
AI translation · View original & related papers at
chinaxiv.org/items/chinaxiv-202405.00198

Research on Trends in U.S. Department of Energy Major Scientific Infrastructure Open Services to China and Implications [Postprint]

Authors: Dong Lu, Li Yizhan, Li Yunlong, Wang Xuezhao, Li Zexia

Date: 2024-05-18T00:00:00+00:00

Abstract

Major scientific and technological infrastructure (hereinafter referred to as “major facilities”) is pivotal for innovation in the era of big science and serves as a crucial indicator of a nation’s scientific and technological innovation capacity and comprehensive national strength. To secure strategic positions in science and technology, major developed countries worldwide are actively developing and optimizing the layout of major facilities while vigorously promoting their open sharing to achieve efficient allocation and utilization of scientific and technological resources, thereby transforming their advantages in scientific infrastructure into innovation-driven development strengths. The U.S. Department of Energy currently manages 28 national major facilities that are open to global scientific research users. This article examines the current status of open sharing of major facilities under the U.S. Department of Energy and provides an in-depth analysis of China’s demand for, achievements in, and challenges with using these facilities from 2015 to 2022, aiming to offer valuable insights for the open sharing, layout, and construction of China’s major scientific and technological infrastructure.

Full Text

Preamble

Citation Format: Dong L, Li Y Z, Li Y L, et al. Analysis and enlightenment on China’s use of major research infrastructure of U.S. Department of Energy. *Bulletin of Chinese Academy of Sciences*, 2024, 39(3): 459-471, doi: 10.16418/j.issn.1000-3045.20231214002.

Abstract

Major research infrastructures (hereinafter referred to as “major infrastructures”) are the key to innovation in the era of big science and represent an important symbol of a nation’s scientific and technological innovation capacity and comprehensive national power. To seize the strategic high ground in science and technology, the world’s leading developed countries are actively developing and optimizing the layout of major infrastructures while vigorously promoting their open sharing to achieve efficient allocation and utilization of scientific and technological resources, thereby transforming their advantages in scientific infrastructure into advantages in innovation and development. The U.S. Department of Energy (DOE) currently manages 28 national major infrastructures that are open to global research users. This paper examines the current status of open sharing of DOE major infrastructures and provides an in-depth analysis of China’s demand, achievements, and challenges in utilizing these facilities from fiscal years 2015 to 2022, with the aim of offering reference and insights for the open sharing, layout, and construction of major infrastructures in China.

Keywords: U.S. Department of Energy, major research infrastructures, open services, layout and construction

1. Characteristics of DOE Major Infrastructure Open Sharing

DOE defines major facilities funded by the U.S. federal government that provide open access services to researchers from academia and industry as national user facilities [11]. As of fiscal year 2022, DOE operates 28 user facilities covering advanced scientific computing (ASCR), basic energy sciences (BES), biological and environmental research (BER), fusion energy sciences (FES), high energy physics (HEP), nuclear physics (NP), and accelerator research and development and production (ARDAP). Since 2015, DOE has been building a user projects/experiments database [12]. This study analyzes user research proposal data from fiscal years 2015–2022 to identify key characteristics of DOE’s open sharing model.

1.1 Long-Term Continuous Operation with Dynamic Adjustment Mechanisms

The United States began constructing major facilities during World War II, with DOE and the National Science Foundation (NSF) conducting comprehensive and continuous strategic planning at the national level. The U.S. federal government strongly supports and encourages open sharing of major facilities. According to the Federal Acquisition Regulation, facility management and operating institutions should maximize social openness while ensuring scientific objectives and serving national strategic interests [13]. DOE user facilities have a relatively early start, having undergone renovations and upgrades while continuing to provide open services to society. During fiscal years 2015–2022, 26

user facilities continuously offered external services [Figure 1: see original paper]. For example, the High Flux Isotope Reactor (HFIR) has been operating since 1966, playing a crucial role in post-irradiation materials testing and neutron scattering, while the Stanford Synchrotron Radiation Lightsource (SSRL), built and commissioned in 1977, has made indispensable contributions to scientific discovery and technological innovation.

