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ABSTRACT

The derivation of the ignition energy for fast ignition inertial confinement fusion is reviewed and one-dimensional simulations are used to produce a revised formula for the ignition energy of an isochoric central hot-spot, which accounts for variation in the radius of the hot-spot r_h as well as the density ρ. The required energy may be as low as 1 kJ when $\rho r_h \approx 0.36\,\mathrm{g\,cm^{-2}}$, $T \approx 20\,\mathrm{keV}$, and $\rho \geq 700\,\mathrm{g\,cm^{-2}}$. Although there are many physical challenges to creating these conditions, a possible route to producing such a hot-spot is via a bright source of non-thermal soft x-rays. Further one-dimensional simulations are used to study the non-thermal soft x-ray heating of dense DT and it is found to offer the potential to significantly reduce hydrodynamic losses as compared to particle driven fast ignition due to the hotspot being heated supersonically in a layer-by-layer fashion. A sufficiently powerful soft x-ray source would be difficult to produce, but line emission from laser-produced-plasma is the most promising option.

In the past two decades, there has been considerable interest in fast ignition (FI),[1] a variant of inertial confinement fusion (ICF). This interest is driven by the potential to achieve high gain ($G > 100$)[2] while reducing the overall capital cost (relative to central hot spot ignition). The central idea of all FI variants is to separate the compression and heating stages, with the compression generating a dense (but cool) mass of DT fuel by established means, and the heating being done by an additional source of highly penetrating particles or radiation. Relativistic electrons, multi-MeV ions,[3] and x-rays have all been considered as possible "ignitors" by various researchers.

Recently, at least two papers[4,5] have been published suggesting that using non-thermal soft x-rays rather than an electron or ion beam for FI could further reduce the ignition energy by an order of magnitude. Hu *et al.*[4] claim to be able to achieve ignition on OMEGA- and NIF-scale targets at laser energies several times below those predicted by the well-known formula for electron-beam-driven FI[6]

$$E_{ign} = 140\rho_{100}^{-1.85}\,\mathrm{kJ}. \tag{1}$$

The explanation given by Hu *et al.* for this is that there is a special advantage in the "layer-by-layer" heating of the x-ray pulse; however, this was not elaborated upon.

In this Letter, we begin by re-analyzing the isochoric ignition problem and showing that the requirements for ignition can be relaxed provided that a hotter hot-spot can be generated. This condition is not a matter of the details of x-ray heating, so these findings are important for all variants of FI as they suggest that tuning FI schemes toward generating hotter hot-spots with lower ρr_h may be a fruitful way to reduce ignition energies and thus the overall cost of FI schemes.

Second, we analyze the radiation hydrodynamics of heating by bright, non-thermal soft x-rays and hence justify the use of the isochoric ignition condition we have derived. We also suggest a possible interpretation of the layer-by-layer heating (which we find to be supersonic) as relating to minimizing hydrodynamic losses. Hu's results are consistent with our revised ignition energy, given that the process is indeed close-to-isochoric. Finally, we discuss possible methods of producing a sufficiently powerful x-ray beam.

Let us start with a brief review of the different ignition conditions. An analytical form for the isobaric ignition energy was first proposed by Tabak *et al.*[7] using the simple formula for the uniform heating of a spherical hot-spot

$$E_{ign} = (4/3)\pi r_h^3 \rho C_p T. \tag{2}$$

The ignition conditions on T and ρr_h were determined by one-dimensional numerical simulations. Tabak's conditions were conservative first estimates, but were later improved by Atzeni (using the IMPLO code)[8] who gave the conditions as $T > 8\,\mathrm{keV}$ and $\rho r_h > 0.25\,\mathrm{g\,cm^{-2}}$. The resulting ignition energy as a function of density is

