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Frontier Issues and Progress of Controlled Nuclear Fusion Science and Technology

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Abstract: Controlled nuclear fusion energy will be an ideal source of clean energy in the future. The International Thermonuclear Experimental Reactor (ITER) project is the focus of research conducted in the field of international magnetic confinement fusion. Frontier issues in scientific and engineering targets of the ITER project are introduced in this paper. Short-term, mid-term, and long-term technical goals of magnetic confinement fusion research in China are proposed, as well as a roadmap of magnetic confinement fusion research in China. In the field of inertial confinement fusion (ICF), Z-pinch has the potential to be a future energy source. Remarkable progress has been made from experiments of Sandia laboratory's Z/ZR machine. In China, a large number of basic studies have been carried out on the physics of the Z-pinch radiation source, the driving ICF technology, and especially the energy-coupling physics of the driver and the Z-pinch load. It is suggested that China should continue working on international collaboration on the ITER project, study advanced science and technology on nuclear fusion reactors, actively promote R&D of key components of the China Fusion Engineering Test Reactor (CFETR), and start the CFETR's construction at the right time. It is also suggested that China should support the construction of a new-generation high-current pulse power test platform, to promote Z-pinch fusion ignition and explore a Z-pinch-driven fusion and fission hybrid reactor.

Keywords: ITER; CFETR; Z-pinch; fusion ignition; pulse power

1 Introduction

Controlled nuclear fusion energy will be an ideal source of clean energy in the future. Tokamak research has taken a leading position in the field of magnetic confinement fusion (MCF). China has officially participated in the construction and research of the International Thermonuclear Experimental Reactor (ITER) project, and is independently designing and developing the China Fusion Engineering Test Reactor (CFETR) simultaneously. In the field of inertial confinement fusion energy, Z-pinch has more potential and is likely to be a competitive fusion-fission hybrid energy source. This paper focuses on the frontier issues of MCF and the progress of Z-pinch research in China.

2 Frontier issues in MCF

2.1 Research significance and current status of MCF

MCF is an approach to generate thermonuclear fusion power that uses special magnetic fields to confine light atomic nuclei (such as deuterium and tritium) and free electrons within a limited volume in the form of an ultra-high temperature plasma, under which conditions a large number of atomic nuclear fusion reactions can be controlled to occur and release energy. MCF achieves the self-sustaining burning deuterium-tritium plasma and maintains it through a low-density and long-term process. The types of MCF devices in the world mainly include the Toka-

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mak, stellarator, and magnetic mirror, among which the tokamak most easily approaches the fusion conditions and is the most developed. Currently, great progress has been made in MCF: China has officially participated in construction and research of the ITER project, and is independently designing and developing the CFETR simultaneously, which aims at bridging the R&D gaps between ITER and a demonstration power reactor (DEMO) [1]. These measures will bring China's MCF research level to the international forefront.

2.2 Frontier issues in MCF

The research and development of MCF is not only costly, but also full of challenges concerning science and technology. Thus, it was not until the 1990s that the knowledge and technology necessary to build MCF experimental reactors became available, after more than 40 years of relatively large-scale international fusion research. MCF is still in the exploratory stage, and there are many physical and engineering issues to be solved. At present, various physical and technical issues related to ITER devices are the main research areas in the international MCF field [2]. ITER is a power-station experimental reactor with a designed total fusion power of 500 MW. ITER's missions are to use a plant-size experimental reactor to prove the ignition and continuous burning of deuterium-tritium plasma, validate the engineering reliability of the fusion reactor system, comprehensively test the high heat flow and nuclear components for fusion power, and achieve steady-state operation, thus establishing the solid scientific and necessary technical basis for building fusion energy demonstration plants. The scientific goals of the ITER project include: ① integrated verification of advanced tokamak operating modes, ② verification of steady-state burning plasma physical processes, ③ fusion alpha particle physics, ④ control of burning plasma, ⑤ determination of the constraint calibration relation within the range of new parameters, and ⑥ tokamak fueling and exhaust technology.

