Theoretical and Computational Studies on Targets for Inertial Fusion Ignition Demonstration at the HiPER Facility*

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Abstract.

Recently, a European collaboration has proposed the High Power Laser Energy Research (HiPER) facility, with the primary goal of demonstrating laser driven inertial fusion fast ignition. HiPER is expected to provide 250 kJ in multiple, 3ω (wavelength $\lambda = 0.35$ μm), nanosecond beams for compression and 70 kJ in 10-20 ps, 2ω beams for ignition. The baseline approach is fast ignition by laser-accelerated fast electrons; cones are considered as a means to maximize ignition laser-fuel coupling. Earlier studies led to identify an all-DT shell, with a total mass of about 0.6 mg as a reference target concept. The HiPER main pulse can compress the fuel to a peak density above 500 g/cm^3 and an areal density ρR of about 1.5 g/cm^2. Ignition of the compressed fuel requires that relativistic electrons deposit about 20 kJ in a volume of radius of about 15 μm and depth of less than 1.2 g/cm^2. The ignited target releases about 13 MJ. In this paper, additional analyses of this target are reported. An optimal irradiation pattern has been identified. The effects on fuel compression of the low-mode irradiation non-uniformities have been studied by 2D simulations and an analytical model. The scaling of the electron beam energy required for ignition (vs electron kinetic energy) has been determined by 2D fluid simulations including a 3D Monte-Carlo treatment of relativistic electrons, and agrees with a simple model. Hybrid (fluid and PIC) simulations show that beam-induced magnetic fields can reduce beam divergence. As an alternative scheme, shock ignition is studied. 2D simulations have addressed optimization of shock timing and absorbed power, means to increase laser absorption efficiency, and the interaction of the igniting shocks with a deformed fuel shell.

1. Introduction

HiPER (High Power Laser for Energy Research) is a proposed facility aiming at the demonstration of the feasiblity of fast ignition [1, 2]. We recall that fast ignition [3, 4], is an approach to inertial confinement fusion in which the stages of fuel compression and ignition are separated. The fuel is first compressed to high density by a suitable driver; the precompressed fuel is ignited by a second ultraintense driver. To achieve its goal HiPER will deliver a 3ω multi-beam pulse of about 250 kJ in about 10 ns, and a 2ω or 3ω ignition pulse of about 70 kJ in 15-20 ns. (Here ω refers to the fundamental frequency of the Nd:glass laser, with wavelength of 1.053 μm.) The baseline approach is fast ignition by laser-accelerated fast electrons; cones [4] are considered as a means to maximize ignition laser-fuel coupling. A reference fusion capsule concept for HiPER was identified by previous studies [2, 5, 6]. Capsule and laser pulse were then designed on the basis of 1-D simulations of irradiation and implosion. Care was taken to limit both plasma and hydrodynamic (Rayleigh-Taylor, RTI) instabilities. Preliminary 2D simulations addressed cone-guided implosion. Ignition of the precompressed fuel by electron beams was studied by 2D simulations. Sensitivity to pulse shaping and to variation of some of the igniting beam parameters was also addressed [7]. A key issue for the feasibility of the scheme is the efficient transfer of the energy ultra-intense laser beam to the hot spot, which involves laser absorption, fast electron generation, and fast electron transport and energy deposition, and the effect of the cone on both fuel compression and beam coupling. Another important aspect concerns the realistic description of the laser irradiation scheme, and the consequences of the unavoidable irradiation non-uniformities.

In Spring 2008 the HiPER project has entered a three-year preparatory phase, with the goal of achieving a detailed design design. In this paper, after a brief description of the present reference capsule concept (Sec. 2), we present the first results of this effort. We discuss the design of the irradiation scheme for fuel compression, and study the effect of low-mode irradiation non-uniformities on fuel compression (Sec. 3). We then present studies of the ignition stage based on improved 3D models of electron transport in the compressed fuel (Sec. 4) and more realistics models of the electron beams. Finally, in Sec. 5, we present results on shock-ignition [8] of the HiPER reference capsule. We consider this concept because, similarly to fast ignition, it separates the stages of compression and ignition, and employs an intense (but not ultra-intense) pulse for ignition. However, it appears potentially attractive since does not involve generation and transport of relativistic electrons.

