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Progress on Octahedral Spherical Hohlraum Study

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In this paper, we give a review of our theoretical and experimental progress in octahedral spherical hohlraum study. From our theoretical study, the octahedral spherical hohlraums with 6 Laser Entrance Holes (LEHs) of octahedral symmetry have robust high symmetry during the capsule implosion at hohlraum-to-capsule radius ratio larger than 3.7. In addition, the octahedral spherical hohlraums also have potential superiority on low backscattering without supplementary technology. We studied the laser arrangement and constraints of the octahedral spherical hohlraums, and gave a design on the laser arrangement for ignition octahedral hohlraums. As a result, the injection angle of laser beams of 50 to 60 degree was proposed as the optimum candidate range for the octahedral spherical hohlraums. We proposed a novel octahedral spherical hohlraum with cylindrical LEHs and LEH shields, in order to increase the laser coupling efficiency and improve the capsule symmetry and to mitigate the influence of the wall blowoff on laser transport. We studied on the sensitivity of the octahedral spherical hohlraums to random errors and compared the sensitivity among the octahedral spherical hohlraums, the rugby hohlraums and the cylindrical hohlraums, and the results show that the octahedral spherical hohlraums are robust to these random errors while the cylindrical hohlraums are the most sensitive. Up till now, we have carried out three experiments on the spherical hohlraum with 2 LEHs on ShengGuang(SG) laser facilities, including improvement of laser transport by using the cylindrical LEHs in the spherical hohlraums on SGII prototype laser facility, spherical hohlraum energetics on SGIII prototype laser facility, and comparisons of laser plasma instabilities between the spherical hohlraums and the cylindrical hohlraums on SGIII laser facility.

Keywords: Indirect-drive inertial confinement fusion, novel spherical hohlraum with 6 LEHs, high and robust radiation symmetry, high energy coupling efficiency, theoretical study, experiments

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I. INTRODUCTION

In indirect drive inertial confinement fusion (ICF)\textsuperscript{[1, 2]}, intense lasers or charged particle beams heat the interior of hohlraums which are often made of high-Z materials to generate soft x-rays. These x-rays are used to produce the ablation pressure that compresses the D-T fuel capsule placed at the center of the hohlraum and drives it to ignition and burn. To achieve the capsule ignition, the hohlraum design is essentially important for providing a radiation field with very high symmetry required by capsule ignition and an acceptable energy. The design of hohlraum includes its wall material configuration and geometrical configuration. Relatively speaking, the wall material design is simpler than the design of the geometry. The Au-U-Au sandwich hohlraum\textsuperscript{[3]} was ultimately decided to be optimal configuration for the ignition study on the National Ignition Facility (NIF)\textsuperscript{[4–7]}, which has all advantages of the golden cocktail hohlraum\textsuperscript{[8]} while being superior in fabrication. More recently, a novel UN-U-Au sandwich hohlraum was proposed for low hard x-ray emission and high radiation temperature \textsuperscript{[9]}. In contrast, the hohlraum geometrical configuration design is rather complex, which includes the design of the hohlraum shape, size and the number of Laser Entrance Hole (LEH), and should be optimized to balance tradeoffs among the needs for capsule symmetry, the acceptable hohlraum plasma filling, the requirements for energy and power, and the laser plasma interactions. Among many requirements, the energy coupling and flux symmetry are of most concern. A higher energy coupling will economize the input energy and increase the fusion energy gain. More importantly, a very uniform flux from the hohlraum on the shell of capsule is mandatory because a small drive asymmetry of 1\% \textsuperscript{[2]} can lead to the failure of ignition. In fact, the small flux asymmetry will be magnified during the compression process due to the varied kinds of hydrodynamic instabilities and results in a serious hot-cold fuel mixture that can dramatically lessen the temperature or density of the hot spot for ignition. Moreover, the hohlraum geometrical configuration also decides the laser beam arrangement and the geometrical configuration of a laser facility, which usually costs billions of dollars for ignition goal. The current largest laser facility in the world, the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) in California, which was funded by the U. S. Department of Energy and costed $3.5 billion, with 192 laser beams at 1.9 MJ and 520 TW. Aiming to achieve ignition via indirect-drive approach, the NIF was designed for the cylindrical hohlraums.

Up till now, various hohlraums with different shapes have been proposed and investigated, such as cylinder hohlraum\textsuperscript{[1, 2]}, rugby hohlraum \textsuperscript{[10–15]} and elliptical hohlraum \textsuperscript{[16], [17]}.
respectively. For lasers in NIF, there are 192 beams entering the target chamber in 48 quads, arrayed in 8 cones, forming angles with the hohlraum axis of 23.5°, 30°, 44.5°, and 50° from each side. These cones of beams contain 4, 4, 8, and 8 quads, respectively, on each side. The lasers at 23.5° and 30° form the inner ring, and the lasers at 44.5° and 50° form the outer ring. The positions of the two laser rings and their separation are designed to control $P_4$, while the power in the individual rings is varied independently, called as beam phasing, to control time-dependent $P_2$ [2]. In NIF, there are wavelength shifts between the inner and outer beams and an additional wavelength shift between the two cones of inner beams, shifted by a few angstroms and called as three-color technology [18, 19]. The slightly different color of the different cones makes it possible to transfer energy from one set of beams to another, providing an additional technique for controlling low modes radiation flux symmetry. With double laser rings, beam-phasing and three-color technology, it was believed that a quasi-spherical radiation with very high symmetry can be creased on capsule and the goal of ignition can be realized on NIF.

Nevertheless, the National Ignition Campaign (NIC), established prior to the completion of NIF in 2009 under the American National Nuclear Security Administration of DOE in 2005 with the goal to demonstrate ignition and gain by the end of financial year 2012, was ended with an unsuccessful result[20–22], and the NIC fails to generate fusion energy until today. From NIF experiments, the low mode asymmetry, the serious Laser Plasma Instabilities (LPI) of the inner laser ring, and the hydrodynamic instabilities of capsule are serious issues that the NIC had met [18].

Recent work [23] at the NIF observed fusion fuel gains exceed unity by using a high-foot implosion method, which is a manipulation of the laser pulse shape in a way that reduces instability in the implosion. Their experiments showed an order-of-magnitude improvement in yield performance over past deuterium-tritium implosion experiments the fuel energy gain. This work is an important milestone in the history of the inertial confinement fusion study. However, from the neutron image measured in that work, the hot spot at bang-time is still far from a sphere. Further analysis showed that its Legendre polynomial mode $P_2$ is as high as 34%. This result indicates that the capsule symmetry, strongly connected to the hohlraum geometry, still remains a serious issue even for such a high-foot design inside a fine designed cylindrical hohlraum. From Ref. [24], the maximum allowed applied $P_2$ and $P_4$ are time-dependent during whole implosion process of capsule, and the allowed $P_4$ is about 3% and the allowed $P_2$ is smaller than 1% at laser peak. Up till now, the experiments fielded on NIF have shown that it is hard to maintain such a high symmetry during the entire capsule implosion process inside the cylindrical hohlraum, even by using the supplementary technologies [24, 25].

Here, we have some comments on the cylindrical hohlraums. (1) It should be kept in mind that the capsule asymmetry inside a cylinder strongly depends on time, direction and radiation spectrum. Also, LPI is a function of time, space and frequency. Therefore, it has to be considered that whether it is possible to use the beam phasing technology and
the three-color technology to control the asymmetry and LPI inside a cylindrical hohlraum in whole dimensions of time, space and radiation spectrum? Driven by a radiation without high symmetry, it is certainly hard to have a capsule implosion with low hydrodynamic instabilities. (2) Compared to elliptical hohlraum and spherical hohlraum, the capsule asymmetry inside the cylindrical hohlraums is most sensitive to random variations, which will be discussed later in Sec. III. (3) The mode coupling inside a cylindrical hohlraum is most serious [16, 17]. In other words, \( P_4 \) can be aroused by \( P_2 \) even if \( P_4 \) is eliminated by designing the positions of the double laser rings while \( P_2 \) still exists due to the unpredictable LPI of inner laser ring, and vice versa. (4) The refracted laser of outer ring and nonlinear phenomena aroused by inner ring may seriously influence the capsule performances. Especially, the inner ring transports very close to capsule, and strong LPI may be aroused by the ablated plasmas of capsule. (5) The energy coupling efficiency from capsule surface to ignition hot spot is strongly affected by the radiation symmetry. Without a high symmetry, this efficiency and therefore the energy efficiency from laser to the hot spot will seriously decrease as compared to one-dimensional case. (6) The laser arrangement is not pure, or not real, two-dimensional on NIF. In fact, it has only four laser quads at 23.5 and four at 30, especially with partially overlapping on hohlraum wall. For the rugby hohlraums and the elliptical hohlraums, although with some improvement on capsule symmetry, they still have cylindrically symmetry with two LEHs on the ends and with \( P_2 \) and \( P_4 \) dominating capsule asymmetry. Therefore, they also need double laser rings to adjust for a quasi-spherical radiation on capsule. Thus, the issues met in the cylindrical hohlraums are hard to be thoroughly avoided in the rugby hohlraums and the elliptical hohlraums.

