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Polar direct drive illumination uniformity provided by the Orion facility

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Abstract. The ten long-pulse laser beams of the Orion facility have been considered as a direct driver for the irradiation of a spherical capsule. The intrinsic root-mean-square illumination non-uniformity σ_0 has been evaluated assuming circular and elliptical super-Gaussian laser intensity profiles. Calculations accounting for nominal uncertainties in power imbalance, pointing error and target positioning have shown a degradation of the irradiation uniformity. Non-uniformity of the irradiation as a function of the capsule radius has been calculated and it has been shown that the use of the polar direct drive technique significantly improves the quality of the irradiation. Finally, it is found that an elliptical focal shape provides better symmetry results in comparison to circular ones, whilst the laser-capsule coupling is reduced.

1 Introduction

Large high-power lasers facilities represent powerful experimental tools useful for different scientific areas. These installations provide one of the few ways to access high energy density states, of interest to different fields such as e.g. astrophysics [1–3], plasma physics, particle accelerator [4–7], warm dense matter [7,8] and inertial confinement fusion (ICF) [9–12]. Several large laser facilities are operating, as for example GEKKO XII [13] in Japan and OMEGA [14,15] in USA providing useful service to a large scientific community. More recently, other laser facilities have been commissioned, the NIF [16–19] in USA, Orion [20] in UK and, still under construction, the LMJ [21] in France. In addition, a feasibility study for a european inertial fusion energy (IFE) facility is being prepared under the HiPER project [22]. The NIF facility is composed by 192 laser beams organized in 48 quads which provide a total energy of about 2 MJ at 3ω. The LMJ will provide 176 beams in 44 quads, thus the total available energy should be about 1.3 MJ.

The NIF and LMJ have been designed to work mainly in the indirect drive (ID) [10,11] context of the ICF. In the indirect drive scheme a fraction of the laser energy is first converted in a spatially uniform X-ray field which heats the target. The ID scheme is less efficient in comparison with the direct drive (DD) scheme [23,24] where several lasers illuminate directly the target. The loss in efficiency of the ID scheme is compensated by a highly-uniform irradiation of the target. Nevertheless, the high-efficiency of the DD approach could be even further improved by applying *zooming* [25–27] techniques, where the laser focal spot is dynamically adapted to the dimension of the expanding plasma corona. Moreover, the development of new direct drive schemes as the shock ignition [28,29] has motivated several groups to consider the possibility to test aspects relevant for direct drive experiments making use of these indirect drive facilities.

In this context, the Orion facility today provides a unique option in Europe to test new ideas related to direct drive schemes, as for instance the promising theoretical predictions of the polar direct drive (PDD) [30] technique. The Orion facility comprises ten long-pulse beams that deliver up to 5 kJ of ultraviolet light ($\lambda = 351$ nm) plus other two short ($\approx$0.5 ps) petawatt pulses (10^{15} W). Indeed, the ten long-pulse laser beams of Orion are organized in two cones at 50° with the polar axis, as consequence, for beam radii comparable or smaller than the capsule radius, the direct illumination of a sphere provides over-irradiation of the polar areas and an under-irradiation of the equatorial zone. In order to mitigate this negative effect it has been proposed to make use of the PDD technique, where the laser beams are re-oriented toward the equatorial plane allowing for a more uniform irradiation of the capsule.

In this work, we analyze the uniformity of the direct irradiation of a spherical capsule provided by the Orion facility. The uniformity of the irradiation is evaluated in

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the illumination approximation [31,32], thus the results should be accurate only for the initial imprint phase of the irradiation [33] when the critical radius does not evolve significantly and the ablation front low mode asymmetries are deeply imprinted by direct irradiation asymmetries. In our illumination calculations we assumed parallel beams neglecting the expansion of the corona and its density gradient scale length which implies linear photon paths. Moreover, these calculations do not deal with laser-plasma interaction (LPI) such as stimulated Raman (SRS) [34] or Brillouin (SBS) [35] scattering, or two-plasmons decay (TPD) instabilities [36,37]. Such kinds of instabilities are triggered above a threshold never achieved in the laser pre-pulse of the implosion and can be neglected.