The main objective of ITER's first operational phase is to build a tokamak fusion reactor that produces 500 MW of fusion power by burning deuterium-tritium plasma, with a fusion gain factor $Q = 10$ and a pulse duration of more than 400 s. In the ITER device, a deuterium-tritium burning plasma similar to that of a future commercial fusion reactor will be produced for scientists and engineers to study its properties and control methods, which is a key step in achieving fusion energy. The second phase of the ITER device operation will explore a steady-state, high-constraint and high-performance burning plasma, with a fusion gain coefficient $Q = 5$, and pulse maintenance longer than 3000 s. This steady-state, high-performance advanced burning plasma is required for the construction of tokamak-type commercial fusion reactors. ITER also plans to explore high-gain burning plasmas later. The realization of ITER's scientific goals will lay a solid foundation for the scientific and engineering technology for the construction of commercial fusion reactors in the future.

In addition, the engineering objectives of the ITER project are to test and implement the integration of various fusion technologies by creating and maintaining deuterium-tritium burning plasmas, and to further research and develop related technologies that can be directly used in commercial fusion reactors. This work is required before the design and construction of a commercial fusion reactor, and it can only be carried out on the ITER device. The engineering and technical issues of fusion reactors that ITER plans to partially verify include:

(1) Research on reactor-level magnets and their associated power supply and control technologies

(2) Steady-state burning plasma technology (production, maintenance, and control), i.e., non-inductive current drive technology, reactor-level high-power auxiliary heating technology, reactor-level plasma diagnostic technology, plasma configuration control technology, and tokamak fueling and exhaust technology

(3) Initial material experiments with high heat loads

(4) Research on blanket technology, neutron energy slowing and energy extraction technology, and neutron shielding and environmental protection technology

(5) Tests of low-activation structural materials, and research on tritium breeding, regeneration, anti-infiltration, recycling, and purification technologies

(6) Research on hot chamber technology, and remote control, operation, replacement, and maintenance technologies of core components.

ITER will inherit the main scientific and technological achievements of current international controlled MCF research, and achieve, for the first time on Earth, a controlled thermonuclear fusion experimental reactor that can be compared with the future practical fusion reactor scale to solve the key issues of fusion plants. The successful implementation of the ITER project will fully demonstrate the scientific and engineering feasibility of the development and utilization of fusion energy, and is a key step for humans in the practical application of controlled thermonuclear fusion research.

2.3 Technical goals and development plans of MCF research in China

Chinese fusion research started in the early 1960s, and although it went through a very difficult phase for a long time, it has always been able to maintain steady and gradual development. Since the 1970s, tokamak research has been chosen as the main approach; multi-experimental devices such as the CT-6, KT-5, HT-6B, HL-1, and HT-6M have been built and operated successfully. At present, the main devices are the J-TEXT at Huazhong University of Science and Technology, HL-2M at the Southwestern Institute of Physics (SWIP) and EAST at the Institute of Plasma Physics Chinese Academy of Sciences (ASIPP).

During the process of design, construction, and experimental operation of these tokamak devices, a group of fusion engineers was formed and trained. A series of important research works has been carried out by Chinese scientists on these tokamak devices. The future fusion development strategy in our country should aim at the international frontier issues and make extensive use of international cooperation, so as to tap the solid foundation of research on the development of MCF energy. Further goals include accelerating the talent training, carrying out research on the frontier of international fusion relying on existing medium- and large-size tokamaks, building a famous MCF plasma experimental base, and exploring the physical and basic engineering problems of future stable, efficient, safe, and practical fusion engineering reactors. The recent, medium, and long-term technical objectives of MCF in China are as follows [3]:

(1) Recent objective (2015–2021): Establishment of a near core-level steady-state plasma experimental platform; digestion, absorption, development, and storage of the key technologies of fusion engineering experimental reactors; design and pre-study of the key components of fusion engineering experimental reactors

(2) Medium-term objective (2021–2035): Construction and operation of a fusion engineering experimental reactor, development of the research on steady-state, high-efficiency, and safe fusion reactors

(3) Long-term objective (2035–2050): Development of fusion power stations, exploration of the engineering, safety, and economic aspects of a fusion commercial power station

In order to commercialize controlled fusion energy as soon as possible, and make full use of our existing tokamak devices and resources, a complete outline of China's MCF roadmap has been developed, which is in line with China's national conditions, as shown in Fig. 1.