$$E_{ign} = 6\rho_{100}^{-2}\,\mathrm{kJ}. \tag{3}$$

However, the isochoric ignition energy is more relevant for fast ignition as the fuel is of almost uniform density, and the hot-spot is at a significantly higher temperature than its surroundings. Accounting for the difference in the amount of mechanical work, the ignition conditions become $T > 12\,\mathrm{keV}$ and $\rho r_h > 0.5\,\mathrm{g\,cm^{-2}}$. Replacing C_p with $C_V = 1.15 \times 10^8\,\mathrm{J\,g^{-1}\,keV^{-1}}$ in Eq. (1), he obtains the isochoric ignition energy function[8]

$$E_{ign} = 72\rho_{100}^{-2}\,\mathrm{kJ}. \tag{4}$$

The widely used formula given in Eq. (1) is the result of a subsequent 2D numerical study by Atzeni and Ciampi using the DUED hydrodynamics code.[9] This assumes that the uniform density DT fuel is heated for 10 ps by a beam of fast unspecified particles. The particles are assumed to follow a straight path (so their penetration depth and range are equal) and have uniform stopping power, and deflections and straggling are ignored. The range used is $R = 0.6\,\mathrm{g\,cm^{-2}}$ but Atzeni also showed that the variation of ignition energy with range is weak[8] for $0.15 \le R \le 1.2\,\mathrm{g\,cm^{-2}}$.

In the case of x-ray fast ignition, it is apparent from the assumptions that the numerical model does not apply, because photons transfer their energy to electrons instantaneously by inverse-Bremsstrahlung absorption,[10] whereas electrons will be slowed down gradually by drag,[11] so the energy deposition profile will be completely different.

However, the ignition energies quoted by Hu *et al.* are still significantly below what we would expect from Atzeni's analytical expression for the isochoric ignition energy, Eq. (4). Atzeni derived this expression by performing one-dimensional simulations to produce a plot showing the ignition region in ρr_h-T space, and then choosing an arbitrary point ($\rho r_h = 0.5\,\mathrm{g\,cm^{-2}}$, $T = 12\,\mathrm{keV}$) close to the separatix between ignition and quenching as the minimum requirement for ignition. This point corresponds to the "minimum hot-spot energy" while still at "moderate temperature."[6] However, examination of his plot[12] suggested that it may be possible to choose a point at a smaller value of ρr_h and a larger but still reasonable T. The fact that we have freedom to choose the "reference point" has quite profound consequences, because the ignition energy must scale as

$$E_{ign} \propto \frac{(\rho r_h)^3 T}{\rho^2}, \tag{5}$$

and thus, modest changes in ρr_h can still lead to significant changes in the ignition energy.

We now determine the values of ρr_h and T, which minimize the ignition energy, and find a general form for the ignition energy in terms of ρ, r_h, and T.

To do this, we carried out an array of simulations in ρr_h-T space using the one-dimensional Lagrangian radiation hydrodynamics code HYADES,[13] and employed a quotidian equation of state (QEOS)[14] and Thomas-Fermi ionization model. Thermonuclear reactions may take place between light isotopes, as well elastic scattering reactions.[15] The useful energy produced was calculated using the number of thermal neutrons produced by the $T + D \rightarrow {}^4\mathrm{He} + n$ reaction.

The target consists of a spherical DT pellet of radius 100 μm (comparable to an imploded NIF capsule) with an initially uniform density ρ and temperature 200 eV, with a perfectly heated central hot-spot of radius r_h and temperature T. These initial conditions are plotted in Fig. 1.

We have defined the gain as the ratio of the output neutron energy to the input thermal energy, and this is recorded at 1400 points in ρr_h-T space in Fig. 2. Both ρ and r_h were varied and we found that the ignition temperature depended primarily on their product ρr_h.

We repeated some of the simulations used to produce Fig. 2 using a Gaussian density distribution with standard deviation $\sigma = r_f/2 = 50\,\mu$m. We found that if the peak density is ρ_p, then the ignition temperature is within 10% of the ignition temperature of a uniformly distributed pellet of the same size, where $\rho = \rho_p$ everywhere, which demonstrates that our assumption of a uniform density pellet is valid.

