Chapter 1

Introduction

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Abstract At the Kyoto University Critical Assembly (KUCA), the accelerator-driven system (ADS) is composed of a solid-moderated and solid-reflected core (A-core) and a pulsed-neutron generator (14 MeV neutrons) or the fixed-field alternating gradient (FFAG) accelerator (100 MeV protons). At KUCA, two external neutron sources, including 14 MeV neutrons and 100 MeV protons, are separately injected into the A-core, and employed for carrying out the ADS experiments. With the combined use of the A-core and two external neutron sources, basic and feasibility studies of ADS have been engaged in the examination of neutronics of ADS, through the measurements of statics and kinetics parameters of reactor physics, including subcritical multiplication factor, subcriticality, prompt neutron decay constant, effective delayed neutron fraction, neutron spectrum, and reaction rates.

Keywords KUCA · ADS · Pulsed-neutron generator · FFAG accelerator

1.1 Kyoto University Critical Assembly

1.1.1 KUCA Facility

The Kyoto University Critical Assembly (KUCA [1]; Fig. 1.1) is a multi-core type critical assembly developed by Kyoto University, Japan, as a facility that can be used by researchers from all the universities in Japan to carry out studies in the field of reactor physics. KUCA was established in 1974, as one of the main facilities of the Research Reactor Institute, Kyoto University (KURRI; currently, Institute for Integrated Radiation and Nuclear Science: KURNS), located at Kumatori-cho, Sennan-gun, Osaka, Japan.

KUCA is a multi-core-type critical assembly consisting of two solid-moderated cores (A- and B-cores) and one light-water-moderated core (C-core). Then, a single

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Fig. 1.2 Solid-moderated and -reflected core (A-core) (Ref. [1])

1.1.2 Solid-Moderated and Solid-Reflected Cores

Two solid-moderated cores (A-core; Fig. 1.2 and B-core) are installed at KUCA. Squared-shaped coupon-type uranium fuel plates (93 wt% enriched) of 2" length, 2" breadth, and 1/16" thick covered with a thin plastic coating are used as the fuel material. Solid moderator materials, including polyethylene and graphite, are combined with highly-enriched uranium (HEU), thorium, and natural uranium plates to form the fuel elements. Polyethylene, graphite, beryllium, aluminum, iron, lead, and bismuth are used as the reflector elements.

A wide variety of neutron spectra could be achieved by varying the composition of the fuel and moderator plates in the fuel element, and also by varying the reflector elements.

The A-core can be used in combination with the pulsed-neutron generator, and also, it is used for carrying out studies on ADS and fission-fusion hybrid reactor systems.

1.1.3 Light-Water-Moderated and Light-Water-Reflected Core

A single light-water-moderated core (C-core; Fig. 1.3) is installed at KUCA. Plate-type uranium fuel (93 wt% enriched) of 600 mm length, 62 mm width, and 1.5 mm thick with an aluminum (Al) cladding of 0.5 mm thick are used in the C-core. In addition, there are two types of curved fuel plates: one 93 wt%, and the other 45 wt%

Fig. 1.3 Light-water-moderated and -reflected core (C-core) (Ref. [1])

enriched of 650 mm length and 1.4 mm thick with an Al cladding of 0.45 mm thick; 32 plates with different curvatures and widths are used.

The fuel element is formed by assembling the fuel plates in aluminum fuel frames. The fuel elements are loaded in a core tank of 2,000 mm diameter and 2,000 mm depth and then immersed in light water to form the core. A part of the reflector region can be substituted for a heavy-water reflector. Three types of fuel frames, each having different fuel loading pitch and thus providing different neutron spectra in the core, are available. The core can be separated into two parts with arbitrary gap width, and it is suitable for coupled core and criticality safety studies.

The C-core is used for carrying out a wide variety of basic studies on light-water-moderated systems, including the development of high-flux research reactor, enrichment reduction in a research reactor, criticality safety, and study of coupled core theory.

The C-core is also used for conducting a graduate-level joint reactor laboratory course in affiliation with many Japanese universities in addition to conducting an undergraduate-level reactor laboratory course in affiliation with the Kyoto University. International reactor laboratory courses for students overseas have been also conducted since 2003.

1.1.4 Pulsed-Neutron Generator

A pulsed-neutron generator (Fig. 1.4) is attached to KUCA. Deuteron (D) ion beams are injected onto a tritium (T) target to generate the pulsed neutrons (14 MeV

Fig. 1.4 Pulsed-neutron generator (D-T accelerator) (Ref. [1])

neutrons) through ${}^3\text{H}(\text{d}, n){}^4\text{He}$ reactions. The pulsed-neutron generator can be used in combination with the critical assembly (A-core). The system consists of a duoplasmatron-type ion source, a high-voltage generator with a capacity of 300 kV, an acceleration tube, a beam pulsing system, and a tritium target. The main characteristics of deuteron ion beams are follows: the acceleration voltage 300 kV at most; the beam current 5 mA at most; the neutron pulsed width ranging between 300 ns and 100 μs ; the pulsed repetition rate between 0.1 Hz and 30 kHz (max. duty ratio 1%).

