The updated advancements of inertial confinement fusion program in China

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Abstract.
The recent achievements of ICF research in China are reviewed. The constructions of laser facilities of SG-III and SG-IIUP are completed in this year and the full energy output operation will be in 2014. The target physics studies involving numerical simulations of a new ignition scheme, which is proposed to enhance implosion velocity and suppress hydrodynamic instability and distortion at interface between hot spot and main fuel, and experimental results (a few selected examples) are presented.

1. Introduction
The goal of the first milestone of the inertial confinement fusion (ICF) program in China is to perform the ignition and plasma burning in laboratory around 2020. The national research institutes, such as the Research Centre of Laser Fusion (RCLF), the Institute of Applied Physics and Computational Mathematics (IAPCM), the National Laboratory on High Power Laser and Physics (NLHPLP), as well as many universities and other institutions are participating in the Program. Since 1993, based on this program, target physics studies involving theories (models and simulations) and experiments (measurement techniques), establishments of precise diagnostic systems, constructions of laser facilities (SG-series) and technology development, and precise target fabrications have been coordinately developed, and the great achievements have been gained. The pre-ignition target design and advanced target physics research, based on the SG-III laser facility, are crucial as the basis for the ignition target design in the coming years, which should identify and solve the essential science and technology issues, to reduce risks, and to scale up the design to the ignition target. Finally, we will demonstrate the ICF ignition on the designing SG-IV laser ignition facility.

2. Development of laser drivers
The SG-series of laser facilities were constructed and/or are being developed to serve for ICF research in China. The SG-II laser facility, which has 8 beams and energy output of 3kJ/3ω with pulse duration of 1ns and is supplemented by a ninth laser beam with energy output of 5.2kJ/1ω (3kJ/3ω) and pulse duration of 2 – 3ns as a backlighter, has provided over 4000 shots related to the ICF experiments since 2000. The SG-III Prototype (SG-IIIP), which has 8 beams and laser energy output of 15kJ/3ω and pulse duration of 3ns, has been operating for physical experiments over 2000 shots since 2006, and a new laser beam as its backlighter is being prepared. Also, the SG-IIU is a combined laser system which is made up of the upgrading SG-II
(8 beams, 24kJ/3ω, 3ns) and a PW laser (≈ 1kJ, 3 − 5ps) to be operating in 2014. The SG-III with 48 beams (6 bundles) and the output laser energy of 250kJ/3ns/3ω and 400kJ/5ns/3ω has been completed in 2013, see Fig.1. All bundles are now operating for experiments and full energy operation and physical shots will be in 2015. The ignition facility (SG-IV) is being designed to serve for ignition demonstration around 2020 in China.

Figure 1. The SG-III laser system with 48 beams (6 bundles) and the output laser energy of 250kJ/3ns/3ω and 400kJ/5ns/3ω has been completed in early 2013.

3. A hybrid indirect-direct drive ignition scheme by a target of spherical hohlraum and layered fuel capsule

For the conventional indirect-drive hotspot ignition scheme of ICF [1], the ignition occurs near stagnation (isobaric) time. For such scheme, there exist at least two issues in implosion dynamics, i.e., strong rarefaction wave due to the ablated plasma expanding towards vacuum at the ablator surface leads to severe reduction of the ablative pressure and implosion velocity; the mix from Rayleigh-Taylor instability (RTI) and asymmetry amplification (distortion) due to the implosion shock multiple-reflection at the interfaces of hotspot/main fuel and others resulting in deceleration, may lead to ignition difficulty.

