Chapter 1
Introduction

Abstract A brief overview of the fluid model to describe most of the plasmas is given. Assuming the velocity distributions of electrons and ions are shifted Maxwellian distribution, plasmas can be described with fluid approximation regardless they are collisional or collisionless. The time evolution of laser plasmas is described with the fluid model with non-ideal equation of state, non-local electron transport, radiation transport, and so on. Modeling atomic state of plasma, effective charge, spectral opacity, and emissivity are calculated to couple with the energy equation of the electron fluid. As a reference to the plasma physics explained in this book, the physics scenario of laser fusion dynamics is used to know what kinds of physics become to couple from laser absorption to the fusion energy production through the implosion dynamics.

It is emphasized that the development of a physics-integrated code is important to study such laser-produced plasmas. Along with the advancement of technology for diagnostics and lasers, the analysis of the experimental data has helped the improvement of the physics models by comparing the experimental data to the corresponding simulations. Considering the technically limited number of implosion experiments with a huge laser facility, the advancement of the physics-integrated codes is becoming the main issue to increase the quality of analysis and design for better performance experiments. The progress of computer performance and advancement of experiments are now non-separable in complicated nonlinear systems such as plasma physics even within the hydrodynamic modeling of plasmas.

1.1 Fluid Model

As studied in Volume 1, intense lasers are used to heat the matter to produce high-temperature plasmas, where extremely high pressure is produced to compress the matter to a density higher than the solid densities. In studying the physics of laser-plasma interaction and the resultant heating of plasmas, the key physics was the mechanical dynamics of electron particles in the electric and magnetic fields of lasers.

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Since the phenomena are so complicated, the particle-in-cell (PIC) simulation has been used widely as seen in Volume 1. The usage of the PIC codes is the direct way to study plasma physics in the case of the interaction with ultra-short and ultra-intense lasers, because the pulse duration is very short less than a pico-second (10^{-12} s) and the density of the interaction region is relatively low compared to solid density. Therefore, PIC simulation is a powerful tool for studying physics under reasonable modeling of the interacting plasma region during the laser pulse duration.

On the other hand, the laser-produced plasma dynamics in the range of more than a nano-second (10^{-9} s), is unable to study with the use of PIC codes the whole dynamics from the low-density region expanding to the vacuum to the compressed high-density region. It is required to model the laser-produced plasma with another mathematics.

The next precise way is to solve Boltzmann equations directly, while the particle distribution functions at each space and time are also a function of particle velocity or energy at each point. Its degree of freedom is infinity and it should be discussed how many numerical grids are affordable in solving Boltzmann equations computationally. Solving the Vlasov equation is equivalent to solving particle dynamics directly in PIC code for collisionless plasma. In general, however, thanks to the progress of computer capability, the PIC codes are widely used because of the simplicity of numerical methods and their numerical stability.

Instead of PIC or kinetic methods, the easier way to solve the physics is to model the plasma as fluids and use the basic equations for fluid dynamics. It is equivalent to assuming that the distribution function is **Maxwellian** locally with particle density n, flow velocity $\mathbf{u}$, and temperature T,

$$f(\mathbf{v}, \mathbf{r}, t) = \frac{n}{(2\pi T/m)^{3/2}} e^{-\frac{m}{2T}(\mathbf{v}-\mathbf{u})^2} \tag{1.1}$$

In the fluid model, the basic fluid equations to n, $\mathbf{u}$, and T are solved as functions of time and space (t, $\mathbf{r}$).

Taking the moments of velocity, v^0, $\mathbf{v}$, and v^2 of the Boltzmann equation, it is well known that the fluid equations are obtained even for the ion and electron two-fluid system. Then, the basic equation to be solved are coupled partial differential equations for

Density n($\mathbf{r}$, t) or mass density ρ ($\mathbf{r}$, t),
Flow velocity or mean velocity vector $\mathbf{u}$($\mathbf{r}$, t),
Temperature T($\mathbf{r}$, t).

Note that depending on the time and space scale of the plasma phenomena, the ions and electrons are assumed to be different densities, velocities, and temperatures. When we are interested in a long time and space scale phenomena, one-fluid one-temperature or one-fluid two-temperature models are used. In discussing two-fluid models, it is usual to take into account the coupling with Maxwell equations, because charge separation and electric current produce electric and magnetic fields working new forces to electron and ion fluids.

