to the larger converter volume. The converter now uses 1.6 MJ. The total energy is $E_{beam}$ = 4 MJ, *Power* = 150 TW Again, this design requires 200 kJ of fast ignition energy delivered to the compressed core. The yield of this capsule, from $\rho r$ scaling, is 350 MJ. This does not include the fuel lost due to the cone or reductions in $\rho r$ that occur because of the cone. Even so, the gain has come down considerably compared to the case with a 2 mm spot size; assuming a 600 kJ laser to deliver 200 kJ for ignition, the gain = 350/(4.6) = 76, 54% of the gain with a 2mm spot. Nonetheless, this gain is still higher than a similar spot size HIF hybrid target with conventional ignition, and the beam illumination for compression is simpler (single sided with a significant illumination angle allowance). The gain might increase close to 100 if lower density compression to 40 $g/cm^3$ were used (2.8 MJ for compression) together with 800 kJ of ion igniter energy.

<u>Hybrid target geometry [Fig. 1]:</u>

The second target geometry, shown in figure (1), is a variation on the hybrid target geometry. The hohlraum is illuminated from two sides by the ion beams. The cone enters from one side-making this truly a 3-D geometry. One advantage of this geometry is that it allows beams with radius about 5 mm.

Energetics for 150 eV, hybrid-style target: We use the same formulas described above for the scaling. The wall area is 6.88 $cm^2$-slightly larger than the distributed radiator target because the cone is included: $E_{wall} = 0.97$ MJ. In the hybrid geometry, the converters have to heat up to around 200 eV before they can radiate effectively. Therefore, we use a temperature of 0.2 keV. We also have to multiply the ion range by 2 ($R=0.06$ $g/cm^2$) since we are stopping ions from both sides and require twice the stopping material: $E_{conv} = 1.3$ MJ, $E_{cap} = 0.43$ MJ. The escaped energy no longer has a factor of 0.5 since there are now two radiating windows again: $E_{esc} = 0.2$ MJ, leading to a compression beam energy $E_{beam} = 0.97+ 1.3+ .43+ .2 = 2.9$ MJ and *Power* = 2.9MJ/(17 ns) = 170 TW. The power required for this case is almost the same as for the one sided design. However, the energy is delivered in a 5 mm spot rather than the 2 mm spot in the one sided design.

Energetics for a 120 eV, hybrid-style target*:* We again use the same scalings but with $T_r = 0.12$ keV, and T = 28 ns, so $E_{wall} = 0.62$ MJ. The converter energy does not change because we still assume the converters have to heat up to 0.2 keV to radiate effectively, so $E_{conv} = 1.3$ MJ, $E_{cap} = 0.26$ MJ, $E_{esc} = 0.15$ MJ, leading to $E_{beam} = 0.62 + 1.3 + 0.26 + 0.15 = 2.3$ MJ, and Power = 2.3 MJ /(28 ns) = 82 TW. Again this is slightly higher than for the one sided target, but allows a much larger spot. We should be able to trade off the larger spot for a shorter ion range. If we assume the ion range can be reduced by a factor of 2, then the hybrid targets become $E_{beam}$ (half-range) = 2.3 MJ and *Power* = 135 TW for 150 eV and $E_{beam}$ (half-range) = 1.7 MJ, *Power* = 61 TW for 120 eV.

Summary for indirect-drive fuel assembly

For the 150 eV capsules, using fast ignition cuts the beam power by about a factor of two from the close-coupled target (peak beam power was 330 TW) and requires 50 kJ of igniter energy delivered to the capsule. For the 120 eV capsule, using fast ignition cuts the beam power by a factor of 4-5, but increases the igniter energy delivered to the capsule to 200 kJ.

**III. Ion Beam Coupling**

In most cases studied for heavy ion fusion, the beam energy deposition appears to be approximately classical, that is, it appears to occur mostly because of collisions between the beam ions and the electrons in the target. No collective beam-plasma instabilities have been found to be important in heavy ion beam stopping experiments in dense target plasmas [22, 23, 24]. For fully ionized plasma, experimental measurements of heavy ion energy loss can be adequately explained by a modified Bethe-Bohr-Bloch stopping theory. It is well known that the energy deposition rate of heavy-ions decreases when the electron thermal velocity becomes comparable to the ion velocity. For fast ignition the temperature of the electrons is significantly higher (of the order of 5 keV) than the typical 100 to 400 eV in the deposition region of conventional targets. At 5 keV the thermal velocity of the electrons is of the order of 0.15 c. This corresponds to a heavy ion (mass = 200) of a few GeV. The density-length products shown in Table I would all require beam energies (for heavy ions) exceeding 10 GeV so, for now, we assume that the ion range is roughly the same as in standard targets for heavy ion fusion. The ion range is roughly 0.1 g/cm$^2$ at 10 GeV and increases approximately as $T^{1.5}$ where T is kinetic energy.