The aim of this paper is to evaluate the use of the ten long-pulse laser beams (5 kJ in ns-length pulses) of Orion as a driver in future experiments to test some aspects of the polar direct drive technique. Moreover, the Orion configuration with ten beams at ±50° is in many aspects similar to the LMJ with 20 quads located in two rings at ±49° or to the NIF with 16 quads in two rings at ±50°; therefore, the results provided by direct drive experiments in Orion will be also of great relevance to validate options for NIF and LMJ facilities as for instance the polar direct drive [38–40] or shock ignition schemes [41,42] that should make use of the quads at around 50° for the fuel assembly.

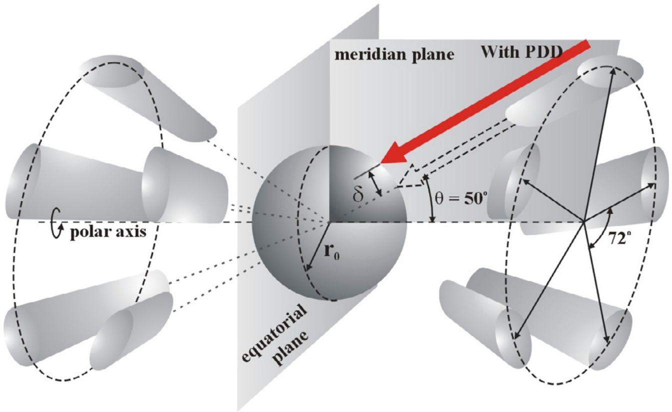

Fig. 1. Sketch of the ten laser beams of the Orion facility and of the polar direct drive scheme where the laser beams are shifted by the distance δ in their corresponding meridian (constant longitude) towards lower latitudes.

2 The Orion facility

The Orion facility (AWE-Aldermaston, UK) is the largest high-power high-energy laser facility in Europe. This laser facility offers the opportunity to perform experiments in the field of high-energy density physics. Orion is composed of twelve lasers beams, 10 of which provide a total energy of up to 5 kJ of ultraviolet light (3ω, 351 nm) in 1−5 ns long pulse. The other two laser beams provide 500 J each at 1ω (1054 nm) in a short pulse of 0.5 ps. The ten beams are located in two cones at the angles of $\theta = 50°$ and 130° with respect to a horizontal axis, which we take to be the polar axis of the capsule. They are longitudinally equally separated by 72° (see Fig. 1). In each hemisphere, pairs of beams have the same longitude so that they are not facing-on. The phase plates have been designed in order to produce a super-Gaussian circular intensity profile ($\exp-[r/\Delta]^m$) in the plane perpendicular to the polar axis of the capsule. Thus, the intensity profile of the laser beams in their own focal plane should be elliptical, with a major axis Δ_a and a minor axis $\Delta_b = \Delta_a \cos(\theta)$, which is always located in the meridian defined by the polar and beam axis.

The current configuration provides a laser intensity whose elliptical profile could be parameterized by $\exp-[(x/\Delta_a)^2 + (y/\Delta_b)^2]^{m/2}$, where (x, y) are Cartesian coordinates in the plane orthogonal to the beam axis and the coordinate y (ellipse's minor axis) is oriented in the corresponding meridian. As with all facilities, the nominal Orion configuration parameters are subject to some uncertainty and accuracy limitations. The specified root-mean-square power imbalance (PI) for the ten long-pulse beams is $\sigma_{\mathrm{PI}} = 10\%$ over a 100 ps period. Two other sources of error characteristic of the Orion facility are the pointing error (PE), which is specified as 25 μm (root-mean-square), and the target positioning (TP) which is estimated at 10 μm (root-mean-square).

3 Illumination non-uniformity

The intensity of the direct illumination $I(\theta, \varphi)$ is computed for a spherical capsule whose radius is r_0 taking into account the contribution of all ten long-pulse laser beams of the Orion facility. The non-uniformity of the irradiation, σ_0, has been evaluated as the root-mean-square deviation of the illumination function $I(\theta, \varphi)$ and is given by:

$$\sigma_0 = \left\{ \frac{1}{4\pi} \int_0^{2\pi} \int_0^{\pi} \left[I(\theta, \phi) - \langle I \rangle\right]^2 \sin(\theta) d\theta d\phi \right\}^{1/2} / \langle I \rangle, \tag{1}$$

where $<I>$ is the average intensity over the capsule surface.

