Recent progress for different inertial confinement fusion schemes: a systematic review

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Abstract. The pursuing of controlled fusion energy has been continuously developed for more than half a century. Inertial confinement fusion (ICF) is one of two major approaches to actualize controlled fusion. Here, we systematically reviewed several typical forms of ICF on the part of their physical principles and encountering technical barriers currently. Besides, some great simulation results of the implosion for each ICF scheme are shown, and the simulation algorithm of Vlasov-Fokker-Planck (VFP) is introduced. In addition, several instabilities in the fusion process are analyzed. These results offer a guideline for future ICF research.

1. Introduction
Inertial confinement fusion (ICF) is an approach of fusion energy attempting to initiate nuclear fusion reactions conducted by way of heat treatment and compression of one fuel target [1]. It is mainly in the form of a pellet with a radius of around 400 μm, which contains an admixture of deuterium and tritium [2]. To this end, the out layer of the fuel target gains energy from extreme intensity laser (in most cases) [3] or heavy ion beam [4]. In this case, the inner part is accelerated inwards, which results in compressing of the fuel. This process is well known as implosion [5], which can generate shock waves, leading to the occurrence of fusion reactions [6].

During the history of ICF development, researchers were devoted to the improvement of devices' efficiency and methods to meet Lason's criteria (so-called ignition) for the first 10 years since the first proposal of ICF in the 1970s [7]. The research continued in the late 1970s make use of infrared lasers for compression experiments that yielded thermonuclear neutrons [8]. Due to super thermal electrons and preheating of the target related to infrared laser wavelength, lasers with shorter wavelengths were required to be built after 1980 [9]. After the evolution of relevant research methods and improved fusion devices, substantial achievements in implosion performance have been accomplished in ICF [10].

With the great development of ICF, it is necessary to summarize the recent situation and issues. In this paper, several typical schemes are introduced to achieve ICF in Sec. 2, including ICF with extreme intensity laser (in the form of direct driven, indirect driven, and fast ignition), heavy ion beam, and Z-pinch. Specifically, part of their principles, several technical barriers encountering currently and
some achieved progress are discussed. Apart from this, some details about insights into the current stage simulations related to the asymmetry of the radiation and implosion would be spread out in Sec. 3 and 4, respectively. Moreover, the instabilities of ICF are discussed in Sec. 5. Finally, a concise and critical summary is given in Sec. 6.

2. ICF applied with typical schemes

2.1. ICF with extreme intensity laser

2.1.1. Direct driven

The concept of compression of a small target with high-power laser to turn the thermonuclear fuel into a condition possible for ignition was first proposed by Nuckolls in 1972 [7]. As shown in Figure 1 [11], the pressure of the plasma is confined by the inertia for a relatively long time (a few ns). It is enough for the burning process of thermonuclear to result in enough fusion reactions producing abundant energy to overcome the Coulomb barrier. Among the approaches in fusion reactions, the deuterium-tritium (D-T) reaction [12] has the largest reaction cross section. It can be achieved under the circumstances with relatively low requirements compared to other reaction channels. Generally, the laser drive ICF is divided into two methods. First is direct drive, where a spherical target containing fusion fuel is directly irradiated by laser beams [13]. Another one is the indirect drive. The laser beams heat the inside of a typically cylindrical enclosure, generating x rays that irradiate a spherical fuel-containing capsule [14, 15]. The physical processes of direct-drive implosion are illustrated in Figure 2 [16].

In the early stage, the target's energy is absorbed by the target, leading to laser ablation over the target material, which forms a hot plasma. A set of low-intensity pulses quantifying from one to three occurs. Then, the laser pulse intensity grows sharply, releasing a stronger shock that combines with the
early ones breaking the inner surface of the ice layer. During the transition, target modulation transforms due to a Richtmyer–Meshkov (RM)-like uncertainty [17,18]. Afterward, the ice layer starts to accelerate inward to the target centre, laser-plasma interactions produce energetic electrons leading to fuel preheat.