DOE dynamically adjusts its user facility roster based on applications from facility operators that undergo review and approval by relevant departments. For instance, the Accelerator Test Facility (ATF) was designated as a user facility in March 2015 and was affiliated with the High Energy Physics (HEP) program before being transferred to the Accelerator Research and Development and Production (ARDAP) program in fiscal year 2022. The Facility for Advanced Accelerator Experimental Tests (FACET), operational since 2012, suspended external services during fiscal years 2017–2019 for upgrades. The upgraded FACET-II was reinstated to the user facility roster in early fiscal year 2020 through the standard application process. Facilities are removed from the roster upon decommissioning, such as the Alcator C-Mod tokamak fusion reactor.

1.2 Leveraging Facilities for Science Diplomacy in International Competition and Cooperation

Science diplomacy represents a nation's soft power in connecting with the world through science [14]. As important platforms for scientific activities, major infrastructures not only play a leading role in science diplomacy but also serve as key nodes for implementing national foreign cooperation policies. The United States actively promotes open sharing of its major facilities, attracting outstanding scientists from around the globe and demonstrating its strength as a scientific powerhouse through international cooperation. However, as competition for strategic dominance in science and technology intensifies, U.S.-China scientific and technological cooperation has gradually tightened amid policy adjustments.

DOE user facilities provide open access services to researchers from nearly 100 countries and regions annually, hosting users from over 70 countries each year. During fiscal years 2015–2022, services to other countries/regions totaled 76,977 instances, accounting for approximately 16% of total services. Specifically, high-performance computing facilities, neutron facilities, and nanoscience research facilities have relatively lower proportions of international services, while fusion energy, high energy physics, and nuclear physics facilities have relatively higher proportions [TABLE:1, FIGURE:2].

Researchers from China, the United Kingdom, and Italy constitute the primary user groups [Figure 2: see original paper]. Countries ranking 3rd to 7th in total usage frequency are all G7 members, which have actively participated in the construction and upgrading of DOE user facilities. The 2023 G7 Summit joint communiqué proposed advancing the digital networking and international utilization of major facilities, exploring FAIR principles to promote open sharing of

research results. Notably, as U.S.-China competitive and cooperative relations evolve, China's utilization of DOE user facilities has significantly declined.

The COVID-19 pandemic impacted DOE user facility service capacity in fiscal year 2020, with some service plans canceled or postponed and on-site visits notably reduced [Figure 3: see original paper]. Subsequently, DOE explored remote service models and developed related technologies to address the pandemic's impact. In recent years, DOE has actively explored new service models while continuously improving service capacity. In January 2022, seven DOE light source and neutron user facilities formed a working group to explore how facility management agencies could create remote experimental environments to ensure researchers could conduct scientific work without physical visits, achieving facility coordination and secure user interaction [15].

1.3 Advancing Remote Access Capabilities and Continuously Optimizing Services

DOE user facilities provide services primarily through two categories: experimental research using facilities and research using facility data services. The former includes on-site use, remote use, and hybrid on-site/remote use; the latter includes facilities such as the Atmospheric Radiation Measurement (ARM) Climate Research Facility and the Joint Genome Institute (JGI) that provide data services. The global COVID-19 pandemic forced a transformation in facility service models, imposing higher requirements for remote services, user interaction technologies, information technology, and standardization.

In recent years, DOE has actively explored new service models while enhancing service capacity. In January 2022, seven light source and neutron user facilities established a working group to discuss how management agencies could create remote experimental environments when researchers cannot visit in person, ensuring normal scientific work through facility coordination and secure user interaction [15]. The pandemic accelerated the transformation of service models, demanding higher standards for remote services, user interaction technologies, IT, and standardization.

1.4 Emphasizing Synergistic Linkage Across Facility Types and Reshaping Innovation Ecosystems

Data obtained through experimental observation and simulation analysis represents the "gold mine" of the digital intelligence research era. Platform-type facilities such as light sources and scientific data infrastructure are actively responding to challenges posed by new research paradigms. During the pandemic, researchers used the Linac Coherent Light Source (LCLS) to obtain SARS-CoV-2 structural data and leveraged the advanced computing power of the National Energy Research Scientific Computing Center (NERSC) and the Energy Sciences Network (ESnet) for real-time image analysis, accelerating COVID-19 vaccine development.

