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Beam Propagation For The Laser Inertial Confinement Fusion-Fission Energy Engine

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BEAM PROPAGATION FOR THE LASER INERTIAL CONFINEMENT FUSION-FISSION ENERGY ENGINE

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Several potential issues concerning laser-beam propagation thorough the LIFE target chambers are addressed. It is found that the absorption due to inverse Bremsstrahlung limits the gas density to approximately 2 μg/cc of xenon gas. A comparison to prior calculations suggests that this results in acceptable first wall heating.

I. INTRODUCTION

The hybrid fission-fusion engine known as LIFE (Laser Inertial Confinement Fusion-Fission Energy Engine) depends on the ability to generate large numbers of fusion neutrons (of energy ~ 14 MeV) via indirect drive fusion.[1] As currently envisioned, hohlraum based targets will be injected into a gas-filled chamber (radius ~ 2.5 m) at a rate of 13.3 Hz. As the target reaches the center of the chamber, laser beams are then fired into the hohlraum from final optics that are set approximately 50 m from chamber center. The laser energy is coupled into the hohlraum, converted to X-rays that drive the DT pellet, ultimately creating sufficiently high densities and temperatures such that thermonuclear burn occurs for a fraction of a nanosecond. The hohlraum-target assembly then disintegrates into ions which, along with of order 90 % of the resulting X-rays, must be stopped by the gas in the chamber. The goal of this work is to determine the chamber gas density that will be low enough such that the laser beams will propagate to the hohlraum with minimal degradation, while at the same time be high enough so that the amount of X-ray energy reaching the first wall will result in negligible damage.

The LIFE engine will be driven by either one of two types of fusion targets. First, there is a Fast Ignition (FI) target that requires 500 kJ of 0.532 micron light in ~ 15 ns, in the form of 25 beams of 20 kJ each to compress the target, and 100 kJ of 1.064 micron light in ~ 10 ps that will ignite the compressed fuel. Secondly, there is a NIF-like compression-only version, where MJ's of energy (1.3 MJ of 0.351 micron light, or 2.5-3 MJ of 0.532 micron light) ignite the DT capsule via conventional hot spot ignition. The propagation characteristics and issues for the compression and fast ignition beams are quite different, and we will consider each separately. We will attempt to find the limitations imposed by beam propagation for both the compression and fast ignition beams.

II. LIMITS ON CHAMBER GAS DENSITY

II.A. Density Limits Imposed by Compression Beams

To determine the beam propagation limitations, we must consider the trade-offs that exists between gas density, first wall damage, and chamber clearing. Each of these has certain limits that cannot be exceeded. For example, the wall temperature spike from the unstopped X-ray flux must not exceed a certain value (~ 1500 K) to prevent fatigue and subsequent destruction.[2] This, in turn indicates the minimum acceptable gas density. At the same time, the beam propagation will indicate the maximum gas density that will allow the laser beams can travel without substantial degradation through the gas. Finally, the question of whether the chamber at this density and holding all the debris from the implosion can be pumped out and replenished with fresh gas (again, with minimal effect on the beam propagation) in the time allotted between shots. It is seen that our task is to provide the maximum gas density allowable due to beam propagation considerations.

To estimate the amount of energy that the wall must handle, consider a typical indirectly driven, compression beam only implosion version of LIFE.[2] The target yield will be 37.5 MJ, repetition rate of 13.3 Hz, resulting in 500 MW fusion power. X-rays will make up 4.5 MJ of this, ions 3.8 MJ, and 29 MJ will be in the form of neutrons. For a 2.5m radius chamber, the neutron wall loading will be ~ 5 MW/m^2. We assume that this took 25 beams of 0.5 micron light that were each 20 kJ, 20 ns, f/9 beams to achieve this yield. A typical radiation profile that would result from this type of target is shown in Fig. 1. This is important for the following reason. Since the hohlraum will be sitting a relatively high density gas (~ 1 Torr,) it will effectively radiate like a black body at the