In the case of a density-length product of 1.2 g/cm$^2$, the appropriate kinetic energy is approximately 50 GeV. Figure 4 shows the range energy relationship for a variety of ion species. Note in Figure 4 the two horizontal lines: the lower one (0.03 g/cm$^2$) for an ion range similar to those required for beams to stop in radiating foams in conventional distributed radiator heavy ion targets [21], and the upper one (1.2 g/cm$^2$) is the requirement for heavy-ions as igniter beams to stop within 4 alpha ranges.

Fig. 4 shows that the high energy requirement for igniter ion beams (50 GeV) comes from the requirement for the ion beams to stop within four alpha ranges, and the desire to use heaviest ions like lead to minimize the beam current required for acceleration, transport, and focusing (section IV). Relativistic effects and improved focusing for heavy-ions above 50 GeV may still be worth exploring. An alternative approach to fast ignition after fuel compression which may avoid the requirement for 50 GeV heavy-ion accelerators for ignition (cost issue), yet retain many of the advantages of fast ignition, might be to drive a segment of the fuel in a cone to > $10^8$ cm/s, similar to Murakami's proposal [8] for fast impact ignition, except using heavy-ion direct drive instead of using laser direct drive. Figure 5 illustrates how Murakami's idea might be adapted to a heavy-ion hohlraum similar to Fig. 3b with ion direct drive on the igniter segment for fast impact ignition. The special requirement for > $10^8$ cm/s for fast impact ignition requires high ablation velocities ~ $10^8$ cm/sec for < 80% mass ablation fractions, ruling out indirect drive for the fast impact segment. However, such ablation velocities can in principle be achieved with ion direct drive, provided the ion range is less than the initial ablator area density.

For the lightest (highest Z/A) ablator (hydrogen), the ion range could ~ 0.004 to 0.01 g/cm$^2$, depending on the ion energy and mass, roughly three times less than for aluminum in Fig.4. Thus, the same voltage accelerator producing ions of range 0.03 g/cm$^2$ for fuel compression could also be close to those used with ~ mm thick hydrogen ablator for the igniter drive. In this scheme, the igniter drive beams can have a similar low range as for the fuel compression phase, and the so the accelerator voltage and cost may be lower. The required pulse length for the igniter drive in this case is estimated to be of order 2 ns, which is shorter than for conventional hohlraum drive, but still very long compared to the 50 ps requirement for direct fast ignition. We can make a rough estimate of the required short pulse beam energy for this scheme. The DT payload mass for an igniter mass at stagnation $(\rho r)_{igniter}$ = 0.6 g/cm$^2$ @ 40 g/cm3 (150 micron radius) = 0.565 mg. By the rocket equation, the hydrogen ablator mass = $e^1$ times this payload mass = 1.5 mg hydrogen (1 -1.5 mm thick initially), and the energy expended at $10^8$ cm/sec exhaust velocity would then be 0.5 (1.5 x $10^{-6}$ kg) ($10^6$ m/s)$^2$ ~ 750 kJ. Actual implosions are likely less efficient than the implied 37% hydro efficiency, so assume 1.1 MJ @ 25%

hydro efficiency. If the compression energy were 2.8 MJ @ 100 eV $T_r$, the overall gain would be about 90, quite adequate for accelerator efficiencies of 30%.

The beam energy in this case might be supplied with overlapping beams as large as 4 mm radius (see sketch in Fig. 5), and within a few ns pulses, in contrast to the 75-micron spot and 50 ps requirements for fast ignition with high range heavy ions. The igniter drive beam perveance in this case is much higher than for 50 GeV igniter beam case, and requires plasma neutralization, but the requirements on longitudinal emittance is much relaxed in this case (less overall longitudinal compression required to 2 ns compared to 50 ps).

Placement

**Figure 4:** Ion range (g/cm$^2$) as a function of kinetic energy (GeV) for various ions in aluminum targets, assuming an average <Z/A> ~0.4 for the target material.

Placement

**Figure 5:** Single ended ion driven hohlraum and direct drive concept for fast impact ignition with separate 4 mm radius ion beams for compression and fast impact drive. If feasible, this approach could use lower cost low range ions for both ignition and fuel compression.

There has been no specific target designs done for this ion-direct drive igniter concept so far, but we point this out for future consideration, because all of the fast ignition concepts assessed in this paper have many unresolved issues. At this preliminary stage, we wish to be as complete in our assessment of approaches as we can.

