CHINA'S BIG SCIENCE FACILITIES

MAN-MADE SUN

EXPERIMENTAL ADVANCED SUPERCONDUCTING TOKAMAK (EAST) FUSION REACTOR

Baonian Wan *Editor*

浙江教育出版社
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China's Big Science Facilities

"Big science" facilities are major elements of science and technology infrastructure, and important symbols of China's scientific and technological development. This popular science book series presents the background, history and achievements of the Chinese Academy of Sciences in terms of constructing and operating big scientific facilities over the past few decades.

The series highlights the major scientific facilities constructed in China for pioneering research in science and technology, and uses straightforward language to describe the facilities, e.g. the fully superconducting Tokamak fusion test device (EAST), the National Protein Science Research Facility, Lanzhou Heavy Ion Accelerator, Five-hundred-meter Aperture Spherical Telescope (FAST), etc. It addresses the respective facilities' research fields, scientific backgrounds, technological achievements, and strategic and fundamental contributions to science, while also discussing how they will improve the development of the national economy. Supplementing the main text with a wealth of images and linked videos, the book offers extensive information for members of the general public who are interested in scientific facilities and related technologies.

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Editorial Board

Series Foreword

As a new round of technological revolution is bourgeoning, it will exert a direct impact on survival of a country whether or not it can gain insight on the future technological trends and grasp new opportunities from the revolution. In face of the major opportunities in the twenty-first century, China is intensively formulating the innovation-driven development strategy and building an innovation-based country in this critical era to achieve a moderately prosperous society in an all-round way.

Scientific and technological innovation and popularization remain two wings for innovation-driven development of a nation. In particular, popular science affects the awareness of the general public for science and technology as well as social and economic development. Scientific education is thus highly practical for implementing the innovation-driven strategy. Contemporary science pays more attention to public experience and engagement. The word "public" covers various social groups that exclude those in scientific research institutions and departments. The "public" also includes decision-makers and management personnel in government agencies and enterprises, media workers, entrepreneurs, science and technology adopters and others. Barriers that impede the innovation-driven strategy will emerge if any of the group fall behind this new revolution; avoiding and removing the possible barriers will strategically improve the quality of human resources, enhance mass entrepreneurship and innovation and build a moderately prosperous society in an all-round way.

Science workers are primary creators of scientific knowledge who undertake the mission and responsibility for science popularization. As a national strategic power in science and technology, Chinese Academy of Sciences (CAS) has always shouldered and attached equal importance to this mission in addition to scientific innovation and incorporated the mission into key measures of the "Pioneering Action" plan. CAS enjoys rich and high-end technological resources, such as the high-caliber experts represented by CAS members, advanced research facilities and achievements represented by the Big Science Project, excellent scientific popularization base represented by the national scientific research and popularization base. With these resources in place, CAS implements the "High-level Scientific Resource Popularization" plan to transform the resources into popular facilities, products and talents to benefit trillions of public. Meanwhile, CAS launches the "Science and China" program, a scientific

education plan, to mobilize more effectively the "popularized high-end scientific research resources" for scientific education targeted at the public and the integration of science and education.

Scientific education requires not only dissemination of scientific knowledge, approaches and spirit to enhance overall scientific literacy of the country, but also creation of scientific environment to enable scientific innovation to lead sustainable and sound social development. For this reason, CAS cooperates with Zhejiang Education Publishing House to launch the CAS Scientific and Cultural Project. This is a large-scale scientific and cultural communication project on the basis of CAS research findings and expert team to improve the scientific and cultural quality of the Chinese citizen in an all-round manner and to serve for the strategy of the national rejuvenation by advancing science and technology. On the basis of the target group, the project is categorized to two series, i.e., the Adolescent Scientific Education and the Public Scientific Awareness, respectively, for the adolescent and the general public.

The Adolescent Scientific Education series aims to create a series of publications that draw on frontier scientific research findings and introduce the status quo of scientific development in China; to cultivate the adolescent's interest in science study; to educate them about basic scientific research approaches; and to inspire them to develop reason-based scientific way of thinking.

The Public Scientific Awareness series aims to educate the general public about basic scientific approaches and the social significance of science and encourage the public to engage in scientific affairs, thus the project will enhance the capacity the public of conscientiously applying science to their life and production activities improve efficiency and promote social harmony. In the near future, publication series of CAS Scientific and Cultural Project will constantly come out. I hope that these publications will be welcomed by the reader and that through coordination among CAS science workers, science icons such as Qian Xuesen, Hua Luogen, Chen Jingrun and Jiang Zhuying will be more familiar to the public. As a result, the truth-pursuing spirit, reason-guided thinking and scientific ethics will be fully promoted, and the spirit of science workers in courageous exploration and innovation stands eternally in the history of human civilization.