In 2020, developers from five light source facilities formed a Data Solutions Working Group to build and develop software, algorithms, and network infrastructure to meet common needs across all light source facilities, from real-time data analysis to data archiving and storage. DOE launched the Integrated Research Infrastructure (IRI) initiative in 2020, formally implementing it in 2023 [Figure 4: see original paper]. This program will utilize dedicated scientific data networks to effectively connect observation and experimental national user facilities, advanced computing facilities, and high-performance data facilities, accelerating the integration of cutting-edge observation technologies with high-performance computing and analytical capabilities. It will also leverage artificial intelligence, digital twins, and other new technologies to accelerate scientific discovery.

2. China's Demand and Challenges for DOE Major Infrastructures

2.1 Chinese Researchers as Important Users of DOE User Facilities

Based on user research proposal statistics, Chinese researchers used DOE user facilities 9,978 times during fiscal years 2015-2022, accounting for 12.98% of international services. Chinese researchers primarily obtain access by submitting research proposals for DOE user facility approval, with only 510 instances of direct data usage. From fiscal years 2015-2019, on-site usage dominated, while remote access became more common during fiscal years 2020-2022 due to the pandemic [Figure 5: see original paper]. Geographically, researchers from 30 Chinese provinces and municipalities have utilized DOE user facilities, with relatively high usage from Beijing (3,387 instances), Shanghai (1,656), Anhui (1,490), Hubei (653), and Gansu (399). This distribution aligns closely with China's national comprehensive science center layout.

In 2016-2017, China's National Development and Reform Commission and Ministry of Science and Technology successively approved construction plans for comprehensive national science centers in Shanghai Zhangjiang, Anhui Hefei, and Beijing Huairou. The 14th Five-Year Plan for National Economic and Social Development supports Beijing, Shanghai, and the Guangdong-Hong Kong-Macao Greater Bay Area in forming international science and technology innovation centers, while supporting qualified regions in building regional innovation hubs. The Chengdu-Chongqing region, Wuhan, and Xi'an have subsequently been approved to build national science and technology innovation centers, with Xi'an also approved for a comprehensive national science center.

Chinese universities, research institutes, and enterprises have all conducted research using DOE user facilities, with the most frequent users shown in [Figure 6: see original paper]. The Beijing High Pressure Science Research Center used the Advanced Photon Source most frequently (1,218 instances), accounting for 40.29% of Chinese usage of this facility, primarily for studying structures and properties of novel iron-based superconductors, thermoelectric mate-

rials, and carbon nanomaterials. The University of Science and Technology of China frequently used the Continuous Electron Beam Accelerator Facility (226 instances), Advanced Photon Source (216 instances), and National Energy Research Scientific Computing Center (166 instances), focusing on metallic glasses, resistive switching devices, superconducting nanowires, and energy-related materials structures and properties. Peking University used the National Energy Research Scientific Computing Center extensively (184 instances) for research on iron-based superconductors and magnetic confinement fusion plasmas. Tsinghua University frequently used the Advanced Light Source (86 instances) for research on graphene, topological insulators, and high-temperature superconductors. The Institute of Plasma Physics, Chinese Academy of Sciences, extensively used the DIII-D National Fusion Facility (262 instances) for joint physics experiments.

2.2 DOE User Facilities Supporting Chinese Researchers' Achievements

Chinese researchers have achieved high-level scientific results and enhanced China's scientific and technological innovation capacity through international collaboration and facility access. Several nationally awarded research achievements utilized both China's domestic major facilities and DOE user facilities for complementary research. For example, researchers from the Dalian Institute of Chemical Physics, Chinese Academy of Sciences, used the Shanghai Synchrotron Radiation Facility, Hefei Synchrotron Radiation Facility, and the Advanced Light Source in the United States during fiscal years 2015-2016 to conduct theoretical research on two-dimensional atomic crystal-confined catalysis. Their work, "Nanoconfined Catalysis," won the first-class National Natural Science Award in 2020. The second-class National Natural Science Award-winning research on "Photoelectron Spectroscopy Studies of Electronic Structures in Iron-Based Superconductors" used the Hefei Synchrotron Radiation Facility and Stanford Synchrotron Radiation Lightsource.