The points at which the fuel just ignites in Fig. 2 have been plotted in Fig. 3. We have plotted $(4/3)\pi(\rho r_h)^3 C_v T$ rather than T, to illustrate that Atzeni's coefficient in Eq. (4) varies significantly with ρr_h, and thus cannot be taken to be 72 everywhere. The minimum value of this coefficient is obtained at $\rho r_h = 0.36\,\mathrm{g\,cm^{-2}}$, which corresponds to a temperature of 21 keV. There are many issues associated with producing such a hot-spot related to the collimation and stopping distance of the source, instabilities, and hydrodynamic losses,[16] but using a soft x-ray driver may have advantages, particularly with regard to optimizing stopping distance and reducing hydrodynamic losses, as is discussed below.

To find a general expression for the ignition energy valid for all r_h and ρ, we have plotted the ignition temperature against ρr_h in Fig. 4. The equation of the fitting curve is

$$T_{ign} = \frac{0.85}{(\rho r_h - 0.15)^2} + 2.5\,\mathrm{keV}, \tag{6}$$

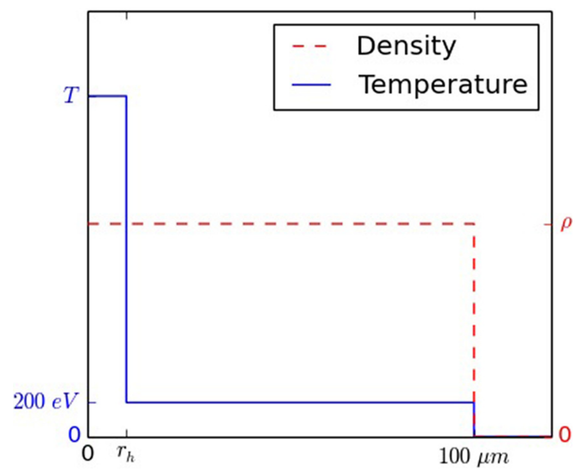

FIG. 1. The initial temperature and density profiles used for our simulations of the isochoric ignition problem.

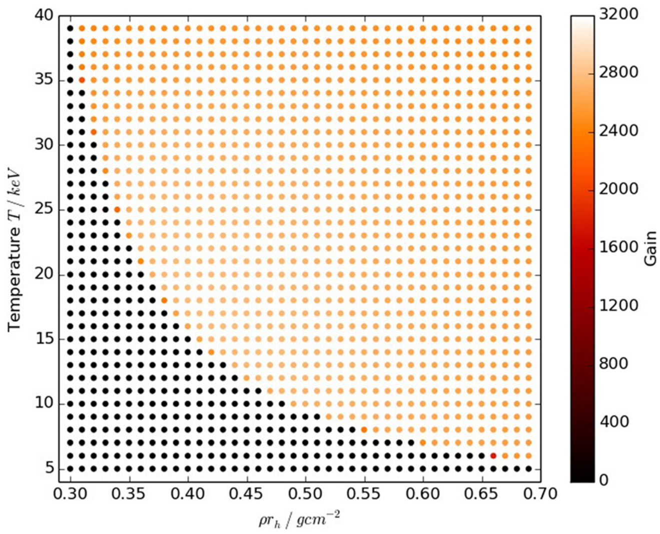

FIG. 2. The gain for a DT pellet of radius $r_f = 100\,\mu$m in $\rho r_h - T$ space. There is a clear boundary between ignition and quenching because of the "runaway burn."

