China's Accelerator Driven Sub-critical System (ADS) Program

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Driven by the national demand for the safe disposal of nuclear waste as well as the potential for nuclear fuel breeding and advanced energy generation, the Chinese Academy of Sciences (CAS) initiated the Accelerator Driven Sub-Critical System (ADS) program in 2011 under the framework of a "Strategic Technology Pilot Project." The ultimate goal for the ADS program is to develop an industrial scale ADS facility for the safe disposal of nuclear waste and advanced fission energy systems, by integrating a high-power superconducting proton accelerator, a heavy metal spallation target and a sub-critical nuclear reactor. In the past four years, we have been focused on developing a deep understanding of the basic principles of ADS and on the R&D of related key technologies such as superconducting LINAC, spallation targets, sub-critical reactors, nuclear materials, nuclear data, and transmutation chemistry. The primary areas of research are briefly introduced in this paper.

INTRODUNTION

China is the world's most populous country with a fast-growing economy and it has become the largest energy-consuming nation in the world. In China, coal is the major energy resource and accounted for 69% of the country's total energy consumption in 2011 [1]. In contrast, nuclear power accounts for a relatively small share (nearly 1%) of China's energy consumption. With rapidly depleting fossil fuel resources and the commitment to cut down CO_2 and greenhouse gas emissions, China is actively developing nuclear energy as a clean, efficient, and reliable source of electricity generation. Compared with fossil fuels, the biggest advantage of nuclear energy is that it generates electricity without emitting carbon dioxide.

Although present light water reactors (LWRs) are capable of fulfilling nuclear energy demands for many decades to come, advanced nuclear energy systems with the merits of environmental friendliness, resource efficiency, cost-effectiveness, and proliferation resistance should be developed to make fission energy sustainable. The commercial deployment of Generation IV nuclear reactors is a key step in this aspect. At the same time, the growing stock of spent fuel or separated plutonium and vitrified high-level waste (HLW) has become one of the main focuses of the criticisms against nuclear energy, where further management of nuclear waste is still uncertain. Transmutation, which is the burning of the minor actinides (MAs) and long-lived fission products (FPs) in HLW with energetic neutrons, is considered to be one of the most promising paths to reduce the radiotoxicity of HLW. In a comparative study, entitled "Accelerator-Driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles," [2] OECD/NEA drew a conclusion that, "ADS has the advantage that it can burn pure minor actinides while avoiding a deterioration of the core safety characteristics."

In response to the urgent needs for the sustainable development of nuclear energy, the Chinese Academy of Sciences (CAS) launched the ADS program in 2011 with a budget of ￥1.78 billion for the first five years. CAS also developed a three-stage "roadmap" for ADS development (shown in Fig. 1). In Phase I, the ADS program will first mainly focus on the R&D of key technologies in accelerators, spallation targets and sub-

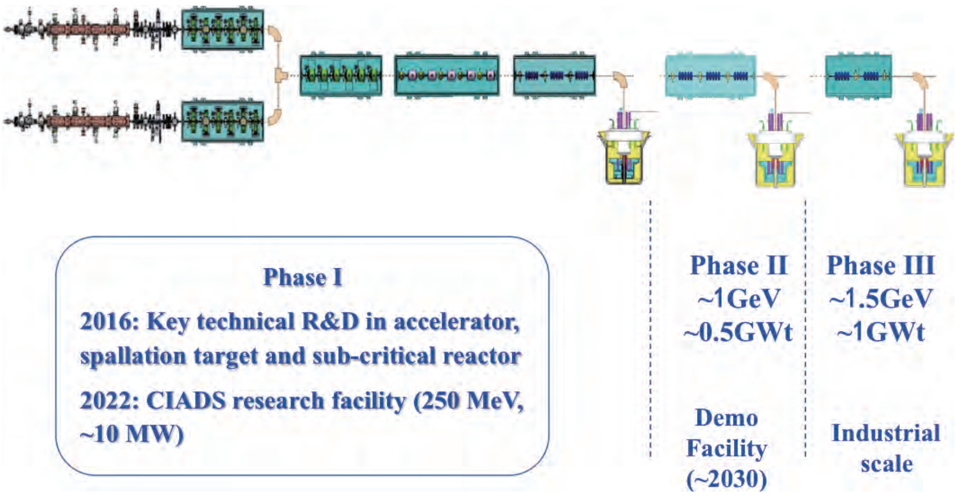


Fig. 1: A roadmap for developing ADS facilities in China.