A parametric study has been performed in order to evaluate the illumination non-uniformity as a function of the laser focal spot. An elliptical super-Gaussian laser intensity profile has been considered (see Eq. (2)).

$$I(x, y) = I_0 \exp - [(x/\Delta_a)^2 + (y/\Delta_b)^2]^{m/2}. \tag{2}$$

The laser focal spot is characterized by the parameter Δ_b (half-width at $1/e$ in the meridian plane) and the super-Gaussian exponent m, while the ratio $\Delta_b/\Delta_a = \cos(\theta)$ defines the elliptical semi-axis Δ_a. A series of calculations have been also performed assuming $\Delta_a = \Delta_b = \Delta$, which corresponds to a circular axis-symmetric super-Gaussian intensity profile $I(r) = I_0 \exp[-(\mathrm{r}/\Delta)^m]$.

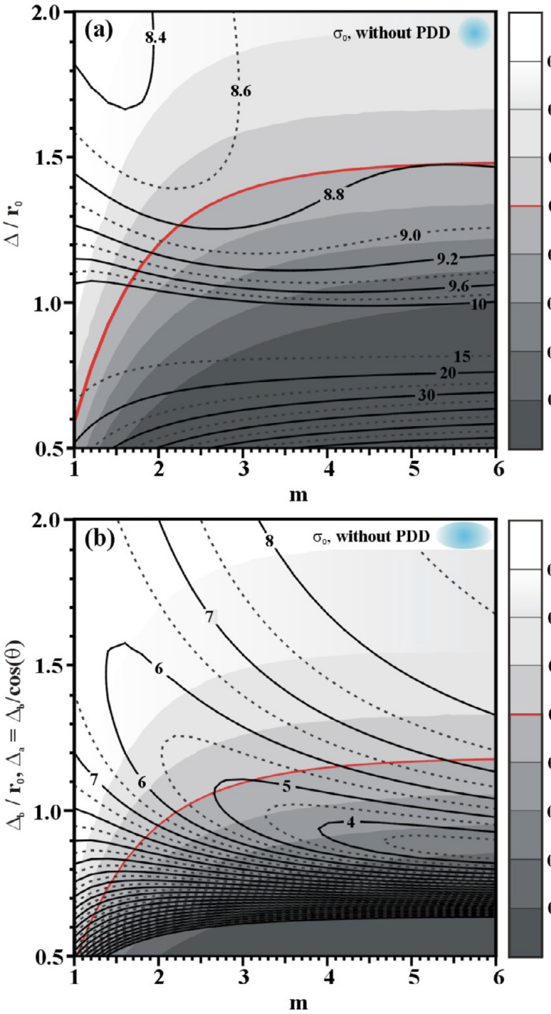

Fig. 2. Intrinsic illumination non-uniformity σ_0 corresponding to (a) the circular profile and to (b) the elliptical profile as a function of the focal spot parameters $\Delta/r_0(\Delta_b/r_0)$ and m. The gray scale shows the laser-capsule coupling η.

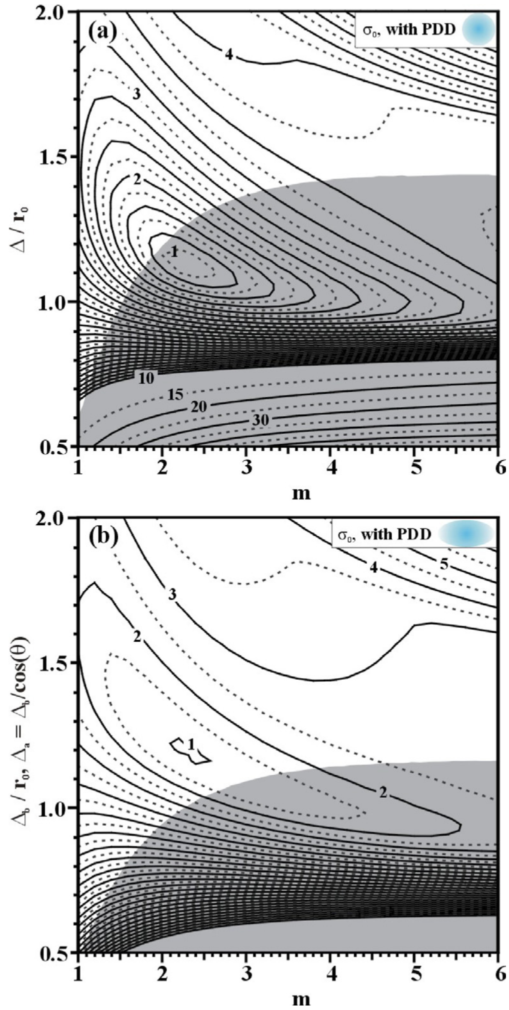

Fig. 3. Minimum non-uniformities $\sigma_0^{\mathrm{PDD}}(\Delta, m)$ evaluated using the PDD technique. (a) Circular intensity profile and (b) elliptical profile, the shadowed areas indicate a laser-capsule coupling better than 50%.

