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Progress in octahedral spherical hohlraum study

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Abstract

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°−60° 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 to now, we have carried out three experiments on the spherical hohlraum with 2 LEHs on Shenguang(SG) laser facilities, including demonstration of improving laser transport by using the cylindrical LEHs in the spherical hohlraums, spherical hohlraum energetics on the SGIII prototype laser facility, and comparisons of laser plasma instabilities between the spherical hohlraums and the cylindrical hohlraums on the SGIII laser facility.

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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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1. Introduction

In indirect drive inertial confinement fusion (ICF) [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 [3] was ultimately decided to be optimal configuration for the ignition study on the National Ignition Facility (NIF) [4−7], which has all advantages of the golden cocktail hohlraum [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 [9]. In contrast, the hohlraum geometrical configuration design is rather complicated, which includes the design of the hohlraum shape, size and the number of Laser Entrance Holes (LEHs), 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% [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 to now, various hohlraums with different shapes have been proposed and investigated, such as cylinder hohlraum [1,2], rugby hohlraum [10−15] and elliptical hohlraum [16]. These hohlraums are elongated with a length-to-diameter ratio greater than unity and have cylindrically symmetry with two LEHs on the ends. Among all above hohlraums, the cylindrical hohlraums are used most often in the US's inertial fusion studies and are chosen as the ignition hohlraum on NIF [2,4,18], though it breaks the spherical symmetry and leads to cross coupling between the modes.

Inside the cylindrical hohlraums, the Legendre polynomial modes P_2 and P_4 dominate the capsule asymmetry. The geometry of a cylindrical hohlraum can be described by three ratios: hohlraum length-to-diameter ratio, hohlraum-to-capsule radius ratio, and LEH to hohlraum radius ratio. For a cylindrical hohlraum designed for ignition, these three ratios are usually taken as 1.6 to 2, 2.5 to 3.5, and 50% to 60%, 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 NIF fails to generate fusion energy until today. From NIF experiments, the low mode asymmetry, the serious Laser Plasma Instabilities (LPIs) 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_4 and P_2 are time-dependent during the 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 to now, the