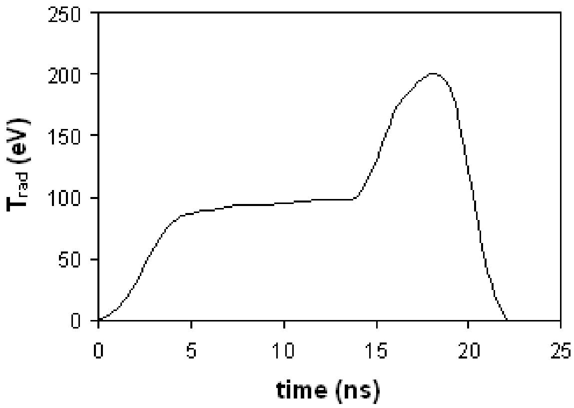

Fig. 1. Profile of a typical hohlraum radiation profile for an indirectly driven hot spot-based LIFE hohlraum design.

radiation temperature and into the gas. The energies from this blackbody are such that sizable regions around the laser entrance holes of the hohlraum will become ionized, forming a large plasma in which the laser beams must then propagate.

Although the gas densities are low (initially ~ 10^{16} cm^{-3} gas or ion densities) we find that the combination of the great distances that must be traversed (~ 1m) and the multiple ionizations per ion (as high as 40 times ionized for Xe) means that plasma effects may significantly alter the laser beam propagation as light enters the hohlraum. Among these effects are Stimulated Raman Scattering, Stimulated Brillioun Scattering, filamentation, and inverse bremsstrahlung. In this paper, we consider only inverse bremsstrahlung (IB). Briefly, this effect can be described as the acceleration of electrons due to the laser electric field and subsequent decorrelation due to collisions with ions and neutrals that cause a gradual loss of energy from the laser beam as it propagates through the plasma. The formula for the spatial decay rate of the laser energy is given by[3]

$$\kappa_{ib} = (n_e / n_c)\nu_{ei} / c \propto Z^3 n_i^2 / T_e^{3/2} \qquad (1)$$

where n_e = the electron plasma density, n_c = the critical plasma density, v_{ei} = the electron-ion collision rate, Z (or Z^*)= the (average) charge state of the ions, n_i = the ion density, and T_e = the electron temperature. Because the determination of Z^* and T_e on distance from the radiation source (the hohlraum laser entrance hole, or LEH) is non-trivial, we resort to numerical simulation.

The radiation-hydrodynamics code HYDRA[4] is the ideal tool to use to solve this problem. By starting with a fixed gas species and density in some volume, we can apply the radiation source associated with the hohlraum through an effective LEH, and get the self-consistent Z^* and T_e along the path that the laser beam will propagate. We begin with a 3-D box of xenon gas at particular density, say 7.0x10^{-6} g/cc, which is equivalent to an ion density of 3.5x10^{16} cm^{-3}. Previous calculations of ion stopping and X-ray penetration for a xenon gas density of 4x10^{-6} g/cc would result in a temperature spike in the first wall (500 mm of tungsten) of 1000 degrees K, which is acceptable. The hohlraum is represented by a blackbody radiation source on the left side of the cube, with an opening of approximately 1 cm. We simulate with the radiation source as seen in Fig. 1. Fig. 2 shows results of the electron temperature and Z^* for this simulation. Plotted is a 2-D planar slice of both Z^* and T_e along a middle of the 3-D box, along the laser propagation direction.