In this study the parameter Δ_b/r_0 (Δ/r_0) varies between 0.5 and 2 (where r_0 is the capsule radius) and the super-Gaussian exponent m varies between 1 and 6. We calculated the intrinsic non-uniformity σ_0 for the circular and elliptical intensity profiles. In these calculations we consider idealized laser beams perfectly balanced in power and perfectly aligned to the capsule centre. It has been found that in the case of a circular intensity profile the rms non-uniformity is larger than 8% on the whole parametric space (Fig. 2a), whilst better results are provided by the elliptical profile which show a minimum of about 3.5% at $\Delta_b/r_0 \approx 0.85$ and $m \approx 6$ (Fig. 2b). We also evaluated the laser-capsule coupling η, which is given by the ratio between the power incident to the capsule surface and the power delivered by all the laser beams. The laser-capsule coupling η is indicated in Figure 2 by the gray shadowed areas. The larger non-uniformities are provided by the circular intensity profile, whilst better results are given by the elliptical shape that allows a better longitudinal irradiation.

One way to improve the irradiation non-uniformity is by using the polar direct drive (PDD) scheme. In the PDD the laser axes are not crossing the capsule centre but are displaced in the meridian plane (at constant longitude) by a quantity δ toward the equatorial plane (see Fig. 1). A second series of calculations has been performed applying the PDD technique and assuming that the $5+5$ beams of the Orion facility are de-pointed by the same quantity δ toward the equator. In these calculations fifty positions from $\delta_{\min} = 0$ to $\delta_{\max}/r_0 = 50\%$ have been considered. For each beam intensity profile characterized by the parameters (Δ, m), we looked for the PDD factor δ/r_0 that minimizes the non-uniformity (σ_0^{PDD}). In this way, the minimum of the irradiation non-uniformity (σ_0^{PDD}) is associated to an optimum PDD factor δ/r_0. The minimum of the non-uniformities $\sigma_0^{\mathrm{PDD}}(\Delta, m)$ is shown in Figure 3. The PDD technique allows for a reduction of the non-uniformity σ_0^{PDD} when compared to the cases (σ_0) with the beam axis centered with the spherical capsule $\delta = 0$. Indeed, both laser profiles show similar results with a minimum of about 1% for a laser focal shape characterized by $\Delta/r_0 \approx 1.1$ and $m \approx 2.5$.

4 Non-uniformity accounting for beam uncertainties

We calculated the results shown in Figures 2 and 3 assuming idealized laser beams, perfectly centered and balanced in power. Moreover, we assume that the spherical target was perfectly located at the center of the whole configuration. These assumptions are somewhat idealised. In reality, as already mentioned, the beam-to-beam power imbalance in the Orion facility is about $\sigma_{\rm PI} = 10\%$, whilst the pointing error and the target positioning are $\sigma_{\rm PE} = 25\ \mu{\rm m}/r_0$ and $\sigma_{\rm TP} = 10\ \mu{\rm m}/r_0$, respectively. Thus, these two last errors depend on the dimension of the target and decreases with the capsule radius. If we assume a capsule radius $r_0 = 300\ \mu$m they become $\sigma_{\rm PE} \approx 9\%$ and $\sigma_{\rm TP} \approx 3\%$. We performed a series of calculations accounting for these beams uncertainties in order to evaluate the degradation of the non-uniformity, assuming $\sigma_{\rm PE} \approx 9\%$ and $\sigma_{\rm TP} \approx 3\%$ and a beam-to-beam power imbalance of $\sigma_{\rm PI} = 10\%$, in that way, the laser power associated to the laser beams would follow a Gaussian distribution centered to the nominal power and characterized by the standard deviation $\sigma_{\rm PI}$.