July 2016

Chunli Bai
President of Chinese Academy of Sciences
Secretary of Leading Party Members' Group

Preface

Energy is a driving source for the development of human society.

Fossil fuels include coal, oil and natural gas and constitute the primary energy in global energy mix. As precious wealth preserved over hundreds of millions of years in nature, fossil fuels have been exploited since the Industrial Revolution in the mid-eighteenth century and have created unprecedented social prosperity for human beings. Nevertheless, the reserve of the non-renewable fossil fuels is limited. This means the fuel will be ultimately run out one day in the future. In this case, how should humanity sustain the huge demand for energy?

Nuclear fusion has the advantages of high-density, abundant raw material reserves, safe and clean usage. It thus presents an ideal major energy option in the future. According to estimates, the energy generated in all fusion reactions of deuterium contained in 1 l seawater is equivalent to the energy generated in full combustion of 300 l gasoline. Deuterium preserved in ocean is available for human beings in billions of years, and the by-products most easily generated by deuterium fusion reactions are helium and neutron. Helium is clean and safe; neutron has extensive usage in addition to the energy stored within it. These advantages make nuclear fusion a strategic energy. Countries around the world, especially developed ones, are relentlessly conducting controlled nuclear fusion research for this purpose.

The energy released by the sun mainly comes from nuclear fusion reactions. Controlled nuclear fusion follows the same principle as the sun, which is why nuclear fusion is also called the artificial sun. Magnetic confinement is one way to achieve controlled fusion. A certain amount of nuclear fusion fuels is heated in various means to a high temperature of 100 million degrees Celsius. Under such high temperature, atoms turn completely ionized and form—together with electrons—plasmas or the so-called the fourth state of matter. Confined by magnetic fields, charged particles can only move along the magnetic induction line. This feature enables setup of a reaction chamber with magnetic condenser to ensure no contact of the high-temperature fusion fuel with the chamber wall and finally achieve controlled nuclear fusion reactions.

Tokamak is an experimental facility developed by humanity to explore nuclear fusion energy. The idea was initially raised by Russian scientists. Tokamak is a form of magnetic confinement. In order to obtain a more stable confinement magnetic field, scientists utilized superconducting materials to produce tokamak fields which

connect to liquid helium. Through the field, tokamak cools down to an extremely low temperature to achieve superconductivity and stable operation of the facility. In the future reactors, plasma discharge in hundreds or thousands of amperes along with toroidal magnetic fields in tens of thousands of Gauss will form spiral magnetic induction lines which twine on the tyro-shaped torus. This configuration helps avoid direct loss of combustion particles along the magnetic induction line, reduce drift loss and prevent the high-temperature plasma from directly contacting the chamber wall through configuration control.

The Experimental Advanced Superconducting Tokamak (EAST) is located in the Science Island of the west suburb of Hefei City. The facility is supported by the Big Science Project under the "Ninth Five-Year Plan" in China. Independently designed and developed by China, it is the first superconducting, non-circular, cross-sectional nuclear fusion tokamak experimental facility successfully developed and operated. EAST is also one of the experimental platforms in the world that enables research on long-pulse fusion plasma physics and engineering technologies with high parameters. Meanwhile, EAST is a nuclear fusion experimental platform and research center open not only to China but also to the rest of the world. EAST has provided guidance for future design and operation of China's fusion projects. What's more, its research findings have laid a pivotal foundation in engineering technologies and physics for building more stable, efficient and secure tokamak fusion reactors.

This book mainly introduces research background and fundamentals of magnetic confinement fusion and the process of magnetic fusion research. Written in popular language, it tries to educate the public about knowledge on what is artificial sun, why we create it and how to realize this vision step by step. We hope that this book can serve as a readable option for popular science. This book is jointly edited by popular science volunteers from the Institute of Plasma Physics, Chinese Academy of Sciences (IPP, CAS). We feel grateful to the editors of Zhejiang Education Publishing House for valuable advice and to all colleagues for planning, editing, proofreading and publishing this book. We hope that readers can have a full understanding of controlled fusion through this book. Controlled nuclear fusion is a research field that requires generations of continuous hard work. This book will be more meaningful if it attracts young readers to embark on China's controlled fusion research.

July 2017

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EAST is the only operating tokamak in the world that is full installed with superconducting magnets and similar to the International Thermonuclear Experimental Reactor (ITER). Despite limitation of fund, EAST was built, developed and put into first operation very quickly, a remarkable achievement that manifests the capacity of the CAS physics and engineering research team.

Complete design, pre-research, development and operation in such short period of time create a remarkable achievement in the world's fusion project. They also serve as an explicit forecast of what China will contribute to ITER in the future. This brilliant success is a historic milestone in nuclear fusion energy development of the whole world.

—EAST International Consulting Committee

China made fusion history.

—Review article from Nature

This is where the value of science is brilliantly displayed.