The neutral fluid equations have a longer history than the Boltzmann equation. From the end of the seventeenth century, the analytical and algebraic aspects of mechanics were advanced, and the laws of conservation of mechanical quantities such as momentum, angular momentum, and energy were proposed, and the equations of motion were formulated.

In the eighteenth century, the consideration of mechanics was extended from point mass to systems with many points, i.e., continua such as rigid bodies and fluids, and the theory of mechanics was applied to them as well. By the middle of the eighteenth century**, Bernoulli's theorem**, the first fundamental law of fluids, was proposed, followed by **Euler's equations** of motion and **Lagrange's equations** of motion. This is said to be the birth of modern fluid mechanics.

1.2 Brief History of Fluid Dynamics

It is useful to give a general description of the development of fluid dynamics. Wikipedia is copied here since it is well-described. Fluid mechanics is the branch of physics concerned with the mechanics of fluids (liquids, gases, and plasmas) and the forces on them. It has applications in a wide range of disciplines, including mechanical, civil, chemical, and biomedical engineering, geophysics, oceanography, meteorology, astrophysics, biology, and plasmas.

It can be divided into fluid statics, the study of fluids at rest; and fluid dynamics, the study of the effect of forces on fluid motion. It is a branch of continuum mechanics, a subject that models matter without using the information that it is made out of atoms; that is, it models matter from a macroscopic viewpoint rather than from a microscopic one.

Fluid mechanics, especially fluid dynamics, is an active field of research, typically mathematically nonlinear and complex systems. Many problems are partly or wholly unsolved and are best addressed by numerical methods, typically using computers. A modern discipline called computational fluid dynamics (CFD), is devoted to this approach. Particle image velocimetry, an experimental method for visualizing and analyzing fluid flow, also takes advantage of the highly visual nature of fluid flow.

The study of fluid mechanics goes back at least to the days of ancient Greece when Archimedes investigated fluid statics and buoyancy and formulated his famous law known now as the Archimedes' principle, which was published in his work "On Floating Bodies" – generally considered to be the first major work on fluid mechanics. Rapid advancement in fluid mechanics began with Leonardo da Vinci (observations and experiments), Evangelista Torricelli (invented the barometer), Isaac Newton (investigated viscosity), and Blaise Pascal (researched hydrostatics, formulated Pascal's law), and was continued by Daniel Bernoulli with the introduction of mathematical fluid dynamics in "Hydrodynamica" (1739).

The inviscid flow was further analyzed by various mathematicians (Jean le Rond d'Alembert, Joseph Louis Lagrange, Pierre-Simon Laplace, Siméon Denis Poisson) and viscous flow was explored by a multitude of engineers including Jean Léonard Marie Poiseuille and Gotthilf Hagen. Further mathematical justification was provided by Claude-Louis Navier and George Gabriel Stokes in the **Navier–Stokes equations** and boundary layers were investigated (Ludwig Prandtl, Theodore von Kármán), while various scientists such as Osborne Reynolds, Andrey Kolmogorov, and Geoffrey Ingram Taylor advanced the understanding of fluid viscosity and turbulence.

1.3 Compressible Fluid Plasma

Most of the classical fluid dynamics cited above are about incompressible fluid, where the fluid density is constant and flow velocity is slow. Compressible fluid dynamics starts to be studied in the field of aerodynamics. Once the flow velocity becomes near and higher than the sound velocity of the fluid, compressibility becomes essential. One of the pioneering good textbooks about compressible fluid dynamics is the book by Liepmann and Roshko [1]. Then, the compressible fluid in high temperature and high density is well described by a famous book by Zel'dovich and Raizer [2]. The shock wave structure of plasmas was studied precisely based on a two-fluid model including the charge separation effect in [3].

The book [2] is unique and highly related to the topics of shock waves and hydrodynamics of laser-produced plasma to be shown in the present book. It is noted, however, that the book is a good one for one-dimensional hydrodynamics, while almost no description of the hydrodynamic instabilities and resultant turbulent mixing is to be discusses in Volume 3. This is because such topics of hydrodynamic instabilities have been mainly developed after the publication of the book. The book "fluid dynamics" by Landau and Lifshitz [4] is also famous as a pioneering book of modern fluid mechanics, where the compressible fluids and stability of fluid dynamics are also discussed.