Fig. 2: Layout of the main systems of the Chinese Initiative Accelerator Driven System (CIADS).

critical cores. A research facility, the Chinese Initiative Accelerator Driven System (CIADS), will be designed and built by 2022. Fig. 2 shows the layout of the main systems of CIADS. In phase II, an ADS demo facility with the thermal power output of hundreds of megawatts is going to be established around 2030. Developing an industrial scale ADS for commercial applications is the ultimate goal in phase III. The successful implementation of the ADS program would provide great opportunities for Chinese scientists to resolve the key issues related to ADS, to obtain experiences in associated experimental and theoretical studies, and to develop advanced partitioning and transmutation technologies for the disposal of nuclear waste.

After four years of efforts, a number of achievements have been made and some of those achievements have been recognized as groundbreaking work in the relevant research fields. More detailed descriptions are presented below.

HIGH-POWER SUPERCONDUCTING PROTON ACCELERATOR

A 25 MeV@10 mA continuous-wave (CW) superconducting proton LINAC will be built to demonstrate the feasibility of a superconducting accelerator. The design of the 0~10 MeV segment has two alternatives. One is based on 162.5 MHz RFQ and half-wave resonators, and the other

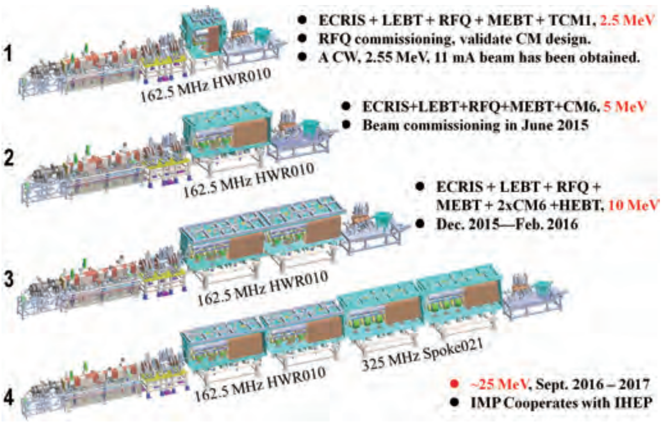


Fig. 3: Time schedule of the 25 MeV proton demo-LINAC.

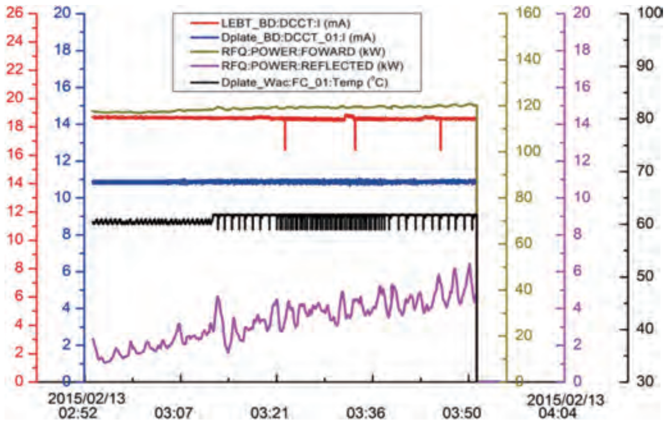


Fig. 5: Historical record of the 11 mA/2.55 MeV/CW beam.

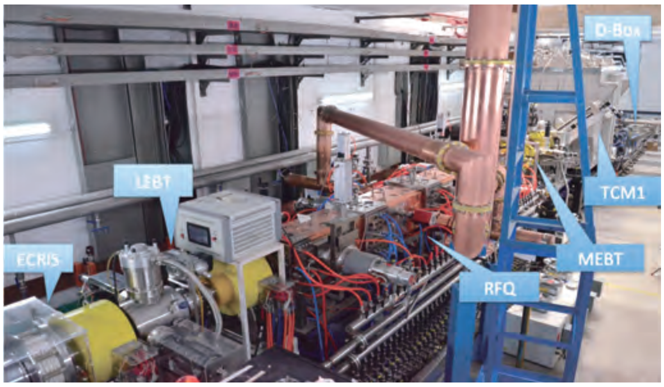


Fig. 4: The demo superconducting LINAC: ECR+LEBT+RFQ +MEBT+TCM+D-Box.