## IV. Constraints on Beams and Accelerators.

Here we make preliminary estimates of transverse and longitudinal emittance requirements to focus 50 GeV heavy ions of mass 200 to 75 micron radius spots (The 120 eV hohlraum case in Table I). The requirements are difficult for one beam, so we assume the ignition beam energy of 200 kJ is provided with 20 beams overlapping onto the ignition spot, or 10 kJ/beam =(0.2 μC/beam. At 50 ps the beam is about 1 cm long. One can show from simple conservation of energy that such a long, thin beam can be focused to 75 microns with a 5 to 10mr convergence angle without neutralization. However, overlapping 20 of such beams would increase the total space charge of the beam array, and neutralization by background plasma would be helpful to reduce beam-beam deflections due to space charge. Fortunately, theory and simulation [25], and experiments [26] indicate that plasma neutralization can be used without deleterious beam-plasma instabilities. The beam must be focused both transversely and longitudinally to the final beam potential; therefore a coherent velocity tilt of 1% that corresponds to 10 mr transversely should compress the beam longitudinally. At 10 mr, the emittance requirement is 0.75 mm*mr corresponding to a normalized emittance of about 0.5 mm*mr. The beam size in the lens for 5 m standoff is 50 mm; so the chromatic aberration at the focal spot would be 200 mm (4 times the beam size) times the velocity spread. This leads to an allowable energy spread of $7.5 \times 10^{-4}$ in the final lenses. Multiplying this by 50 GeV and 50 ps, one obtains a longitudinal admittance of approximately 0.002 eV·s. If we assume a 200 mA source for 1 μs to get the required charge, with an injector voltage of 1 MV at precision of 0.1%, such an injector would create a longitudinal emittance of 0.001 eV·s ignoring all other effects. Based on sources that have been built, it is possible to achieve 0.5 mm-mr normalized transverse emittance at 200 mA.

By these rough estimates, both the transverse and longitudinal emittance requirements for heavy ion driven fast ignition are close to achievable values as long as the emittances don't grow much along the accelerator. Future work could evaluate several favorable effects that could make ignition with heavy ion beams more robust: the favorable effect of Bragg peak in dE/dx, and beam space charge neutralization. There are methods to reduce chromatic aberrations. If the magnetic pressure at the focus exceeds the beam's thermal pressure, the beam might pinch to a smaller radius. Also, we have only given an example set of parameters here, and so optimizing the system should lead to significant improvements. Finally, relaxation of the target requirements, as described above, could have a profoundly favorable effect.

**General considerations for linacs**

Both high current linacs as well as RF linac/storage rings/synchrotrons might be considered for heavy ion fast igniters. The ITEP Moscow group has proposed 100 GeV heavy ion linacs with storage/compression rings [27]. Here we comment mainly on the prospects for high current linacs providing ion beams for ignition.

*Representative linac beam parameters:* For discussion, we will assume the following beam parameters along some type of linac providing the reference case heavy-ion igniter pulse described above on target: a total beam energy of approximately 200 kJ provided by 20 beams of 50 GeV heavy ions, a total beam power of 4 PW, and a pulse duration of 50 ps (bunch length 7.5 mm at target). Near the high-energy output end of the linac, assuming the longitudinal momentum spread is small enough to allow 100 x longitudinal bunch compression between the linac and the target, the pulse duration for a single pulse would be 5 ns (bunch length 90 cm). The number of ions in the bunch would be 1.3 x $10^{12}$. For singly charged ions, the beam perveance at the end of the linac would be small: 3 x$10^{-8}$, so periodic focusing can be done with quadrupole magnets spaced relatively far apart, simplifying beamline design. The beam bunch line-charge density and space potential (for singly-charged ions) are manageable values of 0.2 $\mu$C/m and 2 kV, respectively, in each of the 20 linacs, but would become challenging at high charge states (e.g., q =50), or after 100 X longitudinal compression.

*Linac cost and length considerations.* Considering the 1.5 to 2-x lower compression beam energy and 3 x lower peak power found for indirect-drive hohlraum fuel compression in section II c, fast ignition might conceivably save as much as ~\$1 B (~50%) of the cost of a heavy ion accelerator used only for fuel compression, compared to the cost of an accelerator driving a conventional heavy-ion target design [28]. Thus, for fast ignition using heavy ions to be a desirable choice compared to conventional heavy-ion fusion, the extra cost for any igniter system (laser or heavy ion) must be much less than the potential cost saved on the accelerator used for fuel compression, i.e., < $1B. At linac costs per meter typically ranging from $1 M/m down to $200 k/m, cost-effective linacs for 50 GeV heavy ions for fast ignition must have maximum lengths less than 1 to 5 km respectively, and this implies minimum required average acceleration gradients for singly charged ions of 50 to 10 MV/m, respectively. Alternatively, one might strip the heavy-ions on a crossing gas or plasma jet to a high charge state. Very-high-charge-state heavy ions, such as $U^{90+}$ ions, have been created by progressive stripping on foils in heavy-ion synchrotrons, with little scattering losses [29]. For a heavy-ion igniter linac, stripping to q = 50 to 10 charge states, respectively, could support the above range of economical linac lengths with a conventional induction average acceleration gradient of 1 MV/m [30]. However, such high charge states must be created and limited to those specific values, and the corresponding 2500 to 100 X higher beam perveances (□ $\sim q^2$) would make beam focusing and losses along the linac more difficult to manage.

