Numerical simulations of the HiPER baseline target

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Abstract. The European High Power laser Energy Research (HiPER) project aims at demonstrating the feasibility of high gain inertial confinement fusion (ICF) using the fast ignitor approach. A baseline target has been recently developed by Atzeni et al. [Phys. Plasmas 14, 052702 (2007)]. The comparison between a standard and a relaxation pulse shows that the latter one allows to reduce both the laser power contrast and the growth of perturbation under Rayleigh-Taylor instability. We have found that with 95 kJ of absorbed laser energy one can assemble the fuel with to a peak density around $500 \text{ g/cm}^3$ and to a peak areal density of $1.2 \text{ g/cm}^2$. This implies a total target gain of about 55.

1. Introduction
The High Power laser Energy Research (HiPER) [1] is a project of a flexible physics facility for exploring an fusion-energy production with an energy gain of the order of 100. It is based on the Fast Ignition (FI) approach [2], which implies separate drivers for fuel compression and for ignition. It relaxes the high velocity implosion constraint required in the conventional central hot spot ignition approach. A preliminary design of the HiPER baseline target was performed by Atzeni et al. [3]. The reference target with a 130 kJ compression laser pulse and a 80 kJ ignition pulse yields the gain of about 60. However one needs to know how robust the design point is and how sensitive target performances are, with respect to the physical uncertainties, imperfections in target fabrication, and laser random errors. Among the physical effects which are not completely well understood or modelled, we have to mention the Rayleigh-Taylor instability (RTI) at the ablation front, radiation and electron transport, laser energy absorption. Our study is based on two numerical tools: the radiation hydrodynamic code CHIC and the perturbation code PERLE. The CHIC is 1D/2D code based on a cell-centered Lagrangian discretization model [4]. They are: the flux-limited electron energy transport; multi-group thermal radiation transport [5], 3D ray-tracing with refraction for laser propagation; the laser absorption via the inverse Bremsstrahlung; a realistic equation of state (SESAME), and hydrogenic opacities. For the stability analysis of the 1D base flow, the perturbation code PERLE is used in 2D plane geometry, with a perfect gas equation of state, a Spitzer, flux limited thermal conduction, laser absorption via inverse Bremsstrahlung, but without the radiative transport [7]. More details about the simulations of this work will be given in Ref. [6].
2. HiPER target reference design

The HiPER baseline target [3] is shown in figure 1-a. This is a DT cryogenic spherical shell of 1044\,\mu\text{m} radius, and 211\,\mu\text{m} thickness. The target is driven by a 130\,kJ laser (95\,kJ is absorbed in the target). The pulse profiles are shown in figure 1-b. The 1D-simulations performed in Ref. [3] give the peak density of 550\,g/cm$^3$ and the maximum areal density close to 1.6\,g/cm$^2$. Moreover, the authors estimated the RTI growth rate making use of the Takabe formula and choose the relaxation shock method to mitigate the perturbation growth. To control the shell

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{target.png}
\caption{HiPER reference target (a) : All-DT cryogenic target with 1\,mm radius, 211\,\mu\text{m} of thickness. Fuel mass is 0.59\,mg. (b) The standard pulse shape with 4\,ns of foot pulse duration at 0.6 TW. The peak power is 40\,TW (b1). Relaxation pulse shape with a picket of 150\,ps and 19\,TW followed by a foot 2.5\,ns and 1.6\,TW, the peak power is $\simeq$ 40\,TW (b2).}
\end{figure}

in-flight adiabat and to obtain a high shell compression, it is necessary to control very well the temporal profile of the laser power. The goal is to compress the target on a low adiabat, that is, without strong shocks inside the shell. Two pulses are considered here: the classical low adiabat pulse (a foot and a main pulse noted as b1 in figure 1-b) and the shock relaxation pulse (a short picket followed by a standard pulse noted as b2). The standard pulse b1 has a 0.6\,TW foot duration of 4\,ns, followed by a 4\,ns, Kidder-like rise up to 40 TW . This peak power is kept constant for 2.5\,ns. The shock relaxation pulse b2 contains a 150\,ps, 19\,TW prepulse, followed 4\,ns later by a 1.6\,TW foot and a 40\,TW peak. The energy of both pulses is $\simeq$ 130\,kJ at the wavelength of 0.35\,\mu\text{m}. A summary of the hydrodynamic target performance is presented in the table 1. The relaxation pulse allows to decrease of the laser pulse contrast ratio, which is a positive effect as it relaxes the constrains on the laser facility for the same target performances. Conversely, by comparing the standard and relaxation pulses with the same contrast ratio, we see that the latter one offers a possibility to use a lower adiabat and to increase the peak areal density, that is, the target gain. Moreover, by using laser intensities lower than $10^{15}$\,W/cm$^2$ one can reduce a risk of excitation of the parametric instabilities. For the parameters given in table 1, we find the peak density 540\,g/cm$^3$, the areal density about 1.3\,g/cm$^2$ and a gain $G = 100$ Accounting also for the laser ignition energy, $E_{ig} = 72$\,kJ, the estimated total gain is $G_T \simeq 55$. In order to check the laser energy dependence and to increase the peak areal density, we performed another calculation by using 130\,kJ of absorbed laser energy. In this case we achieved the values of the areal and the volumic densities, $\rho R_{\text{max}} = 1.6$\,g/cm$^2$ and $\rho_{\text{max}} = 600$\,g/cm$^3$, the same as in Ref. [3]. This comparison shows that the areal density depends more on the absorbed energy than the peak density, which is in agreement with the scaling laws [8].