is based on 325 MHz RFQ and spoke resonators. To think of the thermal stability of CW-RFQ, the down-selection of the demo-LINAC mainly includes the ECR ion source (ECRIS), low energy beam transport Line (LEBT), radio frequency quadrupole accelerator (RFQ), medium energy beam transport Line (MEBT), two HWR-cryomodules (which employ 12 superconducting Half-Wave Resonators) and two spoke-cryomodules (which employ 12 superconduting spoke resonators). The injectors of CIADS will also be 162.5 MHz RFQ and HWR. A 325 MHz, 10 MeV linac is being developed to demonstrate the operation of spoke in liquid helium at 2 Kelvin.

The project started in 2011 and will commission a 25 MeV LINAC in September 2016. The time schedule is shown in Fig. 3. The ECRIS can provide 35 keV, 20 mA proton beams in both CW and pulse modes. The first proton beam was extracted from the ECRIS and travelled through the LEBT in March 2013. Then, the RFQ was installed along with the LEBT in April 2014. After a two month conditioning of the RFQ, the first beam signal was detected. In July 2014, 2.1 MeV@10 mA beams were obtained from the RFQ stably with a transmission of 97% for 4.5 hours. Up to now, it has operated for more than 900 hours.

The MEBT and TCM (Test Cryomodule) were installed along with the RFQ in August 2014 (shown in Fig. 4). The beam commissioning was started in early September 2014. The first proton beam from the TCM was obtained on September 29, 2014. On February 13, 2015, an approximately 11 mA, 2.55 MeV, CW proton beam was obtained and lasted 1 hour. The beam power at dumper reached 28 kW. The transmission of the MEBT+TCM was more than 97%. The historical record is shown in Fig. 5. So far, the key technologies for low-energy superconducting LINAC have been developed and proven. Consequently, the 5 MeV superconducting LINAC was installed in a tunnel and will start commissioning in June 2015.

The 325-MHz superconducting LINAC has been installed in a tunnel, including ECR, RFQ and TCM with two spokes (shown in Fig. 6). The 3.2 MeV @11 mA pulsed beam was extracted from the RFQ, and the duty factor was about 70%. The pulsed beam of 130 us /second was obtained with the energy of 3.61 MeV and the beam current of 10 mA.

HEAVY METAL SPALLATION TARGET

The spallation target, which runs by bombarding the heavy metal with high energy and high power proton beams, is to produce neutrons with a broad range of energy to drive the subcritical core. The primary tasks

Fig. 6: The 325-MHz superconducting LINAC.

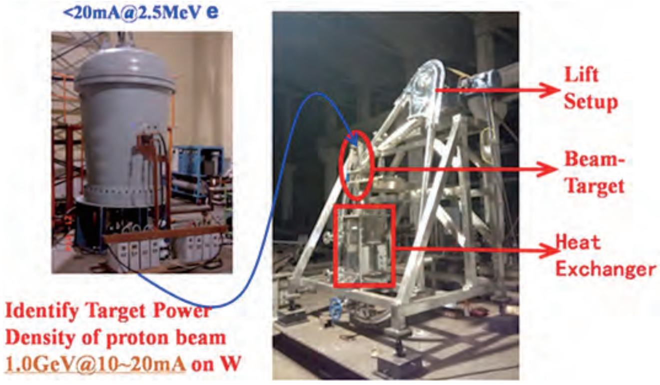


Fig. 8: Experimental facility for granular flow target test.

for spallation target research includes developing the massive parallel GPU simulation methods and the database establishment for the target design; studying the coupling issues among the accelerator, the spallation target and the sub-critical core; and designing and constructing a prototype spallation target system. Based on NVIDIA GPU, the specific software, General Monte-Carlo Transport (GMT), has been developed to perform large scale simulation studies for both liquid flow and granular flow in the spallation target. A nuclear database relevant to spallation reactions has been established as well. The GMT has the ability to simulate spallation reactions in the aspects of neutron yield, energy deposit, and other relevant target parameters.