2. Target concept

The target concept under investigation is a simple shell, with an inserted cone. A preliminary reference shell has been identified as a result of the study summarized in Refs. [5, 6]. This is an all-DT shell, with a total mass of 0.58 mg and the dimensions indicated in Fig. 1a). The shell and target parameters have been chosen to satisfy a number of constraints, including the following: i) the fuel has to be compressed to average density in excess of 300 g/cm^3, with a confinement parameter $\rho R \simeq 1.5$ g/cm^2; ii) the fuel average entropy should be kept as small as possible (i.e. the insentrope parameter should be about 1); iii) the intensity of the compression pulse should be smaller than 5×10^{14} W/cm^2 (at 3ω) to limit plasma instabilities; iv) the RTI growth factor should be limited to 6–7 for the fastest growing mode; v) the in-flight-aspect ratio should be limited to 30–35. The requests on plasma instabilities and RTI led in the choice of a moderately thin target (a ticker target requires higher intensity) and of the pulse shape. Indeed, the reference laser compression pulse, shown in Fig. 1b), consists of a short intense picket, preceding a low intensity foot, a properly tailored raise and a main pulse. The initial picket preceding the main pulse serves to implement adiabat shaping. This allows to increase the entropy of the ablator (to reduce RTI growth), while at the same time keeping the entropy of the inner fuel at a very low level. Irradiation, implosion and compression of the capsule has been studied by three different 1D codes, which produce results in substantial agreement [6, 7]. According to the most accurate and realistic simulations, the target achieves peak density higher than 600 g/cm^3 and $\rho R \simeq 1.5$ g/cm^2, when driven by a pulse of about 180 kJ (asborbed with an efficiency of 67%). Half of the initial mass is imploded, at a (peak) velocity of 2.6×10^7 cm/s. In addition to the reference pulse, we have also considered a pulse without initial picket (see Fig. 1a), leading to essentially identical performances. This is more susceptible to RTI, but studies with a perturbation code [7] led to more optimistic results than the simple model used in Ref. [5], and indicated that RTI growth could still be acceptable.

Ignition of the compressed fuel occurs if about 20 kJ are deposited in 15 ns in a cylindrical volume of radius of 15 μm and mass depth of 1–1.2 g/cm^2; the ignited target releases about 13 MJ of fusion energy. Actual beams reaching the dense fuel have to deliver larger energy to account for inefficiencies due to electron scattering and broad energy distribution of the electrons. The average kinetic energy (temperature) of such electron beams should be

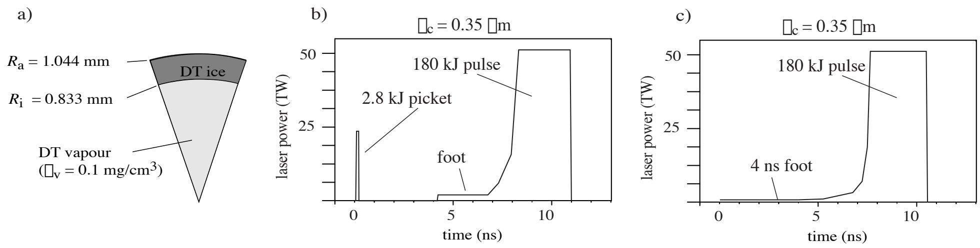

FIG. 1.: Reference capsule and laser pulses.

1–1.5 MeV. The crucial issue for the design of the HiPER target then seems to be the coupling efficiency of the ultraintense beam, which must exceed 20%. This implies good conversion of the laser energy into a forward collimated beam of hot electrons with the desired temperature. Using a standard ponderomotive scaling for the average energy of the hot electrons, $\overline{\mathcal{E}}(\mathrm{MeV}) = [I_{\mathrm{laser}}/(1.3 \times 10^{19}\ \mathrm{W/cm^2})]^{1/2} \cdot \lambda(\mu\mathrm{m})$, such conditions could be met by a laser pulse with intensity somewhat in excess of 10^{20} W/cm^2, and 2ω or 3ω frequency (lower frequencies resulting in the generation of too much energetic electrons). We note, however, that recent studies [9] show that the hot electron temperature can be well below that predicted by the above scaling. This may allow for ignition pulses at ω.