Researchers from the Shanghai Institute of Applied Physics and the University of Science and Technology of China participated in the STAR international experimental collaboration group led by Brookhaven National Laboratory, using the Relativistic Heavy Ion Collider and National Energy Research Scientific Computing Center for experiments and calculations. Their results supported the research on "Antimatter Detection in Heavy Ion Collisions and Hadron Spectroscopy and Collective Properties of Quark Matter," which received a second-class National Natural Science Award. Nine other institutions, including Tsinghua University and the Institute of Modern Physics, Chinese Academy of Sciences, are STAR collaboration members. Additionally, several Chinese Academy of Sciences academicians and National Natural Science Award winners have conducted research at DOE user facilities including the Relativistic Heavy Ion Collider, Stanford Synchrotron Radiation Lightsource, Advanced Photon Source, and Advanced Light Source.

2.3 Tightening Trend in Chinese Access to DOE User Facilities

Due to the COVID-19 pandemic, DOE user facility service capacity declined in fiscal year 2020. However, through rapid adjustments to service strategies such as remote access and virtual interaction, service capacity and efficiency improved. By fiscal year 2021, overall service had returned to normal levels, with remote usage accounting for approximately 66%; in fiscal year 2022, facility service capacity significantly increased, with service instances rising approximately 16% compared to fiscal year 2021, while remote usage proportion decreased to 54%. In contrast, China's usage of DOE facilities, which was relatively high during fiscal years 2017–2019, has significantly decreased in recent years [Figure 7: see original paper]. In fiscal year 2018, China used DOE user facilities 1,813 times, accounting for 17% of international services; in fiscal year 2022, China used these facilities 950 times, representing only 9.53% of international services. The most significant decline occurred at the Advanced Photon Source, where China's proportion of international services dropped from approximately 40% during fiscal years 2017–2019 to about 20% in recent years.

Before non-U.S. users can access DOE user facilities, they must undergo additional security and licensing reviews to determine whether their research technologies require U.S. export control licenses. In recent years, the U.S. Bureau of Industry and Security has added numerous Chinese enterprises and research institutions to control entity lists, affecting their ability to use DOE user facilities. For example, five research institutions—Beihang University, Northwestern Polytechnical University, University of Electronic Science and Technology of China, Sichuan University, and the China Academy of Engineering Physics—were added to controlled entity lists before 2015 and received only 21 usage approvals during fiscal years 2015–2022. Several institutions, including the Beijing High Pressure Science Research Center, entered entity lists in 2020, resulting in significantly reduced access in fiscal year 2022 compared to fiscal year 2018. The Beijing High Pressure Science Research Center's usage dropped from 469 instances in fiscal year 2018 to zero in fiscal year 2022, with no approvals in the past two years. In 2023, the U.S. Senate Intelligence Committee advanced legislation on DOE research security measures that would require screening visitors to DOE national laboratories from sensitive countries, potentially continuing to impact Chinese researchers' access to DOE user facilities.

2.4 Restricted Chinese Access to DOE Scientific Data Infrastructure

The United States has designated high-performance computing, artificial intelligence, and quantum information as national strategic priorities [16–18] and views China as a key competitor. During fiscal years 2015–2022, Chinese researchers used DOE scientific data infrastructure far less frequently than other countries. China used the Argonne Leadership Computing Facility 46 times, far fewer than the United Kingdom (236) and Switzerland (166); used the Oak Ridge Leadership Computing Facility 44 times, far fewer than the United Kingdom (211) and Germany (154); and used the National Energy Research Scientific

Computing Center relatively frequently but still less than the United Kingdom. Moreover, China has never obtained access to ESnet, while nine countries including India, South Korea, Switzerland, and Denmark have used this facility. This high-performance scientific data network facility's core service is providing international scientific data communications, enabling DOE researchers and their international collaborators to efficiently utilize massive data generated by artificial intelligence, high-resolution instrument imaging, and long-term scientific research.

Since the 1980s, China has vigorously promoted scientific data sharing and data infrastructure construction. As of December 2023, China has deployed 20 national scientific data centers and 14 national supercomputing centers by discipline area, including high-energy physics and space science. While China has achieved certain results in scientific data resource construction, its focus has been relatively skewed toward "hard" infrastructure such as networks and computing power, with insufficient attention to and support for "soft" content like research data and knowledge bases. Compared with the United States, significant gaps remain in scientific data infrastructure layout and capacity building. Overall, scientific data generation, transmission, storage, and computing capabilities are fragmented, failing to create an integrated data ecosystem, and the value of scientific data has not been fully exploited, affecting scientific discovery efficiency.

