3D ray-tracing package dedicated to the irradiation study of a directly driven inertial confinement fusion capsule

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Abstract. The compression of a directly driven all-DT capsule has been simulated by the hydrodynamic code Multi1D. The capsule absorbs a total energy of about 100 kJ allowing for a maximum density of 650 g/cm³ and a maximum confinement parameter ρR of 1.6 g/cm². An ad-hoc 3D ray-tracing package has been developed to evaluate the uniformity of the deposition energy provided by the direct irradiation of the capsule. Two irradiation configurations with 32 and 48 laser beams characterized by a super-gaussian intensity profile have been considered. A robustness study has been performed as a function of the power imbalance. Neglecting any pointing errors and taking into account only for the power imbalance it is found that half of the shots performed with the two configurations provide the same irradiation uniformity. The 3D ray-tracing package has been also used to estimate the direct irradiation of a re-entrant cone inserted into the capsule. It is found that the direct irradiation of the cone surface reach a maximum intensity of 3 \times 10^{14} W/cm².

1. Introduction

In the Direct Driven Inertial Confinement Fusion, a spherical capsule is irradiated by multiple overlapping laser beams. A fraction of the laser energy is deposited into the external side of the shell of the capsule which expands and compresses a small amount of nuclear fuel contained in the capsule. A successful implosion allows for generation of the ignition conditions of the Deuterium-Tritium fuel which can provide energy gain as high as 100. The uniformity of the irradiation is crucial [1-4] to avoid the growth of the Rayleigh-Taylor (RT) [5,6] instability. During the acceleration phase such hydrodynamic instability tends to mixes the low-density fluid of the corona with the high-dense plasma of the compressed shell. Furthermore, during the deceleration phase, the inner surface of the compressed shell becomes RT instable [7]. The uncontrolled growth of the hydrodynamic instability could damage or destroy the capsule before reaching the stagnation thus reducing the energy gain or even avoiding ignition. To prevent the early development of this hydrodynamic instability is crucial to control the uniformity of the energy deposition.

A 3-D ray-tracing code [8] has been developed in order to evaluate the uniformity of the absorbed energy in the capsule. The spherical capsule is irradiated by a given number Nb of beams. The degree of the uniformity is evaluated as the root-mean-square (rms) deviation of the deposited energy into a volume over the sphere surface close to the critical density. The capsule implosion is assumed perfectly spherical and is calculated by mono-dimensional hydrodynamic simulations.
2. 3D Ray-tracing package
A ray-tracing package has been developed to calculate the spatial energy deposition and the absorption of a laser beam. The 1D hydrodynamics simulation performed with the code Multi-1D [9] provides the radial density and temperature profiles of the plasma. From the point of view of the ray tracing package the plasma has spherical symmetry, thus density and temperature vary only along the radial direction. The ray-tracing algorithm considers a laser beam with arbitrary direction and power profile. The beam is divided in beamlets with associated a fraction of the laser power. The directions of the beamlets are initially parallel to the beam axis. The photon trajectories of each beamlet are evaluated by solving the eikonal equation and the energy deposition along the trajectories is calculated via inverse bremsstrahlung. A detailed description of the raytracing methods is given in the Section 3 of reference [10].

2.1. 1D capsule calculations
The capsule is similar to the baseline target designed for the HiPER project [11]. The capsule shown in Fig. 1 is composed by a cryogenic shell of Deuterium-Tritium with an internal radius of 800 μm and thickness of 250 μm thus the total fuel mass is 0.68 mg. The hydrodynamic evolution of the implosion of the capsule is simulated using the Multi-1D code. The incident laser pulse power is shown in Fig. 1, the laser wavelength is 351 nm and the total incident laser energy is around 100 kJ. A maximum fuel density of 650 g/cm³ is reached in the compressed shell while the maximum areal density $\rho R = 1.6$ g/cm² and the maximum in-flight-aspect-ratio (IFAR) is 30. The density and temperature profiles evaluated by the Multi-1D code are used as input for the ray-tracing package which evaluates the laser energy deposition via inverse-bremsstrahlung.

Fig. 1. (a) All-DT capsule. (b) Temporal evolution of some selected lagrangian cells. The IFAR parameter and the incident laser power (P) are also shown as a function of time.

2.2. Irradiation uniformity
Two different laser beam configurations with 32 and 48 laser beams are considered. It is assumed that the directions of all the beams are centered. The laser intensity profile of the beams is supergaussian $I(r) = I_0 \exp(-r/\Delta)^m$, where $\Delta$ is the full width at 1/e and m the supergaussian exponent. A parametric study is performed to estimate the rms deviation $\sigma$ of the laser energy absorption. The ray-tracing package evaluates the energy deposition into the volume of plasma close to the critical density $\rho_c$ in a volume limited by the sphere where the plasma density is equal to $\rho_c$ and $\rho_c/10$.