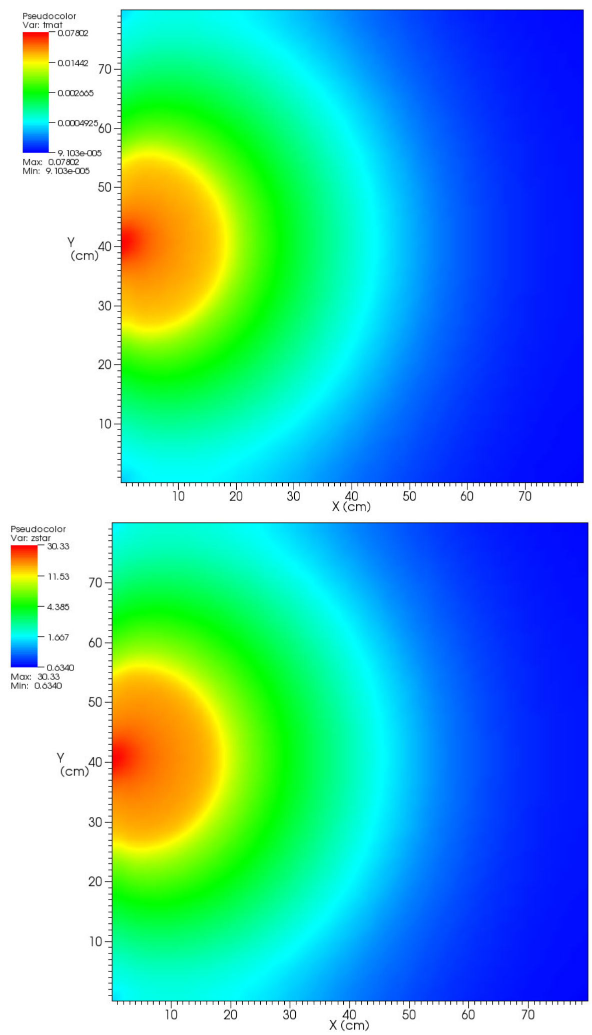

Fig. 2 (a) A 2-D slice of electron temperature and (b) Z* down the middle of a 3-D box at time t = 9 ns arising from the source as given in Fig. 1 at y= 40 cm and x =0 cm.

We can now determine how much absorption would arise from IB, by integrating along this path

$$f_A = 1 - \int_{-\infty}^{0} e^{-\kappa_{IB}(x)x} dx \qquad (2)$$

starting from the far left (at x = 80 cm) and proceeding to the middle of the right side (the effective LEH that the laser would enter.) The result of this particular case is shown in Fig. 3. It is seen that for this case, namely ρ_{Xe} = 7.0e-6 g/cc, the laser absorption that takes place as the laser propagates into the hohlraum is unacceptable, even for blue light, and certainly for green or red.

It is interesting to note that if one plots Z* vs. T_e, it appears that Z* scales with Te as

$$Z = 10(T_e / 0.01)^{0.54} \qquad (3)$$

for xenon. Substituting this into the above equation for the IB coefficient, one obtains

$$\kappa_{ib} \propto T_e^{0.12} n_i^2 \qquad (4)$$

which implies that the absorption is an extremely weak function of electron temperature. This means that even if laser beams are self-consistently heating the plasma as they propagate, the absorption continues to be more or less constant, and no "bleaching through" of the laser is possible in this case, as it would be for a low Z^* gas. What we mean by this is that typically, the gases that laser beams must propagate through for any appreciable distances in the context of conventional Inertial Confinement Fusion (ICF) indirect drive are low Z^*.[5] For example, a low Z^* ablator in direct drive, or helium fill in a hohlraum for indirect drive. Thus, Z^* usually saturates at some constant value, and as the laser

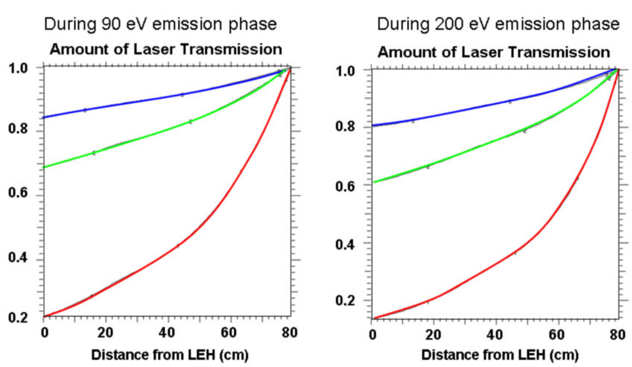

Fig. 3 (a) Amount of laser transmission, for 0.3 micron (blue), 0.5 micron (green), and 1.0 micron (red) light, through a path 80 cm from the LEH.

continues to deposit its energy via IB, the electron temperature rises. Thus, as more of the laser beam propagates into the same region, the absorption continues to decrease as the temperature rises. This was confirmed by a simulation that self-consistently included the laser heating as the laser propagated across the system, and into the effective LEH. Fig. 4 shows a plot of the background electron temperature and Z^* both increasing, such that the IB coefficient remains essentially constant. The transmission was essentially identical to that shown in Fig. (3).