Specifically, major facility scientific data management is still in its infancy, with no unified scientific data standards yet formed, making efficient data aggregation and sharing difficult [19]. National scientific data centers still suffer from fragmentation and compartmentalization, remaining at the stage of scientific data collection and submission [20], with considerable room for development in comprehensive governance, application, FAIR principle compliance, and sharing [21]. China's current network information environment and conditions are insufficient to meet the needs of massive scientific data transmission [22], and software and hardware for scientific data storage, analysis, and mining remain constrained by developed countries. National supercomputing centers predominantly use foreign system architectures and application software, with weak software development capabilities and imperfect application scenarios, focusing mainly on traditional fields such as meteorology, climate, petroleum exploration, and cosmological simulation, while providing weak support for data-intensive scientific research.

In October 2022, the U.S. Commerce Department added certain advanced high-performance computer chips and computers containing such chips to its commercial export control list, restricting 28 entities including the National Supercomputing Center in Changsha from obtaining U.S. high-performance computing technology and services. In February 2023, the U.S. Commerce Department added multiple Chinese institutions, including the Wuxi National Parallel Computer Engineering Technology Research Center and Wuxi Institute of Advanced Technology, to entity lists. Going forward, China's use of DOE

high-performance computing facilities may face further restrictions.

3. Deficiencies in China's Major Infrastructure Open Services

3.1 Insufficient Support Capacity of Platform-Type Facilities

China's major infrastructure construction began in the 1960s, but the overall pace has been relatively slow, with support capacity still lagging behind developed countries. Before 2015, China had only three platform-type facilities in operation, with the High Energy Photon Source, Hefei Advanced Light Source, and Hard X-ray Free Electron Laser Facility still under construction. Since the 12th Five-Year Plan, China has accelerated major infrastructure deployment, but actual support capacity remains insufficient. Taking platform-type facilities as an example, significant gaps exist in experimental capability layout compared with developed countries. Currently, China's three synchrotron radiation light sources operate approximately 60 experimental stations combined—only one-third of Japan's (approximately 180) and less than one-third of the United States' (approximately 200). Going forward, China must maintain stable, high-speed development of its major facilities to narrow the gap in scientific infrastructure support capabilities with developed countries.

Remote services play an important role in improving major facility utilization rates, expanding open sharing, and reducing costs, making service model transformation an inevitable trend. However, beyond quantity, China's platform-type facilities offer relatively single-mode user support, with few facilities and experimental stations providing remote services. The vacuum ultraviolet spectroscopy, small-angle scattering, and high-pressure experimental stations at the Beijing Synchrotron Radiation Facility can implement remote experimental modes. The Shanghai Synchrotron Radiation Facility's biological macromolecular crystallography experimental station achieved remote experimental access in 2021 using self-developed robotic arms and data acquisition systems.

Since the 1980s, China has vigorously promoted scientific data sharing and data infrastructure construction. As of December 2023, China has deployed 20 national scientific data centers and 14 national supercomputing centers by discipline area. While China has achieved certain results in scientific data resource construction, its focus has been relatively skewed toward "hard" infrastructure such as networks and computing power, with insufficient attention to and support for "soft" content like research data and knowledge bases. Compared with the United States, significant gaps remain in scientific data infrastructure layout and capacity building. Overall, scientific data generation, transmission, storage, and computing capabilities are fragmented, failing to create an integrated data ecosystem, and the value of scientific data has not been fully exploited, affecting scientific discovery efficiency.

Specifically, major facility scientific data management is still in its infancy, with

no unified scientific data standards yet formed, making efficient data aggregation and sharing difficult [19]. National scientific data centers still suffer from fragmentation and compartmentalization, remaining at the stage of scientific data collection and submission [20], with considerable room for development in comprehensive governance, application, FAIR principle compliance, and sharing [21]. China's current network information environment and conditions are insufficient to meet the needs of massive scientific data transmission [22], and software and hardware for scientific data storage, analysis, and mining remain constrained by developed countries. National supercomputing centers predominantly use foreign system architectures and application software, with weak software development capabilities and imperfect application scenarios, focusing mainly on traditional fields such as meteorology, climate, petroleum exploration, and cosmological simulation, while providing weak support for data-intensive scientific research.

In October 2023, China established the National Data Bureau to coordinate the layout of digital infrastructure, which will help break through China's scientific data links and improve the data governance system [23].