In the next 10 years, the focus will be on high-level experimental research on two main MCF devices (EAST and HL-2M). At present, the EAST device has been upgraded; the research capabilities and experimental conditions have been greatly improved. A large number of steady-state high-performance plasma studies for future ITER and next-generation fusion engineering reactors can be carried out, and the scientific goal of obtaining 400-s stable and repeatable high-parameter near-core plasma with steady 3.5-T magnetic field operation and a plasma current of 1.0 MA can be realized. Thus, the EAST will become an international large-scale advanced test platform that can provide an important database for ITER. According to the new characteristics of the full superconducting tokamak, two or three advanced tokamak operating modes suitable for steady-state conditions will be explored and realized to realize steady-state plasma performance at the international leading level. At this stage, emphasis will be placed on the development of specialized physical diagnostic systems, especially those for in-depth understanding of plasma stability, transport, fast particles, and other aspects. On the basis of a thorough understanding of the physical mechanism, real-time control theory and technology of plasma profile parameters and instabilities will be developed to explore advanced tokamak operating modes and methods un-

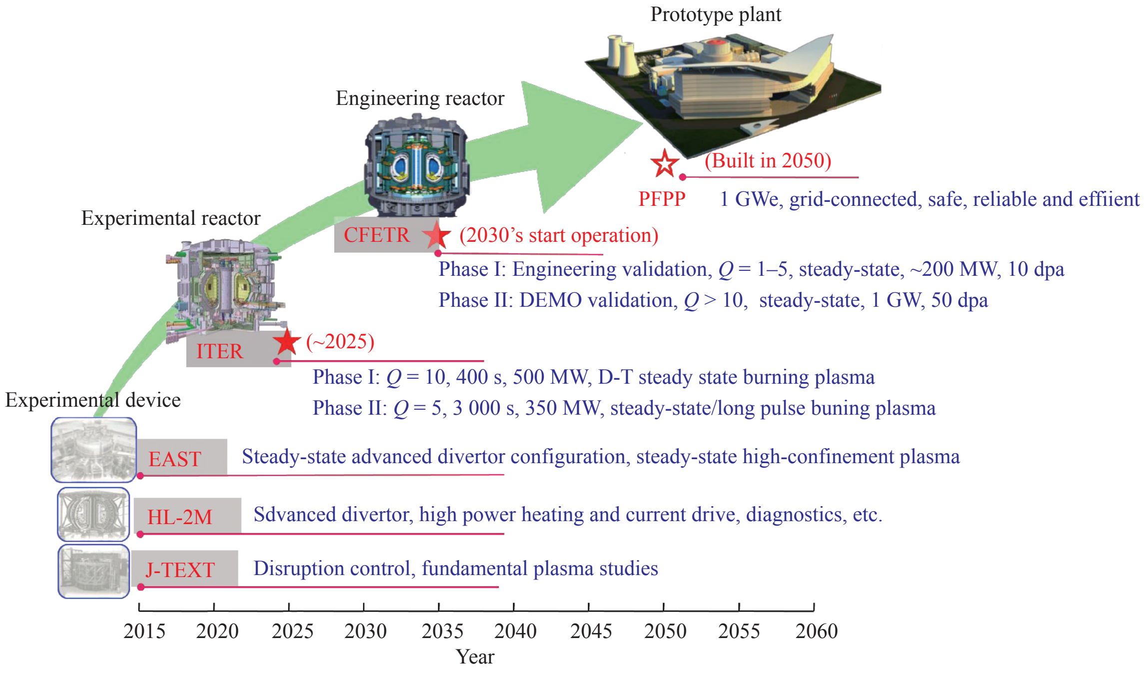

Fig. 1. Roadmap of China's magnetic confinement fusion development.