To solve the issues, we proposed a new ignition scheme of indirect-direct hybrid drive for ICF: a layered fuel capsule inside a spherical hohlraum (SH) is compressed first by indirect-drive (ID) x-ray ablation with laser energy of about 0.5MJ and pulse duration of 12.7 ns, and then by intense direct-drive (DD) lasers with laser energy of about 0.85MJ and pulse duration of last 2ns (figure 2c, green colour). The SH, which has a radius of 3.5 mm with six laser entrance holes (LEFs) and octahedral symmetry (figure 2a), is designed by using plasma-filling model under conditions of the specific indirect-drive (ID) radiation temperature (figure 2c, red colour) and the filling density. The non-uniformity of about a few thousandth on the capsule surface, which has total deuterium-tritium (DT) fuel mass of 0.19 mg and an initial outer radius of 850μm.
(figure 2b), is obtained by view factor code simulations if the radius ratio of SH to capsule is greater than 5, the incident angles of laser beams are between $50^\circ$ – $60^\circ$, the radii of the laser bundle and LEH are properly chosen.

![Figure 2](image)

**Figure 2.** (a) The SH configuration; (b) capsule cross section; (c) indirect-drive radiation temperature (red) and direct-drive laser power (green).

The implosion dynamics of the capsule is investigated by using LARED-S code. The 1D simulation results are plotted in Figure 3. The ablator (CH material with initial density of $1.0g/cm^3$) of the capsule is ablated by 4 radiation-temperature steps with a top $Tr = 270eV$ (figure 2c, red colour), a radiation ablation front (RAF) appears in the ablated CH surface. Meanwhile four shocks are generated and propagates in the capsule that is imploded and compressed. Beginning at time $t = 10.7ns$, the DD lasers with intensity of $3.4 \times 10^{15}W/cm^2$ are imposed at a critical surface, where is $950\mu m$ away from the capsule centre, in the corona region. A supersonic electron thermal wave with an electron ablation front (EAF) is formed there and runs from the critical surface towards the RAF about $650\mu m$ away from the capsule centre. The thermal wave gradually slows down to a sonic/subsonic one due to the energy deposition in corona during propagation, followed a DD shock wave is driven. The four shocks driven by ID and the DD shock merge into a merged shock (MS) near inner wall of the main fuel. When the MS runs into the DT gas filling cavity a hot spot involving the DT gas and a part of innermost main fuel is formed and compressed by the MS, then the MS rebounds from the capsule centre and moves towards the interface of the hot spot and main fuel.

![Figure 3](image)

**Figure 3.** (a) and (b) are the density (red), pressure (green), ion temperature (blue) vs radii of the imploding capsule in different time, and (c) is the 2D profile (hot spot, main fuel, ablator) at ignition time.
Meanwhile a compression wave with the EAF followed the DD shock, like a snowplow, drives the ablated CH of density \( \rho \ll 1.0 \text{g/cm}^3 \) in the corona, which is gradually piled into a higher CH density plateau between the EAF (sonic) and RAF(subsonic). At \( t = 12.3 \text{ns} \), the plateau has a spatial width of \( \sim 40 \mu\text{m} \) (figure 3a, grey), the density \( \rho \sim 2.0 \text{g/cm}^3 \) and the maximal radiation temperature \( T_r \sim 270 \text{eV} \), and thus, the peak pressure \( P \sim 380 \text{Mbar} \); at \( t = 12.8 \text{ns} \), the plateau has a spatial width of \( \sim 60 \mu\text{m} \), the density \( \rho \sim 3.0 \text{g/cm}^3 \) and the peak pressure \( P \sim 570 \text{Mbar} \), it is far greater than ID ablation pressure of \( \sim \text{tens Mbar} \) as shown at \( t = 11.2 \text{ns} \) in figure 3a.

Such a plateau likes an extreme-high pressure piston to push out an enhanced shock (ES). The ES fast runs in the imploding capsule. At \( t \sim 13.02 \text{ns} \) the ES reaches the interface of hot spot/main fuel and collides with the MS that just arrives there from the hot spot centre, thus the MS is stopped to reflect at the hot spot interface. Then, the ES runs in the hot spot that is further compressed and heated. At \( t \sim 13.34 \text{ns} \), the non-isobaric ignition ( particle heating rate equals to electron cooling rate) occurs before stagnation when the ES rebounded from the hot spot centre arrives near the interface of the hot spot/main fuel in a lower convergent ratio of 25 (figure 3b). As a result, the RTI, mix, and the interface distortion are prevented due to no deceleration phase happened. Finally, the fusion energy of 17.4 MJ and a gain of 13 for total laser energy of 1.35MJ are achieved. This hybrid scheme is robust, even if the laser energy is reduced to 1.1MJ the yield still has 16MJ.

