Fast ignitor target studies for HiPER

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Abstract. The HiPER facility has been proposed recently to demonstrate fast ignition of laser driven inertial fusion targets. According to the present design, HiPER will have a 3ω, multi-beam, multi-ns-pulse of about 250 kJ and a 2ω or 3ω ignition beam delivering 70 kJ in about 15 ps. We present here studies on laser-driven fast-ignitor targets driven by 100-300 kJ compression pulses, followed by 70-100 kJ ignition pulses.

1. Design space analysis.

The HiPER project [1] intends to demonstrate fast ignition of laser-driven targets by means of a multi-beam, multi-ns laser pulse of about 250 kJ for implosion and a short pulse of about 70 kJ delivered in 15 ps for ignition. The goal of the present study has been to make a preliminary design of targets for such a facility. The integrated gain model presented in Ref. [2] shows that ignition and significant energy gain can be achieved at a total laser energy of 100 – 200 kJ, about 100 – 150 kJ at 3ω (0.35 μm wavelength) for the compression laser and 80 – 100 kJ for the ignition laser. This result is based on assuming that adiabat shaping is used in the compression, an in-flight entropy parameter αif ≈ 1 and a laser absorption efficiency ηa = 0.7. Target ignition is characterized by the coupling efficiency of the igniting beam to the dense fuel ηig and the parameter fRλig. Adequate beam coupling requires ηig = 0.25 and fRλig ≤ 0.4 μm, where λig is the wavelength of the igniting beam, fR accounts for possible range reduction in the electron penetration depth formula R = fR 0.6 Tf (g/cm²) [3], and Tf is the mean energy of fast electrons, which is assumed to be given by the ponderomotive scaling. The condition fRλig ≤ 0.4 μm implies the use of 2ω light (λig = 0.53 μm) for the igniting beam and to take fR = 0.8, in agreement with the electron range calculations shown in [4]. Higher values of fRλig (for instance, due the use of the first harmonic) lead to ignition energies well over those envisioned for HiPER, unless a mechanism of range reduction is found. Therefore, according to present understanding, a 2ω ignition beam is required to make the hot-electron range comparable to the required hot spot size.

The design space at a total (compression + ignition) laser energy of 250 kJ for the parameters discussed above is shown in Fig. 1, where iso-gain contours are plotted in the (Ic, Aif) plane. Here Ic is
the laser intensity and \( A_{\text{if}} \) is the target in-flight-aspect-ratio (IFAR). The contours of the Rayleigh-Taylor instability (RTI) maximum exponential growth factor (\( \Gamma_{\text{max}} \)) are also shown. Introducing constraints on the ignition laser energy (\( E_{\text{ig}} < 100 \text{ kJ} \)) and on RTI growth (\( \Gamma_{\text{max}} < 6 \)), narrows the design space, as shown in Fig. 1(b). We have chosen \( I_c \) in the range \( 3 \times 10^{14} \text{ W/cm}^2 \) and \( A_{\text{if}} \) around 40 for the reference design. The details are given in Ref. [2].

![Figure 1](image1.png)

**Figure 1.** Iso-gain contours in the intensity (\( I_c \)) – in-flight-aspect-ratio (\( A_{\text{if}} \)) plane for 250 kJ total drive energy, (b) the same as (a), but with maximum RTI exponential growth limited to \( \Gamma_{\text{max}} < 6 \) and ignition laser energy limited to \( E_{\text{ig}} < 100 \text{ kJ} \). Our reference design point is indicated by the dot.

2. Reference target design.
A family of “all-DT” targets driven by compression pulses in the range 90 – 260 kJ has been designed based on 1-D fluid simulations of implosion and 2-D calculations of ignition and burn [2]. The parameters of the reference target are shown in Fig. 2(a) and Table I. The target is driven by the laser pulse plotted in Fig. 2(b) using the adiabat shaping technique [5]. The intense picket has a power of 19 TW and FWHM of 125 ps. It launches a shock, which is followed by decompression, leading to a relaxed density profile. The first shock launched by the main pulse produces a decaying entropy profile in the target, while the rest of the pulse generates weak shocks that arrive at the inner shell surface almost equally spaced in time to minimize entropy generation of the imploding DT. Some implosion results are collected in Table I. The peak density achieved is about 500 g/cm\(^3\) and densities are higher than 300 g/cm\(^3\) over a large portion of the target. The areal density \( pR \) stays above 1.2 g/cm\(^2\) for about 200 ps, which is a relatively long time interval to launch the igniting beam. The 1-D design shown in Fig. 2(a) has been cross-checked with the radiation-hydrodynamics codes developed at CELIA and GIFI-UPM [6]. It has also been scaled to smaller (\( x/3 \)) and larger (\( x \)) target masses, keeping the laser intensity fixed to achieve nearly the same peak density [2].