PFPP: Protoype Fusion Power Plant; CFETR: China Fusion Engineering Test Reactor; ITER: International Thermonuclear Experimental Reactor; EAST: Experimental Advanced Superconduction Tokamak; HL-2M: HuanLiuqi-2M; J-TEXT: Joint-TEXT der steady-state conditions. Realization of high-power density plasma discharge suitable for future reactor operation will lay the scientific and engineering foundation for achieving near-core steady-state plasma discharge. At the same time, the internal structure of the device needs to be upgraded to meet the requirements for high-parameter steady-state and high-power plasma discharge [4].

In the next few years, the HL-2M device will complete its upgrades with good flexibility and proximity. It will further promote the total heating and current drive power to 20–25 MW, focusing on the development of a high-performance neutral beam injection (NBI) system (8–10 MW), increasing the power of an electron cyclotron and low hybrid wave, and developing a new 2-MW electronic cyclotron heating system. By taking advantage of the unique advanced divertor configuration, emphasis will be given to the research on boundary plasma physics under high power conditions, especially for exploring effective methods and means for exhaust particles, heat flux, and helium ash under the conditions of high power, high heat load, strong plasma, and material interactions in the future demonstration reactor, which is complementary with the EAST device [4].

In addition, on the basis of comprehensive digestion and absorption, ITER's design and engineering construction technology, CFETR ($R = 7.2$ m, $a = 2.2$ m, $Bt = 6.5$ T, $k = 2$, as shown in Fig. 2) will start its detailed engineering design and pre-research on necessary key components. Combined with the previous physical design database, CFETR physics-related verification experiments can be carried out on EAST and HL-2M to lay a solid foundation for CFETR construction. In the recent "13th Five-Year Plan", independent construction of CFETR with a design power of 200 MW to 1 GW will begin around 2021, and will be completed around 2035. Compared with the ITER device currently under construction, the CFETR device mainly solves the scientific issues that are necessary for the future commercial fusion demonstration reactor but not covered by the ITER device, such as steady-state burning plasma control technology, tritium cycle and self-sustaining operation, fusion energy output, and other issues; in engineering and technology, CFETR will focus on the work that cannot be carried out on ITER devices, such as fusion reactor materials, fusion reactor blanket and fusion power generation, and mastering and improving the engineering and technology required for the construction of a commercial fusion demonstration reactor. The construction of CFETR can not only lay a solid scientific and engineering foundation for the further independent development and utilization of fusion energy in China, but also makes it possible for China to take the lead in utilizing fusion energy to generate electricity and realize the leap-forward development of energy [4].

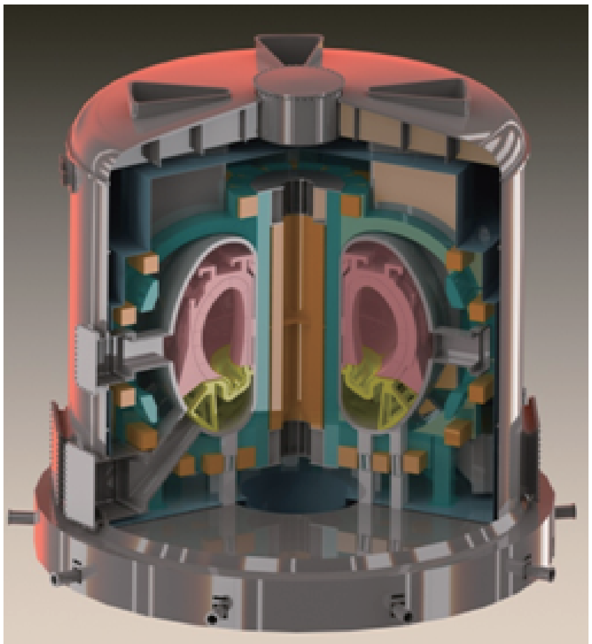

Fig. 2. Sketch of the CFETR device.