A novel concept of the spallation target, the Granular Flow Target (GFT), had originally been proposed to meet the requirements of the China ADS project (Fig. 7). The GFT is expected to have some advantages over the liquid heavy metal target and conventional solid spallation target in some aspects. For instance, the GFT can sustain high proton beam power by transferring heat through granular flow, and can avoid the erosion problems occurred in liquid lead bismuth eutectic (LBE) target.

To test and optimize the granular target design, a 1:10 scale experimental facility, as shown in Fig. 8, has been built and has been tested by coupling with an electron accelerator. The result shows that the target flow rate is quite stable as predicted.

In the experiment, an electron beam of 1.5 MeV@0.1 mA was used to offer an equal volume heat deposit density as the 250 MeV@10 mA proton beam. According to the experimental results, the heat load could be removed efficiently by granular flow, and agreed well with the prediction of numerical simulations. The experimental and simulation results are shown in Fig. 9.

In addition, experimental study of the LBE target is also conducted concurrently. The STELA (Spallation

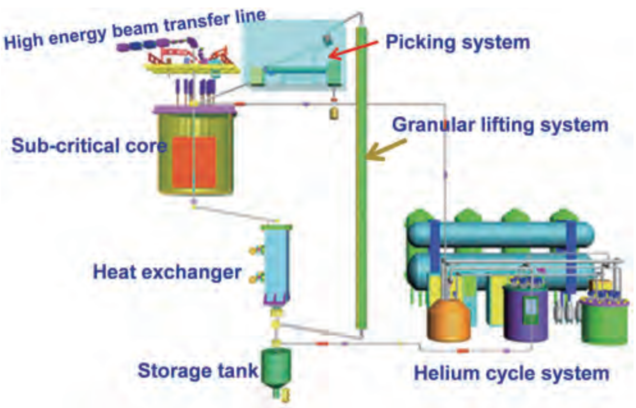


Fig. 7: Schematic diagram of the granular flow target.

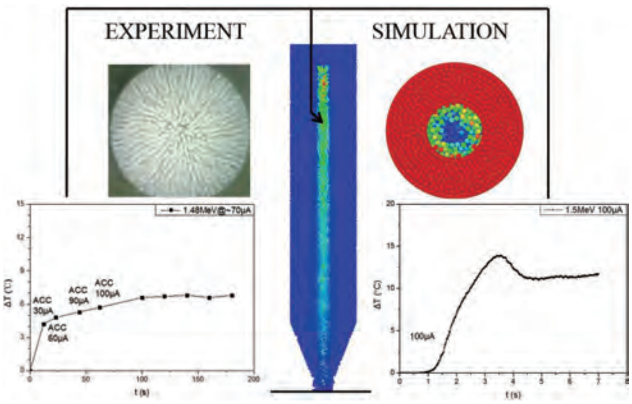
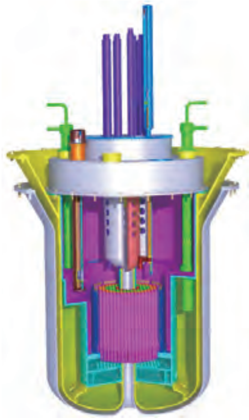


Fig. 9: 1.5 MeV electron beam coupling thermal effect (left: experimental results; right: simulation result).

Fig. 10: Spallation target experimental loop for ADS.



System Parameter	value
Thermal Power (MWt)	10
Core Diameter (mm)	970
Core Height (mm)	800
Cladding Material	316Ti
Structural Material	316L
External Vessel Diameter (m)	4.48
Vessel Height (m)	6.8
Primary Coolant	LBE
Flow (kg/s)	529.5
Coolant Temperature (°C)	300/385

Fig. 11: Diagram of the sub-critical reactor core and its major design parameters.

Target Experimental Loop for ADS) test facility has been designed and built. STELA aims at developing technical infrastructure and programs for experiments, such as thermal hydraulics, circulation method, instrumentation, and measurement techniques. The maximum operation temperature of the loop is 600 °C and its total power is 75 kWt. As shown in Fig. 10, the main loop consists basically of the electromagnetic pump with cooling, air-cooled heat exchanger, LBE filter, electromagnetic flow meter, expansion tank and sump tank, and heater. The maximum flow rate is up to 27 m^3/hr. Based on STELA's results, the heat transfer characteristics of Pb-Bi/air and the cooling of the beam window will be studied. The thermal-hydraulic data for code validation will also be provided.