Since voltage breakdown limits usually improve with shorter pulses, one might take advantage of the very short ion pulses desired (e.g., 5 ns) for a heavy-ion igniter linac. Advanced RF accelerators are capable of achieving 10 MV/m average gradients, but only for much lower currents implied with a typical limit of $10^{10}$ ions per bunch for RF “bucket” confinement. A thousand such R.F. buckets might be accelerated separately, and then some scheme would have to be devised to merge the 100 pulses onto the target. There are alternative line-induction-type linac concepts that might potentially meet high gradients of 10 to 50 MV/m for pulses of a few ns duration. One concept, called the Dielectric Wall Accelerator (DWA) [31], is based on a series of asymmetric radial transmission lines (Fig. 6).

Placement

**Figure 6:** Dielectric Wall Accelerator (DWA) concept may be capable of 20 to 50 MV/m for short pulses ~ 5 ns. (From Caporaso [31])

In this radial line-driven approach, the pulse length is equal to the difference in radial wave propagation speeds due to different dielectric constants of adjacent lines, after switches short the outer ends of the radial lines. Development needs to assess the DWA potential to provide heavy-ion igniter beams include: long lasting, repetitive fast switches for the outside of the radial lines, a suitable high current, short pulse injector, means to provide periodic focusing for radial confinement of the heavy-ion bunches within the DWA channel, and means to provide longitudinal control through tailoring of the acceleration waveforms while the ion bunches accelerate.

**V. Potential for ion fast ignition of advanced fuel.**

Advanced fuels such as catalyzed DD and D-He3 may offer environmental advantages in power plants, especial when the chamber can be surrounded by carefully selected low activation liquid blanket materials (like molten boron oxide glasses), and by eliminating the need for tritium breeding and associated fuel processing. A major feature of such fuels is that, with appropriate design, the majority of the fusion reaction energy escapes the target as energetic charged particles and not as fast neutrons. This suggests the potential for coupling charged particle energy directly to advance, high-efficiency energy conversion schemes thus bypassing the need for complex and expensive conventional thermal conversion. However, because of the lower reactivity of these fuels, such targets will require typical areal densities of $\geq$10g/cm$^2$ for adequate fuel burn up and gain. Accordingly, fast ignition will be needed to keep (compression) driver energies in the $\leq$10 MJ range [32]. There is a reason to rely on ion driven fast ignition for such advanced fuels because they may produce higher x-ray – and, in the case of DD, higher neutron fluxes – *per average fusion watt compared to DT*, and so final optic protection is an even bigger challenge for advanced fuels than for DT. The advantage of using shielded magnets for focusing compared to user laser optics likely becomes an imperative for advanced fuels.

In Table II, we present 1-D spherical LASNEX calculations of the burn parametrics of a fast-ignited D-He3 capsule compared to a conventional DT capsule. The fast ignition energy for the former is deposited in a small ignitor region composed of DT (~1% of the overall fuel inventory) which is needed to boost the ignition temperature in the main D-He3 to ~30keV. External tritium breeding is not required as the capsules are effectively self-sustaining in tritium from one to the next through the D(d,p)T branch of the D-D reaction.

From the table we see that the charged particle to neutron energy output ratio in DT of ~24/75 has improved in the advanced fuel target to ~55/8. We note, however, that some 37% of the latter target output is appearing in radiation, although this could be reconverted to plasma kinetic energy by increasing the thickness of the hohlraum case.

Placement

**TABLE II** Burn parametrics and output spectra from fast-ignited DT and D-He3 capsules.

## VI. Conclusions

All approaches to accelerator- driven fast ignition we have examined in this assessment have some potential advantages compared to conventional ignition in higher overall gain, lower peak beam power for fuel compression, and simplified beam illumination geometry compatible with thick liquid protected chambers. Potentially, ion fast ignition targets should also have advantages of lower target precision and cryo handling requirements compared to conventional ignition targets, similar to that hoped for in laser driven fast ignition, although we have not tried to estimate target fab and cryo advantages here. However, all of these potential advantages of accelerator driven fast ignition depend critically on low transverse and longitudinal beam temperatures to achieve the small focal spots and short pulses required for fast ignition, and on affordable accelerators to produce the high ion ranges (~ 1 g/cm$^2$) required.

We have only considered a few examples for heavy-ion beam driven fast ignition in this assessment, and much more study is required, both for solutions to critical issues as well as for optimizing a system to find the lowest cost parameters. Until this is done, it is premature to make conclusions now regarding the ultimate potential costs savings for heavy-ion driven fast ignition. There is also uncertainty for fast electron coupling in laser driven fast ignition, and while achieving < 100 micron spots and < 100 ps pulses with ion accelerators are at least as challenging and uncertain as the divergence and coupling of laser-driven hot electron beams, conclusions about the best approach to fast ignition await the outcome of future work. In any case, large Petawatt laser installations under construction around the world will expedite the study of focusing and coupling of hot electron beams to pre-compressed fuel. For these reasons, we recommend continued research on the emittance growth, compression and focusing of heavy-ion beams with an eye towards fast ignition applications, and also, we recommend further study of control, focusing and standoff for proton beams that might be generated by the large Petawatt facilities, as hedges against the uncertainties of electron-driven fast ignition.