The study of the equation of state (EOS) of non-ideal matters and plasmas are not simple and self-consistent statistical physics should be studied. Plasma emits radiation in the X-ray region to affect the fluid dynamics via energy transport. The so-call **radiation-hydrodynamics** should be modeled as basic equations. In addition, electron transport becomes important and a simple diffusive approximation violates. This is because the laser energy is deposited dominantly near the cut-off density and the heated electrons transport their energy into a relatively cold region. Then, most of the energy is carried by high-energy electrons whose Coulomb mean-free path is proportional to the square of the kinetic energy. Suck non-local transport should be modeled in the fluid equations.

Different from most of the fluids cited above, the hydrodynamic equation is not appropriate to understand other plasma phenomena, because high-temperature plasma is almost collisionless and the velocity distribution function easily departs from Maxwell distribution in (1.1). A variety of plasma instabilities are induced when non-Maxwellian electrons or ions tend to be in a thermos-dynamics equilibrium state after the growth of electromagnetic energy. For example, an electron beam is injected into plasma, and electro-static and electromagnetic waves are induced to grow their energies into a nonlinear stage where particle-field nonlinear interaction is essential. Such a phenomenon is in general to be studied by so-call kinetic theory of plasma, which will be given in Volume 4.

1.4 Hydrodynamics of Laser Fusion

The author researched the possibility of laser fusion and its related physics to apply to studying astrophysics with intense lasers in the laboratory. The starting point is to study physics-integrated radiation hydrodynamics of laser fusion as shown in Fig. 1.1 [5]. The engineering scenario – an optimistic scenario – for fusion energy production is shown in the array at the center. This concept of laser-driven implosion is proposed in 1972 by Nuckolls et al. [6].

Why engineering (or optimistic) is because the physics scenario is assumed to be in spherical symmetry as schematically shown in Fig. 1.2. However, the physics in the laser fusion has been clarified to be not so simple through a lot of implosion experiments. In the laser-plasma interaction, energy loss by reflection and nonlinear physics of the interaction discussed in Volume 1 should be modeled. In general, the nonlinear interaction produced hot electrons to pre-heat the solid target, preventing the ideal hydrodynamic implosion.

Electrons obtain energy from the laser and transport it to the ablation front. On the right side in Fig. 1.1, the non-ideal fluid physics is listed. The transport is not diffusive and anomalous physics should be considered because of non-local transport, radiation transport, and the effect of self-generated magnetic and electric fields. We need to study plasma turbulences as shown in Volume 4.

After accelerating the fuel plasma in the in-flight phase, the kinetic energy is converted to the thermal energy to ignite a fusion reaction at the center of a spherical target as shown in Fig. 1.2. The compressed fuel should be controlled so that it consists of the central ignitor (red) and the surrounding main cold fuel (blue) as shown at “ignition” in Fig. 1.2. In such one-dimensional scenario, it is possible to obtain fusion energy production larger than 100 times the input laser energy. The fusion product of alpha particles works to induce the nuclear-burn of the main fuel. It should be noted that for generation of electric power with such high-gain laser fusion, very challenging implosion with the compressed fuel radius less than 1/30 ~ 1/50 of the initial radius is required, very different from the image of the cartoon in Fig. 1.2.

On the left in Fig. 1.1, on the other hand, the physical issues to be studied are listed regarding the multi-dimensional effect of the laser implosion process. In the direct-drive laser fusion scheme, non-uniformity of laser absorption energy flux on the target surface initiates uneven hydrodynamics. This is called the “imprint” of hydrodynamic instability. How the imprint is serious depends on the thermal transport and the equation of states of ablating plasma and shocked solid material.