The average non-uniformity $\sigma_e^{\rm PDD}$ evaluated after a new optimization of the PDD factor and assuming the beam uncertainties $\sigma_{\rm PI} = 10\%$, $\sigma_{\rm PE} \approx 9\%$ and $\sigma_{\rm TP} \approx 3\%$ are shown in Figure 4. In both cases the PDD technique provides a significant reduction of the non-uniformity. In the case of the circular focal shape it is found a relatively wide area where the non-uniformity is about $\sigma_e^{\rm PDD} \approx 5.5\%$ whereas the elliptical profile exhibits a parametric space characterized with non-uniformities around $\sigma_e^{\rm PDD} \approx 5.0\%$. In the frames of Figure 4, the focal spot parameters that minimise the non-uniformity whilst still providing laser capsule coupling around 50%, are indicated by a black dot. In both cases the optimum laser intensity profiles are quite similar. In the case of the circular focal shape the minimum non-uniformity is $\sigma_e^{\rm PDD} \approx 5.4\%$ with $\Delta/r_0 = 1.2$, super-Gaussian exponent $m = 2.5$ and the optimum PDD parameter $\delta/r_0 = 16\%$. In the case of the elliptical laser intensity profile, the minimum non-uniformity is slightly better $\sigma_e^{\rm PDD} \approx 4.8\%$ with $\Delta_b/r_0 = 1.2$, $\Delta_a = \Delta_b/\cos(\theta)$, $m = 3$ and $\delta/r_0 = 10\%$. It is worth noting however, that the elliptical profile is associated with a lower laser-capsule coupling.

In these calculations we assumed a capsule radius $r_0 = 300\ \mu$m for which the Orion facility provide the relative beams uncertainties $\sigma_{\rm PI} = 10\%$, $\sigma_{\rm PE} = 9\%$ and $\sigma_{\rm TP} = 3\%$. In order to evaluate the relative contribution to the non-uniformity a series of 10 000 calculations have been performed varying randomly only one of the three errors and keeping constant the other two. The results are shown in Figure 5, where the three frames on the top refer to the circular intensity profile ($\Delta/r_0 \approx 1.2$, $m = 2.5$ and $\delta/r_0 = 16\%$) and the frame in the bottom correspond to the elliptical profiles ($\Delta_b/r_0 = 1.2$, $\Delta_a = \Delta_b/\cos(\theta)$, $m = 3$ and $\delta/r_0 = 10\%$). In all frames, the red continuum lines showed the average non-uniformity, whilst the dashed lines indicate the position at the distance of one standard deviation calculated assuming that the data follows a normal distribution. As can be seen both intensity profiles shown that the pointing error as well as the target positioning do not affect significantly the quality of the illumination. Indeed, the non-uniformity remains always around 5% while these errors vary from 0 to around 10%. Differently, it is found that the average non-uniformities, as well as their associated spread (one standard deviation) are mainly determined by the power imbalance. The larger gradient of the non-uniformity is found with respect to the power imbalance and the non-uniformity is reduced by more than a factor two when the power imbalance reduces from 10% to 0.

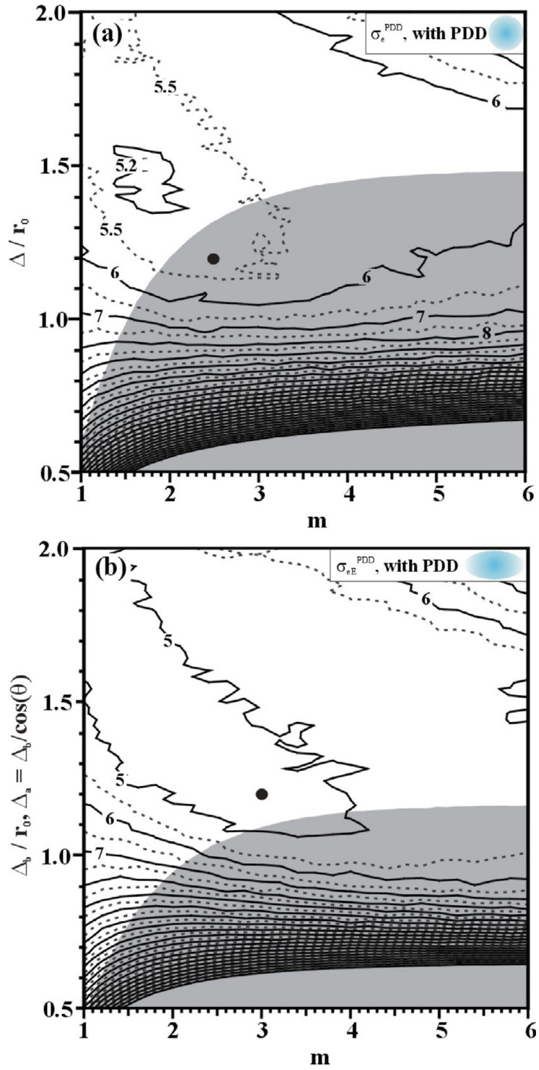

Fig. 4. Average root-mean-square non-uniformity accounting for beam uncertainties and PDD. (a) Circular intensity profile and (b) elliptical profile, shadowed areas indicate a laser-capsule coupling better than 50%.