Given the challenging beam requirements and accelerator developments implied for accelerator driven fast ignition visa vis conventional heavy ion fusion, the quantitative target advantages we have estimated in this limited assessment, namely, of order or less than a factor of two improvement in target gain, do not appear large enough to make a compelling case for ion-driven fast ignition compared to conventional ignition. Advanced fuels, on the other hand, would require fast ignition to keep the driver energies reasonable. Heavy ion power plant designs based on conventional DT ignition targets already have ample margin in target gain to achieve products of driver efficiency x gain > 20. Rather, the desirability for accelerator-driven fast ignition, if any, is more likely to be discovered in further exploring innovative target concepts that might simplify the beam illumination geometry, reduce target fabrication precision and costs, and that ultimately reduce, rather, than increase, the accelerator beam requirements and accelerator costs for heavy ion fusion. In that respect, we have only briefly touched upon some example alternative target schemes that, like direct fast ignition, separate compression and ignition drive processes, and which may achieve similar benefits as direct fast ignition, but with less demanding beam requirements. Our point is that the fundamental flexibility offered by ways to separate compression and ignition drives should open up many new target concepts, and we encourage further exploration of such new target concepts.

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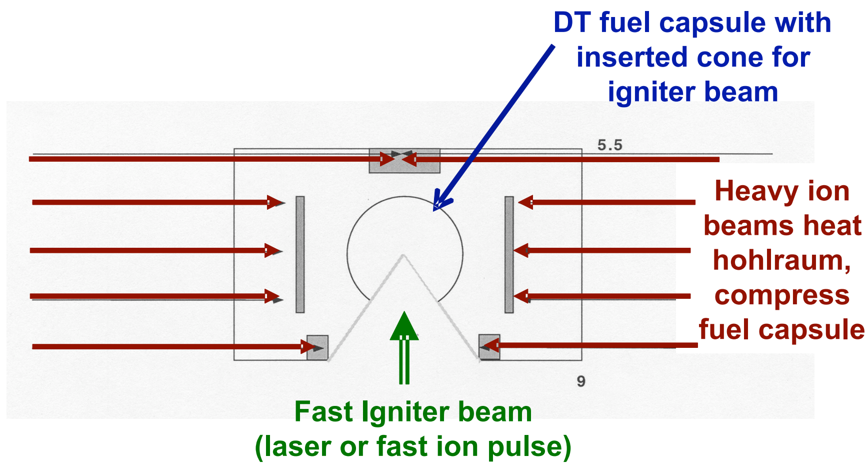
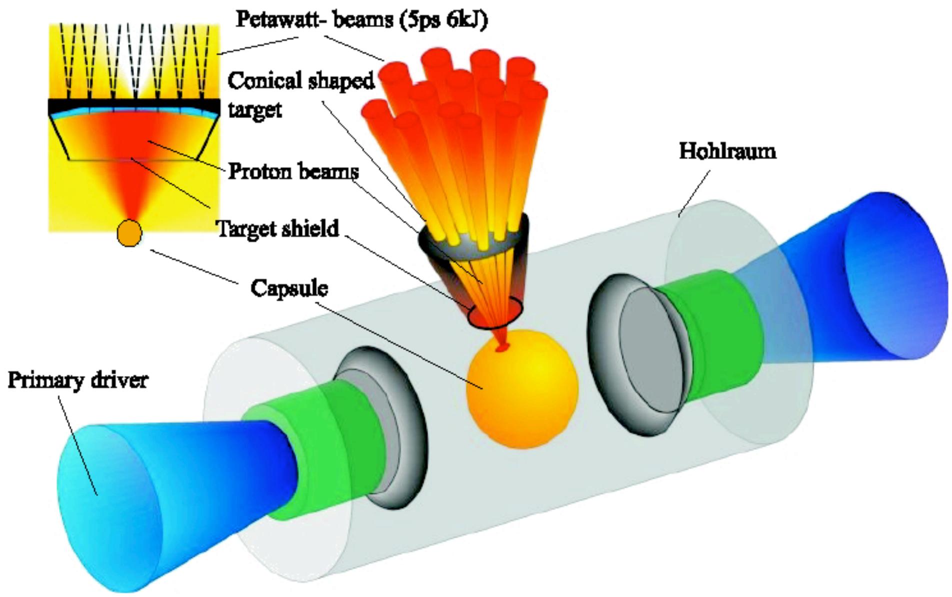