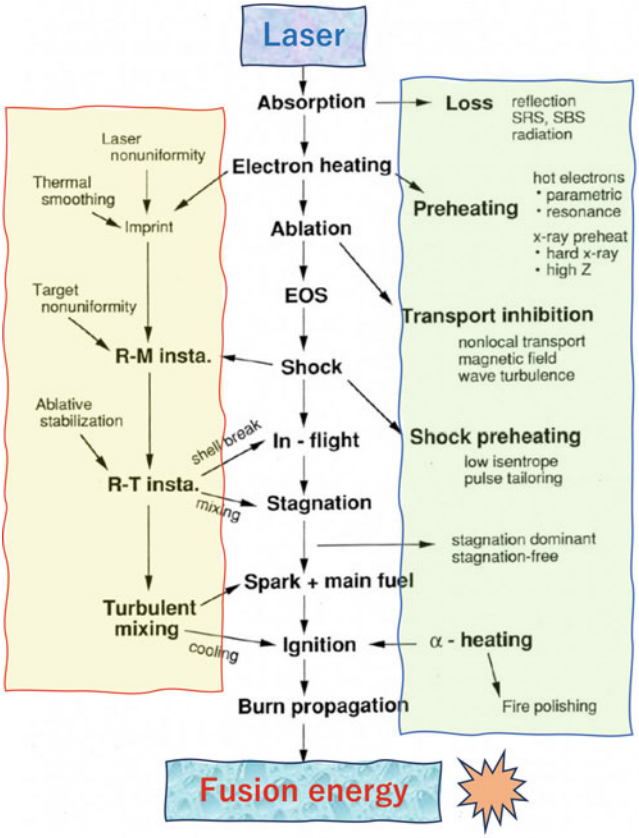

Fig. 1.1 The laser fusion physical scenario. The central scenario is the spherically symmetric implosion and burn scenario in fluid assumption. The nature is, however, not so kind to allow us to keep in one dimension and fluid assumption. The right-hand-side represents the importance of transport issues and high-energy electron production. Long range heating by alpha particles helps smoothing of the non-uniform core. The scenario on the left-hand-side is related to multi-dimensional effects. From instability to turbulence, challenging subjects will be described in Volume 3. Reprint with permission from Ref. [5]. Copyright by IAEA

Since the laser intensity is extremely high, the initial shock wave induces Richtmyer-Meshkov instability. In the in-flight and final stagnation phases, **Rayleigh-Taylor instability** becomes important as the instability prevents the engineering scenario of implosion. Linear instability, nonlinear physics, and finally material mixing by **turbulent mixing** are the critical issue to realize the fusion energy, while their physics are still under intensive study. One fortunate physical phenomenon is known as **ablative stabilization** of the classical Rayleigh-Taylor instability, where the ablation flow and heat conduction by electrons and radiation reduces the growth rate of the Rayleigh-Taylor instability at the ablation front. The

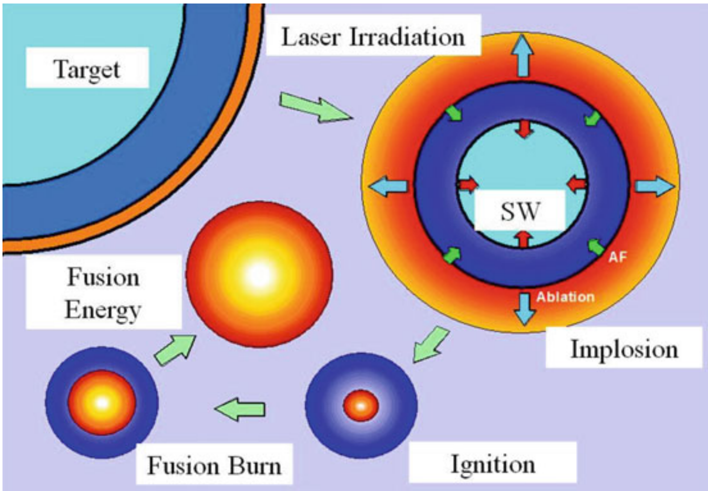

Fig. 1.2 Schematics of Engineering scenario of laser fusion. The target with ablator (orange) and frozen DT fuel (blue) are irradiated by many laser beams for implosion with shock waves. The fuel DT are required to squeeze about 30 times smaller radius to ignite the imploded fuel. Ignition is triggered and fusion product alpha particles heat whole the compressed fuel to produce about 100 times energy of input laser energy

physics of hydrodynamics instability and turbulent mixing will be shown in Volume 3.

A review on the direct drive laser fusion is given for example, by Craxton et al. in [7]. One of the top runners in the theory, computing, and experiments of direct-drive laser implosion and fusion research has been the Laboratory for Laser Energetics, Univ. of Rochester. The review paper has summarized most of the accomplishments in direct-drive laser fusion with the OMEGA laser facility including all the other activities from the beginning of laser fusion research. The most critical issue of laser fusion is the physics stemming from the multi-dimensional effect, and more detail of the implosion physics will be given in Volume 3.