Fig. 1. (a) All-DT capsule. (b) Temporal evolution of some selected lagrangian cells. The IFAR parameter and the incident laser power (P) are also shown as a function of time.
The parameters $\Delta$ and $m$ that define the laser profiles have been varied between $\Delta=500\ \mu m$ and $\Delta=1000\ \mu m$, while the exponent $m$ varies from 1 to 6. For each couple of values, the rms deviation $\sigma$ of the energy deposition is calculated. Fig. 2 shows the isocontour of $\sigma$ evaluated at time 1 ns as a function of $\Delta$ and $m$. It is possible to see that the minima values of $\sigma$ are near 0.16% for both configurations with 32 and 48 beams. Moreover, the configuration with 48 beams provides two minima of the rms deviation located approximately at $\Delta=650\ \mu m$, $m=2$ and at $\Delta=870\ \mu m$, $m=4.2$. The configuration with 32 beams shown only one minima around $\Delta=800\ \mu m$ and $m=3.5$ [8].

![Fig. 2. Rms deviation ($\sigma$) of the energy deposited as a function of the parameters $\Delta$ and $m$ for the (a) 32 and (b) 48 beams configurations. (c) Densities of probability to obtain a given $\sigma$ of the uniformity for the 32 and 48 beams configurations and a power imbalance of 5 %.

The uniformity in Fig. 2 is calculated assuming that all the laser beams are perfectly balanced. To perform a robustness study a set of 10000 calculations are performed varying randomly the power of the Nb beams. The power of the beams follows a Gaussian distribution characterized by a standard deviation $\sigma_P = 5\%$. The rms deviation of the uniformity provided of the 10000 calculations is fitted by a gaussian law with a mean value and a standard deviation. These Gaussian fits represent the density of probability shown in Fig. 2(c) for the two beam configurations. In this figure it is shown that for a power imbalance of 5 % the average $\sigma$ produced by the 48 beam configuration is smaller than the one due to the 32 beams configuration. Nevertheless, a quite large overlap (shadowed area) of the two densities of probability (53%) indicates that the two configurations provide the same $\sigma$ in about half of the shots [8].

3. Irradiation of a conically guided capsule.

The 3D ray-tracing package is also used to evaluate the direct irradiation of the cone of a conically guided ICF capsule. In this case, a cone with a full aperture of 30° is inserted in the capsule irradiated by the 32 beam configurations. The same capsule and laser pulse discussed in Sec. 1 are considered. The ray-tracing package is used to evaluate the direct irradiation of the cone surface $I(r,t)$ [W/cm$^2$], where $r$ is the distance from the capsule centre and $t$ the time. The intensity $I(r,t)$ has been averaged over the azimuthal angle $\varphi$. The total irradiation of the cone surface is shown in Fig. 3 as a function of the position $r$ and the time $t$. The vertical dashed line indicates the initial position of the external radius of the capsule. It is possible to see that the maximum irradiation is located inside the capsule and reach a maximum of $3 \times 10^{14}$ W/cm$^2$ [12].

The intensity $I(r,t)$ has been used as input to the code MULTI2D [13] in order to simulate the behavior of the cone under irradiation. Considering a gold cone, it is found that ablation pressures up to 5 Mbar are generated, providing a strong shock through the cone wall. In Fig. 4, are shown the density into the gold cone as a function of the distance $r$. The density refers to the time $t = 14$ ns which is one ns later the end of the laser pulse. At that time the maximum penetration of the shock wave is
about 30 μm. Thus, for our specific laser-capsule configuration, a gold cone thicker than 30 μm is needed to avoid the shock breakout [12].

4. Conclusion
A 3D ray-tracing package dedicated to the direct irradiation of an inertial confinement fusion capsule has been developed [8]. The ray-tracing has been used to evaluate the uniformity of the irradiation provided by a 32 and 48 laser beam configurations. It has been shown that the 48 beams configurations allows for a better uniformity. Nevertheless, a power balance study indicates that in about half of the shots the two configurations provide the same irradiation uniformity. The ray-tracing has been also used to analyze the direct irradiation of the external surface of a cone in a conically guided target. For a specific laser-capsule configuration it has been shown that the cone is irradiated with a peak intensity of 3 \times 10^{14} \text{ W/cm}^2 [12].

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