![Figure 2](image2.png)

**Table I** Drive parameters and implosion results

| Parameter                        | Value                          |
|----------------------------------|--------------------------------|
| Laser wavelength                | 0.35 µm                        |
| Focusing optics                 | f/18                           |
| Laser energy                    | 132 kJ                         |
| Absorbed energy                 | 95 kJ                          |
| Target mass                     | 0.59 mg                        |
| Implooding mass                 | 0.29 mg                        |
| Implosion velocity              | \( 2.5 \times 10^7 \text{ cm/s} \) |
| Hydrodynamic efficiency         | 10.5%                          |
| Overall coupling efficiency     | 7.2%                           |
| IFAR at \( R = 0.75xR_{\text{initial}} \) | 36                             |

**Figure 2.** (a) Sketch of the reference target, (b) compression laser pulse, (c) flow diagram, and (d) shock diagram \[d(\log p)/dt\].
Two-dimensional simulations of ignition and burn of the reference target driven by a perfectly collimated beam of 20 µm radius and with a deposition range of 1.2 g/cm² give an ignition energy of 20 kJ delivered in 16 ps. Assuming an overall igniting beam coupling efficiency \( \eta_{ig} \approx 0.25 \), it corresponds to a laser energy of 80 kJ at 2\( \omega \), of the same order as that envisioned for HiPER [1].

3. Cone effects on shell compression.
Cone guided targets are considered as one of the most promising alternatives for fast ignition. Recent experiments have indicated very good (20-30%) energy coupling from laser to core [7]. We have performed a simplified study of cone-target compression that combines 1-D and 2-D hydrodynamics calculations. We start with 1-D implosion simulations. When the shell is approaching the target centre (outer shell radius around 300 µm), the 1-D profiles are remapped onto a 2-D Eulerian mesh and calculations are continued with the cone inserted. A sequence of snapshots of the shell evolution is shown in Fig. 3. It is worthwhile noticing that the shell collapses in a nearly spherical blob, pushing away the DT gas located at the centre and reaching higher peak density (660 g/cm³) and \( \rho R \) (1.7 g/cm²) than without cone. This configuration is obtained when a polar P₁ asymmetry is imposed to the implosion velocity at the remapping time, i.e., velocity peaks in front of the cone tip and is minimum at the cone surface. Otherwise, the imploded core would have a horseshoe-shaped configuration, reaching a substantially lower \( \rho R \). Notice that the asymmetric implosion is compatible with the asymmetric drive necessary to avoid the direct interaction of the compression beams with the cone. The configuration of the compressed core shown in Fig. 3(c) agrees with the experiments of cone-target implosion discussed in [8].

4. Fast electron energy deposition and target ignition.
Fast electron transport and energy deposition from the laser interaction zone to the compressed core is crucial for fast ignition target design. The 2-D/3-D hybrid approach used here [9] allows us to investigate important transport features such as collective magnetic effects simultaneously with ignition physics. We found that energy deposition takes place in the high density core almost exclusively by classical Coulomb energy deposition, while self-generated fields play an important role for core heating but in an indirect way, via collimation and resistive filamentation of the fast electron beam [9]. We have analyzed here the imploded cone-guided configuration shown in Fig. 4, which is a simplified version of that depicted in Fig. 3(c). Target ignition has been studied as a function of the electron beam energy, the distance \( d \) from cone-tip to dense core and the initial divergence half-angle of the relativistic electron beam \( \theta \). We have chosen the reference value of \( \theta = 22^\circ \) reported in cone-target experiments [7]. The mean kinetic energy of fast electrons is 2 MeV. The electron beam coupling efficiencies and ignition energies are depicted in Fig. 5. Notice the large sensitivity of the coupling efficiency to \( d \) and \( \theta \) and the important role played by the magnetic collimation of the fast electron beam. The results shown in Fig. 5 indicate that ignition can be
achieved with the igniting beam energies of 70 – 100 kJ envisioned for HiPER for distances $d$ lower than $\approx 100 \mu m$ and divergence half-angles lower than 30º, assuming laser-to fast electron conversion efficiency $\varepsilon_{fe} = 0.4$. Fast electron calculations are discussed with more detail in Ref. [10].

Figure 5. Electron beam coupling efficiencies and minimum ignition energies of the target shown in Fig. 4. Dashed lines correspond to simulations with self-generated fields artificially suppressed.

6. Conclusions.

We have designed a target family for HiPER defined by laser intensities within the range of 3-5x$10^{14}$ W/cm$^2$ and in-flight-aspect-ratio about 40. One-dimensional simulations show that DT densities $= 500$ g/cm$^3$ can be achieved with compression laser energies about 130 kJ. The minimum ignition energy of the imploded 1-D target is 20 kJ, assuming a perfectly collimated electron beam with a deposition range of 1.2 g/cm$^2$.

Cone effects have been taken into account in a simplified manner by combining 1-D and 2-D hydrodynamics calculations. We found that the density distribution of the imploded target consists of a high density blob without a dip at the centre with a peak density and $\rho R$ higher than without the cone.

Realistic electron beams with initial angular divergences from 22º to 30º, a spectral distribution with mean energy of 2 MeV and Gaussian profiles in space and time can ignite the imploded target shown in Fig. 4 with the laser beam energies of 70 - 100 kJ envisioned for HiPER, provided a distance $d = 100 \mu m$ and a laser-to-fast-electron conversion efficiency $\varepsilon_{fe} = 0.4$.

Crucial issues for the design that have not been studied in detail yet include direct-drive, high convergence, cone-guided implosions, as well as the generation of the hot electron beam and its transport in low-to-moderate density plasmas. However, we have begun studying the hydrodynamics of cone-guided targets with radiation-hydrodynamics codes and we are tackling aspects of intense laser interaction and hot electron transport with PIC codes. Results will be reported in the near future.

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