At the same time, it is interesting to note that Eq. (4) is a strong function of ion density, so that a small decrease in density could lead to a dramatic increase in laser transmission. Therefore, a Xenon gas density of 2.3e-6 g/cc, which should result in a factor of 10 difference in the absorption coefficient was simulated. The results are shown in Fig. 5, where it can be seen that the blue and green laser beams suffer minimal absorption, but the red beam would still suffer an unacceptable loss of energy. By comparing with detailed ion, X-ray, and heat transfer calculations, we expect that the temperature spike could be kept to under 1200 degrees K.

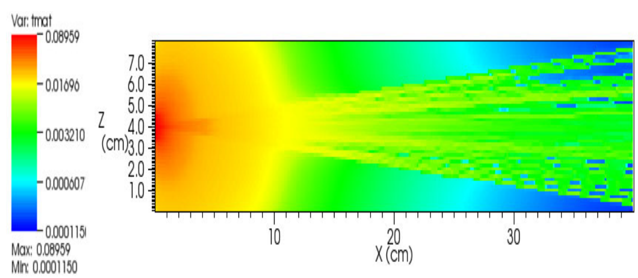

Fig. 4. Electron temperature showing self-consistent beam heating, but which also resulting in increasing Z*, therefore keeping IB coefficient essentially constant. (Need to generate the Z* plot, to show increase.)

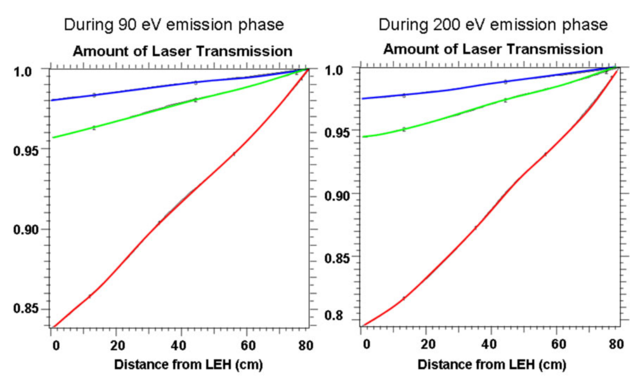

Fig. 5 Laser transmission for 2.3e-6 g/cc of xenon gas case.

II.A. Density Limits Imposed by Ignition Beams

Fortunately, all compression beam scenarios us either blue or green beams. The ignitor beam, on the other hand, is usually thought of as 1 micron, and therefore would be susceptible to some amount of absorption, if an LEH were to exist on the ignitor beam side of the hohlraum. It may be possible to design a target such that all the ignitor beams come in on one side, and all compression beams come in from the opposite side. This would allow the ignitor side to be designed such that only the cone is seen by the ignitor beam and it would be a completely closed hohlraum as seen from that side.

Even in the case of a completely closed ignitor side hohlraum, there are many issues that will be faced by the ignitor beams. We have assessed several of these issues, and they will be discussed below. The issues relating to propagation through the chamber gas are: (1) estimates on the effects of gas turbulence in the chamber due to pumping during the clearing phase, (2) estimates on the amount of B-integral, or self-focusing induced via the Kerr effect as the ignitor beams propagate through the gas. At some point, the ignitor lasers are so intense, as to cause Above Threshold Ionization (ATI) of the chamber gas. Therefore, an estimate as to when and where it can be expected that plasma will be created is also given. Given this plasma, we then estimate the effects of various plasma instabilities on the beams, such as Stimulated Raman Scatter (SRS) and relativistic self-focusing.