The 2D simulation results are investigated by using LARED-S. The non-uniformity from DD laser irradiation at critical surface is suppressed by the thermal smoothing effect [2] during the supersonic electron thermal wave propagation from the critical surface (\( \sim 950 \mu\text{m} \)) to the RAF (\( \sim 650 \mu\text{m} \)) of the implosion capsule. The growth factors (GFs) of hydrodynamic instabilities varying with mode \( l \) for hybrid scheme are shown in figure 4, and compared with the traditional 1D one. The hybrid GF at interface of hot spot/main fuel is suppressed as shown in figure 4a, while the GFs at interfaces of ablator/main fuel and RAF are about 220 and 150 (figure 4b and 4c), respectively, which are lower than that for the traditional 1D scheme as seen in figure 4 (green). The simulation results also showed that the profile of imploding core at ignition time is quite close to symmetry and 2D effects seem to be neglectable. Therefore, the yield in 2D simulations is same as 1D result.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{The growth factors of hydrodynamic instabilities vs mode \( l \) for hybrid scheme (red) to compare with the traditional 1D one (green). At the interface: (a) hot spot/main fuel, (b) ablator/main fuel, (c) radiation ablation front (RAF).}
\end{figure}

The expected efficiency of the laser energy coupling to the SH for ID phase is over 90% higher than the cylindrical and rugby hohlraum, and is \( \sim 20\% \) for the DD lasers of intensity of \( 3.4 \times 10^{15} \text{W/cm}^2 \) [3] with a relatively low hot electron temperature of \( \sim 30 \text{keV} \), which is easily stopped by the compressed surplus ablator.
4. Physical experiments (selected examples)

4.1. Hohlraum test experiments with the first two bundle beams of SG-III

The hohlraum test experiments reported here were performed at the SG-III laser facility with the first two bundles of beams. In these experiments we compared the radiation temperature $T_r$ of the Au hohlraums that were heated with the different incident angle lasers. We use two kinds of hohlraum in these experiments: hohlraum A is 1.4mm in diameter, 2.1mm in length, and has LEH diameters of 1.0mm; hohlraum B is 2.4mm in diameter, 3.4mm in length, and has LEH diameters of 1.6mm. The hohlraum A was heated by 16 beams using a 3 ns flattop laser pulse with a total energy of up to 80kJ and 45kJ, and The hohlraum B was heated with a 1ns flattop laser pulse with a total energy of up to 16kJ. Temperature $T_{r,\text{up}16}$ ($T_{r,\text{up}42}$, $T_{r,\text{up}64}$) was diagnosed from upper-half-chamber with an angle of $16^\circ$ ($42^\circ$, $64^\circ$) between observation direction and hohlraum axis; $T_{r,\text{down}20}$ ($T_{r,\text{down}42}$) was diagnosed from down-half-chamber with an angle of $20^\circ$ ($42^\circ$) between observation direction and hohlraum axis. The temperature differences are shown in figure 5.