1.5 Modeling Radiation-Hydrodynamics in Astrophysics

One of the most attractive applications of the physics of laser plasma is to study astrophysical phenomena in the laboratory. This is called "**laboratory astrophysics**". There are two points of view linking laser-generated plasma and astrophysics; that is, sameness and similarity. The sameness is that the physics are identical, and the similarity is that the physical phenomena or dynamics are similar in non-dimensional time and space. For example,

1. Sameness of physics
   (a) Ionization of plasmas, equation of state,
   (b) Opacity, emissivity
   (c) Nuclear reaction
2. Similarity of physics
   (a) Dynamical phenomena of compressible plasma fluids,
   (b) Non-equilibrium atomic processes,
   (c) Radiation transport, particle transport

The class (1) is easy to understand. For example, a laser fusion implosion experiment has achieved a plasma state comparable to the temperature and density of the Sun. The thermodynamic properties of astronomical objects can be studied in detail by generating small pieces of them in the laboratory. This is also the case of radiation properties like emission and absorption spectra of x-rays.

Class (2) is an attempt to elucidate various physics of compressible fluid phenomena, atomic processes, and so on by transforming time and space scales to the power of 10–20 ($10^{10\text{–}20}$) on the basis of a similarity law. It is possible to reduce the phenomena to the time scale of density ratio ($\sim 10^{20}$) from phenomena in astrophysics to those in the laboratory. Therefore, for example, we have considered the hydrodynamic similarity between laser implosion and supernova explosions.

It is too much to explain more about laboratory astrophysics and interested readers are recommended to refer to a review paper [8] and the references cited therein. The following ten topics are reviewed about how laser experiments are carried out to clarify the physics in Universe.

1. Equation of state experiment of high-energy-density plasmas compressed by shocks by lasers
2. Opacity measurement of hot-dense plasmas produced by lasers
3. Photo-ionized plasma experiment modeling Black-Hole binary system
4. Blast waves generated by intense lasers
5. Hydrodynamic instability and the physics of turbulent mixing
6. Magnetic reconnection experiments
7. Magnetic turbulence experiments
8. Collisionless shock mediated by Weibel instability and magnetic turbulence
9. Modeling cosmic-ray generation via relativistic laser and charged particle interaction
10. Electron-positron plasma generation by ultra-intense Lasers

In the present Volume 2, topics (1)–(4) will be discussed. A typical example to model photo-ionizing plasma near a black hole or neutron star is shown in the figure on the front page of the present book. By use of laser implosion, it is possible to generate Planckian radiation of radiation temperature 500 eV which is almost the same as from the surface of compact objects such as black holes or neutron stars [9]. On the right in the figure, a comparison of the measured spectrum in the model experiment and observed from the photo-ionized plasmas near the compact objects are shown for silicon atoms to clarify the ionization process. The detail of this topic is described in Chap. 5.

1.6 Verification and Validation (V&V)

One of the typical approaches in studying the laser-plasmas is to focus the development of computer simulation code with all of related physics as mathematical models, which is called "**physics-integrated code**". In Fig. 1.3, the elements of the integrated code are listed in relation to each other. Mostly, all the elements couple in a nonlinear manner, and the performance of the simulation is sensitive to the most unreliable modeling of physics.

In the early time of research, one-dimensional integrated codes have been developed. It is because the computer performance was still low and multi-dimensional hydrodynamic simulation was not possible. At that time, physics modeling of laser heating, atomic physics, and equation of state were the main issues in modeling the physics as simply as possible so that it fits the computer capability at that time. Then, the modeling done already in astrophysics has been adapted to the laser fusion codes. The kinetic effect of radiation and particles has been newly installed because of the discrepancy in the experimental result from the simplified model used in astrophysics.