Due to above problems met in the cylindrical hohlraums, people have to think about a hohlraum which has natural high symmetry without supplementary technologies. Intuitively, spherical hohlraum has the feature of the most symmetry compared to other geometric shapes. In fact, the spherical hohlraums with 4 LEHs or 6 LEHs began to be investigated both theoretically [26, 27] and experimentally [28–30] since more than twenty years ago. At the ISKRA-5 laser facility of Russian Federal Nuclear Center in Russia, an iodine laser with 12 beams operating at a 1.315 \( \mu \)m laser wavelength was used to drive a Cu spherical hohlraum of 6 LEHs with a 10 kJ laser with pulse duration of 0.3 - 0.4 ns. In their experiment, a glass capsule filled with DT gas was used, and the hohlraum-to-capsule radius ratio was taken as 7. The neutron yield observed from their experiment agreed well with calculations from their 1D spherically symmetrical hydrodynamic code SNDP[29], and a flux asymmetry of 3% was obtained. At the OMEGA laser facility of University of Rochester in America, the 60 laser beams were used to test the concept of tetrahedral hohlraum, i.e., spherical hohlraum with 4 LEHs. Again, the observed capsule neutron yields agreed with their 1D simulations using the radiation-hydrodynamics code LASNEX, which gave time-averaged flux asymmetries as low as 1% rms over a 2.2-ns laser pulse. All these investigations have shown the advantage of a spherical hohlraum in high uniformity. However, three sets of laser beams are needed for a 4-LEH spherical hohlraum in order to minimize the flux asymmetry by varying the relative power [27, 28], thus a 4-LEH spherical hohlraum has no superiority over a traditional cylindrical hohlraum on this point. For the 6-LEH spherical hohlraums, a wide range of the hohlraum-to-capsule radius ratio from 2.5 to 7 was used in the studies [26, 29], but an optimum ratio has not been addressed. As we know, the radius ratio is a crucial parameter which strongly concerns the flux symmetry and hohlraum energetics in an ignition target design. Moreover, a detailed study and a design of the laser arrangement for the octahedral spherical hohlraums have not been discussed in previous publications, which is crucial important for building a laser facility for using the octahedral hohlraums to achieve ignition.

In fact, the spherical hohlraums with 4 LEHs, also called as tetrahedral hohlraum, was also considered by the LLNL scientists in their proposal work for NIF design [2] and was considered as the third ICF alternative to cylindrical hohlraums and direct drive in the NIF design [56]. However, they rejected the spherical hohlraum in their ignition study and design because...
of the following reasons: “In a spherical geometry, proper placement of the beams would result in very high angles of incidence as the beam pass through the LEHs. Such high angles can result in clipping of the beam on the LEH or a very large LEH. Alternatively, in a sphere, the beams can be aimed past the capsule toward the opposite LEH. This can work for short pulses, but capsule blowoff interferes with beam propagation for longer pulses. There are some spherical laser-driven hohlraums that have more than two holes. These designs must balance the increased LEH radiation losses with a potentially smaller case.” They chose the cylindrical hohlraum because of the following reasons: “In general, laser-driven hohlraums designed to achieve radiation symmetry with two laser entrance holes (LEHs) are elongated with a length-to-diameter ratio greater than unity. Such a geometry arises from the need to balance the absence of x-ray emission from the LEH by locating the laser beams, which have higher emission than the rest of the hohlraum wall, relatively close to LEH.” [2].

In China, we began to study the spherical hohlraums with 6 LEHs of octahedral symmetry, called as octahedral spherical hohlraum, for both indirect-drive fusion and hybrid drive [32] fusion in theory since 2013 [33–38], and began to do spherical hohlraum experiments on Shenguang (SG) series of laser facilities [40–43] since 2014. From our theoretical study, the octahedral spherical hohlraums have a natural high and robust symmetry on capsule and a high coupling energy efficiency from laser to ignition hot spot without supplementary technologies. We studied the laser arrangement and constraints of the octahedral hohlraums, and gave a design on laser arrangement for ignition octahedral spherical hohlraum. In order to mitigate the influence of the wall ablations on laser transport and to increase the laser coupling efficiency and improve the capsule symmetry, we proposed a novel octahedral hohlraum with LEH shields and cylindrical LEHs. The experimental study is very important for checking our theoretical results and helping to improve physical understanding for a practical octahedral spherical hohlraum design for ignition goal. However, our SG series of laser facilities were all designed for the cylindrical hohlraums, and they are not suitable for the experiments on the spherical hohlraums with 6 LEHs. Shown in Fig. 1 is the laser bay of SGIII laser facility, and in Fig. 2 is the target chamber. Nevertheless, many essential physics included in the hohlraum energetics, such as the laser transport inside hohlraum, laser-plasma coupling, laser-plasma instabilities and LEH closure of the octahedral hohlraums, can be studied by using a spherical hohlraum with 2 LEHs. Therefore, the experiments on these processes can be done on SG laser facilities with the spherical hohlraums of 2 LEHs. Since 2014, we have done experiments on improving laser transport by using the cylindrical LEHs in the spherical hohlraums on SGIII prototype laser facility, on spherical hohlraum energetics on SGIII prototype laser facility, and on comparison of LPI between the spherical hohlraums and the cylindrical hohlraums on SGIII laser facility. We have got very nice data with good reproducibility from all these experiments, and the experimental results agree well with our theoretical predictions.

The octahedral hohlraum and its corresponding laser arrangement geometry is flexible and can be applicable to diverse inertial fusion drive approaches such as indirect drive, direct drive [30], and hybrid indirect-direct drive [32]. In this paper, we focus on the Indirect Drive inertial fusion, and will present our theoretical and experimental progress on the octahedral spherical hohlraum study. In Sec. II, we will present our theoretical study on the capsule symmetry inside the octahedral spherical hohlraums by using the view-factor model. In Sec. III, we present our results on the sensitivity of the octahedral spherical hohlraums to random errors arising from the power imbalance, the pointing errors of laser quads, and the assemblage error of capsule. In Sec. IV, we discuss on the energy coupling efficiency of the octahedral spherical hohlraums. In Sec. V, we discuss the laser arrangement and the constraints of the laser arrangement inside the octahedral hohlraums. In the octahedral hohlraum, the laser transport inside the hohlraum may be a critical issue because of the geometrical curvature of sphere. In addition, both the laser-to-capsule energy coupling efficiency and the capsule symmetry may decrease when big LEHs are used. We therefore proposed a novel octahedral hohlraums which can alleviate these potential issues. In Sec. VI, we present this kind of novel octahedral spherical hohlraums. In Sec. VII, we introduce the spherical hohlraum experiments implemented on SG Laser Facilities. In Sec. VIII, we present a summary.

![FIG. 5: (color online) Variations of $|\Delta F/F|$ as $R_C/R_C^*$.](image)

![FIG. 6: (color online) Variations of $C_{\text{loss}}$ as $R_C/R_C^*$.](image)
For convenience, we consider that an octahedral hohlraum has two poles and an equator though it is round. In our reference frame, we put the six LEHs of octahedral hohlraum in this way: one at per pole and four along the equator coordinately. In the hohlraum system, \( \theta \) denotes the polar angle and \( \phi \) denotes the azimuthal angle. We use \( R_H \) to express the hohlraum radius, \( R_C \) the capsule radius and \( R_L \) the LEH radius. The laser beams are clustered in quads of several beams. For example, a quad is a sets of four beams on NIF. We assume the quad shape at LEH to be round and use \( R_Q \) to denote the quad radius at LEH. Each quad through a LEH is characterized by \( \theta_L \) and \( \phi_L \), where \( \theta_L \) is the opening angle that the quad makes with the LEH normal direction and \( \phi_L \) is the azimuthal angle about the normal of the LEH. According to our design for the octahedral hohlraums, the laser beams are arranged at the same \( \theta_L \) for each LEH. In other words, 1/6 of total laser beams enters into hohlraum from each LEH at only one cone in our octahedral hohlraum design. Here, it is worth to compare our octahedral hohlraum design with the cylindrical hohlraums designed for NIF. In the latter, 1/2 of total laser beams enters into hohlraums from each LEH at four different laser cones with angles varying from 23.5° to 50°. Obviously, the cylindrical hohlraums have very “crowed” LEHs, while the octahedral hohlraums have relatively “easy” LEHs. Thus, a smaller LEH size should be allowable for the octahedral hohlraums, which certainly needs to be checked in future experiments.