3. Fuel capsule irradiation and generation of the compressed fuel assembly

3.1 Beam pattern and irradiation uniformity

The irradiation pattern for HiPER has been defined by using the geometrical optics code CECLAD. We choose a 48 beams configuration pattern made of 3 rings on each side of the target hemispheres (21.23°, 47.03°, 74.95°). The rings have respectively 4, 8 and 12 beams. The offsets are 0° for the 4 beams on the first ring, $\pm 23.4°$ for the 8 $(4+4)$ beams of the second ring and 0° and $\pm 29.8°$ for the 12 $(4+4+4)$ beams of the last ring (see Fig. 1). The robustness of this pattern with respect to random deviations from nominal was evaluated: the symmetry indicator σ_{rms} remains close to 1% under a normal repartition of the beam to beam imbalance (10%), of the beam pointing (5%), and of the beam centering (2% of initial target radius). CECLAD has also been used to evaluate the incident intensity on the re-entrant cone of a fast ignition target, to assess issues concerning damage to the cone. In order to give input to low mode asymmetry studies, a Legendre polynomial expansion has also been carried out. It shows that the main modes of illumination nonuniformity are $l = 12$, 8 and 10, with a maximum relative nonuniformity of 0.5% for mode $l = 12$.

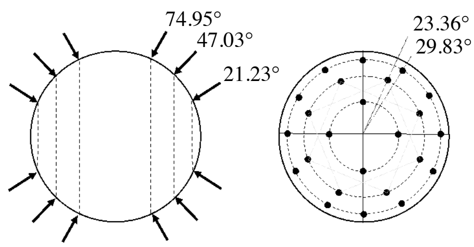

FIG. 2.: The 48 beams HiPER illumination scheme.

3.2 Fuel assembly under low-mode asymmetry

We have then studied the effect on capsule implosion of laser illumination nonuniformities [10]. We assume perfectly smooth focal spots, so the non uniformity spectrum consists of low modes only. Typically modes $1 < l < 20$ of a Legendre expansion of the incident laser intensity on target surface are considered. The main part of our analysis relies on a linear model of the Ablative Rayleigh-Taylor (ARTI) growth of the induced perturbation.

The linear assumption is justified by 2D implosion simulations using the multimode irradiation spectrum provided CECLAD. It turns out that the $l = 12$ mode dominates at all times, little mode coupling occurs, and the amplitude of the perturbation of the compressed fuel remains moderate until the time of maximum compression (see Fig. 3). We have then used an ARTI model employing established theory [11]. The input parameters of the model are taken from 1D numerical calculations [12]. Model results are shown to agree reasonably well with CHIC single-mode calculations at $l = 12$–20; at lower l the model predicts larger growth than CHIC. The ARTI model has then been used to predict areal density modulations at stagnation time for different target designs and irradiation patterns. This allows to estimate effective areal densities and expected target yields. For the irradiation pattern of Fig. 1, the ratio of the perturbed yield to the 1D yield is found to be 0.80 for the HiPER baseline target.

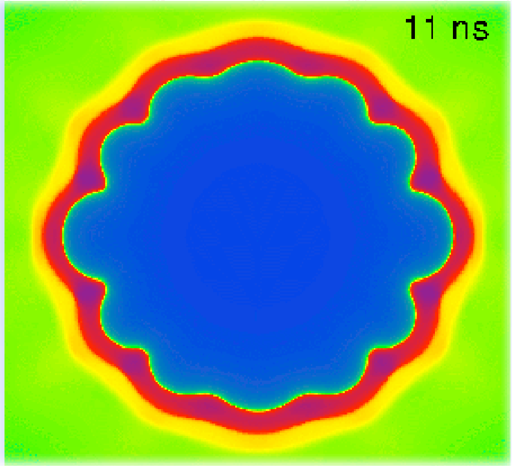

FIG. 3.: Multimode, 90°, CHIC simulation of the Hiper reference design. View of density contours just before time of maximum areal density (≈ 11.17 ns).

4. Elecron beam driven ignition of the compressed fuel

Accurate determination of the ignition conditions is a key element of target design. Studies on the ignition of the HiPER reference capsule showed that the minimum ignition energy $E_{\rm ig}$ depends critically on the average electron energy $\overline{\mathcal{E}}$ and on beam divergence [6]. Here, we show that the dependence of $E_{\rm ig}$ on $\overline{\mathcal{E}}$ can be accurately reproduced by a simple model (Sec. 4.1). In addition, we show that beam-induced magnetic fields can reduce beam divergence (Sec 4.2).