Exponential growth on ablation-surface modulations occurs resulting from the Rayleigh–Taylor (RT) instability [19, 20], which will be harmful for the ignition (discussed in Sec. 5). The deceleration phase begins after its reflection from the target center and reaches the converging shell. The DT fuel is squeezed and heated with kinetic energy, converting into thermal energy. Eventually, the peak compression session begins, which converts the energy in the DT fuel to fusion neutrons. As a consequence, it further compresses fuel to fusion temperatures, i.e., triggers the catenated burn (known as ignition) [21].

The main restrictions on the development of direct driven ICF consist of reduced uniformity of the illumination, low-mode asymmetries, and laser-plasma instabilities (mainly occurring during the interaction between the laser light and the ablated plasma) [22]. Another current research on low-mode asymmetries proposed an innovative asymmetry alleviation method, in which the assessed hot-spot velocity to ascertain the ideal target position to diminish mode-one asymmetries [23]. In regard to the progress in laser-plasma instabilities, recent research based on the SGIII-P facility played a key role [24].

2.1.2. Indirect drive

Indirect drive inertial confinement fusion applies small cylindrically-shaped, high-Z radiation cavities called hohlraums to transform extreme intensity laser into X-rays. At the center of the hohlraum locates a spherical capsule containing DT fuel. The physical principle of the hot spot ignition process for the indirect drive is similar to the direct drive, which has been covered in the 2.1.1 part (Figure 1.). The material for capsules was traditionally made of plastic or beryllium [25-29]. Fusion is initiated by compressing DT gas, creating a crucial hot spot. Under the right conditions, the self-heating could be achieved through capturing alpha particles from fusion reactions, resulting in the hot spot igniting. After the formation of the robust burning plasma, ablation, and heating of the inner surface of the ice layer, the target sets up a propagating burn producing multi-megajoule neutron yields [30].
The technical points which still need optimization mainly lie on low-mode asymmetries in the X-ray drive (implosion symmetry), X-ray transformation, and capsule hydrodynamic durability. Consequently, it may cause critical impacts on some recent experiments leading to $\rho R$ asymmetries [31]. In X-ray conversion, literature proposed a unique means for adjusting the X-ray flux inside hohlraums applying burn-through obstacles, which utilizes multiple chambers separated by burn-through barriers [32]. Some current stage information related to capsule hydrodynamic stability can be found in Sec. 5[33].

2.1.3. Fast-ignition
Fast-ignition opens a new route to directly heat up the high-density fuel after compression, i.e., it can separate the heating phase and the compressing phase [34]. By this means, the target is first compressed as the process in other ignition schemes. Thereby, the target is dramatically heating with a high possibility to start fusion ignition [35].

There are 2 types of fast ignition: 1) the plasma bore-through method and 2) the cone-in-shell method. In method 1, the petawatt laser is designed to penetrate through the outer plasma of an imploding capsule and impact and heat the dense core [36]. For the latter, the capsule is installed with a small projecting high-z cone (e.g., Au shown in Figure 3) in the core. However, the interaction between the cone and the implosion process remains unclear, too complicated to clarify.

![Figure 3. Cone in shell geometry for fast ignition [36].](image)

2.2 ICF with heavy ion beam
To meet the criteria of ignition (producing high fuel densities and temperatures), About one milligram of DT fuel needs to be compressed to a very high density in several ns. In ICF with a heavy ion beam (seen from Figure 4), this compression is achieved by intense beams striking an external region of the fuel-containing pellet. The generated heat leads to compression of the fuel core and ignites the burning process.

HIB has several characteristics which own advantages on the construction of nuclear fusion power plant [37, 38]. It's flexible for accelerators to regulate the HIB constraints [38]. Depositing HIB energy inside material is another significant favourable feature. The collaboration of HIB ions with samples is nearly traditional, the Coulomb interaction [39-42]. In this case, HIB ion interaction is relatively understandable and could be specified inside materials [43,44].
Figure 4. Schemes of (a) HIBs illumination onto a direct-drive fuel target and (b) a fuel target injection into a reactor [37].