To upgrade the codes to two- and three-dimensions, we have to wait for the progress of the computer performance. This situation very resembles the case of the simulation of global warming. S. Manabe was awarded the Nobel Prize in physics in 2021 for "the physical modeling of Earth's climate, quantifying variability and reliably predicting global warming" [10]. His pioneering work is the temperature change on the earth's surface in one-dimensional thermal equilibrium of the

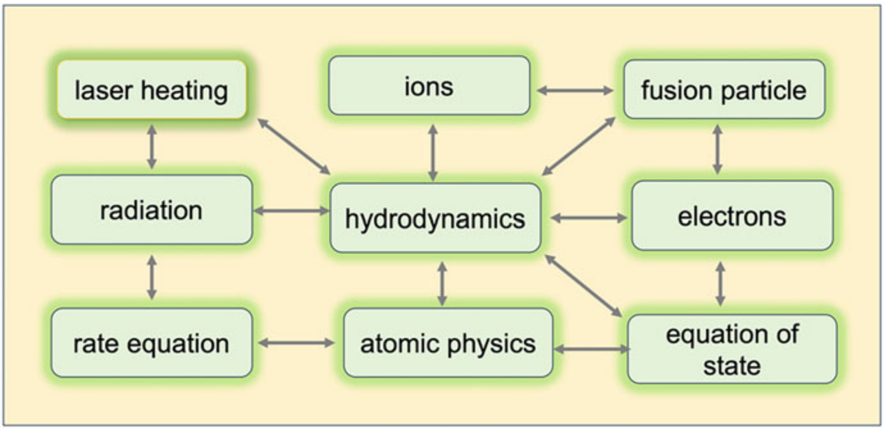

Fig. 1.3 Physics elements in the integrated code for laser fusion research. Note that now hydrodynamics is required to be of three-dimensional

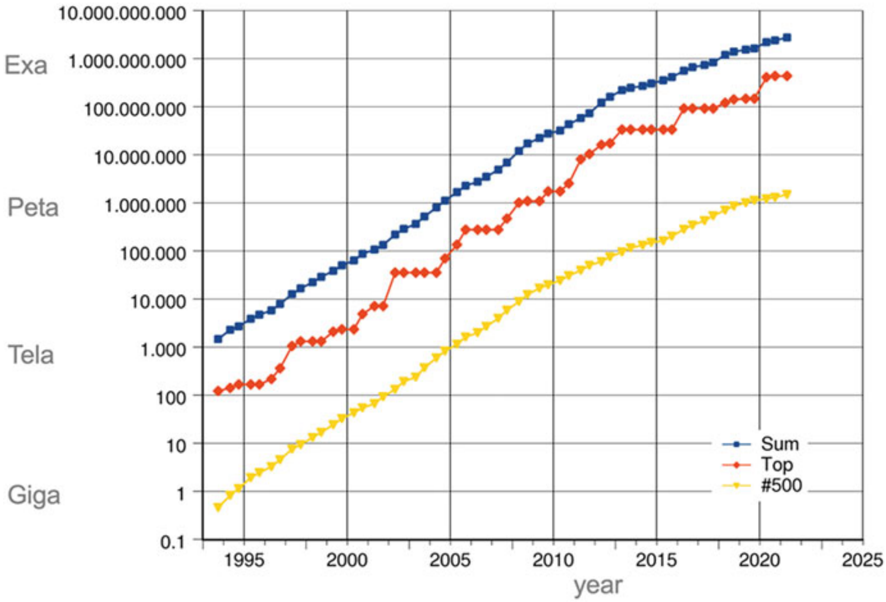

Fig. 1.4 Rapid growth of supercomputer performance, based on data from the top500.org website. The logarithmic *y*-axis shows performance in Giga flops. Combined performance of 500 largest supercomputers (blue). Fastest supercomputer (red). Supercomputer in 500th place (yellow). [From data of https://www.top500.org/]

atmosphere due to the increase of CO_2 gas in 1967. He has modeled many physics elements based on microphysics and developed one-dimensional code to solve nonlinear coupled systems. Such work has led the world to consider seriously about global warming and to decide on the carbon-neutral policy.

Thanks to the rapid progress of computer capability as shown in Fig. 1.4, now three-dimensional radiation-hydrodynamic codes become an essential tool to study the performance of implosion experiments and to design and predict better experiments. Multi-dimensional hydro-code also requires a heavy calculation of non-local transport, where the energy space needs multi-group transport. In addition, each physics model has been replaced by a new model with more sophisticated physics. It is noted that a magnetic field is generated in the multi-dimensional plasma fluid. Although its energy density is much less compared to the thermal energy, its effect on the energy transport coefficient of electrons is sensitive to alter the hydrodynamic phenomena.