SUB-CRITICAL REACTOR CORE

A sub-critical reactor is designed to couple the granular spallation target. Fig. 11 shows the diagram of the sub-critical core together with its major design parameters. LBE is chosen as the primary coolant for the sub-critical core since LBE has the advantages of excellent neutron properties, good thermal conductivity, and low chemical activity. However, before the ADS design is finalized, some important issues, such as the compatibility of LBE and structural materials, flow and heat transfer characteristics, and precise oxygen control, need to be experimentally investigated. For these purposes, a series of LBE experimental loops and related verification facilities have been designed and built. In 2014, an integrated experimental loop KYLIN-II for lead-bismuth cooled reactor technologies has been established and started commissioning (shown in Fig. 12). Its successful construction and commissioning will play an important role for the further research on ADS technologies. With this loop, a series of experiments with respect to the corrosion of structural materials exposed to LBE, the thermal-hydraulic behavior of LBE, components and system safety, and other key issues are conducted.

OTHER PROGRESSES

Material is essential for the development of advanced nuclear energy systems since its service behavior determines the systems' feasibility, safety and economy. An advanced nuclear material research project was assigned under the ADS program to focus on the R&D of materials with good performance regarding resistance to intense particles irradiation, high temperatures, high stresses as well as liquid metal corrosion, and to explore novel materials with a level of high quality to meet demands of the ADS facilities.

Fig. 12: KYLIN-II lead-bismuth loop.

In collaboration with the Institute of Metal Research, CAS, a novel material, tentatively named as SIMP steel, was fabricated. According to the preliminary testing results, its routine performances, such as high temperature properties and resistances to ion irradiation and liquid metal corrosion are better than or comparable to that of commercially used T91 and other RAFM steels. In Fig. 13, the cavity swelling test result is shown. Further study and evaluations are in progress.

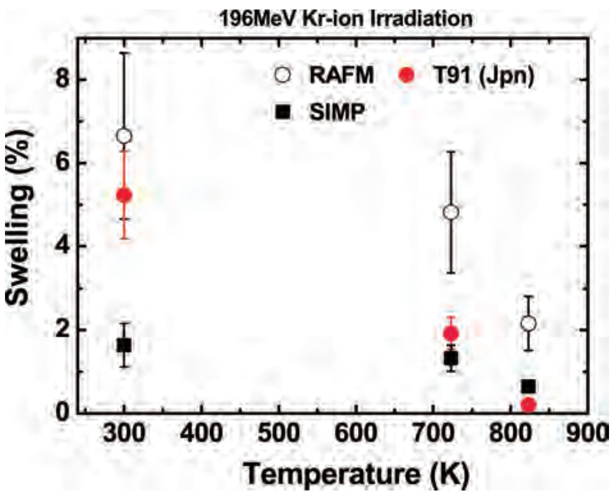


Fig. 13: Cavity swelling values at peak damage regions irradiated by Krypton ions for SIMP, T91 and RAFM steels.

CHALLENGES AND PERSPECTIVES

Based on the progress that we have achieved so far, the preliminary design of the research facility, CIADS, is accomplished and will be optimized continuously according to the latest findings in the following areas of research.

CIADS will be located in Huizhou, Guangdong province, and built under the support of the National Development and Reform Commission with a budget of ¥2 billion.

The site is near by the planed Huizhou Nuclear Power Plant. From the point view of geographical condition, the site is appropriate to build the ADS facility and to carry out related research work. Currently, a series of works for site evaluation and environmental impact assessment are extensively conducted.

The ADS program still faces great technical challenges since there is no prototype facility running in the world so far. Although we have made some important achievements, there are still a lot of problems that need to be solved. The economy of the ADS system should be evaluated in the whole fuel cycle. In addition to the reliability of the high power spallation target, and the coupling of the target with the accelerator and the sub-critical reactor are essential issues to pay special attention. Public communication and management are always the issue for the development of ADS facilities.

Furthermore, a novel conceptual design of an ADS-based nuclear energy system, the Accelerator Driven Advanced Nuclear Energy System (ADANES), is also presently under development. ADANES is capable of providing thousands of years' of secure energy with low emissions and low costs by integrating nuclear waste transmutation, nuclear fuel breeding and nuclear safety production. A detailed description about ADANES will be reported in the near future.

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