In Fig. 3, we present the scenography of the octahedral hohlraum with six LEHs and laser spot of 48 quads and its pattern in the \( \theta \phi \) plane, by taking \( R_H=5.5 \) mm, \( R_L=1.2 \) mm and \( \theta_L=55^\circ \). The laser beam shape at LEH is round with 0.55 mm in diameter. Notice that the round laser spot shape on hohlraum wall is different from what we used in our previous papers, in which the laser beam waist is round while its profile at LEH plane is elliptical. The lasers used in this paper have an elliptical waist and their profiles at LEH plane are round, in order to balance tradeoffs between the laser intensity and the possibility of clipping the LEH. Before discussing the capsule symmetry inside the octahedral hohlraums, it is worth to have a look at the flux distribution on capsule surface inside the octahedral spherical hohlraum. We consider an capsule with radius of 1.1 mm. The relative flux of the laser spot, the hohlraum wall and LEH are denoted as \( F_{\text{spot}} \), \( F_{\text{wall}} \) and \( F_{\text{LEH}} \), respectively. According to the experimental results and theoretical studies [2, 44, 45], we take \( F_{\text{spot}} : F_{\text{wall}} : F_{\text{LEH}} = 2:1:0 \). Shown in Fig. 4 is the flux distribution on the capsule. We define the ratio \( |\Delta F|/\langle F \rangle \) as the flux asymmetry, in which \( |\Delta F| = \langle F_{\text{max}} \rangle - \langle F_{\text{min}} \rangle \) and \( \langle F \rangle \) is the average value of flux \( F \) upon the capsule. As shown, the flux asymmetry on capsule is about 0.2% for this case. This result is obtained by using our three-dimensional(3D) View Factor code VF3D, which was exploited by using the view factor model [10] to investigate the three-dimensional radiation flux distribution on the capsule surface numerically.

As presented in our previous paper[33], we used a a simple model to prove that a golden hohlraum-to-capsule radius ratio around 5 exists for an octahedral hohlraum, at which the flux asymmetry can reach its minimum. In that simple model, the LEHs are treated as the negative sources, and the wall and the laser spots are treated as a homogeneous background by neglecting their flux differences. This result from the simple model was further confirmed by calculation results from VF3D[33]. In this review paper, we check the golden hohlraum-to-capsule radius ratio by varying the capsule radius inside a given octahedral hohlraum to mimic the capsule implosion process. We take the same laser parameters as presented in Fig. 3, while consider an octahedral hohlraum with \( R_H=4.4 \) mm and \( R_L=1 \) mm. We vary \( R_C/R_C^* \) from 1 to 8, here \( R_C^* \) is the imploding capsule radius. Notice that \( R_C \) is the initial radius of capsule. The black solid line shown in Fig. 5 is variation of \( |\Delta F|/\langle F \rangle \) as \( R_C/R_C^* \) on the capsule. As indicated, an asymmetry minimum does exist at \( R_C/R_C^* \approx 2 \), i.e., \( R_H/R_C=4.86 \), close to the golden ratio which we got in our previous paper [33] but with
some difference. This difference is caused by the assumptions used in the simple model. In order to distinguish the asymmetry contributions from LEH and laser spot, we use VF3D to calculate the asymmetry of spherical hohlraum with only octahedral 6 LEHs or only 48 laser quads, respectively. As shown in Fig. 5, the asymmetry contributed by the LEHs is larger than that by the spots, and the asymmetry minimum is thoroughly due to the six LEHs. That is why \( R_H/R_C \) of the minimum asymmetry from the simple model agrees so well with that from the view factor model. In fact, it is reasonable that the LEH dominates the asymmetry inside an octahedral hohlraum, because the LEH number is much less than the laser spot number and also the large numbers of laser spots distribute much more homogeneously on hohlraum wall. Because the contribution of the laser spots to capsule asymmetry is small, so the asymmetry is insensitive to the movements and other nonlinear properties of the laser spots. This is one of the superriorities of the octahedral hohlraum, quite different from the case for the elongated cylindrical hohlraums with two LEHs on the ends. Notice the red line in Fig. 5, which is the asymmetry contribution of six LEHs and the wall, reaching its minimum at \( R_H/R_C = 1.244 \), i.e., \( R_H/R_C = 4.98 \), much closer to the golden radius ratio from the simple model. Here, it is worth to mention the pioneer experiments on 6LEH spherical hohlraum fielded at the ISKRA-5 facility with 12 laser beams [29], in which the ratio is taken as \( R_H/R_C = 7 \). Obviously, it costed much more laser energy than the case if an octahedral hohlraum with \( R_H/R_C \leq 5 \) were used in their experiment, or a much higher radiation flux can be obtained if they had used a smaller octahedral hohlraum with \( R_H/R_C \).

It is very interesting to notice that the minimum of \( C_{4m} \) happens at around \( R_H/R_C = 5 \), the minimum of \( C_{6m} \) at around \( R_H/R_C = 4 \), and the minimum of \( C_{8m} \) at around \( R_H/R_C = 6 \). In fact, it is thoroughly due to the asymmetry smoothing factor on capsule inside a concentric spherical hohlraum[1, 2, 10]. The smoothing factor depends on mode number \( l \) but not on the directional mode number \( m \), because the choice of the direction of the polar axis is arbitrary for spherical symmetry. Presented in Fig. 7 is the smoothing factors of \( Y_{2m}, Y_{3m}, Y_{6m}, Y_{8m} \) in a spherical hohlraum versus \( R_H/R_C \). As shown: (1) the smoothing factor decreases as the \( R_H/R_C \) increases, and tends to constant at very large \( R_H/R_C \); (2) the smoothing factors of \( Y_{2m} \) and \( Y_{3m} \) are much less reduced, especially at \( R_H/R_C \leq 5 \); (3) the smoothing factor of \( Y_{4m} \) reaches zero at around \( R_H/R_C = 5 \), and \( Y_{6m} \) at around \( R_H/R_C = 6.4 \); (4) the smoothing factor of \( Y_{6m} \) reaches zero twice, respectively at around \( R_H/R_C = 2.9 \) and 4.06; and it is smaller than 0.2% in between.

By using the smoothing factor, it is easy to understand why the double laser rings are needed for the 2LEH cylindrical hohlraums or the 4LEH spherical hohlraums, in which it is \( Y_{2m} \) or \( Y_{3m} \) dominating their capsule asymmetry while the smoothing factors of \( Y_{2m} \) or \( Y_{3m} \) are hard to be reduced by using a hohlraum with \( R_H/R_C \) less than 5. Therefore, these hohlraums need double laser rings to help to create a quasi-spherical radiation on capsule via beam phasing technology. This technology is very effective in simulations. Nevertheless, the NIF experiments have shown that it is not so effective in the experiments as expected in the simulations [18, 23].

For the octahedral spherical hohlraums, the asymmetry is dominated by \( Y_{4m} \) whose smoothing factor reaches zero when \( R_H/R_C \) is about 5, just around the golden radius ratio. Thus, the golden radius ratio is very important if one wants to have a very small initial capsule asymmetry inside an octahedral hohlraum. Usually, the symmetry requirements are strong during the initial phases of an ICF implosion in order to have the shock synchronism to generate the appropriate entropy profile to across the shell and uniform enough velocity to achieve a high convergence ratio.

Also, the ignition capsule requires a much smaller time-averaged capsule asymmetry than time-dependent asymmetry [2, 24]. According to Ref. [2], the capsule can tolerate less than about 1% time-averaged asymmetry, while it can tolerate from 5% to 10% time-dependent swings in asymmetry that last for about 2 ns, and can tolerate even larger swings if they last much less than 2 ns. Notice that what we used in Fig. 5 is the absolute value of \( \Delta F/F \), and in fact \( \Delta F/F \) changes its sign at the golden radius ratio. It means that the averaged asymmetry inside an octahedral hohlraum can be smaller than

![FIG. 9: (color online) Contours of initial \( C_{44} \) in the plane of \( R_H/R_C \) and \( R_L/R_C \).](image-url)
both initial asymmetry and the asymmetry when capsule is several times compressed inside an octahedral hohlraum with $R_H/R_C$ smaller than the golden radius ratio. In other words, both time-averaged and time-dependent capsule asymmetries can be very small inside an octahedral hohlraum with well desig

![Graph](image1.png)

**FIG. 10:** (color online) Contours of $C_{40}$ in the plane of $R_H/R_C$ and $R_L/R_C$. In this figure, we assume that the capsule is 4 times compressed and take $R_C^* = 0.25R_C$ in calculation.

![Graph](image2.png)

**FIG. 11:** (color online) Contours of $C_{44}$ in the plane of $R_H/R_C$ and $R_L/R_C$. In this figure, we assume that the capsule is 4 times compressed and take $R_C^* = 0.25R_C$ in calculation.

