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From concept to reality − A review to the primary test stand and its preliminary application in high energy density physics

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Abstract

Pulsed power technology, whereas the electrical energy stored in a relative long period is released in much shorter timescale, is an efficient method to create high energy density physics (HEDP) conditions in laboratory. Around the beginning of this century, China Academy of Engineering Physics (CAEP) began to build some experimental facilities for HEDP investigations, among which the Primary Test Stand (PTS), a multi-module pulsed power facility with a nominal current of 10 MA and a current rising time ~90 ns, is an important achievement on the roadmap of the electro-magnetically driven inertial confinement fusion (ICF) researches. PTS is the first pulsed power facility beyond 10 TW in China. Therefore, all the technologies have to be demonstrated, and all the engineering issues have to be overcome. In this article, the research outline, key technologies and the preliminary HEDP experiments are reviewed. Prospects on HEDP research on PTS and pulsed power development for the next step are also discussed.

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1. Introduction

High energy density physics (HEDP) is a fast developing frontier of modern physics. It mainly concentrates scientists' understanding on basic behaviors and general rules in systems with energy densities above 10^{11} J/m^3 or equivalently with pressure exceeding 100 GPa or 1 Mbar [1]. The regime of HEDP covers many important challenges in the fields of nuclear fusion, astrophysics, material science and so on [2]. HEDP research may help scientists find the limit of already proposed physical theories and provide possible access to new science.

A variety of methods can be used to generate HEDP states, such as focusing high power lasers on matter, bombarding targets with intense particle beams and delivering mega-ampere pulsed currents into loads. With the development of high power laser (such as the National Ignition Facility [3] and OMEGA [4]) and pulsed power technology (such as the Z machine [5]) in the past decades, laboratory investigations

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into HEDP became more and more popular around the world. Laser-driven and electromagnetically-driven are physically complementary, as electro-magnetically driven HEDP experiments usually involve longer timescale (several to hundreds of nanoseconds) and larger spatial scale (millimeter to centimeter), while laser-driven HEDP experiments are better to generate systems with higher energy density, but smaller volume and shorter time scale.

The essence of electromagnetically-driven HEDP is to compress or drive a specific sample or structure with electromagnetic force, which is caused by a pulsed high current and its induced magnetic field [6]. Typically, pulsed currents with an amplitude of 10^0–10^1 MA and rise time of 10^{-9}–10^{-6} s are transmitted from the pulsed power generator to the load on a centimeter scale, achieving the high energy density condition. It is believed that plasma implosion can be a cheap and effective method to realize high energy compression for inertial confinement fusion (ICF). Once the related instability issues are solved, it will greatly improve and promote the understanding in fusion research [7,8].

In the 1970s, scientists' prediction that fast Z pinches would be more stable to magneto-Rayleigh-Taylor (MRT) instabilities led to the growth in Z-pinch research for X-ray sources. This started the beginning of modern TW-class pulsed power technology in the 1980s, when the first multi-module electrical drivers for Z-pinches were established, such as Blackjack 5, Double Eagle, Saturn and Angara-5-1. The currents of these pulsed power drivers are a few mega-amperes and the rising time is about 100 ns.

Since the breakthroughs in X-ray power generation were achieved in the 1990s when a series of wire array experiments were conducted on the Saturn generator and the Z-machine of the Sandia National Laboratories (SNL) [9–11], which demonstrated extremely intense X-ray emission, Z-pinch has been regarded as one promising route for achieving inertial confinement fusion. Roughly at the same period, Z-pinch and other HEDP research related to pulsed power drew attentions in China. A roadmap towards Z-pinch fusion was made at China Academy of Engineering Physics (CAEP), of which, building a Primary Test Stand (PTS) was an important step. The PTS is then the first multi-module pulsed power project in TW range, whose nominal current is 10 MA with a current rise time of ~90 ns. The driving capability is equivalent to Saturn facility [12], but the current rising time is longer.

Additionally, with the rapid development of pulsed power technology in the past 20 years, magnetically driven method has become an important loading technique for dynamic material properties investigation[13-17]. Because the stress-wave loading path depends on the current pulse, we can control the loading history on sample by shaping the current waveform.

When the PTS project started, the Z machine at SNL was under its upgrading to the Z refurbishment (ZR) [18]. New design and upgrading in the pulsed power system both made it possible to try some novel ideas. As a great event, the first Euro-Asia Pulsed Power Conference, which was held in 2006 in China, provided an opportunity to exchange and share innovations and progresses. In the next few years, the ZR facility and the PTS were operated practically, and the research capability in electromagnetically-driven HEDP was greatly improved in both countries. In this paper, the development of the PTS facility and the preliminary HEDP experiments since operation will be reviewed. Some future plans will also be presented.

2. Development outline of PTS

Electromagnetic implosion researches including the Z-pinch have been conducted at the Institute of Fluid Physics (IFP), CAEP for many years since the 1990s with driving currents of 1–4 MA [19]. With increasing demands, a new facility with higher driving capability, the PTS for the Z-pinch, was proposed at IFP in the end of last century.

In 2002, the PTS project was started on the basis of some investigations into the Z-pinch with small-scale pulsed power facilities. The Yang accelerator, which is a prototype module of the Angara-5, and the Qiangguang accelerator were the most important platforms in China for Z-pinch experiments at that time. Since the current was no more than 2 MA, the X-ray yield was poor. But they served pretty well to understand Z-pinch physics experimentally and provided platforms to develop necessary diagnostics.

According to the roadmap, there would be a primary test stand for Z-pinch investigations, by which the X-ray yield would be up to several hundreds of kJ, and the peak power would be several tens of TW, and the plasma temperature would be 50–100 eV when driving a wire array. Accordingly, the output current for the pulsed power system was 8–10 MA, and the current rising time was about 90 ns. At the same time, a pulsed power facility with such capability would be able to drive solid material to pressure larger than 100 GPa. This would supply the fundamental capability for electromagnetically-driven HEDP experiments.

The PTS project includes pulsed power system, infrastructures and affiliated systems such as oil, gas, water, safety guard and so on. The project covers an area of more than 10,000 m^2.

The pulsed power system consists of 24 modules connected in parallel and divided into two layers (see Fig. 1). Each module includes a Marx generator, an intermediate storage capacitor, a water pulse forming line, a laser-triggered spark gap switch, a self-breakdown water switch, and a tri-plate transmission line. The currents of every two modules are added at the output of the triplate transmission lines, and all the currents of 12 pairs of modules are added at the insulator stack and transmitted to the load through the insert four-level vacuum magnetically insulated transmission line (MITL). All the 24 Marx generators are triggered by 24 electrical pulses generated by a pulse generator. The 24 laser-triggered switches are triggered by 12 individual lasers, each triggering two switches.

Since it is the first multi-module pulsed power facility in TW class in China, no former experience could be referred to. The planned strategy was to divide the project into several stages.