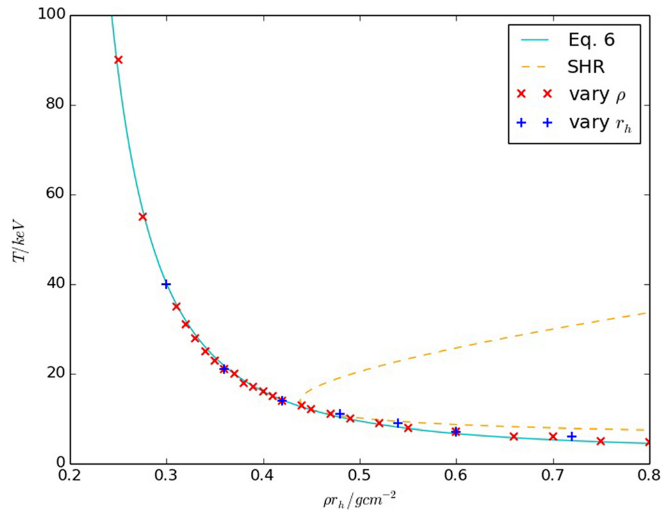

FIG. 4. The ignition temperature as a function of ρr_h with a fit given by Eq. (6). The analytical self-heating region (SHR)[12] has also been plotted.

where ρr_h is in g cm^{-2}. This is only a fit for the ignition temperature, and is not analytically derived. However, it is a good fit for $0.25 \le \rho r_h \le 0.8$ g cm^{-2}, where ignition can realistically be achieved.

Equation (6) can be substituted into Eq. (2) to give the ignition energy of a perfectly heated isochoric central hot-spot

$$E_{ign} = \frac{(\rho r_h)^3}{\rho_{100}^2}\left(\frac{41}{(\rho r_h - 0.15)^2} + 120\right)\,\text{kJ}. \tag{7}$$

It can be seen from Eq. (7) and Fig. 3 that the minimum ignition energy will occur when $\rho r_h = 0.36$ g cm^{-2} and ρ is as large as possible. These results are not specific to x-ray heating, but are true for any isochoric hot-spot.

To compare this with the inverse square laws stated above, they have all been plotted in Fig. 4, assuming $r_h = 5\,\mu$m. Also included in Fig. 4 are data from Hu *et al.*'s simulations of x-ray driven FI.[4] They claim that they can achieve (1) break-even ignition at $E = 850$ J using an OMEGA-sized target[17] with maximum density $\rho = 720$ g cm^{-3} and (2) ignition with gain 30 at $E = 1.65$ kJ using a NIF-sized target[18] with maximum density $\rho = 550$ g cm^{-3}.

Figure 5 demonstrates that the quoted ignition energies lie very close to our relaxed condition for ignition. This shows that their results are not so surprising as they might seem at first glance. They do not "beat" the isochoric ignition condition, because the commonly cited

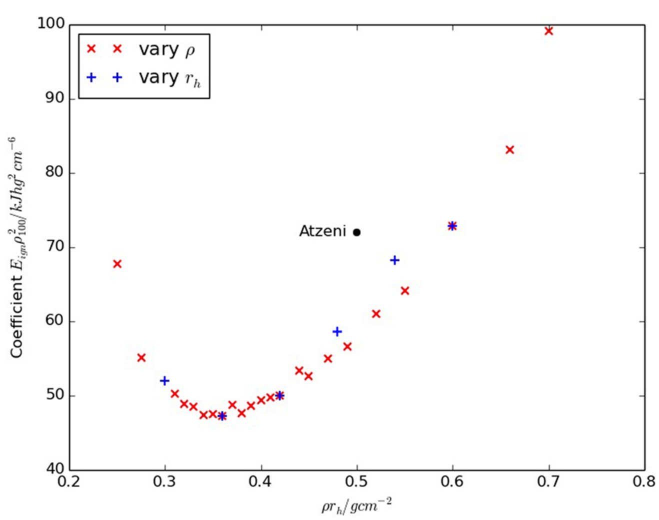

FIG. 3. The value of the coefficient as a function of the ρr_h. We varied ρ at constant $r_h = 5\,\mu$m and varied r_h at constant $\rho = 600$ g cm^{-2}. Atzeni's coefficient of 72 (corresponding to $\rho r_h = 0.5$ g cm^{-2} and $T = 12$ keV) is also shown.