4.1 Minimum ignition energy: dependence on the electron kinetic energy

In Refs. [13] and [14] the minimum ignition energy of a uniform, equimolar DT sphere with density ρ was calculated using the 2D hydro-code DUED by assuming that a cylindrical region with depth $\mathcal{P}$, corresponding to the penetration depth, was heated by particles with constant stopping power, giving

$$E_{\rm ig} = 18 \left(\frac{\rho}{300\ {\rm g/cm^3}}\right)^{-1.85} \max\left(1, \frac{\mathcal{P}}{1.2\ {\rm g/cm^{-2}}}\right)\ \ {\rm kJ}. \tag{1}$$

This is not directly applicable to electron fast ignition because nonuniform stopping power, angular scattering and the broad energy distribution of laser-generated electron beams lead to a wide range of penetration depths. To address this we have added a 3D Monte Carlo electron energy deposition routine to DUED; the expressions for the stopping power and the scattering coefficients are given in Ref. [15]. The first application of this improved model was to ignition of the HiPER capsule [6]. We now show how Eq. (1) can be modified to agree with the new model and to explicitly include the dependence on electron kinetic energy.

We have repeated the calculations from [13] for parallel, cylindrical electron beams with uniform intensity profiles, a constant power, a radius of 20 μm and a pulse duration of 20 ps at $\rho = 300\ \mathrm{g/cm^3}$. The radius and pulse duration are the values that were found to be optimal in the previous study. We considered mono-energetic and exponential energy distributions $\exp(-\mathcal{E}/\overline{\mathcal{E}})$. The code was also run without angular scattering for the mono-energetic beam. The results are given in Fig. 4. They show that: i) scattering has little effect on the optimal mean energy and increases the ignition energy by 10–20%, ii) the minimum ignition energy is $\approx$ 22 kJ, iii) the optimal energy is 0.75–1.5 MeV for a monoenergetic distribution and iv) the optimal mean energy is 0.3–0.5 MeV for an exponential distribution.

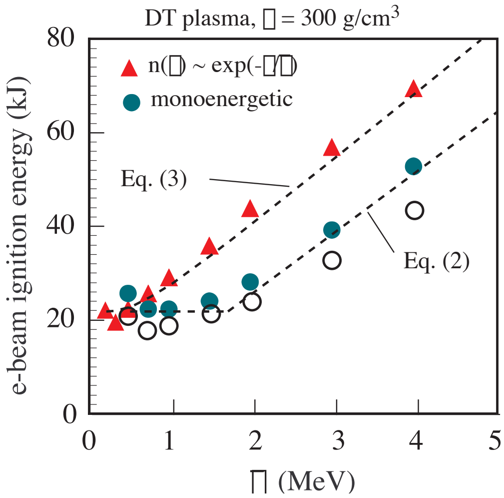

FIG. 4.: Ignition energy from full simulations (filled symbols) and approximated expressions (dashed curves). The void circles refer to simulations for monoenergetic beams, neglecting scattering.

We have developed a simple model that accurately reproduces these results. First, by running the Monte Carlo routine for densities from 100 to 1000 g/cm^3 and temperatures from 1 to 10 keV we have found that the penetration depth (along the initial electron axis) by which 90% of the energy is deposited can be fitted by $\mathcal{P}_{90\%} \simeq [\mathcal{E}/(1.4\ \mathrm{MeV})][\rho/(300\ \mathrm{g/cm^3})]^{0.066}\ \mathrm{g/cm^2}$, for $1.5 \leq \mathcal{E} \leq 5$ MeV. We then assume that: i) equation (1) gives the energy that must be deposited up to a depth of 1.2 g/cm^2, ii) angular scattering increases the ignition energy by a factor of 1.2 and iii) electron energy deposition is uniform in depth up to $\mathcal{P}_{90\%}$. This gives

$$E_{\mathrm{ig-mon}} \simeq 22 \left(\frac{\rho}{300\ \mathrm{g/cm^3}}\right)^{-1.85} \max\left(1, \frac{\mathcal{E}}{1.7\ \mathrm{MeV}}\right)\ \mathrm{kJ} \quad (2)$$

$$E_{\mathrm{ig-exp}} \simeq 22 \left(\frac{\rho}{300\ \mathrm{g/cm^3}}\right)^{-1.85} \{1 - \exp[-1.54/\overline{\mathcal{E}}(\ \mathrm{MeV})\}^{-1}\ \mathrm{kJ}, \quad (3)$$

for monoenergetic beams and for beams with exponential energy distributions, respectively. These approximations are also plotted in Fig. 4, for DT plasmas with density of 300 g/cm^3.

Our calculations give the minimum beam energy required on entering the core, and do not consider the transport of the electrons to the core. Further work is required to determine the initial electron beam parameters required for ignition, and eventually the ignition laser requirements.