During the implosion process, the capsule is compressed and its radius becomes smaller and smaller. Thus, the solid angle of LEH opened to capsule becomes larger and larger, which may changes the capsule asymmetry during implosion. Nevertheless, from Fig. 5, the capsule asymmetry changes little when the capsule radius is compressed to more than 2.8 times of its initial radius. Considering that the ignition capsule is usually compressed to one-fourth of its initial radius when the drive laser stops, we can therefore use the asymmetries at $R_C^*/R_C = 1$ and 4 to characterize the capsule asymmetry during whole implosion process. In another hand, the capsule asymmetry dominated by $C_{40}$ and $C_{44}$ inside the octahedral hohlraums depends only on two ratios, i.e, $R_H/R_C$ and $R_L/R_C$. Hence, we can give the contour lines of $C_{40}$ and $C_{44}$ in the plane of $R_H/R_C$ and $R_L/R_C$ at $R_C^*/R_C = 1$ and $R_C^*/R_C = 4$, as shown in Figs. 8-11, to approximately describe the radiation asymmetry on an imploding capsule inside an octahedral hohlraum. Also, we can use these four figures to give an initial design of $R_H$ and $R_L$ of an octahedral hohlraum for a given ignition capsule with radius $R_C$ if the requirements on $C_{40}$ and $C_{44}$ are known, before using 2D or 3D hydrodynamic codes to select the optimum hohlraum size by simulations which usually costs huge computer resources and times for design.

From Figs. 8-Fig. 11, we obtain following results: (1) The values of $C_{40}$ and $C_{44}$ are very close, and $C_{44}$ is little larger than $C_{40}$ in the ranges of $R_H/R_C$ and $R_L/R_C$ which are concerned in the ignition target design. (2) $C_{44}$ at $R_C^*/R_C = 1$ is very tolerable to $R_L/R_C$ at $R_H/R_C \geq 4.7$. Assuming that an initial $C_{44} < 0.8\%$ is required by an ignition target design,
then we can take $R_L$ up to $1.45R_C$ at $R_H = 4R_C$ and $R_L$ up to $1.6R_C$ at $R_H = 4.1R_C$. (3) However, $C_{44}$ at $R_C/R_C = 4$ is relatively sensitive to both $R_L/R_C$ and $R_H/R_C$, and a smaller $R_L/R_C$ is required at a given $R_H/R_C$ if the requirement on $C_{44}$ at $R_C/R_C = 1$ is the same as that at $R_C/R_C = 4$. For example, again assuming that $C_{44} < 0.8\%$ at $R_C/R_C = 4$ is required, then we can take $R_L$ only to $1.12R_C$ at $R_H = 4R_C$, and $R_L$ to $1.36R_C$ at $R_H = 5R_C$. For a capsule with $R_C = 1.1$ mm inside the octahedral hohlraum shown in Fig. 3, we have $R_H/R_C = 5$ and $R_L/R_C = 1.09$. Then, we get initial $C_{40} = 8.8 \times 10^{-5}$ and $C_{44} = 1.08 \times 10^{-4}$ from Fig. 8 and Fig. 9, and $C_{40} = 4.4 \times 10^{-3}$ and $C_{44} = 5.3 \times 10^{-3}$ at $R_C/R_C = 4$ from Figs. 10 and 11.

Notice that the limitation on the choice of the LEH size discussed above is only due to the capsule symmetry requirement. In fact, the LEH size is also determined by the available laser energy, the laser plasma instabilities, the radiation flux produced in hohlraum, and the laser parameters including the laser injection angle and beam size at LEH [34]. The radiation flux leads the closure of LEH, and it must leave enough room for the LEH closure in the LEH size design. However, the influence of the laser plasma instabilities on the LEH size is not clear yet and it needs to be further explored in future experimental and theoretical study.

One may be interested in why we call a spherical hohlraum with 6 LEHs as an octahedral hohlraum. Here, we give the reasons. For a spherical hohlraum with 6 LEHs, it is an octahedron when one connects the 6 LEH centers by straight lines. In addition, it separates the spherical hohlraum into 8 coordinate parts with the same laser spot distribution on each when one connects the 6 LEH centers by the shortest curves along the sphere surface. At the golden radius ratio, it is the laser spots from these 8 coordinate parts which mainly arouse the asymmetry on capsule and it is the spherical harmonic modes $Y_{8m}$ which dominate the capsule asymmetry, while the asymmetry from the six LEHs goes to zero [33].

### III. ROBUST HIGH SYMMETRY

The radiation asymmetry on capsule can be divided into the intrinsic component and the random component. The intrinsic asymmetry arises from the hohlraum design, including the hohlraum geometrical structure, the laser spot distribution on hohlraum wall and the corresponding parameters. The random asymmetry arises mainly from the laser power imbalance, the laser pointing accuracy and the assemblage accuracy of capsule. The intrinsic asymmetry is decided by the natural characteristic of hohlraum in radiation symmetry, while the random asymmetry is strongly connected to the hohlraum sensitivity to the random errors. In last section, our investigations have demonstrated that the spherical hohlraum has the natural superiority in radiation symmetry because of its very low intrinsic radiation asymmetry. In this section, we present our results on the asymmetry sensitivity of the octahedral spherical hohlraum shown in Fig. 3 to random errors.

We adopt the strategy of randomly sampling to investigate the random radiation asymmetry arising from the power imbalance and pointing errors of laser quads and the assemblage error of capsule [36]. By statistically analyzing the results obtained by the 3D view factor model, we can get the sensitivity of the spherical hohlraum to the random variations. In Fig. 12, we present the random radiation asymmetry $|\Delta F/F|_R$ as a function of assemblage accuracy of capsule, power imbalance and pointing accuracy of laser quads in the octahedral spherical hohlraum. The sampling ranges are up to 150 $\mu$m for assemblage accuracy of capsule, 15% for power imbalance and 170 $\mu$m for pointing accuracy, respectively. As shown, $|\Delta F/F|_R$ increases up to less than 0.4% in these sample ranges. Therefore, the capsule asymmetry is extremely insensitive to these random errors, and the octahedral hohlraums have a robust high symmetry.

![FIG. 13: (color online) Contours of $\eta_{H-C}$, the energy coupling efficiency from hohlraum to capsule, for the octahedral hohlraums in the plane of $R_H/R_C$ and $R_L/R_C$.](image1)

![FIG. 14: (color online) Contour lines of $\eta_{H-C}$ (green lines) and contour regions of $C_{44} \geq 8 \times 10^{-3}$ at $R_C = R_C$ (grey part) and at $R_C = 0.25R_C$ (black part) for the octahedral hohlraums in the plane of $R_H/R_C$ and $R_L/R_C$. This figure is used to give an initial design of the octahedral hohlraums at the available laser energy by assuming that the asymmetries of $C_{40} < 8 \times 10^{-3}$ and $C_{44} < 8 \times 10^{-3}$ is required both at $R_C = R_C$ and at $R_C = 0.25R_C$. The grey and the black regions should be avoided in the design. Because $C_{40}$ is usually smaller than $C_{44}$, so the contour regions of $C_{40}$ is not presented in this figure.](image2)
and rugby hohlraums to these random errors in our previous work [36]. From our study, the random radiation asymmetry in the spherical hohlraums arising from the power imbalance of the laser quads is about half of that in the cylindrical hohlraums; the random asymmetry arising from the pointing error is about an order-of-magnitude lower than that in the cylindrical hohlraums; and the random asymmetry arising from the assemblage error of capsule is about one third of that in the cylindrical hohlraums. These results mean that the spherical hohlraum is the most robust to these random errors, while the cylindrical hohlraum is the most sensitive to these random variations. Thus, the octahedral hohlraums can remarkably relax the requirements to the power imbalance and pointing accuracy of laser facility and the assemblage accuracy of capsule, and therefore they have naturally high robust high symmetry without any additional technologies.

In fact, it is easy to understand why the spherical hohlraum is the most insensitive to the random variations and has a robust high symmetry. For a capsule inside an octahedral hohlraum, the 48 laser spots look like stars distributed on a round sky. Caused by the plasma evolution, the spot movement and the capsule implosion, all “stars” are synchronously either closer or farer to the capsule during the laser pulse, always keeping a round sky for the capsule with a high symmetry. Nevertheless, it is quite different for a 2-LEH cylinder hohlraum. For the latter, the sky of the capsule is a cylinder and the asymmetry on capsule is strongly connected to the length-to-radius ratio of the cylindrical emission sky, while this ratio is changed remarkably with plasma evolution and the spot movement, and it becomes larger and larger during the laser pulse. Thus, the capsule asymmetry inside a cylinder is strongly time-dependent and needs to be controlled with the inner/outer cone ratio for the cylindrical hohlraums on NIF.