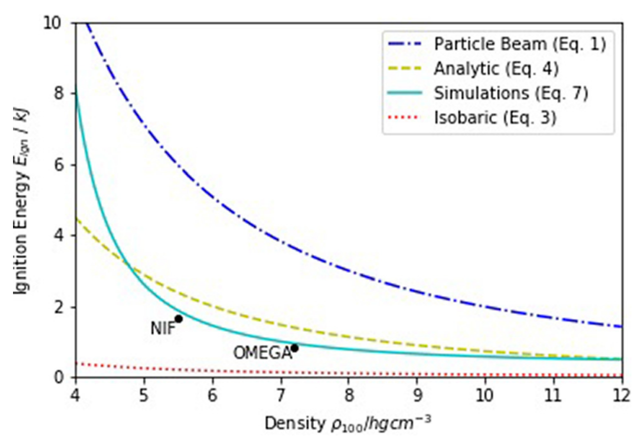

FIG. 5. The ignition energy functions discussed above and the data from Hu.[4] Equation (7) is plotted assuming $r_h = 5\,\mu$m. The others are independent of r_h. The "NIF" point is slightly lower than expected because Hu gives the energy when gain $= 1$, rather than when runaway burn begins—these points do not coincide at very high temperatures.

version of this condition is based on an arbitrary reference point and one can thus relax this condition if one can produce a hotter hot-spot.

We have also briefly analyzed how bright x-rays deposit their energy in a dense DT plasma, and therefore how the ignition energy for heating using a non-thermal soft x-ray beam should compare with that of a perfect isochoric hot-spot. We used HYADES with a QEOS and Thomas-Fermi ionization model (and thermonuclear reactions turned off) to model a monochromatic 500 eV x-ray beam (with a temporal profile given by Fig. 6) incident on a DT slab with density profile given in Fig. 7(a). The total energy deposited by the beam over 20 ps in a 5 μm radius is 2 kJ, which is what we expect would be required for isochoric ignition from Eq. (7). The results of the simulation at 10 ps intervals are given in Fig. 7.

The x-rays initially penetrate by a Planck mean free path into the plasma, heating and ionizing the outer layer. As it is heated, its opacity to the incident radiation reduces, allowing the radiation to penetrate to the layer below.[19] Assuming that all of the soft x-ray power is transferred to the region immediately ahead of the heatfront, for an adiabatic shock traveling through a perfect gas, the change in the internal energy $\varepsilon = P/\rho(\gamma - 1)$ of the heated region of length w can be written in terms of the x-ray intensity I and heating time t_{heat} as

$$I = \frac{w}{t_{heat}}\rho\varepsilon = \frac{w}{t_{heat}}\frac{P}{\gamma - 1}, \tag{8}$$

where P is the pressure ahead of the heatfront. We expect a rarefaction to propagate a distance w at the speed of sound in time $t_{expand} = w/c_s = w\sqrt{\mu/RT}$, where R is the ideal gas constant and $\mu = A/(Z+1)$ is the fully ionized mean molecular mass, which is 5/4 for DT. Using the ideal gas equation and taking $\gamma = 5/3$ we have[20]

$$\frac{t_{expand}}{t_{heat}} = \frac{I}{\frac{3}{2}\rho(4RT/5)^{3/2}}. \tag{9}$$

For the duration of pulse (0–20 ps) the ratio $t_{expand}/t_{heat} \gg 1$, meaning that the time taken for a region of depth w to heat up to temperature T is much less than the time for a rarefaction to propagate a