![Figure 5. Hohlraum temperature experiment on SG-III laser system with only two bundles of beams.](image)

4.2. Target physics—cryogenic capsule experiments

Cryogenic deuterium-deuterium (DD) capsule direct-drive experiments are carried on SG-IIIP. The target assembly (figure 6a) is made up of a copper cylinder clamped by two cooling arms; the plastic capsule cooled by helium gas to below the deuterium triple point; supported and filled with D2 gas by fill tube of 10μm in diameter; ice thickness is uniformed by tuning the temperature difference between two cooling arms; inserted into target chamber on a six-dimensional adjustable platform. The experiments are carried out with a polar direct drive mode: beam pointing is optimized for best irradiation uniformity. The laser has a pulse shape of two steps with power contrast of 1 : 10 to minimize the energy loss on the sealing film. The experiments showed that the cryogenic capsule (ice layer of 115μm) implosion achieved DD neutron yield of $4.7 \times 10^6$, while warm plastic capsule implosion achieved neutron yield of $7.8 \times 10^7$. As shown in Fig. 6, the target alignment accuracy in cryogenic condition is demonstrated, the technique for fuel areal density is validated, and the implosion dynamics is measured.

4.3. Monochromatic imaging for implosion measurement

Monochromatic imaging (MI) based on spherically bent crystals (BCs) was developed and used to explore implosion dynamics. Implooding ablator performance was measured on SGII using this MI system. Here, 5th order of reflection of the mica spherical crystal was used and the measured photon energy $E_{\text{photon}} = 3.14\,\text{keV}$ (Pd). The detrimental long-range spatial structure from backlighter non-uniformities are absent using monochromatic imaging system. The experimental results showed that crystal resolution is smaller than 5μm, system resolution (involving streak
Figure 6. Preliminary experimental results of cryogenic deuterium-deuterium (DD) capsule direct-drive experiments on SG-IIIP: (a) cryogenic capsule involving He and D2 filling tubes, diagnostic hole; (b) primary proton spectrum; (c) evidence of condensation; (d) gated x-ray imaging.

camera) is about 10μm. The uncertainty in this experiment is that the implosion velocity is about 10% and the residual mass is about 15%, see Fig. 7.

Figure 7. (a) A schematic of the experimental setup for the imploding process measurement; (b) 3.14keV monochromatic streaked radiograph; (d) Implosion velocity; and (d) Residual mass.
4.4. *K-shell photoabsorption edge of strongly coupled matter*

Warm dense matter (WDM) is a non-ideal plasma with full and partial degenerate and exhibits the continuum lowering of efficient ionization potential, phase transition, pressure ionization, etc., it is very important to measure WDM properties for target simulations. Here K-edge shift of Potassium Chloride (KCl) of $E_k = 2.8\text{keV}$ is investigate experimentally. A sandwich sample (KCl) target (figure 8a) is compressed (figure 8c) by shocks driven by x rays from "dog bone" hohlraum (figure 8), then short pulse backlighting (130\text{ps} laser from SG-II) is applied to get the time-resolved absorption spectroscopy from the compressed KCl sample (figure 8b). The red shift of K edge up to 11.7 eV and broadening of 15.2 eV from backlighting spectra in the maximal compression, resulting in K-shell ionization energy increase and continuum lowering, are clearly observed, and it shows that the WDM KCl is in partial degeneracy [4].

![Figure 8](image)

**Figure 8.** The "dog-bone" hohlraum schematic for partial degeneracy experiments: (a) the sandwich sample (KCl) target, (b) typical spectral image, (c) the shock compressed sample (KCl), (d) the time-resolved absorption spectroscopy from the compressed KCl sample.

**Final remarks**

In summary, we are performing the ignition target design to improve the conventional indirect central ignition target and to explore new ignition schemes involving hybrid drive, and as well will provide physical data for the SG-IV ignition driver design. Target physics research on SG-III is a quite important step towards ignition, and would find and solve substantial issues in science and technology before transiting to ignition. The SG-IV ignition facility with laser energy of around 1.5MJ for third harmonics is being designed. China is going to be toward moderate/high gain ignition and burning goal around 2020.

**References**

[1] J.D. Lindl et al., Phys. Plasmas 11, 339 (2004).
[2] M. Keskinen, Phys.Rev.Lett. 103, 055001(2009).
[3] W. Theobald et al., Phys. Plasmas 19, 102706(2009).
[4] Y. Zhao et al., Phys.Rev.Lett. 111, 155003 (2013).