DT fuel capsule with
inserted cone for
igniter beam
5.5
Heavy ion
beams heat
hohlraum,
compress
fuel capsule
9
Fast Igniter beam
(laser or fast ion pulse)

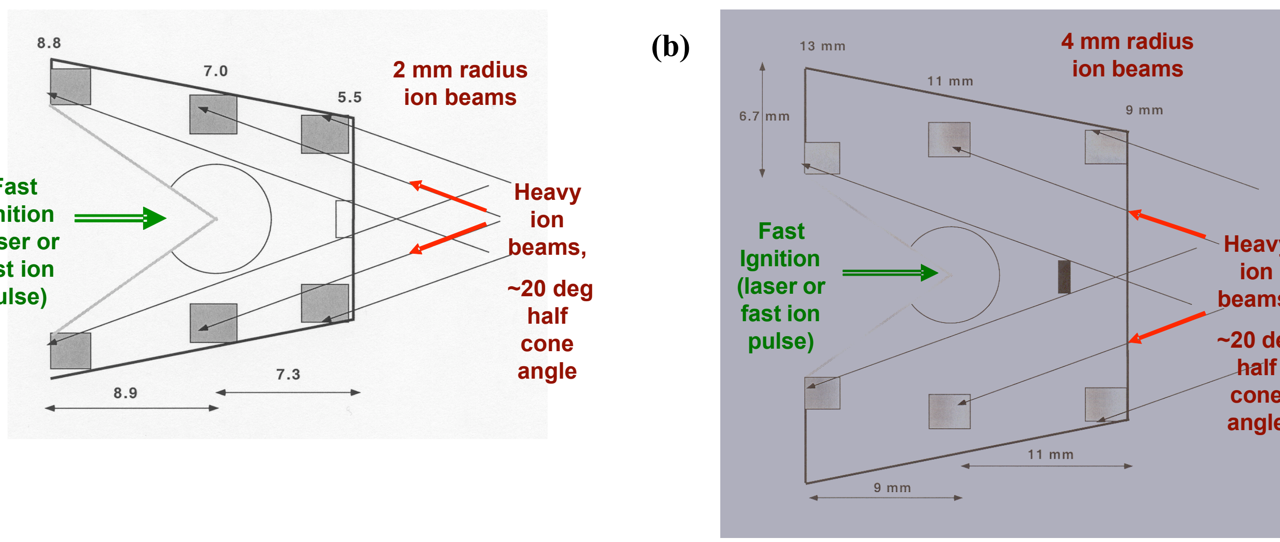
**Figure 1**



Petawatt- beams (5ps 6kJ)
Conical shaped target
Proton beams
Target shield
Capsule
Hohlraum
Primary driver


**Figure 2**

(a) (b)



8.8
7.0
5.5
2 mm radius ion beams
Fast Ignition (laser or fast ion pulse)
Heavy ion beams, ~20 deg half cone angle
8.9
7.3
13 mm
11 mm
9 mm
4 mm radius ion beams
6.7 mm
Fast Ignition (laser or fast ion pulse)
Heavy ion beams, ~20 deg half cone angle
11 mm
9 mm