IV. HIGH ENERGY COUPLING EFFICIENCY

In a hohlraum driven by a laser pulse, the radiation temperature in steady-state conditions can be related to the input laser power by the power balance:

\[ \eta_{AL} \eta_{LX} E_{L} = \sigma \tau T_{e}^4 [(1 - \alpha_{W}) A_{W} + (1 - \alpha_{C}) A_{C} + A_{L}], \]

where \( \eta_{AL} \) is the absorbed laser efficiency, \( \eta_{LX} \) is the laser-to-x-ray conversion efficiency, \( E_{L} \) is the laser energy used to drive the hohlraum, \( \sigma \) is the Stefan-Boltzmann constant, \( \tau \) is effective laser pulse width, \( \alpha_{W} \) is wall albedo, \( \alpha_{C} \) is capsule albedo, \( A_{W} \) is hohlraum wall area, \( A_{C} \) is capsule area and \( A_{L} \) is LEH area. Defining the coupling efficiency from hohlraum to capsule is:

\[ \eta_{HC} = \frac{(1 - \alpha_{C}) A_{C}}{(1 - \alpha_{W}) A_{W} + (1 - \alpha_{C}) A_{C} + A_{L}}. \]

Then \( E_{C} \), the laser energy absorbed by capsule, can be expressed as:

\[ E_{C} = \eta_{AL} \eta_{LX} \eta_{HC} E_{L}. \]

Thus, the laser to capsule efficiency is decided by three efficiencies: \( \eta_{AL} \), \( \eta_{LX} \) and \( \eta_{HC} \). The second efficiency \( \eta_{LX} \) is mainly decided by wall materials. Usually, \( \eta_{LX} \) is around 87% for uranium under an ignition pulse. The other two efficiency are connected with hohlraum geometry. In the following, we discuss these two efficiencies respectively.

As we know, the stimulated backscatter of the laser beam, including Brillouin scattering and Raman scattering, is a function of the beam intensity, of the density, temperature, and velocity fields along the path of the beams in the hohlraum and the beam path length [4, 6, 46]. Both laser beam overlapping and beam crossing may seriously increase the simulated backscatter. Thus, the absorbed laser efficiency \( \eta_{AL} \), mainly decided by the laser plasma instabilities, strongly connects with laser parameters, laser arrangement and hohlraum geometry.

According to the experimental results on NIF, \( \eta_{AL} \) is about 84% for the cylindrical hohlraums [6] and about 93% for the rugby hohlraums [11]. For \( \eta_{AL} \) in the octahedral hohlraums, it should be even higher than the rugby hohlraums because of the following reasons. First, the octahedral hohlraums contain only one cone at each LEH, so all laser beams are the same and the issue of crossed-beam transfer does not exist. In contrast, for a cylindrical ignition hohlraum, it has four different laser cones entering together at each LEH, with three times the laser beam number of the octahedral hohlraum, thus the crossed-beam transfer can not be avoided either at LEH or inside the cylindrical hohlraum and more, it has laser spot overlapping on the cylindrical hohlraum wall. Second, the volume of an octahedral hohlraum is larger than a cylindrical hohlraum with the equivalent wall area, and therefore it has a lower plasma filling density than the latter. A lower plasma filling certainly benefits suppressing the increase of LPIs. With a lower backscatter, the octahedral hohlraums should have a higher laser absorption efficiency than the cylinders. Nevertheless, a quantitative assessment of the potential laser plasma instabilities effects inside the octahedral hohlraums still remains a significant uncertainty, and it needs experiments to check.

From Eq. (2), the hohlraum-to-capule efficiency \( \eta_{HC} \) is mainly decided by wall material, capsule material and hohlraum geometry. For a given capsule and wall materials, \( \eta_{HC} \) is totally decided by the hohlraum geometry. To estimate and compare \( \eta_{HC} \) for the octahedral hohlraums and the cylindrical hohlraums, we take \( \alpha_{W} =0.8 \) and \( \alpha_{C} =0.3 \). First, we consider the cylindrical hohlraums. For the CH Rev5 capsule designed for NIC [4], the CH capsule has a radius of \( R_{C} =1.108 \) mm, which is inside a cylindrical hohlraum with \( R_{H} =2.72 \) mm, length \( L =10.01 \) mm and \( R_{L} =1.55 \) mm. We take these geometrical parameters into Eq. (2) and get \( \eta_{HC} =16.3\% \) for CH Rev5. For the near-vacuum hohlraums which was recently designed for driving fusion implosions with high density carbon [47, 48], the capsule with \( R_{C} =1.086 \) mm is inside a cylindrical hohlraum with \( R_{H} =3.36 \) mm, \( L =11.26 \) mm and \( R_{L} =1.95 \) mm. From Eq. (2), we have \( \eta_{HC} =11.4\% \) for this near-vacuum target design. For the octahedral hohlraums with given laser drive and given target materials, including capsule material and hohlraum wall material, \( \eta_{HC} \) is decided by two geometrical ratios: \( R_{H}/R_{C} \) and \( R_{L}/R_{C} \). Recall that the capsule symmetry inside the oc-

\[ \eta_{LX} = \frac{(1 - \alpha_{C}) A_{C}}{(1 - \alpha_{W}) A_{W} + (1 - \alpha_{C}) A_{C} + A_{L}}. \]
The radiation asymmetry is of critically important in hohlraum design, which not only affects the coupling efficiency from laser to capsule, but also causes the failure of ignition. As we have discussed in this paper, the radiation asymmetry on capsule totally depends on hohlraum geometry design for an octahedral spherical hohlraum. In contrast, for the cylindrical hohlraums, the rugby hohlraums and the tetrahedral spherical hohlraums, the radiation asymmetry depends not only on the hohlraum geometry, but also on the symmetry tuning technologies and the simulation codes. Because of the natural robust high symmetry inside the octahedral hohlraums, we can expect a much higher \( \eta_{CS} \) of the octahedral hohlraums than in the cylindrical hohlraums. As a result, we can expect a high \( \eta_{LA} \eta_{LX} \eta_{HC} \eta_{CS} \), i.e., a high coupling efficiency from laser to capsule hot spot inside the octahedral spherical hohlraums.

V. LASER ARRANGEMENT

We studied and gave the laser arrangement for ignition octahedral spherical hohlraum in Ref. [34]. In this review paper, we consider the octahedral hohlraum shown in Fig. 3, and present the main points of our previous work on the laser arrangement for the octahedral hohlraums. The laser arrangement is of critically important in hohlraum design, which not only strongly influences the capsule symmetry, laser-plasma coupling, laser-plasma instabilities, hydrodynamic instability...
and mix on capsule, but also decides the geometrical configuration of laser facility and laser building. In this section, we discuss the laser arrangement and constraints of the golden octahedral hohlraum. We define the hohlraum pole axis as z axis. Axis x is defined by the centers of two opposite LEHs on equator, and y is defined by the other two. We name the LEHs centered on z axis as LEH1 and LEH6, the LEHs centered on y axis as LEH2 and LEH4, and the LEHs centered on x axis as LEH3 and LEH5. Each quad through a LEH is characterized by $\theta_L$ and $\phi_L$. There is only one cone in our design, so all quads coming from the six LEHs have the same $\theta_L$. We use $N_Q$ to denote the quad number per LEH. The quads come in each LEH coordinately around LEH axis at the azimuthal angles of $\phi_{LM} + k \times 360^\circ/N_Q$ ($k = 1, ..., N_Q$). Here, $\phi_{LM}$ is azimuthal angle deviated from x axis in the xy plane for LEH1 and LEH6, from x axis in the xz plane for LEH2 and LEH4, and from y axis in the yz plane for LEH3 and LEH5. From the geometrical symmetry, we have $0^\circ < \phi_{LM} < \phi_{LM}$, here $\phi_{LM} = 360^\circ/2N_Q$.

The choice of $\phi_{LM}$ should avoid laser spot overlapping on hohlraum wall and laser beam transferring outside hohlraum from a neighbor LEH. Shown in Fig. 15 is schematics of laser spot overlapping on hohlraum wall and laser transferring outside from LEH. The determination of $\phi_{LM}$ is strongly connected with $\theta_L$, $R_H$, $R_L$, $R_Q$ and $N_Q$. For $\theta_L \geq 50^\circ$, we usually take $\phi_{LM} = 0.5\phi_{LM}$. For the model in Fig. 3, we take $\phi_{LM} = 11.25^\circ$.