—Review article from Science

Contents

The Conquest of the Energy Kingdom

Suzhen Zhang

Abstract What is energy? What are energy resources? What does energy look like? Where does energy in the universe come from? Where does energy of the sun which lights up the earth and nurtures living beings come from?

1 Energy Is All Around

What is energy? Physicists will tell you that energy is the dynamic form of matter. To put it simple, energy and matter are equivalent and mutually converted. Energy is the matter released and matter is the concentrated energy. If the world is made of matter, it is also made of energy. This will be more easily understood if you know about Einstein's mass-energy equation—$E = mc^2$.

What is energy? What does it look like? These are hard to explain. Energy is like Sun Wukong in *the Journey to the West* who masters 72 earthly transformations. Energy can turn into heat, sound, or vibration. Energy is everywhere; it's everything in the world.

Energy is omnipotent; without energy everything is impossible. Energy is closely related to social progress of humanity. Activities of the human body and manual labor both consume energy. Energy plays a critical role in everyday life. Without energy, nothing will be possible for humanity.

Energy is very friendly. We can use energy to boil water, cook meal and drive vehicles; or we can use it to transmit electricity to power TVs, computers and other home appliances. Humanity can't live without energy. However, energy sometimes is very unfriendly. It also induces earthquakes, floods and tropical storms which can destroy family of humanity (Figs. 1 and 2).

How energy comes about is a mystery. How does energy in the universe originate? There is no certain answer yet. Most physicists believe that all energy in the universe came from a Big Bang in which the universe was born. Energy maybe the residues formed after the opposite matters were annihilated or the byproduct from negative

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Fig. 1 Humanity can't live without energy

energy of gravitation. Anyway, energy has existed before we know about the universe (Fig. 3).

Knowledge Link

Matter and Energy, Which Came About First?

Matter and energy, which came about first? A probe into the universe reveals that energy obviously came before matter, because the later didn't even exist when the Big Bang occurred. And even electrons, protons and neutrons which constitute atoms did not exist at that time. These all came into being after the Big Bang according to the equation $m = E/c^2$. In this sense, energy is more fundamental than mass.

Fig. 2 Energy also leads to disasters

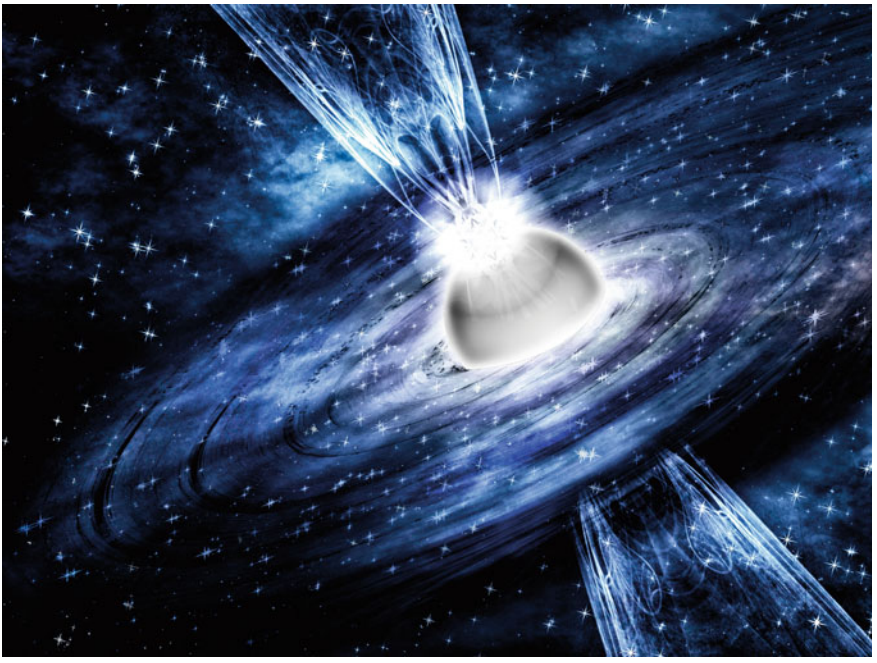

Fig. 3 Energy has existed since the universe began

Fig. 4 Energy resources offer humanity energy

For most of us, how energy came about is not important. What's important is how to obtain energy for our daily use. Therefore, humanity constantly search for matter that can offer us energy such as water, wind and oil. The matter from which we gain energy is called energy resources which mean "the source of energy" (Figs. 4 and 5).

There are three forms of energy on earth. The first is from outside earth, mainly the sun; the second is from inside earth, including thermal energy and nuclear energy; the third is from interaction between earth and other planets, exemplified by tidal energy.

2 All Living Things on Earth Live on the Sun

The sun has been chanted in verses, ditties, odes and songs—the four forms of poetry since ancient times. Despite a very ordinary star, the sun is our center compared with