2.1. Ablative Rayleigh-Taylor instability

In order to study the shell stability with respect to the RTI, we performed a series of simulations with a perturbation code in the planar geometry. The code PERLE [7] calculates simultaneously a one dimensional flow and the time evolution of a given initial modal perturbation. The shell
Table 1. Target performances for two laser pulse shapes.

| Performance                      | Standard Pulse | Relaxation Pulse |
|----------------------------------|----------------|------------------|
| Laser energy                     | ~132 kJ        |                  |
| Absorbed energy                  | ~95 kJ         |                  |
| Peak intensity                   | ~3 \times 10^{14} W/cm² |      |
| Laser pulse contrast ratio       | 70 (standard)  | 25 (relaxation)  |
| In-flight mass                   | ~0.28 mg       |                  |
| Implosion velocity               | ~2.4 \times 10^7 cm/s |     |
| Kinetic shell energy             | ~8 kJ          |                  |
| Absorbed efficiency              | ~72%           |                  |
| Hydrodynamic efficiency          | ~8.4%          |                  |
| Adiabat parameter                | ~1.0           |                  |
| Peak density                     | ~500 g/cm³     |                  |
| Peak areal density               | ~1.2 g/cm²     |                  |

stability was studied for a time $\Delta t$ during the acceleration phase. During $\Delta t$ the shell is thinner, i.e. the most fragile. The interval $\Delta t$ was chosen from the temporal evolution of the shell thickness, where the In-flight Aspect Ratio (IFAR = $R/\Delta R$) reaches its maximum value. The wavelength of perturbations studied with PERLE, $\lambda_m \approx 100 \mu m$, is much smaller than the ablation front radius, $R_a \approx 700 \mu m$. Therefore, the sphericity effect is not important and the perturbations may be studied in planar geometry. The time interval $\Delta t = 1.7$ ns for both pulses is shown in figure 2. Within this time interval the acceleration remains constant and the IFAR varies between 25 and 35. These values are close to those of Ref. [3]. The time evolution of the shell thickness is shown in figure 2. It remains about $\Delta R \approx 20 \mu m$ for both pulses during this time interval. Figure 3 displays the number of e-foldings $N_e$ for a perturbation with wave-number $k$ for two pulse shapes. The e-folding number is defined by the time integration of the RTI growth rate during $\Delta t$. The code results are compared with the Takabe-like formula for the DT [9]. The agreement is quite good, nevertheless, the relaxation pulse demonstrates a more stable implosion in comparison with the standard pulse. This is due to the enhancement of the ablation velocity via the adiabat shaping. The maximum number of e-folding is close to 4.5 for the relaxation pulse, while it is around 7 for the standard pulse. The calculated e-folding values are close to the estimations [3] for the relaxation pulse, but they are 20% below for the standard pulse. This difference can be explained by the laser pulse shaping and also by the difference in the length of the acceleration time interval. The most dangerous mode, $k_c \Delta R \approx 1$, corresponds

![Figure 2](image-url)
to $k_c \simeq 500 \text{ cm}^{-1}$. The number of e-folding for this mode is close to 2 with or without picket (see Figure 3), the expected $N_e$ for the disruption to occur is about 6. The proposed target appear to be relatively safe, even without picket, for this crude criterion. Nevertheless, according to [10], an other advantage of the relaxation pulse is to reduce the pulse contrast.

**Figure 3.** Number of e-foldings for the small periodic perturbations found with the code PERLE. The circles show the simulation results and the solid lines give the fit with the Takabe-like formula for the standard (a) and relaxation (b) pulses.

### 3. Conclusion

The radiative hydrodynamic code CHIC in 1D spherical geometry together with the code PERLE (2D perturbations of a 1D planar flow) have been used for study of the HiPER reference target. Two laser compression pulses were considered. Our simulations indicate that for a 130 kJ laser drive (95 kJ absorbed) and for two types of the pulse, a peak density around 500 g/cm$^3$, and peak areal density around 1.2 g/cm$^2$, with a target gain around 55, are achieved. These parameters are in a good agreement with Atzeni et al. [3], except for the areal density. This discrepancy can be attributed to a difference in the numerical treatment of the radiation losses in the DT gas during the shell stagnation. Moreover, the performance are in good agreement with the scaling laws developed by Betti et al. [8]. The linear perturbation study shows that the shell is relatively insensitive to the Rayleigh-Taylor instability even for the standard pulse, if we consider the most dangerous mode given by $k_c \Delta R \simeq 1$. The main advantage of the relaxation pulse is to decreased the laser contrast ratio or the adiabat parameter and, consequently, to increased the target performance.

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