The choice of $\theta_L$ is somewhat a complicated and several constraints must be taken into consideration. First, a high symmetry must be maintained. From our study [33], it has a relatively high symmetry at $\theta_L \leq 35^\circ$ or $\theta_L \geq 55^\circ$. This result is understandable, because the positive sources of laser spot and the negative sources of LEH partially cancel each other out, and the canceling is more effective when the two kinds of sources are closer. Second, the laser beams cannot cross and overlap with other beams in order to avoid arousing nonlinear phenomena and complicated laser plasma interaction issues. From our calculations, it has beam crossing inside the octahedral hohlraum at $\theta_L < 50^\circ$, especially serious at $\theta_L \leq 45^\circ$. Shown in Fig. 16 is the case for $\theta_L = 35^\circ$. Notice that each quad beam crosses three beams for this case. In contrast, there is no beam crossing for the model in Fig. 3 at $\theta_L \geq 50^\circ$. Presented in Fig. 17 is the case for $\theta_L = 55^\circ$. In fact, the laser transfer distance inside hohlraum is shorter at a larger $\theta_L$, which is also good for suppressing the increase of LPI. However, the laser cannot enter the hohlraum at a very shallow angle in order to avoid absorbing by blowoff from the wall and making unclearance of the hole. This is also the third constraint for choosing $\theta_L$. From the geometry, it requires $\cos \theta_L \geq \max(\frac{R_L}{R_H}, \frac{R_Q}{R_L})$. For the model in Fig. 3, it requires $\theta_L < 64^\circ$. However, the upper limitation on $\theta_L$ is also strongly connected with the laser pulse, including its energy, power and shape, and should be determined by future experiments. As a result, we propose $\theta_L = 50^\circ$ to $60^\circ$ as the optimum candidate for the octahedral hohlraums.

In fact, the optimum laser injection angle for the octahedral hohlraums can also be obtained, approximately, by using a very simple model. The circle shown in Fig. 18 is a cross section of the octahedral hohlraum, which passes the four LEH centers in the xy plane. We assume that the eight laser spots distribute homogeneously along the circle, with each LEH in the middle of two spots. The definitions of angles $\alpha$ and $\beta$ are shown in the figure. We define $\theta$ as the injection angle of laser. From Fig. 18, we have $\alpha = 45^\circ$ and $\beta = 45^\circ$.

We denote the shortest distance from a laser beam to the capsule surface inside a hohlraum as $D$. Here, it is worth to compare $D$ inside the octahedral hohlraums with that inside the cylindrical hohlraums. For the octahedral hohlraums, $D = R_H \times \sin \theta_L - R_C$. We take $\theta_L = 55^\circ$, and have $D = 2.08R_C$ at $R_H/R_C = 4$ and $D = 3.1R_C$ at $R_H/R_C = 5$. For the cylindrical hohlraums, $D = 0.5L \times \sin \theta_L - R_C$, here $L$ is the
hohlraum length. Because the laser beams at 23.5° are closest to capsule on NIF, so we only calculate $D$ for this laser cone. We consider CH Rev5 target [4], for which $L = 10.01$ mm and $R_C = 1.108$ mm, and we have $D = 0.8 R_C$ for the laser cone at 23.5°. Obviously, the shortest distance from a laser beam to the capsule surface inside the cylindrical hohlraums is much shorter than that inside the octahedral hohlraums. Thus, the ablated plasmas from capsule have much less influence on the laser transferring inside the octahedral hohlraums than that inside the cylindrical hohlraums, and this is beneficial to generate a clean hohlraum environment for the capsule and also a clean passage for the laser transport.

VI. NOVEL SPHERICAL HOHLRAUMS

According to our study, the octahedral spherical hohlraums are superior to the cylindrical hohlraums in both high symmetry during the capsule implosion and low backscatter without any supplementary technology. However, the laser beams injected at angles $> 45°$ transport are close to the hohlraum wall inside the spherical hohlraums, thus the wall blowoff may arouse strong laser plasma interactions and cause the LEH to close faster. This issue also exists for the rugby [11] and the elliptical hohlraums [16]. In addition, both the coupling efficiency from the drive laser energy to the capsule and the capsule symmetry decrease remarkably when big LEHs are used in the octahedral spherical hohlraums. In this section, we present a novel octahedral hohlraum with cylindrical LEHs and LEH shields to alleviate these issues. [35].

FIG. 19: (color online) Scenography of the octahedral hohlraum (Fig. 3) with cylindrical LEHs of 2.8 mm in radius.

The potential problem of laser transport inside the octahedral hohlraums is due to the geometrical curvature of the sphere, which leaves only a narrow space between the wall plasmas and the beams injected at $\theta_L = 50°$ to 60° and makes the laser to transport through the dense plasmas. As a result, the wall blowoff may shift the laser deposition closer to the LEH and cause the LEH to close faster, and moreover, it can enhance the strong laser plasma interactions when lasers transport through dense plasmas. However, this problem does not exist for the cylindrical hohlraums because of the geometrical structure between the cylinder part and the ends, which provides a large "bay" for the wall plasmas. In order to solve this potential problem of the octahedral hohlraum, we propose the cylindrical LEHs for the octahedral hohlraums, as shown in Fig. 19, which takes the advantage of the LEH in the cylindrical hohlraums. To verify the effect of the cylindrical LEHs by simulations, we used a 2D radiation hydrodynamic code LARED [41] to simulate the spherical hohlraums with two LEHs. From our simulation results, the lasers at peak power deposit along their whole transportation inside the spherical hohlraum with normal LEHs due to the dense plasmas blown off from the wall. In contrast, the laser deposition changes little inside the spherical hohlraum with the cylindrical LEHs. The details of the our simulation model and results are given in Ref. [35].

The LEH shields are used often in ICF experiments to increase the laser coupling efficiency and the capsule symmetry [2], and the addition of LEH shields was proposed as the final improvement of ignition targets for NIF[49]. However, this improvement was ultimately rejected for the point design target on the NIF ignition campaign because of the constraint they impose on the beam size and the short wavelength asymmetry that they can introduce [4]. However, it is feasible to mount the LEH shields inside the octahedral hohlraums. According to our octahedral hohlraum design, there are 8 laser quads (assuming 48 quads in total) entering into each LEH, arrayed in only one cone with the same $\theta_L$. Thus, the distance between a laser beam and the capsule surface is $R_H \times \sin \theta_L - R_C$, leaving enough room between the capsule and the laser beams to mount LEH shields that can completely block the capsule’s view of the LEH. Shown in Fig. 20 is a scenography of the octahedral hohlraum with LEH shields.

FIG. 20: (color online) Scenography of the octahedral hohlraum (Fig. 3) with LEH shields (in grey and orange), in which $R_S = 0.75 R_H$ and $r_S = 0.6 R_L$. To make it clear, only two laser quads entering from one LEH is presented.
In Ref. [35], we apply the power balance [2] to the octahedral hohlraums with LEH shields and obtain their coupling efficiency from hohlraum to capsule. From our calculations, the coupling efficiency can be enhanced by the LEH shields. The effect is more remarkable inside an octahedral hohlraum with a larger $R_L/R_H$, because a relatively large hole is blocked. Furthermore, from our 3D view factor model, the asymmetry inside the octahedral hohlraums can decrease remarkably when the LEH shields are used. Especially, a very low asymmetry of about 0.15% can be reached inside the golden octahedral hohlraum with LEH shields of suitable size.

The design of the shield location and size is very important. Relatively, the choice of shield location is simpler. The nearer the shield location to LEH is, the higher symmetry and the higher coupling efficiency from hohlraum to capsule can be obtained, just in case the shields cannot be hit by the laser beams after expanding under radiation. In contrast, the choice of the shield size is a little complicated. The choice of the shield location is a compromise of two effects. First, it should be located far enough from the LEH so it cannot be hit by the laser beams. Second, it should be located far enough from the capsule so the capsule can have a clear and full view of the laser spots. The choice of the shield size is also a compromise of two effects. First, it should be large enough so it can completely block the capsule’s view of the entire LEH. Second, it should be small enough so it does not block the laser beams after expansion caused by radiation.

We studied the influences of laser entrance hole shields on capsule symmetry and coupling efficiency of an ignition octahedral spherical hohlraum by using analytical model and simulations [38] from our three-dimensional Monte-Carlo radiation transport code IMC3D[39]. As a result, there are two critical shield radii at which the capsule asymmetry tends to minimum, and the coupling efficiency from hohlraum to capsule reaches its maximum when the shield size is taken around the second critical radius. Therefore, it has much flexibility in the shield radius design even the shields have an expansion under radiation ablation. The initial shield radius can be taken around the first critical radius in the ignition target design, not only to have a minimum initial capsule radiation asymmetry, but also to get a minimum asymmetry and highest coupling efficiency during the main pulse of drive. Nevertheless, the influences of the LEH shields on laser transport must be studied carefully by experiments and simulations before one decides to use the LEH shields in ignition target design.