3 Z-pinch driven ICF

3.1 Meaning and development of Z-pinch driven ICF study

In the concept of inertial confinement fusion (ICF), energy with a particular form is loaded directly or indirectly onto the fusion target, compressing and heating the fusion fuel by the inertial confinement; this results in thermonuclear fusion ignition and burning. Fast Z-pinch, based on pulsed power technology, can translate the generator-stored energy effectively into Z-pinch implosion kinetic energy and the consequent X-ray radiation energy. Considering the benefits, such as sufficient energy, low-cost driver construction, and the future realization of rep-rated pulsed power drivers, fast Z-pinch has the potential to be the energy source for driving ICF and inertial fusion energy (IFE).

In the late 1990s, on the world's most powerful electrically pulsed power generator, the 20-MA Z machine at Sandia National Laboratories (SNL), 280-TW and 1.8-MJ bursts of soft-X-ray radiation were produced by a nested-wire array, which became the most powerful X-ray radiation source created in the laboratory, and the energy transition efficiency exceeded 15%. In the research of Z-pinch-driven ICF, the Z-pinch dynamic hohlraum (ZPDH) is used by SNL to indirect-drive fusion target implosion. The brightness temperature of hohlraum radiation created on the Z machine exceeded 210 eV, and 3×10^{11} deuterium-deuterium (DD) thermonuclear neutron yield was obtained with a Be + CH capsule filled with deuterium gas. In 2010, a magnetized liner inertial fusion (MagLIF) concept was proposed by SNL. In the integrated experiments carried out on the Z machine in 2014, a beryllium liner was imploded directly on the prefilled DD gas fuel, which was magnetized and preheated, and more than 2×10^{12} neutron yield was obtained.

The China Academy of Engineering Physics (CAEP) has professional teams in fields such as pulsed power generators, theoretical and numerical study of Z-pinch physics, experimental and diagnostic technology, and load fabrication, and have carried out theoretical and experimental studies such as fast Z-pinch implosion dynamics and Z-pinch radiation characteristics. The successful construction of the 8–10 MA Primary Test Stand (PTS) facility provides an important experimental platform for the further study of Z-pinch implosion and Z-pinch-driven ICF physics [5,6]. Z-pinch X-ray radiation and Z-pinch-driven ICF cover multi-physics processes and complex physical effects such as magneto-hydrodynamics, radiation transport, atomic physics, plasma instability, and transport under ultrahigh-pulse magnetic fields. For such a multi-scale and multi-physics process, there is no experimental evidence so far that directly demonstrates the feasibility of fusion ignition, and numerical simulation is still the important means to study Z-pinch-driven ICF physics. Since 2000, a special research team focusing on the theoretical and numerical study of Z pinch was founded in the Institute of Applied Physics and Computational Mathematics (IAPCM), which has developed deep research on the physics of Z-pinch radiation sources and Z-pinch-driven ICF [7]. 1D and 2D magnetohydrodynamics (MHD) codes were developed to study key processes, such as the coupling physics of the pulsed power drive and Z-pinch load energy, wire ablation, precursor formation, and the processes of main plasma acceleration, implosion, stagnation, and radiation. The radiation scale, magneto-Rayleigh-Taylor (MRT) instability, and effects of the natural azimuthal non-uniformity of the wire array were analyzed, and the spatial distribution of the radiation source, as well as its spectrum characteristics, were obtained. The whole process of ZPDH-driven ICF were studied, and the kinetic loading technology and the direct-drive technology were explored. Since 2006, the research team from CAEP proposed and developed the concept of a Z-pinch-driven fusion-fission hybrid reactor (Z-FFR) [8]. A Z-FFR consists of a Z-pinch driver, energy target, and subcritical blanket for energy. It is estimated that the construction cost for a 1-GWe Z-FFR power plant is about 3 billion US dollars, which is only one-third that of a pure fusion reactor. Z-FFR can provide several thousand years of energy for mankind, and has both a high level of inherent safety and a simplified reprocessing strategy.