4.2 Simulations of ignition of a model fuel assembly, including self-generated fields

The study of electron transport in a low density corona requires kinetic (e.g. Particle-in-Cell) codes and can only be performed for systems much smaller than an actual target. In the halo of the compressed fuel, with density of the order of 1 g/cm^3, the effect of self-generated fields can instead be studied by simulations with codes using a hybrid treatment (see below). Notice that in cone-inserted fast ignitors one aims at producing the hot electrons just at the tip of the cone, at small distance from the highly compressed plasma core. We have then studied ignition of a spherical fuel core with a peak density of 500 g/cm^3, surrounded by a low density

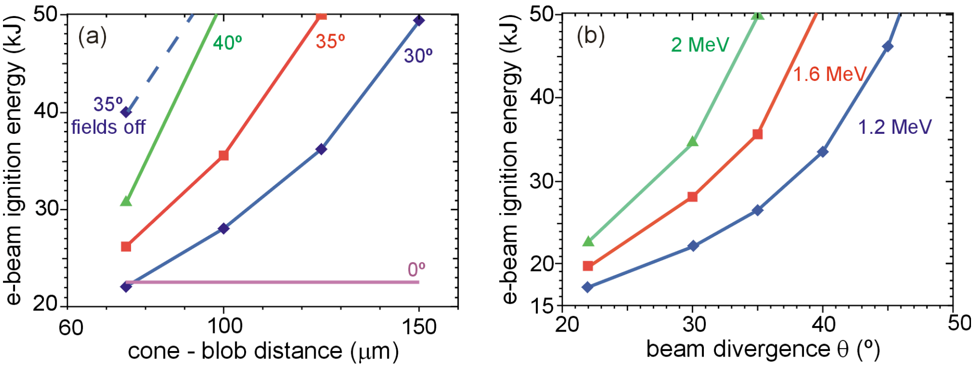

FIG. 5.: (a) Ignition energy as a function of the cone - core distance for $\overline{\mathcal{E}}$ = 1.6 MeV. Curves are labeled with $\langle\theta\rangle$. The dashed line corresponds to the case with self-generated fields artifdicially suppressed. (b) Ignition energies as a function of divergence half-angle with $\overline{\mathcal{E}}$ as a parameter for d = 100 μm.

halo. as a function of injected electron energy, distance d of cone-tip (i.e. the electron source) to dense core, initial divergence half-angle $\langle\theta\rangle$ and mean kinetic energy of the electron beam $\overline{\mathcal{E}}$. We have performed simulations including hybrid PIC modelling of fast electron transport, hydrodynamics, DT ignition and α-particle transport. We find that fast electrons propagate up to the dense core and deposit there (by classical Coulomb collisions) a significant fraction of their energy without beam disruption or breaking-up due to the self-generated magnetic fields. The main results are summarized in Fig. 5, showing the electron beam energy required for ignition vs $\langle\theta\rangle$, $\overline{\mathcal{E}}$ and d. Notice the strong dependence of E_{ig} on $\langle\theta\rangle$, $\overline{\mathcal{E}}$ and d, and the important role played by self-generated fields via beam collimation. Comparison of the ignition energies with that obtained for a perfectly collimated beam ($\theta = 0°$ and fields turned off) indeed shows that for $\langle\theta\rangle = 30°$ and $d = 75$ μm, the beam is almost perfectly collimated. For higher values, beam collimation is still important, but the beam diverges when propagates toward the dense core. We found ignition energies 20-30% lower than those reported in previous works [16, 17] due to the sharper radial profile of the fast electron beam assumed here (supergaussian instead of Gaussian) which concentrates the energy deposition and enhances magnetic field generation at the beam edge. If the distance from the electron source to the dense core is smaller than 125 μm, ignition can be achieved by electron beams with energy about 40 kJ for $\langle\theta\rangle$=30–35° and $\overline{\mathcal{E}} \leq 1.6$ MeV.

5. Shock ignition studies

In shock ignition (SI) [8] the energy required to ignite a precompressed target is provided by a properly timed strong shock launched at the end of the coasting phase of the implosion, by means of a final spike in the laser pulse. SI is attractive because it does not require any specific ignitor laser nor cone-in-a-shell targets. Moreover, the physics at work in the hot spot heating is laser driven hydrodynamics, for which calibrated, predictive codes exist. Here, we discuss SI of the HiPER reference capsule. For a detailed presentation, see Ref. [18].

Two important parameters characterizing the ignition shock are launching time and absorbed laser power. We have studied their optimal values and tolerable variations by means of a series of 1D CHIC simulations [12]. We assume the HiPER compression pulse shown in Fig. 1c), followed by an intense spike towards the end of the implosion. The calculated thermonuclear yields are plotted in Fig. 6 as a function of spike launch time and absorbed laser power during the spike.