2.3 Z-pinch
Note that Z-pinch is one application of Lorentz force [45]. Hopefully, as shown in Figure 5, the Z-pinch configuration is to become a compact fusion device due to the corresponding regular geometry, unity beta, and non-existence of external magnetic field coils. A rapid increase in the fusion reaction rate could be achieved via raising the axial current to compress the plasma. The Z-pinch has been restricted by rapid rising instabilities, limiting plasma lifetime. Latest development aiming at providing stability is supported by a method exploiting sheared-flow equilibrium to create an equilibrium Z-pinch [46,47].

Figure 5. Scheme of the Z-pinch equilibrium [46].

3. The simulation of implosion in ICF
3.1. The simulation of laser-driven ignition devices
NIF is the world’s largest laser-driven laser fusion device. To achieve the ignition, the driving of the fusion needs to be fairly symmetric and uniform. The hydrodynamic instabilities and mix are very important for the degradation of implosion in ICF. To study them further and more comprehensive, some focused platforms were developed for measurement in some planned experiments [33]. For example, the measurements of the velocity non-uniformities of shock fronts were conducted by the two-dimensional imaging velocimetry technique [48]. For the materials used, the beryllium is usually employed as the materials for the capsules in the implosion for its high mass ablation ratio. The initial comprehensive experimental investigation about beryllium capsules with a cryogenic deuterium-tritium fuel layer in the indirectly driven fusion was done in 2019[49]. Then, a study applied the same dimension hohlraums on tactics to increase the capsule diameter and found that using a ‘picketless’ pulse can improve performance [50]. Recently in 2016, a thin-glass-shell, D3He-filled exploding-
pusher implosion of ICF at NIF was developed and demonstrated as a proton resource, which is the first promising attempt to develop a monoenergetic proton, \( \alpha \), and triton backlighting platform at the NIF [51]. This is hopeful to develop further and create a new platform at the NIF for some related research. Another famous laser-driven device is LMJ (Laser Megajoule) of the French Atomic Energy Commission (CEA). To study the ion dynamic structure of the front of planar collisional shock for the fully ionized plasma, the Vlasov-Fokker-Planck code was first employed in 1991 [52]. In 1993, the code was used to simulate the plasma collision in aircraft geometry [53] and the ion dynamics simulation of formation and propagation of plasma shock [54]. Besides, the code for the calculation of thermonuclear fuel fluid dynamics in the ICF was added to solve the Vlasov-Fokker-Planck equations [55]. The simulation results show that the ion transmission between the target core and outer side is enhanced compared with standard hydrodynamics methods. Subsequently, a locally split-step explicit (LSSE) algorithm was developed to solve the highly non-uniform and highly non-isotopic diffusion tension problems in the multi-dimensional advection-diffusion type equation in 2007 [56]. The optimization made the application of the Vlasov-Fokker-Planck code in the simulation of the slowing-down process of fast charged-particle.

3.2. The simulation of heavy ion inertial fusion (HIF)

For the heavy ion inertial fusion, the code OK1 came up to simulate the irradiation of the heavy ion beam on the directly driven spherical fuel pellets [57]. From 2004-2010, the code was developed to fit the target with any shape and structure [58]. As shown in Figure 6, the significant wobbling beam illumination capability was added [59] to increase the stability. Finally, the codes are combined as a program system named O-SUKI [60, 61]. Then in 2020, the O-SUKI was applied in practice to research how the beam input pulse parameters affect the fuel implosion and the implosion non-uniformity [62], which proved that the codes are very meaningful and can be a tool to research the HIF target implosion with high efficiency.