VII. SPHERICAL HOHLRAUM EXPERIMENTS ON SG LASER FACILITIES

The hohlraums provide the appropriate spectral, temporal, and spatial x-ray field to drive capsule for ignition. Thus, the hohlraum physics study contains radiation symmetry on capsule and hohlraum energetics including the laser transport inside hohlraum, the laser-plasma coupling, and the x-ray generation and transport. An octahedral spherical hohlraum with 6 LEHs is three-dimensional in geometry, including laser injection and absorption, plasma generation and movement, radiation transport and symmetry, and therefore it needs a 3D simulation code for theoretical study and a laser facility which can provide laser injection in the way designed for the octahedral spherical hohlraums for experimental study. However, what we currently have for the hohlraum simulations is a 2D radiation hydrodynamic code LARED [41], and our series of SG laser facilities were all designed for the cylindrical hohlraums. As we know, the development of a 3D radiation hydrodynamic code needs at least several to ten years, and the building of a new laser facility is a giant project, to say nothing of money and time. It is known that the capsule symme-
try inside the octahedral spherical hohlraums is three dimensional, and it needs a laser facility designed for the octahedral hohlraums to demonstrate whether a quasi-1D and quasi-spherical radiation field can be created for the capsule. Nevertheless, many essential physics included in the hohlraum energetics of the octahedral hohlraums can be studied by using the spherical hohlraums with 2 LEHs, such as laser transport inside hohlraum, laser-plasma coupling, laser-plasma instabilities and LEH closure. Therefore, the experiments on these processes can be done on the laser facilities designed for the cylindrical hohlraums, and approximately, the 2LEH spherical hohlraum experiments can be simulated by using a 2D hydrodynamics code.

The experiments using 2LEH spherical hohlraums on SG laser facilities have been done since 2014. Up till to now, we have implemented experiments on improving laser transport by using the cylindrical LEHs in the spherical hohlraums on SGIII prototype laser facility, on spherical hohlraum energetics on SGIII prototype laser facility, and on comparison of LEH between the spherical hohlraums and the cylindrical hohlraums on SGIII laser facility. We have got very nice data with excellent reproducibility from all these experiments, and the experimental results agree well with our theoretical predictions. These results will be published in separate papers in near future. In this review paper, we simply present the experimental setup and contents of these experiments.

As we pointed out in Sec. VI, the laser transport is a potential issue inside the octahedral spherical hohlraums because of the geometrical curvature of the sphere. Inside the spherical hohlraums, the space between the wall plasmas and laser beams injecting at angle of \( \theta_{i} = 55^\circ \) is narrow, thus the laser may transport through the dense plasmas and cannot deposit at its designed position. We therefore theoretically proposed the cylindrical LEHs to alleviate this potential issue. Nevertheless, we need experiment to demonstrate that the cylindrical LEHs can improve the laser propagation inside the spherical hohlraums. We implemented this experiment at SGIII prototype. The experimental setup and the view fields of X-ray framing camera for the laser transport experiment are shown in Fig. 21. The empty golden spherical hohlraums with 2 LEHs were used. Because the gold M-band (between 1.6 keV and 4.4 keV) emission mainly comes from the non-equilibrium corona where most of the laser energy is absorbed, we therefore image the laser spot movement by using an X-ray Framing Camera (XRFC) [51] which observes the M-band emission through an observation slit on hohlraum wall. The slit of 400 \( \mu \text{m} \) width is parallel to the hohlraum axis. In addition, a time-resolved pinhole camera [50] was used to observe the M-band emission through LEH, and a Flat X-Ray Diode (FXRD) was used to measure the temporal radiation flux emitted out from the hohlraums. One of the eight laser beams on the SGIII prototype, which shots at the slit position, was not used in the experiment, and the other seven laser beams simultaneously irradiate the hohlraum from two ends at an incidence cone of 45\(^{\circ}\) angle with 2ns duration and 800 J per beam at 0.35 \( \mu \text{m} \). It is worth to mention that the four laser beams from one LEH have 45\(^{\circ}\) difference in azimuthal direction with those from the other LEH on the SGIII-prototype.

In order to observe the effect of the cylindrical LEH on laser propagation, two kinds of spherical hohlraums are used in the experiments, one with plain LEHs and the other with cylindrical LEHs. The size of the spherical hohlraums is designed by using the extended plasma-filling model [16, 52–55] with the criterion of \( n_e = 0.1 \). Here, \( n_e \) is the average electron density in laser hot channel at filling time, which is normalized to the critical density. The contour lines of \( n_e =0.08, 0.1, \) and 0.12 in the plane of sphere radius and laser energy is presented in Fig. 22, which are obtained from the extended plasma-filling model. Because the beam smoothing technology is used in the experiment, the backscatter is neglected in the initial design. In the initial design, the drive laser is considered to be a pulse of 6 kJ. As a result, we take 850 \( \mu \text{m} \) as the radius of the spherical hohlraums. The LEH radius \( R_{LEH} \) is 400 \( \mu \text{m} \), and the radius of the cylindrical LEH outer ring is taken as 1.5\(R_{LEH} = 600 \mu \text{m} \). From our observations, the laser inside the spherical hohlraums with plain LEHs is deposited along the entire laser path during later drive time when the dense plasmas ablated from the wall enter into the laser passage. In contrast, the laser is deposited almost at the initial pointing position inside the spherical hohlraums with the cylindrical LEHs until the laser pulse ends. Thus, our experimental work conducted on the SGIII-prototype laser facility unambiguously demonstrates that a simple design of cylindrical LEH can dramatically improve the laser propagation inside the spherical hohlraums.

The experiments on the spherical hohlraums have not been done widely in the world, and we had not gotten any data on the spherical hohlraum energetics in China until to 2015. We therefore did the spherical hohlraum energetic experiment on SGIII prototype laser facility, and the experimental setup is shown in Fig. 23. The purpose of this experiment is to investigate the radiation environment of the spherical hohlraums and compare the radiations inside the spherical hohlraums with plain LEHs and with the cylindrical LEHs. These two
kinds of spherical hohlraums have equivalent wall area and LEH size, except the shape of their LEHs. The empty golden spherical hohlraums were used. The witness plates Al and Ti are mounted over a diagnostic hole at the middle of the hohlraum. One of the eight laser beams on the SGIII prototype, shotting at the witness plate position, was not used in the experiment, and the other seven laser beams simultaneously irradiate hohlraum from two ends at an incidence cone of 45° angle with 1ns duration and 800 J per beam at 0.35 μm. The hohlraum radiation temperature and M-band fraction were simultaneously measured by using the shock velocity measurement technique with two witness materials of aluminum and titanium [42]. The FXRD and the M-band X-Ray Diode (MXRD) were used to measure the temporal radiation flux and spectrum emitted out from the hohlraum at angles with the hohlraum axis of 20°, 30°, 45° and 55°. The stimulated backscatter of the drive laser was measured by using the FABS and NBI. The Pinhole Cameras were used to measure the X-ray image at LEHs, and the Filter Fluorescer (FF) was used to measure the hot electron and hard x-rays. We had 18 shots in this experiment, and got very nice data with high repetition in all these shots. Under equivalent laser energy, all the radiation flux, the M-band fraction and the backscattering observed from these two kinds of spherical hohlraums are almost equivalent. Thus, the influences caused by the cylindrical LEHs on the hohlraum energetics can be neglected. These results agree approximately with our simulation results from LARED, and the detail comparisons are still underway.

Inside the hohlraums, the stimulated backscatter of the drive laser is aroused by ion waves (Brillouin scattering, SBS) or electron waves (Raman scattering, SRS). SBS and SRS are functions of the beam intensity, of the density, temperature, and velocity fields along the path of the beams in the hohlraum, and of the beam path length. They can be enhanced by filamentation, in which bright spots in the beams self-focus and become brighter. However, they can also be minimized and controlled by using beam smoothing technologies. From NIF experiments, it has been demonstrated that LPI of the outer laser ring inside the cylindrical hohlraums is acceptable and controllable, while LPI of the inner laser ring is very serious and out of currently theoretical predictions, and can not be controlled by present tuning technologies. Then, how about LPI in the octahedral hohlraums? Is it close to the inner ring or the outer ring of the cylindrical hohlraums? There are two opposite view points. The first view point thinks that LPI in the octahedral hohlraums is close to the outer ring of the cylindrical hohlraums and should be very small and acceptable, because of the following reasons. First, according to our design for the octahedral hohlraums, the laser injection angle is taken as 55°, which means that the angle between the laser beams and the wall is 35°, close to the inner ring of the cylindrical hohlraums designed for NIF. Second, the transportation length of the laser beam injected at 55° inside the octahedral hohlraum is close to that of the laser beam injected at 35° inside the cylindrical hohlraum with same hohlraum length-to-diameter ratio and same radius ratio of hohlraum-to-capsule as that designed for ignition. Here, we assume that the two kinds of hohlraums have equivalent areas of wall and LEH. These two reasons support the second view point. Because our 2D code can not give a believable simulation to judge which view point is correct, we therefore need an experiment to give a practical judgement. In experiment, we can measure LPI of the laser beam injecting at 55° inside the spherical hohlraums and compare it with LPI of the inner ring of the cylindrical hohlraums. This is the purpose of our LPI experiment which was just implemented at SGIII laser facility. It is very lucky for us to have 55° injection angle on SGIII laser facility.