We first describe the ignitor beam parameters. As currently envisioned, there will be 20 beams, each with 5 kJ of 1.064 micron light within a (temporal) pulse length of 20 ps. The beams will be focused to a 60 micron spot residing on the tip of a cone connected to the hohlraum, each with an effective f/9. The total power is 250 TW. Since the beams will not overlap until very close to the cone that they are focused into, we consider the propagation of individual beams only. Fig. 6 shows the profile of a single ignitor beam on its way to the cone portion of a target, which would be located on the left boundary. In order to determine what the plasma effects that this beam will experience before it reaches the cone, we must estimate the plasma density that it will create in a gas of yet to be determined density. The high intensity igniter pulse itself will multi-photon ionize the gas, stripping the first few outer electrons around 10cm from the target where the laser intensity first exceeds about 10^{14} W/cm2 and ionizing all but the K-shell within a Rayleigh length of focus. Using Eq. (4.5) from Auguste et. al.'s barrier suppression model[6] one can construct a model for the ionization state along the ignition laser's path. An example plasma electron density is plotted in Fig. 7, where a background Argon ion density of 10^{16} cm^{-3} was assumed in the chamber.

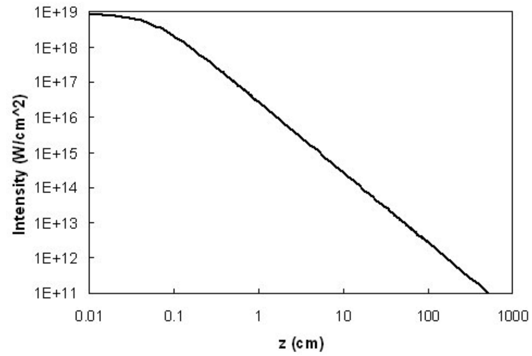

Fig. 6 Electron density as a function distance along the chamber.

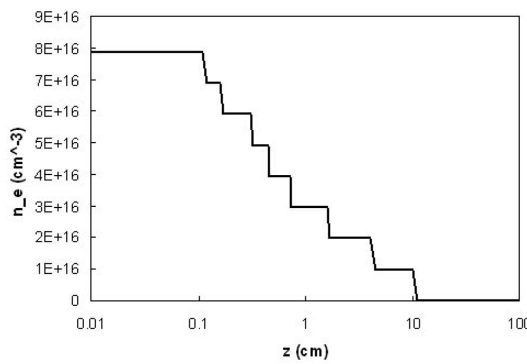

Fig. 7. Laser intensity as a function of distance along the chamber for a single ignition beam.

From Figs. 6 and 7, we can see that the beam propagates through unionized gas on its path from the final optic (at 50 m from the target) until it gets to about 10 cm from the cone in the target. There are two issues that arise during this phase of propagation. The first is how much B-integral this will contribute to the pulse. This is related to the Kerr effect, a nonlinear self-focusing mechanism that may distort the beam such that it might prematurely focus and spray the light, and not reach the inside of the cone as required for ignition. The critical power for this to occur in a representative gas such as Argon at a pressure of 1 Torr (1 mbar) is around 3.7 TeraWatts, well below the 250 TW for each ignitor beam. Here we have taken n_2, the second-order nonlinear refractive index to be approximately $4x10^{-26}$ m^2/W in this case. However, the question as to how much focusing will occur is answered by calculating the B integral over the gas propagation length of gas that must be propagated through. The B integral is essentially the total on-axis phase shift that is accumulated over the path. This is