The ignitor pulse is the same for all simulations, with a rise time of 200 ps, a plateau of 300 ps and a 200 ps decrease time. The ignition threshold is found around 50 TW for a spike launched at 10.1 ns. We define as "Ignition Window" (IW) the time interval ensuring a yield larger than 80% of the maximum yield at given power. One can observe that the IW broadens as power increases from 50 TW up to 80 TW. At 80 TW a 250 ps window warrants a yield larger than 16 MJ. Notice that, for a given spike power, the dependence of yield on the launch time is not symmetric (in agreement with Ref. [8]): a low positive slope in yield appears for early spikes, whereas a steep cliff can be seen for late launch times.

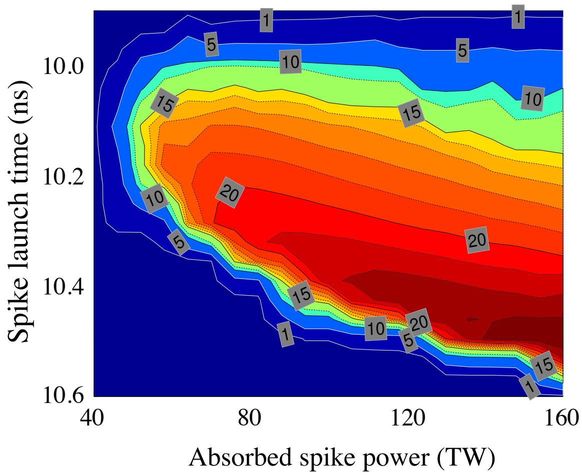

FIG. 6.: Dependence of the target thermonuclear yield in MJ on the launch time and absorbed power of the ignition shocks.

Using the same irradiation pattern as described in Sec. 3.1 for the compression pulse, the 3D ray-tracing package of CHIC predicts an average absorption of 35% during the spike. This means that 230 TW of incident laser power would be necessary for the SI of the HiPER target. Such a low absorption is due to the small value of the critical radius at the shock launching time. Indeed, during the spike, the critical radius varies from 500 to 400 μm, while in order to ensure an optimal irradiation uniformity at the beginning of the target implosion, the focal spots have a gaussian intensity distribution, with a 610 μm radius at 1/e. Therefore, a significant part of the incident laser rays misses the critical surface during the spike laser pulse. A solution is to use dedicated laser beams to deliver this part of the pulse. By decreasing the focal spot diameter and optimising the radial intensity distribution in the focal spot one may increase the absorption up to 50-60%. We have found that a 160 TW, 80 kJ ignition pulse with 400 μm radius, top-hat focal spot, delivered by specific beam lines ignites the HiPER target. In order to assess the possibility to irradiate the target with a limited number of beamlines, we calculated the ignition of a spherical fuel assembly driven by clusters of ignition beams placed at different polar angles. Preliminary simulations indicate that the thermonuclear yield remains almost constant (20 MJ) whatever the angle is, this being mainly due to a very efficient thermal smoothing in the conduction region.

Another important issue for shock ignition concerns Rayleigh-Taylor instability (RTI), that may strongly perturb the shell-hot spot interface during the shell deceleration and subsequent stagnation. We then computed the growth of perturbations of the SI HiPER baseline target seeded by an $l = 12$ Legendre perturbation of the compression pulse. The 150 TW laser spike was delivered by beams oriented at $54.7°$ with respect to the polar axis in order to produce a nearly spherical ignitor shock. Despite of the strong RTI occurring at stagnation, the target ignites and produces

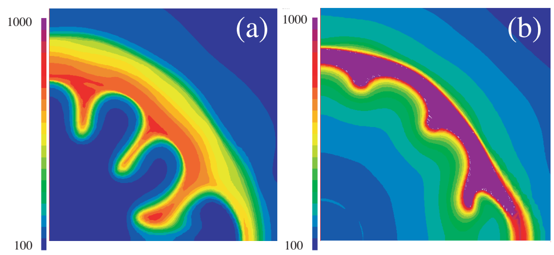

FIG. 7.: Density at t=11.125 ns (g/cm^3), i.e., just before ignition with shock. Without shock (a) and with shock (b).

20 MJ of thermonuclear energy. The comparison between Fig. 7a) and Fig. 7b) shows that the shocks strongly mitigates RTI, in agreement with the improved stability of implosions driven by shock-ignition-like pulses observed in Omega experiments [19].

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