Second, the inner laser ring inside the cylindrical hohlraums transports near the capsule and the transportation can be influenced by the capsule ablation, while inside the spherical hohlraums the distance between the laser beams and the capsule is much farther and the influence from the capsule ablation on laser transportation should be small and can be neglected. Third, we use the cylindrical LEHs for the octahedral hohlraums to alleviate the potential influence from the wall plasmas on the laser transportation. Therefore, it is believed in the first view point that LPI inside the octahedral hohlraums should be very small and acceptable. The second view point thinks that LPI in the octahedral hohlraums should be very serious and close to the inner ring of the cylindrical hohlraums, because of the following reasons. First, according to our design for the cylindrical hohlraums, the laser injection angle is taken as 55°, which means that the angle between the laser beams and the wall is 35°, close to the inner ring of the cylindrical hohlraums designed for NIF. Second, the transportation length of the laser beam injected at 55° inside the octahedral hohlraum is close to that of the laser beam injected at 35° inside the cylindrical hohlraum with same hohlraum length-to-diameter ratio and same radius ratio of hohlraum-to-capsule as that designed for ignition. Here, we assume that the two kinds of hohlraums have equivalent areas of wall and LEH. These two reasons support the second view point. Because our 2D code can not give a believable simulation to judge which view point is correct, we therefore need an experiment to give a practical judgement. In experiment, we can measure LPI of the laser beam injecting at 55° inside the spherical hohlraums and compare it with LPI of the inner ring of the cylindrical hohlraums. This is the purpose of our LPI experiment which was just implemented at SGIII laser facility. It is very lucky for us to have 55° injection angle on SGIII laser facility.
The SGIII laser facility is a 48-laser beam at 0.35-µm Nd:glass laser system, and began to be used for experiments since 2014. The 48 laser beams are arrayed in eight cones, forming angles with the hohlraum axis of 28.5°, 35°, 49.5°, and 55° from each side. These cones of beams contain 4, 4, 8, and 8 beams, respectively, on each side. Beams coming in along 28.5° and 35° are called as the “inner cone”, while along 49.5° and 55° are called as the “outer cone”. The 48 laser beams can output 180 kJ with a time duration of 3 ns. Shown in Fig. 24 is the setup of the experiment on LPI comparison between the octahedral spherical hohlraum and the cylindrical hohlraum at SGIII laser facility. In this experiment, the hohlraums with two kinds of geometrical structure were used: the gold spherical hohlraums with 2 cylindrical LEHs and the gold cylindrical hohlraums. In this experiment, to mimic the laser arrangements of the octahedral hohlraum and the cylindrical hohlraum designed for ignition, only 8 beams at 55° are injected for the spherical hohlraums at the hohlraum end where LPI is measured, while 24 beams at angles of 28.5°, 35°, 49.5°, and 55° are injected for the cylindrical hohlraums at the hohlraum end where LPI is measured. Each laser beam entering into the hohlraum from this end is about 2.7 kJ. We measured both SRS and SBS, and the backscatter is the sum of SRS and SBS.

We considered three kinds of filling inside the hohlraums: vacuum, filling gas but without capsule, and filling gas with capsule. The filling gas is C6H12 with a filling density of 0.9 mg/cm³. In our design, we take the equivalent hohlraum wall area, LEH area and drive laser energy for the spherical hohlraum and the cylindrical hohlraum. As a result of our theoretical design, the spherical hohlraum is 3.6 mm in diameter, and the cylindrical hohlraum is 2.4 mm in diameter and 4.3 mm in length. The LEH diameter is 1.2 mm and the LEH ring diameter is 2 mm for the cylindrical LEHs. The total laser energy used in the experiment is 90 kJ at 0.35 μm with 3 ns in duration. The focus of the laser beams is elliptical, with sizes of 500 μm × 439 μm at 28.5°, 500 μm × 409 μm at 35°, 500 μm × 325 μm at 50°, and 500 μm × 287 μm at 55°. The laser intensity is about 5 × 10¹⁴ W/cm² at 28.5° and 8 × 10¹⁴ W/cm² at 287 μm at 50°, 500 μm at 55°. All diagnostics are shown in Fig. 24. We only measure the backscatter at 55° for the spherical hohlraums and 28.5° for the cylindrical hohlraums. For all shots, CPP (Continuous Phase Plate) is used. Especially, we measure the backscatter before and after the smoothing technologies of spectral dispersion (SSD) and polarization smoothing (PS) were used for the cylindrical hohlraum with filling gas and capsule inside.

From our observations, the backscatter is very low in the vacuum hohlraums, including both spherical hohlraums and cylindrical hohlraums, about 3% to 4% even without SSD and PS. However, it is quite different for the gas-filling hohlraums. For the gas filled spherical hohlraums, including with or without capsule inside, with or without the smoothing technologies, the backscatter ranges from 3.5% to 5.8%. In contrast, the backscatter ranges from 20% to 33% for the gas-filling cylindrical hohlraums with and without capsule inside, even by using all smoothing technologies. From this LPI experiment, we have following conclusions. (1) LPI is very small for the vacuum hohlraums, which is similar to the NIF results for the near-vacuum hohlraums [47, 48]. (2) For the gas-filling cylindrical hohlraums, LPI at inner rings is very serious, which is again similar to the NIF results [18]. (3) The LPI observed in the gas-filling spherical hohlraum at 55° is much lower than that of gas-filling cylindrical hohlraums at 28.5°. This result supports the first view point, i.e., LPI in the octahedral hohlraums is very small and acceptable, and is close to the outer ring of the cylindrical hohlraums. In this experiment, we also measure and compare the energetics between the spherical hohlraums and the cylindrical hohlraums. Especially, we observed and compared the the M-band fraction in these two kinds of hohlraums. It is known that the M-band portion of the radiation spectrum can affect preheat and hydrodynamic instabilities in the capsule, and it usually needs mid-Z dopant to absorb M-band and minimize its influence. As a result of our observations, the M-band fraction inside the spherical hohlraums is obviously lower than that inside the cylindrical hohlraums. The detail comparisons of these data with our simulation results from LARED are also underway.

VIII. SUMMARY

In summary, we presented a review on our recent theoretical and experimental progress on novel octahedral spherical hohlraum study.

From our theoretical study, the octahedral hohlraums with 6 Laser Entrance Holes (LEHs) have robust high symmetry during the capsule implosion and high coupling energy efficiency without supplementary symmetry tuning technologies. A golden hohlraum-to-capsule radius ratio of about 5 exists for the octahedral spherical hohlraums, at which the capsule asymmetry tends to minimum. Inside the octahedral hohlraums, the capsule asymmetry is mainly contributed by the 6 LEHs and is insensitive to the movements and other nonlinear properties of the laser spots. We gave a design on laser arrangement for ignition octahedral spherical hohlraum, and the injection angle of laser beams of 50 to 60 degree was proposed as the optimum candidate range for an ignition octahedral hohlraums. We proposed a novel octahedral hohlraum with cylindrical LEHs and LEH shields to mitigate the influence of the wall blowoff on laser transport and to increase the laser coupling efficiency and improve the capsule symmetry. We studied on the sensitivity of the octahedral spherical hohlraums to random errors, and the results show that the octahedral spherical hohlraums are robust to these random errors while the cylindrical hohlraums are the most sensitive.

We began to do spherical hohlraum experiments on SG laser facilities since 2014, and up till to now, we have implemented three experiments on spherical hohlraums on SG laser facilities, including improvement of laser transport by using the cylindrical LEHs in the spherical hohlraums on SGIII prototype laser facility, spherical hohlraum energetics on SGIII prototype laser facility, and comparison of LPI between the spherical hohlraums and the cylindrical hohlraums on SGIII laser facility. From all these experiments, we got
very nice data with excellent repetition, and the experimental results agree well with our theoretical predictions. These experiments demonstrated that: (1) a simple design of cylindrical LEH can dramatically improve the laser propagation inside the spherical hohlraums; (2) the influences caused by the cylindrical LEHs on the hohlraum energetics can be neglected; (3) the backscatter of the spherical hohlraums at 55° is much lower than that of the cylindrical hohlraums at 28.5°; and same as the NIF results, LPI of the inner laser ring of the cylindrical hohlraums is very serious even with smoothing technologies. In our next work on the octahedral spherical hohlraums, we plan to develop a 3D hydrodynamic code to simulate the hohlraum physics and radiation symmetry, and do experiments on LEH closure on SGII laser facility in order to determine a suitable LEH size for the ignition octahedral spherical hohlraum.

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