3.2 Energy coupling of the pulsed power drive and Z-pinch load

The application of Z-pinch technology depends on the energy coupling relationship between the pulsed power drive and the Z-pinch load. The Z-pinch load is the carrier of the energy transition, and its dynamic evolution is determined by the pulsed power drive and its initial status. Pulsed power technology, used to drive the Z-pinch implosion and ICF ignition, faces a great challenge. Obviously, the intense drive-load coupling is one the most important characteristics of Z pinch. The variation of load parameters results in a change of drive-load matching and energy coupling, which consequently alters the current parameters and the Z-pinch implosion as well. We developed a full-circuit model (FCM) to study the electromagnetic energy transport and pulse compression of the generator. By coupling the FCM and MHD models, the current and voltage profiles at different positions on the generator, as well as the load current and X-ray radiation power, can be simulated for the study of drive-load energy coupling [9]. Fig. 3 shows the electrical power at intermediate storage, pulse forming line, tri-plate output transmission lines

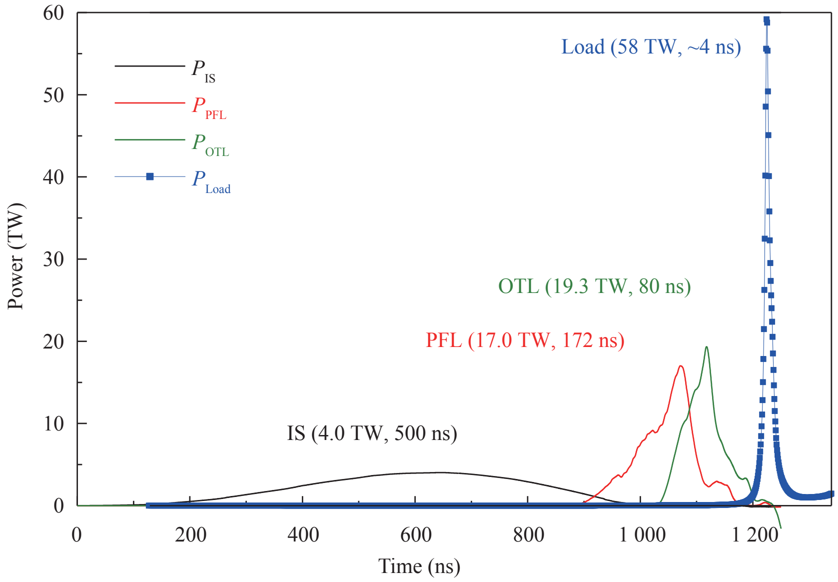

Fig. 3. Electrical power and X-ray radiation power of the PTS facility.
Note: Load, OTL, PFL, and IS mean the wire array, tri-plate output transmission line, pulse forming line, and intermediate storage, respectively.

of the PTS facility, and the X-ray radiation power. We successfully developed a simplified circuit model of the PTS facility (Fig. 4), which was verified by several PTS Z-pinch experiments, and provides a valuable tool for the physical design of Z-pinch experiments.

As the electromagnetic energy transports through the facility, the power increases, and the pulse width is shortened. The microsecond-scale electrical pulse at the Marx generator turns into a ten-nanosecond-scale pulse at the tri-plate transmission lines, which compresses the energy and increases the power. Consequently, an X-ray radiation pulse with higher electrical power can be obtained. With the same pulse compression process of the facility, the change in load parameters impacts the X-ray radiation power output remarkably. The plant cannot obtain the best energy coupling with a load that is too light or too heavy for the driver, and the peak radiation power will be relatively low. Therefore, the Z-pinch load must be optimized for the facility to obtain powerful X-ray radiation.