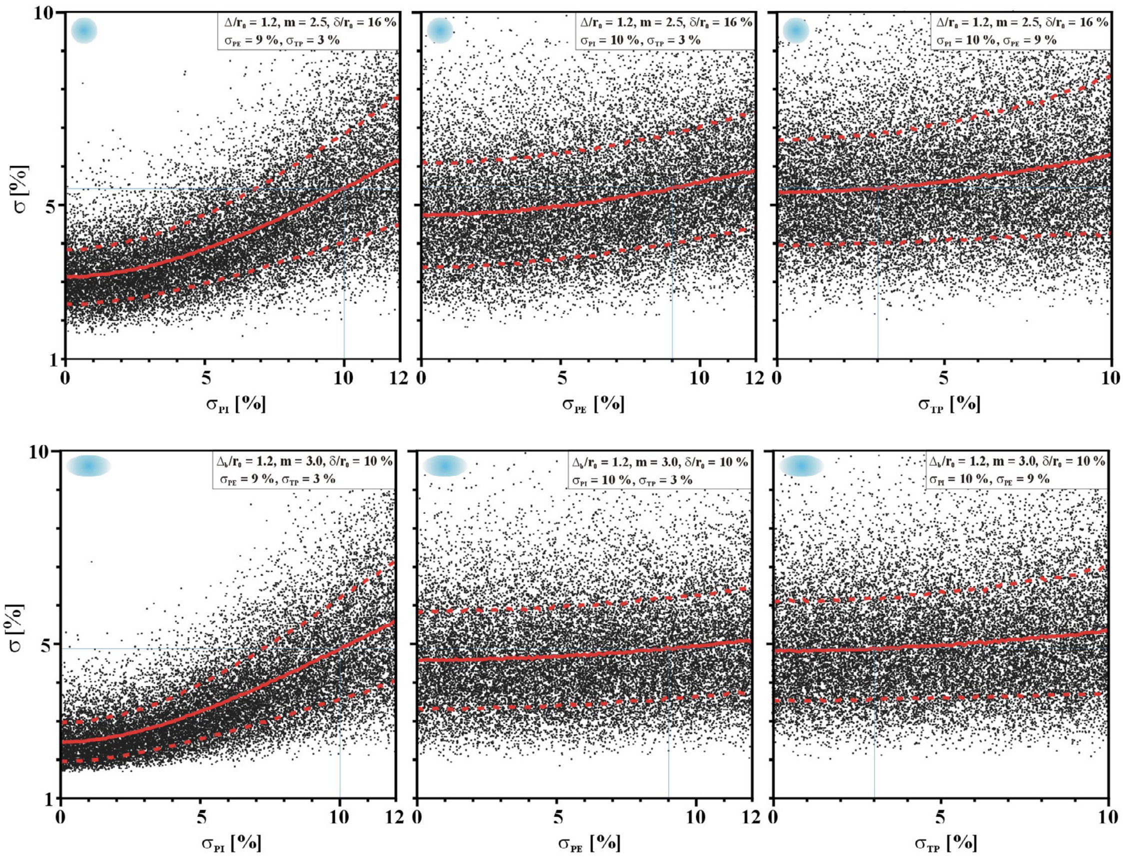

Fig. 5. Non-uniformity as a function of the power imbalance (left), pointing error (centre) and target positioning (right). The red continuum lines show the average non-uniformities and the dashed lines indicate the distance of a standard deviation. Top (bottom) frames correspond to circular (elliptical) laser intensity profiles.