It is surprising to know that the performance (speed) of supercomputers increased 10,000 times in the last 20 years. This means the increase of one order of performance (speed) has been accomplished every 5 years. This progress suggests that the research method has changed from mostly experimental data analysis to analysis with the physics-integrated codes in laser fusion research. At the same time, such code development verified with experimental data has been regarded to be beneficial for the improvement of astrophysics research.

Let us here consider more general importance of verification and validation of simulation codes and the collaboration with experiments [11]. Simulation models are increasingly being used to solve many problems and to aid in decision-making like the carbon-neutral policy. The developers and users of these models, the decision makers using information obtained from the results of these models, and the individuals affected by decisions based on such models are all rightly concerned with whether a model and its results are “correct”. This concern is addressed through model **verification and validation (V&V)**.

Verification is the process of checking that software achieves its goal without any bugs. It is the process to ensure whether the program that is developed is right or not. It verifies whether the developed program fulfills the requirements that we have. Verification is static testing. Verification means “Are we building the code right?”.

Validation is the process of checking whether the software product is up to the mark or in other words product has high-level requirements. It is the process of checking the validation of the code i.e., it checks what we are developing is the right to predict the experiments. It is the validation of actual and expected experimental products. Validation is dynamic testing. Validation means “Are we building the right code to explain and predict the product?”. Here we can regard the product as the implosion experiments. If not right, further improvement of the physical models and/or finding new physics are required. It is of course that the integrated codes can’t predict the real physics without checking with corresponding experimental results and model experiments, and continuous effort of improving the physics models.

The rapid progress of computer performance has made it possible to use computers for machine learning, neural network, big data analysis, statistical modeling, and so on. **Artificial intelligence (AI)** helps more advanced study of the integrated physics system. By activating the deep-neural network system shown in Fig. 1.5, it is advantageous for us to use wide knowledge of science and deep thinking to the input data. Such artificial intelligence starts to be used in many kinds of research, and its review has been published in the plasma physics field [12–17].

In the present volume, the physics of compressible hydrodynamics is introduced. The hydrodynamics is limited to only one-dimensional one, and multi-dimensional hydrodynamics will be studied in Volume 3. Atomic physics of plasma and the equation of the state of dense plasmas are explained as advanced models of plasma fluids as functions of density and temperature, including the case of non-local thermodynamic equilibrium (non-LTE) states. Most of the description is focused on theoretical physics, with which especially young researchers can obtain the image of physics in studying any kind of plasmas. Collisionless plasmas are also an interesting subject and are to be discussed in Volume 4.

1.7 Brief in Each Chapter

In Chap. 2, basic equations governing a variety of fluid models of plasmas are shown with simple explanations. In general, high-density plasmas are approximately modeled with neutral compressible fluid with heating and loss terms, and energy

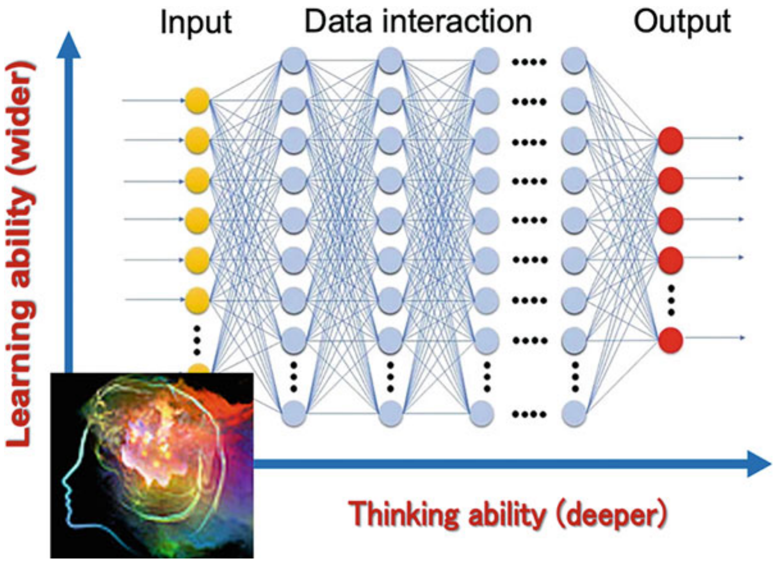

Fig. 1.5 Schematics of human brain and artificial intelligence. (Courtesy of TU Dresden)

transport terms. It is called "radiation-hydrodynamics". Although the plasma is assumed as a neutral fluid, the equation of state should cover from the cold solid material to an electron-degenerated high-density state. The generation of the magnetic field is also briefly explained and the properties of the magneto-hydrodynamic (MHD) equation are discussed. A variety of waves in plasmas are derived and the importance to know the waves is discussed.