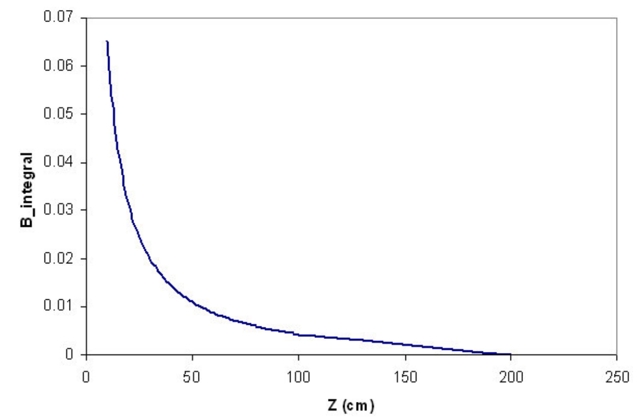

Fig. 8 B-integral for an ignition laser propagating through an Argon gas at 1 mbar.

plotted in Fig. 8, and since it is well below 1, is not an issue. In fact, the amount of B-integral that the laser pulses will gain during the amplification process will be far larger than this value.

However, another issue is that the laser beams face the effects of turbulence during propagation through the unionized gas. Since the gas in the chamber is injected and disposed of several times a second, gas density fluctuations will exist in the chamber. In order to quantify this, we calculate the C_n^2, the refractive index structure constant value for the gas.[8] Here we assume (1) a Kolmogorov turbulence frequency spectrum, (2) the turbulence is homogeneous over the whole propagation path, (3) the pressure is 1 mbar, (4) that the outer scale is given by ½ the chamber radius (1.25 m), (5) a propagation distance of 10 m, and (6) that the temperature in the gas varies from 1000^o K to 5000^o K. The results are plotted in Fig. 9, where a value of $C_n^2 \sim 5x10^{17}$ $m^{-2/3}$ is considered extremely weak turbulence. Once obtained, the refractive index structure constant can be used to calculate the coherence diameter, also known as r_0 or the Fried parameter,[9] which is a measure of the size of the effective lenses that are set up due to the eddies in the gas. The condition for coherent propagation is that r_0 exceed the beam diameter where the beam enters the turbulent region (assumed to be the chamber), which in our case is ~ 1 m. As shown in Fig. 10, even for 10 m propagation, the coherence diameter is 10 m, and so is much greater that the required 1 m. Finally, since the hot electron temperature is an important parameter in the fast ignition fusion scheme, and it depends heavily on the ignition beam intensity, we must determine whether the intensity will be severely modified upon propagation through the gas as well. A measure of the ability to focus the beam (and therefore achieved the desired intensity) is the Strehl ratio, given by $S \sim \exp(-6.88/2*(\rho/r_0)^{5/3})$ and is 1 for an perfect beam. We find that we can still attain a Strehl ratio of 0.96 for 10 m propagation through a 1 mbar gas, an

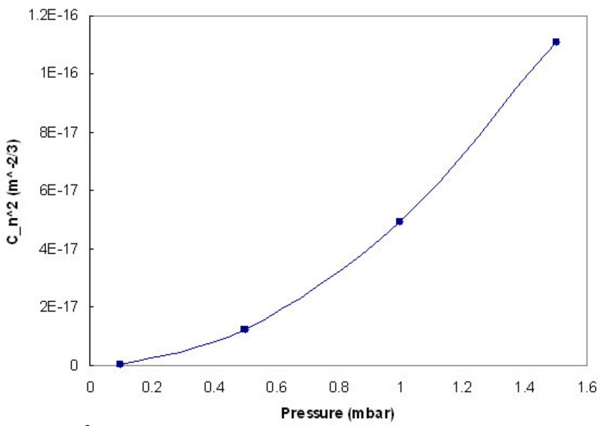

Fig. 9 C_n^2 as a function of pressure for a 10 m propagation length and other parameters as described in text.

acceptable departure from the intensity that would be attained with a perfectly focused beam. Therefore, the compression beams are still providing the limiting maximum density that we can achieve in the chamber.