5 Non-uniformity as a function of the capsule radius

The pointing error in the Orion facility is estimated to be about 25 μm and the target positioning is around 10 μm. This means that the beam uncertainties are a function of the capsule radius and become $\sigma_{\rm PE} = 25\ \mu{\rm m}/r_0$ and $\sigma_{\rm TP} = 10\ \mu{\rm m}/r_0$. A set of calculations with and without applying the PDD technique have been performed assuming a power imbalance $\sigma_{\rm PI} = 10\%$ and varying the capsule radius r_0 from 100 μm to 1000 μm. The average rms non-uniformity with ($\sigma_e^{\rm PDD}$) and without PDD (σ_e) calculated for both circular and elliptical laser intensity profiles are shown in Figure 6 as a function of the capsule radius. The parameters used are $\Delta/r_0 = 1.2$, $m = 2.5$, $\delta/r_0 = 0.16$ for the circular profile and $\Delta_b/r_0 = 1.2$, $m = 3.0$, $\delta/r_0 = 0.10$ for the elliptical case. The average rms non-uniformity has been evaluated for a set of thousand calculations for each capsule radius r_0. The non-uniformities evaluated without PDD are indicated by dashed lines in Figure 6 and shows that the elliptical intensity profile provides a better illumination.

In the calculations accounting for the PDD technique the average non-uniformities decrease considerably for both intensity profiles. In the case of a capsule radius $r_0 = 300\ \mu$m, the non-uniformities without PDD are $\sigma_e \approx 10.5\%$ and $\sigma_e \approx 7.2\%$ (circles in Fig. 6) for the circular and elliptical intensity profile, respectively. These non-uniformities decrease to $\sigma_e^{\rm PDD} \approx 5.4\%$ and $\sigma_e^{\rm PDD} \approx 4.8\%$ (black dots) applying the polar direct drive technique. Thus, for the circular profile the PDD technique allow for a reduction of around 50% whilst for the elliptical case the non-uniformity reduces about 35%. Moreover, the elliptical profile always provides an average non-uniformity lower than the circular intensity profile; furthermore, increasing the capsule radius causes a reduction of the related beam pointing and target positioning uncertainties and consequently decreases the illumination non-uniformity.

As has been shown, for a capsule of radius $r_0 = 300\ \mu$m the optimum polar direct drive parameter is about $\delta = 48\ \mu$m ($\delta/r_0 = 0.16$) and $\delta = 30\ \mu$m ($\delta/r_0 = 0.10$) for the circular ($\Delta/r_0 = 1.2$, $m = 2.5$) and the elliptical ($\Delta_b/r_0 = 1.2$, $\Delta_a = \Delta_b/\cos(\theta)$, $m = 3.0$) profile, respectively. The sensitivity of the non-uniformity with respect to the deviation from these optimal polar direct drive parameters has been analyzed. The non-uniformity evaluated for the two laser intensities profiles (black dots in Fig. 4) has been calculated as a function of the PDD parameter δ with and without beam uncertainties and the results are collected in Figure 7. It has been found that the non-uniformity varies smoothly around the optimum

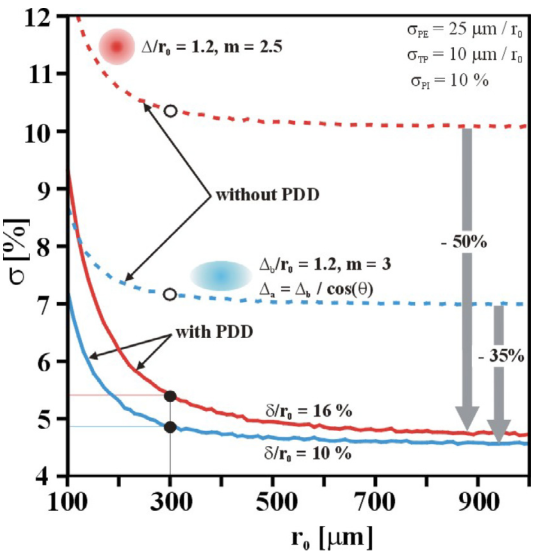

Fig. 6. Average root-mean-square non-uniformity accounting for the beam uncertainties ($\sigma_{\rm PI} = 10\%$, $\sigma_{\rm PE} = 25\ \mu{\rm m}/r_0$, $\sigma_{\rm TP} = 10\ \mu{\rm m}/r_0$) as a function of the capsule radius r_0. Calculations accounting for polar direct drive ($\sigma_e^{\rm PDD}$) are indicate by full lines and without PDD (σ_e) by dashed lines. Red lines: circular intensity profile with $\Delta/r_0 = 1.2$, $m = 2.5$, $\delta/r_0 = 0.16$; blue lines: elliptical profile with $\Delta_b/r_0 = 1.2$, $m = 3.0$, $\delta/r_0 = 0.10$.