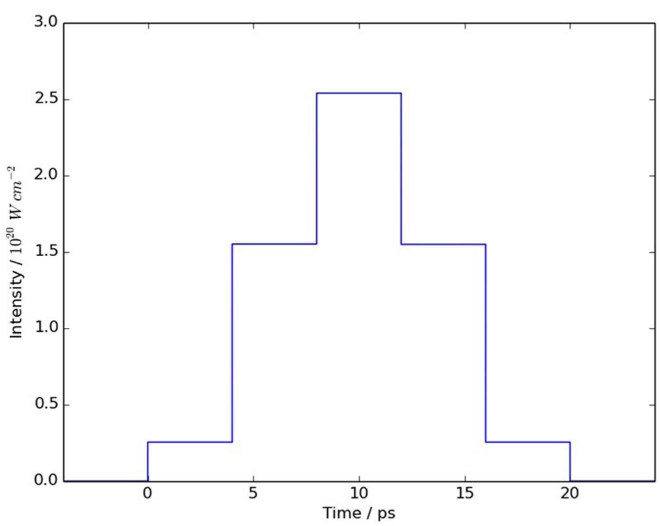

FIG. 6. Intensity profile for the 10 ps FWHM, 500 eV pulse.

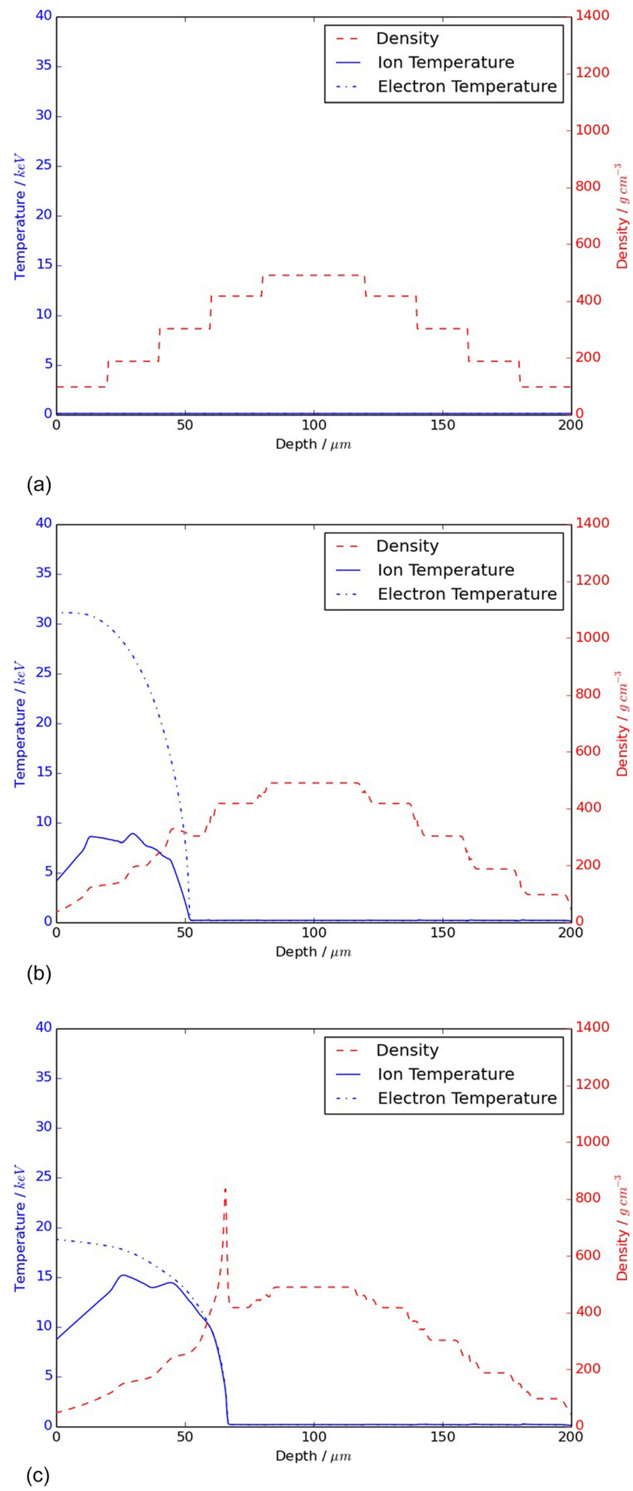

FIG. 7. Density and temperature profiles of a NIF-scale DT pellet resulting from heating by non-thermal soft x-ray pulse (a) before heating, (b) at the peak of the pulse, and (c) immediately after the end of the pulse. Note that thermonuclear reactions were not included in this model.

distance w, so the heat front propagates supersonically. At the end of the pulse, the intensity of the radiation arriving at the heat front falls to zero, so t_{expand}/t_{heat} falls below 1 and the heat front becomes subsonic, allowing a shockwave to begin to form ahead of it.

Since the heating process is supersonic for most of the duration of the pulse, we would expect an ignition scheme which is close to the isochoric volumetric scheme, and we can therefore justify the use of the isochoric ignition condition found above.

Given that we have used one-dimensional simulations to compute the x-ray heating, and thermonuclear reactions cannot be included in HYADES in this geometry, it is difficult to determine if and when ignition would occur. However, by comparing Fig. 7 with our ignition condition it seems possible that the plasma would ignite at about 20 ps in a comparable fast ignition geometry. At this point, in our one-dimensional simulations, approximately 65% of the beam's initial energy have been converted into ion thermal energy.

Going back to Hu's initial analysis, and the unexplained comment which is made there regarding the benefit of the layer-by-layer heating, the authors suggest that a possible reason for the for the high radiation-ion coupling observed is that the hot spot heating here transitions from supersonic to subsonic at approximately the same time as we would expect ignition to occur. It is well known that in fast ignition, hydrodynamic losses are a significant concern, and such a heating scheme effectively reduces the forward going hydrodynamic losses to a negligible level. In other words, the key difference as compared to a particle heated hotspot is that the x-ray heated hotspot boundary only reaches optimum size at the end of the heating pulse, and up to this time it moves supersonically outward, which means that at no point are there significant hydrodynamic losses in the forward direction.