![Figure 6. Schematic diagram of the model of the helical swing beam irradiating the fuel target [60].](image)

3.3. The simulation of fast ignition devices

Simulations for fast ignition were developed by ILE group. The one-dimensional hydrodynamic implosion code and Fokker-Planck equation were used to study the kinetic energy effect of electron heat transfer in plasma [63]. The Fokker-Planck equation is solved by simplifying it into multiple sets of transmission equations in the implosion simulation. The reproduction findings are extremely coherent with the experiment. The results in the simulation experiment showed that the electron heat transfer ought to be explained using the Fokker-Planck (FP) equation in the fluid implosion code. In contrast, Spitzer-Helm (SH) heat conduction model is not appropriate [64]. Afterward, a simulation code was developed to describe the dynamics of spherically symmetric implosion water. The Fokker Planck equation of electron transmission was resolved to define non-local effects in 2008 [65].

4. Vlasov-Fokker-Planck (VFP) algorithm

VFP kinetic energy equation, together with Maxwell's equation, has wide applicability in the fusion
experiments. One successful example is a high-fidelity Vlasov-Fokker-Planck code, iFP code, developed by the Los Alamos National Laboratory. In 2014, a new model for the analysis of fluid dynamics and burn of thermonuclear fuels was conducted in line with a two-velocity-scale Vlasov-Fokker-Planck kinetic model, which is specially for the supra-thermal $\alpha$ particles in the fusion [66]. Later, the model was applied to describe the transmission of super-thermal $\alpha$ particles in the ICF target [67], which means the Fokker-Planck codes can simulate a complete DT target implosion at the ion dynamics level, including ignition and burn processes. At the end of 2014, the ion Fokker-Planck model was applied to analyze the different behaviors of deuterium and tritium at different stages in the implosion of marginally-igniting cryogenic ICF [68]. Additionally, in 2015 and 2016, a fully implicit algorithm [69] and an adaptive velocity-space separation scheme [70] were proposed for the multi-species, multi-dimensional Rosenbluth-Fokker-Planck (RFP) equation. Besides, a collision particle intracellular simulation is used to explore the kinetic energy effect generated during the mixing process of unmagnetized plasma media to correct the diffusion speed conditions [71]. Moreover, a discretization approach was employed to maintain discrete in arbitrary multidimensional geometry [72]. In order to study the basic structure and the dependence of the parameters of the plasma, the state-of-the-art VFP code, iFP was applied to analyze the steady-state planar shocks in D-3He plasmas. The simulation results was compared with multi-ion hydrodynamic simulations and semi-analytic results [73]. Besides, in order to verify that the iFP can produce correct results in weak shocks with multi-ion hydrodynamics conditions. The electron and ion temperature of iFP and the multi-ion hydro results were compared and shown in Figure 7, where the results tally well with each other.

![Figure 7. Electron and ion temperature profiles for weak shock](image)

Besides, some similar simulations based on the iFP codes were done to analyze the features of the plasmas shock in different environments [74] and the early transients of the interface between two species [75]. Besides, in 2018, the temporal stiffness was solved with implicit time stepping and the velocity-space scheme in 2016 was developed to an adaptive, implicit, conservative, spatially inhomogeneous system to build a 1D-2V multi-species VFP multi-scale solver in planar geometry [76]. Considering the non-thermodynamic equilibrium of ions composed of a mixture of fuel and strong thrust fuel, a mixed hybrid ion kinetic-fluid mathematical model was developed to simulate the kinetic behaviors of the implosion [77]. In 2020, the hybrid iFP codes were then employed [78]. Subsequently, the iFP code was used to confirm the pictures of two dynamical fuel implosion stages to reach ignition: a shock phase and an adiabatic compression phase [79]. Recently, a conservative configuration and moving-grid strategy of velocity-space for the planar geometrical VFP equation was developed. In this case, some more complex simulation cases were performed to show the beneficial features of the configuration and strategy with good integration capability of the algorithm [80]. Finally, the moving-mesh strategy was developed to spherical geometry to make a phase-space adaptive Eulerian VFP simulation of inertial confinement fusion capsule implosions available [81]. Some cases include the test problems were implemented to verify the strategy and finished the first ever reported verification.
of Guderley and Van-Dyke problem with VFP. The integrated algorithm can be applied to simulate the implosion of the Omega capsule in real cases.