In Chap. 3, the physics of shock waves is discussed. Laser-driven ablation plasma produces extremely-high pressure called "ablation pressure". Its physical mechanism is shown by relating to the slow combustion wave, namely the deflagration wave. The ablation pressure scaling law is obtained by solving a hydrodynamic equation in steady state assumption. Such simple theoretical results are compared to the data obtained in model experiments with intense lasers. The dynamics of plasma acceleration by the ablation pressure is also compared to the corresponding experiments with advanced diagnostics.

In Chap. 4, the time-dependent dynamics of laser plasmas is an essential issue to be studied and to be used for applications. It is needed to solve nonlinear partial differential equations even in one-dimensional assumptions. Especially, in spherical geometry, it is hard to find simple analytical solutions. However, it has been shown that the self-similar mathematical method provides a variety of analytical solutions as a function of self-similar variable $\xi \propto r/t^{\alpha}$, where r is the radius, t is time, and α is a constant found finally as an eigenvalue of the problem. Several examples are described there related to the implosion dynamics in spherical symmetric systems. It is important to know such self-similar solutions to obtain the physics image of the implosion and shock dynamics in a converging system.

In Chap. 5, atomic physics and the atomic process of partially ionized atoms are explained within an isolated atom or ion model. While re-reviewing the physics of the atomic structure of the multi-electron atomic system, the quantum physics of all atomic processes are also re-reviewed with intuitive images of the processes. It is not applicable to assume the atomic state of the laboratory plasmas is in the thermodynamic equilibrium (LTE) state, and the non-LTE atomic process should be considered. Photo-ionizing plasma is a typical example of a non-LTE atomic state, and its model experiment with intense laser is compared to the astrophysical plasmas.

In Chap. 6, it is emphasized that rapid heating of plasma by intense laser produces a steep temperature gradient, where the heat flux by the diffusion model is not applicable and the flux should be evaluated with the Fokker-Planck equation of electrons. This is because the plasma size is shorter than the mean free path of the electron component mostly transporting the heat flux. Different mathematical models have been proposed and compared to the Fokker-Planck simulations. The advanced modeling is explained and the importance for studying the direct-drive laser fusion is discussed. The progress of the improvement of the models is reviewed.

In Chap. 7, a brief review of the kinetics of radiation transport with many groups of photo energy is given. In this topic, the toughest job is to calculate the spectral opacity and emissivity, especially of partially ionized medium- and high-Z ions. Once the spectral line opacity becomes important in the radiation energy transport, the numerical modeling becomes complicated for optically thick plasmas. The density dependence of line profiles is discussed by paying attention to related microphysics. The same type of Boltzmann equation should be solved for neutrino transport in gravitationally collapsing supernova explosions of massive stars. Big computing of 3-D simulations is shown as a related topic of radiation transport.

In Chap. 8, the basic knowledge to study dense and non-so-high-temperature plasmas produced by laser shock waves in solid materials is described. In general, the ions are treated as isolated ones in plasma in the case of magnetically confined plasma, space plasma, and so on. As we know, condensed matter shows a many-body effect like band structure. This means with an increase in density and temperature, the many-body effect should be taken into account in any theoretical model and computation. Thanks to the progress of computing, it became possible to carry out “ab initio” calculations. The widely used model, Density Functional Theory (DFT), is briefly derived to prepare its application to the physics of equation of state and warm dense matter.

In Chap. 9, the physics of warm dense matter is discussed. A study of the equation of state with shock waves is introduced. The other method to study high-pressure physics with static high-pressure is also shown, and the long-standing physics of insulator-metal phase transition is discussed. The theory of strongly coupled plasma is studied backing to the old time when computer capability is not enough. It is shown that the warm dense mater can be studied precisely in experiments with X-ray Free-Electron-Lasers (XFEL) and precise theoretical analysis is introduced by the use of density-functional-theory.

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