However, it remains very difficult to produce an x-ray source capable of meeting these requirements. The most powerful source of uncollimated non-thermal soft x-rays is line emission from laser-produced plasma, but even the most powerful examples[21] are at least $100\times$ weaker than we would require. In order to focus the uncollimated rays onto a hotspot, a material with very high normal-incidence soft x-ray reflectivity would be needed: Cr/Sc multilayer mirrors[22] have been produced with an experimental reflectivity of 14.5% at $\lambda = 3\,\text{nm}$, but this is only for a particular angle of incidence ($\sim 2.5^\circ$ from normal) and it is not clear how well they would perform at the very high intensities we are proposing.

In conclusion, we have argued in this paper that the results of Hu *et al.*[4] are mostly the result of the isochoric ignition condition being relaxable as a result of producing a very hot hot-spot, rather than violating the isochoric ignition condition. These findings are not specific to x-ray heating and thus suggest that any FI variant might be able to reduce the ignition condition provided that it can produce hot-spots with ρr_h near $0.36\,\text{g}\,\text{cm}^{-2}$ and temperatures in excess of 20 keV, although we acknowledge this is on the limit of what is physically possible. We have also produced one-dimensional simulations of a high-brightness soft x-ray ray beam incident on a DT plasma, and our results suggest that the radiation-ion coupling is very efficient, and may even reduce the hydrodynamic losses below what is assumed by the isochoric ignition condition due to the transition from supersonic to subsonic coinciding with the expected ignition point. We hope that this letter can stimulate further research into fast ignition using x-ray drivers as well as more powerful laser-produced-plasma line emission sources.

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