**Figure 3**

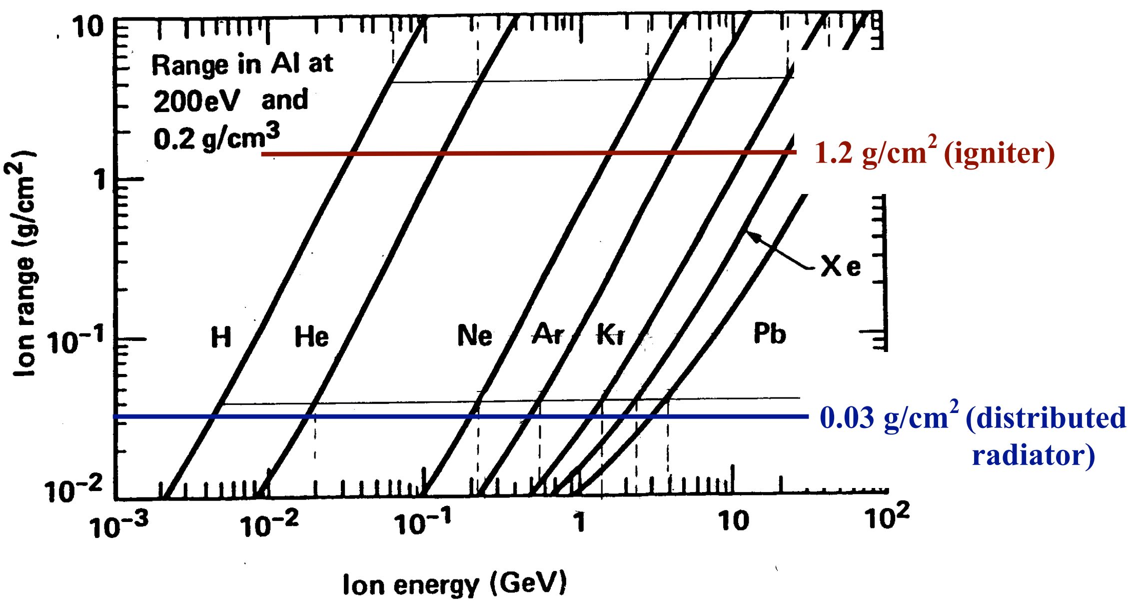

Range in Al at
200eV and
0.2 g/cm3
1.2 g/cm2 (igniter)
0.03 g/cm2 (distributed
radiator)
Ion range (g/cm2)
10
1
10-1
10-2
H
He
Ne
Ar
Kr
Xe
Pb
10-3
10-2
10-1
1
10
102
Ion energy (GeV)

**Figure 4**

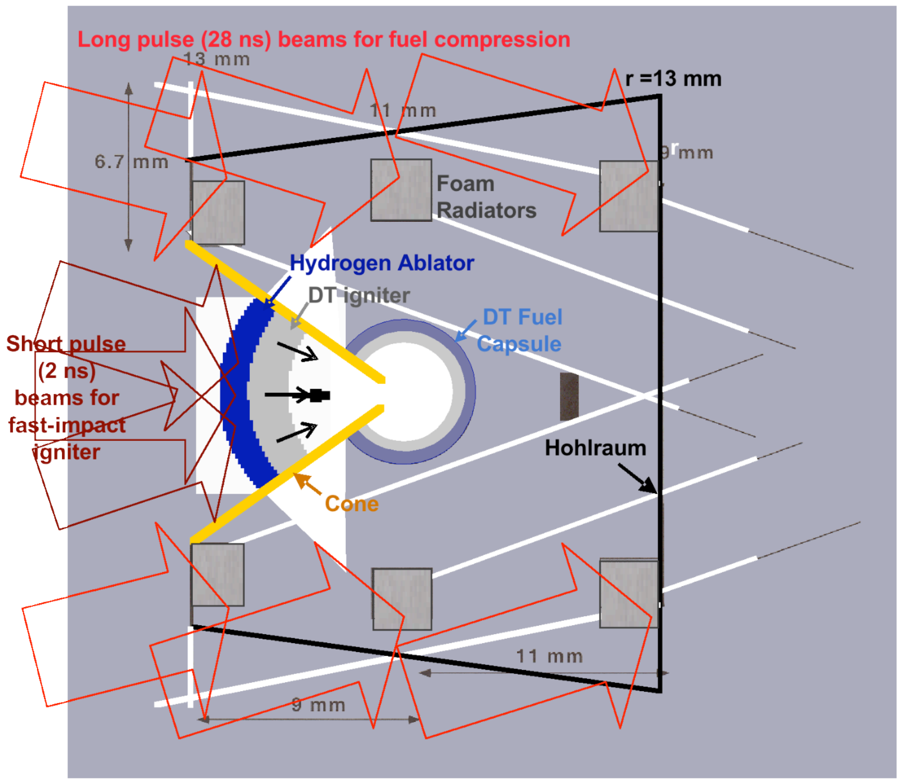

Long pulse (28 ns) beams for fuel compression
13 mm
r =13 mm
11 mm
6.7 mm
9 mm
Foam
Radiators
Hydrogen Ablator
DT igniter
DT Fuel
Capsule
Short pulse
(2 ns)
beams for
fast-impact
igniter
Hohlraum
Cone
11 mm
9 mm