4 Direction and future programming for Chinese Z-pinch-driven ICF research

In China, Z-pinch plasma implosion dynamics and its radiation physics have been studied in depth, and abundant research results have been obtained. The integral concept design of Z-FFR has evolved greatly [10]. However, questions on the relationship among current rise front, load parameters, and implosion dynamics on the radiation power scale of Z-pinch plasma, the energy scale of ZPDH radiation (temperature), and the energy transition processes within several key physical processes of Z-pinch-driven ICF need further study.

An ultrahigh pulsed magnetic field is the distinct characteristic of Z-pinch implosion. Under such a circumstance, the formation of plasma and MRT instability play important roles for the implosion process and affect the implosion quality. Because, in the strong non-linear process, the transition among electromagnetic energy, Z-pinch plasma kinetic energy, and radiation energy is highly complex, the Spitzer model cannot describe the electrical resistance of the Z-pinch load, and its abnormal mechanism is not clear yet. How to describe and explain the radiation formation process and its physical principle is highly important. Facilities with higher current can provide larger parameter ranges for experimental study of Z-pinch plasma physics.

Typical Z-pinch implosion is cylindrical, whereas the fusion target needs a spherical implosion. Designing proper hohlraum structures, which enable effective spatial and temporal separation between the Z-pinch implosion and target implosion, is the key issue for Z-pinch-driven ICF. However, the now-active facilities in China cannot provide the necessary drive conditions for this kind of study. Compared with laser-driven ICF, Z-pinch radiation has a larger spatial scale and longer temporal scale, but its pulse shape is difficult to adjust exactly. It is necessary to design new fusion target structures, which helps to compress the fuel more effectively and then increase the energy gain.

Building a new-generation high-current pulsed-power test platform will benefit the experimental study and demonstration of key issues in Z-pinch ICF, such as the Z-pinch radiation, hohlraum, and target implosion. This suggests that China should support the construction of a new-generation high-current pulsed-power test platform with a peak current of 50–70 MA, from 2018 to 2025, so as to realize the fusion ignition in the near future. It is also suggested that China officially start the construction of Z-FFR from 2030 and the demo plant in 2035.

5 Conclusions and suggestions

The development of fusion energy is extremely difficult and requires long-term and sustained effort. It is suggested that China should deepen the ITER international cooperation plan, comprehensively master the fusion test reactor technology, actively promote the research and development of key components of the CFETR mainframe, and start the overall CFETR construction in a timely manner. Z-pinch development should also be encouraged to achieve ignition as soon as possible, as well as to explore

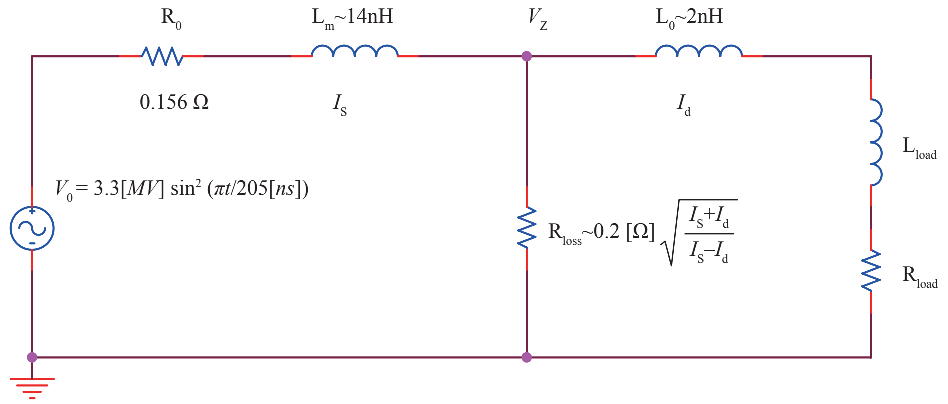

Fig. 4. Simplified circuit model for PTS Z-pinch experiments.

the inertial confinement fusion-fission hybrid reactor driven by Z-pinch. In addition, the tracking of new fusion concepts should be strengthened.

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