Up to this point, we have only been dealing with the gas in the chamber up to the last 10 cm before the cone, at which point, the gas begins to be ionized, and a plasma forms. Although this is typically a very low density (~ $1x10^{17}$ cm^{-3}) which is $1x10^{-5}$ of the critical plasma density, the fact that the laser intensity is extraordinarily high (~ $1x10^{19}$ W/cm^2), and the distances are so long (~ cm) that instability growth rates are quite large, and things like SRS and filamentation are predicted to occur for these beams. Interestingly, even though SRS growth does occur, it saturates at such extrememly low values, that essentially no light is lost due to reflection. We find that even at densities of 5x1017 cm-3 that this is negligible. In fact, the limiting plasma effect so far investigated is

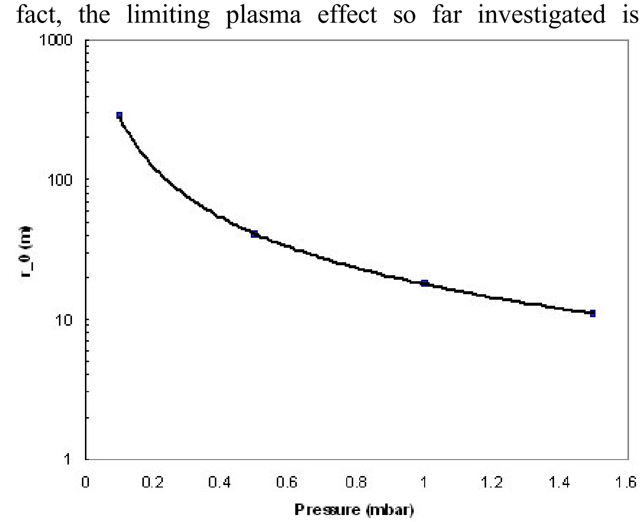

Fig. 10 The coherence diameter, or Fired parameter, r0 as power is exceeded a function of pressure for a 10 m path.

relativistic self- focusing, which gives a maximum electron density of $3x10^{17}$ cm^{-3} allowable, before the critical and even then, as with the Kerr effect, even higher densities might be achievable when the integrated effect along the path is taken into account.

III. CONCLUSIONS

We have addressed several major issues concerning laser beam propagation in the LIFE engine. Inverse bremsstrahlung absorption for the 20 ns compression beams was found to limit the electron density to ne ~ $1x10^{17}$ cm^{-3}. Plasma propagation of the ignitor pulse limits densities to ne ~ $3x10^{17}$ cm^{-3}. Currently the compression beam propagation is setting a limit of ρ_{Ar} = $7.5x10^{-7}$ g/cc or ρ_{Xe} = $2.3x10^{-6}$ g/cc on the maximum density allowable in the target chamber.

Outstanding issues that have yet to be addressed are: (1) SRS and filamentation of the compression beams; (2) whether the gas exists in a highly excited state as the lasers fire, and if so, does this alter the estimates on plasma formation and density; (3) what fraction of the gas will be high Z atoms that were not cleared out during the prior pumping cycle. Further studies relating to the ignitor beams include beam overlapping near the cone, and the effects of pre-pulse.

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REFERENCES

1. E. MOSES, et. al., LIFE paper, this issue (2008).
2. J. F. LATKOWSKI *et. al*, pp. xx-xx, this issue (2008).
3. W. L. KRUER, *The Physics of Laser Plasma Interactions*, Addison-Wesley Publishing Company, Inc. ISBN 0-201-15672-5 (1988).
4. M. MARINAK, et. al., *Phys. Rev. Lett*. **75**, 3677 (1995).
5. J. Lindl, *Inertial Confinement Fusion*, AIP Press, Springer, ISBN 1-56396-662-X, (1998)..
6. T. Auguste, P. Monot, L.A. Lompre, G. Mainfray and C. Manus, *J. Phys. B: At. Mol. Opt. Phys*., **25** 4181 (1992).
7. G. P. Agrawal, *Nonlinear Fiber Optics*, 4th edn., Academic Press, New York (2006).
8. J. W. Hardy, Adaptive Optics for Astronomical Telescopes, Oxford University Press, Oxford (1998).
9. D. L. Fried, J. Opt. Soc. Am. **56**, 1372 (1966).