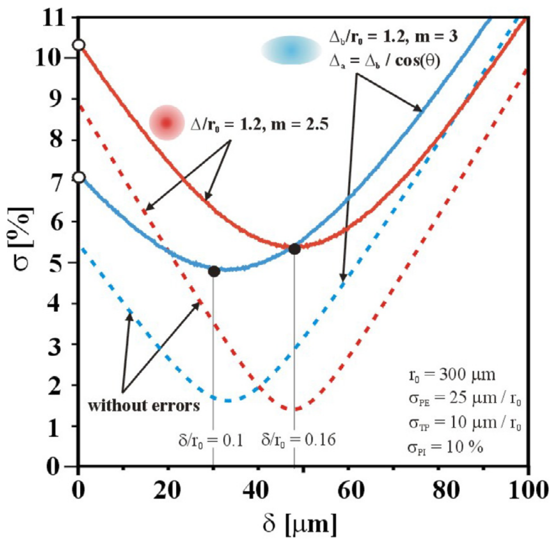

Fig. 7. Average root-mean-square non-uniformity as a function of the polar direct drive parameter δ for a capsule radius $r_0 = 300\ \mu$m. Red lines: circular intensity profile with $\Delta/r_0 = 1.2$, $m = 2.5$; blue lines: elliptical profile with $\Delta_b/r_0 = 1.2$, $m = 3.0$. Dashed lines correspond to the case without beam errors whilst full lines take into account for beam uncertainties.

PDD parameter, in the two cases accounting for beam errors the non-uniformity increases by about 10% for a shift of the PDD parameter of $\pm 20\ \mu$m.

6 Conclusions

The non-uniformity of the irradiation of a spherical capsule provided by the Orion facility has been calculated. A parametric study has been performed assuming a super-Gaussian laser-intensity profile with circular or elliptical focal shape. The circular profile is characterized by the half width at $1/e$ Δ, whilst for the elliptical focal spot the smaller half-width at $1/e$ is Δ_b and the larger semi-axis is $\Delta_a = \Delta_b/\cos(\theta)$, where $\theta = 50°$ is the angle of the laser beams with respect to the polar axis. For both intensities profile the super-Gaussian is characterized by the exponent m. Considering the circular intensity profiles, it has been found that the intrinsic non-uniformity σ_0 is always larger than 8% over a wide range of the parameters space Δ and m. Differently, in the case of elliptical profiles the intrinsic non-uniformity exhibits a minimum of about $\sigma_0 = 3.5\%$ at $\Delta_b/r_0 \approx 0.85$, $\Delta_a = \Delta_b/\cos(\theta)$ and $m \approx 6$. Beam uncertainties as power imbalance ($\sigma_{\rm PI} = 10\%$), pointing error ($\sigma_{\rm PE} = 25\ \mu{\rm m}/r_0$) and target positioning ($\sigma_{\rm TP} = 10\ \mu{\rm m}/r_0$) have been also taken into account. The average non-uniformities for a capsule radius $r_0 = 300\ \mu$m and assuming a power imbalance $\sigma_{\rm PI} = 10\%$, pointing error $\sigma_{\rm PE} = 9\%$ and a target positioning $\sigma_{\rm TP} = 3\%$ have been calculated as a function of the circular (elliptical) beams parameters $\Delta\,(\Delta_b)$ and the super-Gaussian exponent m. It has been shown that for the Orion facility the power imbalance is mainly responsible for the detriment to the illumination uniformity, whilst the pointing errors as well as the target positioning affect only marginally the final non-uniformity. For a capsule radius $r_0 = 300\ \mu$m and assuming circular (elliptical) intensity profiles a minimum non-uniformity of $\sigma_e \approx 10.5$ % ($\sigma_e \approx 7.2\%$) has been found. A significant improvement of the non-uniformity is found applying the polar direct drive technique that relocates the laser beams toward the equatorial plane. Indeed, for the capsule radius $r_0 = 300\ \mu$m, the intrinsic non-uniformity is reduced to $\sigma_e^{\rm PDD} \approx 5.4\%$ and $\sigma_e^{\rm PDD} \approx 4.8\%$ for the circular and elliptical intensity profiles, respectively. Thus, the polar direct drive reduces the average non-uniformities by about 50% for the circular profiles and around 35% for the elliptical one with respect to the results without PDD. This parameter study provides a starting point for more detailed assessments of specific configurations using hydro-codes.

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