**Figure 5**

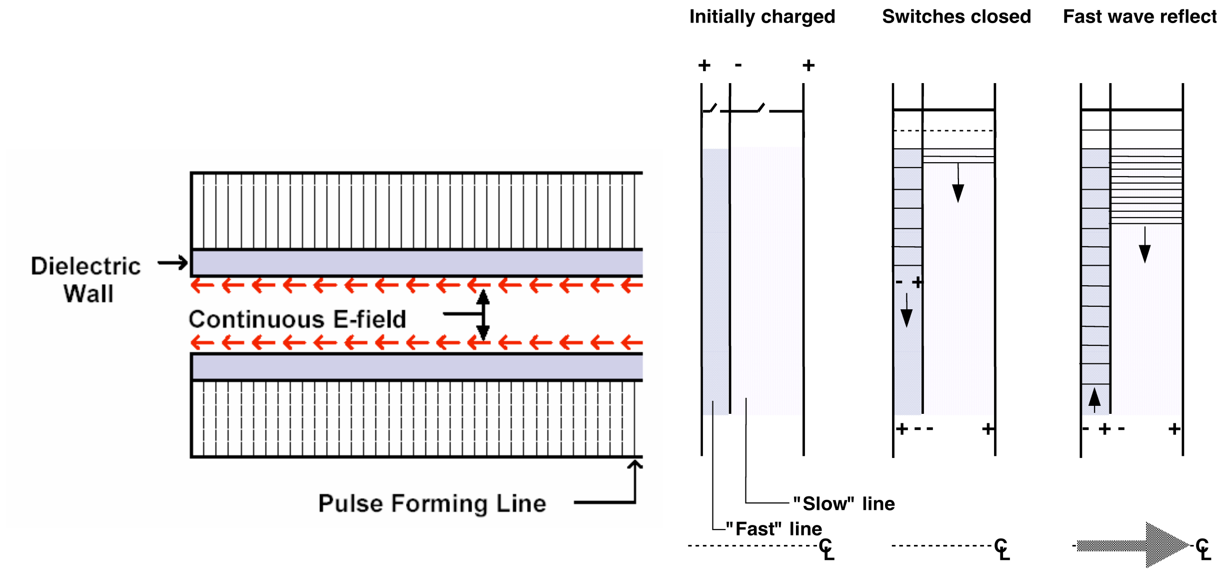


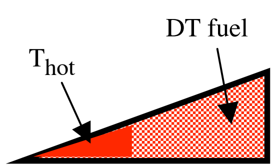
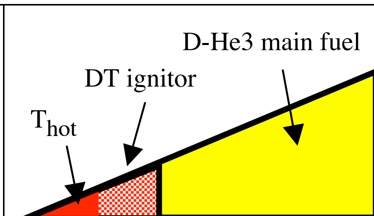

**Figure 6**

| $T_r$(eV) | $\rho r_{fuel}$ | $\rho_{fuel}$ | $\rho r_{ig}$ | $2\ r_{ig}$ | $E_{ig}^{*}$ | $T_{ion}$ | $\tau_{dep}$ | $P_{ig}$ |
|---|---|---|---|---|---|---|---|---|
| eV | g/cm2 | g/cm3 | g/cm2 | $\mu$m | kJ | GeV | ps | PW |
| 150 | 3.3 | 175 | 0.6 | 75 | 50 | 50 | 25 | 2 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **120** | **2.25** | **80** | **0.6** | **150** | **200** | **50** | **50** | **4** |

** Ignition energy using Atzeni's formula (see Sec IIc]*

**Table I**

| |   **DT capsule at ignition** |   **D-He3 capsule at ignition** |
|---|---|---|
| Fuel mass (mg) | *7* | *14* |
| Density (g/cm$^3$) | *130* | *980* |
| $\rho$-R (g/cm$^2$) | *3.0* | *15* |
| $\rho$-$R_{DT}$ (g/cm$^2$) | *Same* | *4.0* |
| $\rho$-$R_{DT,hot}$ (g/cm$^2$) | *0.5* | *1.5* |
| $T_{ign}$ (keV) | *10* | *10* |
| Tritium inventory | *50%* | *1%* |
| Yield (MJ) and partition fraction: | *317*<br>*75%* | *850*<br>*8%* |

| | | |
|---|---|---|
| *Fast neutrons*<br>*Radiation escaping*<br>*Charged particles escaping* | *1%*<br>*24%* | *37%*<br>*55%* |
| Fraction of yield from D-T | *> 0.99* | *0.16* |
| Av. peak fuel temp $\langle T_i(t) \rangle_r$ (keV) | *46* | *190* |
| Energy in hotspot (kJ) | *37* | *16* |
| Compression energy in fuel (kJ) | *71* | *570* |

**TABLE II**

List of Figure captions:

**Figure 1:** An example of an ion driven fast ignition target using heavy-ion beams to compress the fuel via x-ray conversion in an indirect-drive hohlraum, with direct fast ignition provided separately either by a short intense laser or fast ion pulse.

**Figure 2:** Schematic view of Proton Fast Ignition of fuel compressed in indirectly driven hohlraums. (Figure not to scale). The rear surface of the laser target is shaped to focus the proton beam into the spark volume.

**Figure 3:** Hohlraums for fuel compression with single-ended illumination by heavy ion beams of 2 mm radius (a) and 4 mm radius (b).

**Figure 4:** Ion range (g/cm$^2$) as a function of kinetic energy (GeV) for various ions in aluminum targets, assuming an average <Z/A> ~0.4 for the target material.

**Figure 5:** Single ended ion driven hohlraum and direct drive concept for fast impact ignition with separate 4 mm radius ion beams for compression and fast impact drive. If feasible, this approach could use lower cost low range ions for both ignition and fuel compression.

**Figure 6:** Dielectric Wall Accelerator (DWA) concept may be capable of 20 to 50 MV/m for short pulses ~ 5 ns. (From Caporaso [27])

List of Table Caption:

**TABLE I** Requirements for ion-driven fast ignition for two hohlraum temperatures used for fuel compression discussed in section IIc

**TABLE II** Burn parametrics and output spectra from fast-ignited DT and D-He3 capsules.