4. Reflections and Implications

Scientific and technological infrastructure capacity is an important manifestation of national comprehensive scientific and technological strength and a strategic support for achieving high-level scientific and technological self-reliance [24]. As a vital component of scientific infrastructure capacity building, China attaches great importance to the construction and open sharing of major facilities to seize opportunities and gain initiative in the new round of scientific and technological revolution and industrial transformation. The high-level construction and operation of major facilities not only provide crucial support for frontier scientific research and solving key core issues related to national economic and social development and strategic security, but also help gather and cultivate high-end talent and demonstrate national scientific and technological innovation strength. While China has made considerable progress in major facility development, significant gaps remain compared with the requirements for building a strong science and technology nation and education powerhouse, necessitating accelerated construction and improved service efficiency. Based on the above analysis, we propose three recommendations for China's major facility construction, layout, and open sharing.

- (1) Continuously improve the comprehensive performance and service efficiency of major facilities to support the construction of a strong science and technology nation. Advancing the layout and construction of major facilities is of major strategic significance for China to achieve high-level scientific and technological self-reliance. In May 2022, the U.S. Senate Intelligence Committee held a public hearing on "Threats to U.S. National Security: Countering China's Economic and Technological Plans," proposing to modify the definition of "basic research" and suggesting that

once basic research reaches the level and type of controlled technologies, it should be subject to the same controls as controlled technologies. If implemented, China may lose access to DOE user facilities, impacting China's scientific research activities. Meanwhile, to obtain access to U.S. facilities, Chinese users must submit research proposals for review by the U.S. side, posing certain scientific and technological security risks. Therefore, we recommend fully assessing future Chinese user demand for major facilities, rationally planning major facility layout, and appropriately accelerating construction progress while ensuring high quality and standards. Facility capabilities and advanced levels should be continuously improved from the perspective of scientific objectives to meet the needs of high-quality scientific and technological development in China.

- (2) Accelerate the construction of data integration, utilization, and sharing ecosystems for major facilities. A healthy scientific data ecosystem is a new engine driving major scientific discoveries and important technological breakthroughs. We recommend deploying new scientific data infrastructure according to research development needs, coordinating the collaborative layout and management of “soft environment” and “hard conditions” during major facility construction, and further promoting the application of artificial intelligence, machine learning, and deep learning technologies to achieve interconnectivity between China's major facilities and national scientific data centers. This will accelerate the breaking of scientific data barriers and enable cross-domain integration. Consider incorporating scientific data infrastructure into China's major facility management system and developing corresponding application, review, and management rules tailored to its construction, usage, and management characteristics. Further enhance software development and application capabilities of China's national high-performance computing facilities, build a full-lifecycle scientific research ecosystem that integrates scientific data from generation to value mining and application, and actively promote the digital-intelligent transformation of major facilities to support the shift to data-intensive research paradigms.
- (3) Enhance the international potential of major facilities and strengthen high-level cooperation and exchange. Currently, China has relatively few facilities built through international cooperation, and the accumulated international user base is relatively small. Most international cooperation remains at the level of general exchange, lacking substantive international financial, technical, and scientific human resource investment [2]. Influenced by the international situation, the United States has reduced or restricted opportunities for Chinese users to conduct scientific research using its major facilities, and China will face more severe challenges in international scientific and technological cooperation in the future. We recommend that major infrastructure layout fully consider international potential, leverage the advantages of science diplomacy, and actively pursue leadership in initiating international big science programs and projects based on fa-

ilities. Simultaneously, further expand channels for Chinese researchers to use major facilities in Europe, Asia, and other countries, such as the European X-ray Free Electron Laser and European Synchrotron Radiation Facility. Strengthen deep cooperation between major facilities and domestic and international research institutions and enterprises, emphasize the cultivation of potential users, further expand the international user base, and continuously improve open sharing service capabilities.

Authors:**DONG Lu**

Librarian, National Science Library, Chinese Academy of Sciences. Research focus: Strategic intelligence on major research infrastructure and scientific instruments.

E-mail: donglu@mail.las.ac.cn

LI Zexia (Corresponding author)

Ph.D., Professor, National Science Library, Chinese Academy of Sciences. Research focus: Scientometrics, strategic intelligence research, and information analysis of major research infrastructure.

E-mail: lizexia@mail.las.ac.cn

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv – Machine translation. Verify with original.