5. Instabilities in the fusion

5.1. R-T instabilities
In practical there will be some fluid instability problems in the interface of the interface of thermal nuclear fuel medium because the shape of the pellet is not a uniformly distributed sphere, and the energy of the laser is hard to distribute evenly. One of the instabilities is called Rayleigh-Taylor instability which is a hot topic focused on by researchers. In 1993, the radiation effects on pellet implosion were studied by statistical method [82]. However, the classical method does not work in the reduction of the R-T instability [83], which shows that the perpendicular vibration of an R-T unstable interface will not benefit, and some other methods are needed. Then, a new mitigation method for the instability came out by a rotating or oscillating HIB illumination onto a pellet [84]. The principal is to add a dynamically adaptive perturbation to increase the total instability. Typically, a sketch of R-T instability is presented in Figure 8. For a perturbed plasma system, taking the time at Figure 8 (a) as the initial time point, and, if the perturbation added has the inverse phase as shown in Figure 8 (b), the total amplitude growth can be mitigated when time pass to \( t = \Delta t \) (seen from figure 8 (c)). The effect of the method had been proved by the R-T instability analysis and numerical simulations. Another smoothing method by a high-intensity charger-particle beam to accomplish consistent illumination over a fitting region of the target in the HIF was proposed in a research in 2010 [85]. The wobbler's mitigation method was applied by controlling and decreasing the perturbation growth though defining the imposed perturbation phase and amplitude at every wobbling cycle in 2012 [86]. Furthermore, studies found that the original imprint of the wobbling HIBs will bring a great deplorable energy gathering nun-uniformity [87]. On this basis, the robustness of the method was discussed further in 2015 [88]. Later, the robustness and the alleviation of the non-uniform implosion process for the ICF target by the HIB wobbler are discussed together to prove that in a further step [89]. Moreover, the following filamentation instability of them was studied by the dynamic stabilization when an electron beam was introduced into plasma [90]. The results denote that the application is successful, and the filamentation instability can also be stabilized similarly. In 2019, the method was developed to a dynamic smoothing method in the plasma systems with perturbation. The results demonstrated that the HIBs wobbler would help improve the stability and uniformity of the fuel target implosion [91].

Figure 8. A sketch of R-T instabilities [91].
5.2. Laser plasma instabilities (LPI)

Due to the inevitable initial density disturbance in the plasma, LPI is very easy to be excited. Typical LPI includes Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS) [92]. A theoretical research method based on Coupled Mode Equations is established for the three-wave coupled LPI process, starting from Maxwell's equations and fluid mechanics equations. The growth characteristics of typical processes such as SRS and SBS are investigated [93]. For SRS, it is reported that applying particle-in-cell simulations to study SRS excited by incoherent light showed that the growth of SRS and electron heating greatly could be decreased by large incoherent light bandwidth in the linear stage [94]. Subsequently, there might be some effects from the electron beam for the stimulated Raman side-scattering [95]. Some useful conclusions are obtained for the relationship between beam radius/plasma density and SBS [96]. The materials own a great impact on the SBS [97]. This can be employed for the material selection for SBS reduction.

6. Conclusion

In summary, we introduce the ICF ignition schemes and simulation of implosion and discuss the instabilities during the ignition. Specifically, three kinds of ICF driven by different methods (laser/particle beam/Z-pinch) are demonstrated. Subsequently, simulations of implosion in each type of ICF are mentioned, indicating some valuable methods or results in the field. Afterward, the development and example of the useful VFP algorithm are introduced. Finally, the vital problems instabilities that affect the ignition are reviewed, including R-T instabilities and some parameter instabilities. This paper provides some milestones of ICF, which offers a guideline for further studies.

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