The pulsed-neutron generator has been used, in combination with the A-core, for carrying out basic studies on ADS and fission-fusion hybrid reactor systems.

1.1.5 Fixed-Field Alternating Gradient Accelerator

Fixed-Field Alternating Gradient (FFAG) accelerator, which was originally proposed forty years ago, attracts much attention because of its advantages, such as a large acceptance or a possible fast repetition rate, compared with that for synchrotrons. Furthermore, the operation of an FFAG accelerator is expected to be very stable because no active feedback is required for the acceleration. From these features, FFAG accelerator is considered a good candidate for the proton driver in ADS.

FFAG accelerator is available to combine strong focusing optics like a synchrotron with a fixed-magnetic field like a cyclotron. Unlike a synchrotron, the magnetic field experienced by the particles is designed to vary with radius, rather than time. This naturally leads to the potential to operate at high repetition rates limited only by

Fig. 1.5 FFAG accelerator complex at KURRI (<https://www.rrl.kyoto-u.ac.jp/facilities/irl>)

the available RF system, while strong focusing provides a possibility of maintaining higher intensity beams than in cyclotrons.

A revival in interest since the 1990s has seen a number of FFAGs constructed, including scaling and linear non-scaling variants. However, high bunch charge operation remains to be demonstrated. A collaboration has been formed to use an existing proton FFAG accelerator at KURNS to explore the high-intensity regime in FFAG accelerators.

At KURNS, the FFAG accelerator complex (Fig. 1.5; Refs. [2–4]) was installed in the experimental facility for the basic study of ADS in 2003. The main characteristics of proton beams are follows: the energy 150 MeV at most; the beam current 1 nA at most; the repetition rate 30 Hz; the pulsed width less than 100 ns. Other than ADS experiments, irradiation for the materials, aerosol, and living animals (e.g., rats) are performed for the basic studies in various research fields.

1.2 Accelerator-Driven System

1.2.1 Overview of Research and Development

ADS was first proposed as an energy amplifier system [5] that couples with a high-power accelerator and a thorium sustainable system. Another possible function of ADS was resolving the issue of transmuting minor actinide (MA) and long-lived fission product (LLFP) generated from nuclear power plants. ADS has attracted worldwide attention because of its superior safety characteristics and potential for

burning plutonium and nuclear waste. An outstanding advantage of its use is the anticipated absence of reactivity accidents when sufficient subcriticality is ensured. Also, ADS is expected to provide capabilities for power generation, nuclear waste transmutation, and a reliable neutron source for research purposes.

The ADS experimental facilities are being prepared for the investigations of nuclear transmutation of MA and LLFP, as are the Transmutation Experimental Facility (TEF) [6] at the Japan Atomic Energy Agency and the Multi-purpose Hybrid Research Reactor for High-tech Applications (MYRRHA) [7] at SCK/CEN in Belgium. Research activities on ADS involved mainly the experimental feasibility study using critical assemblies and test facilities: MASURCA in France [8–10], YALINA-booster and-thermal in Belarus [11–13], VENUS-F in Belgium [14–17], and KUCA in Japan [18–78]. At these facilities, feasibility studies on ADS have been conducted by combining a reactor core (fast or thermal core) with an external neutron source by the D-T accelerator (14 MeV neutrons) or 100 MeV proton accelerator (KUCA only), through experimental and numerical analyses of reactor physics parameters, including statics parameters: reaction rates, neutron spectrum, and subcritical multiplication factor; kinetics parameters: subcriticality, prompt neutron decay constant, effective delayed neutron fraction, and neutron generation time. Here, to ensure measurement methodologies of the statics and kinetics parameters and confirm numerical precision by stochastic and deterministic calculations, many attempts were made for uniquely developing new-type and high-precision detectors, and interestingly for introducing advanced-numerical approaches, respectively.

1.2.2 Feasibility Study at KUCA

At KURRI, a series of preliminary experiments on the ADS with 14 MeV neutrons was officially launched at KUCA in 2003, with sights on a future plan (Kart & Lab. Project) [79, 80]. The goal of the plan was to establish a next-generation neutron source, as a substitution for the current 5 MW Kyoto University Research Reactor established in 1964, by introducing a synergetic system comprising a research reactor and a particle accelerator. High-energy neutrons generated by the interaction of high-energy proton beams (100 MeV) with heavy metal was expected to be injected into the KUCA core, and finally, the world's first injection [21] of high-energy neutrons obtained by a new accelerator was successfully conducted into the KUCA core in 2009. The new accelerator is called the FFAG accelerator of the synchrotron type developed by the High Energy Accelerator Research Organization in Japan.

Prior to actual ADS experiments with 100 MeV protons, it was requisite to establish measurement techniques for various neutronics parameters and the method for evaluating neutronic properties of the ADS with 100 MeV protons. Uniquely, KUCA has outstanding features of two external neutron sources (14 MeV neutrons and 100 MeV protons) and a variety of neutron spectrum cores, although the KUCA cores provide almost a thermal neutron spectrum. For the accomplishment of research objectives, a series of basic experiments with 14 MeV neutrons obtained by the

D-T accelerator had been carried out using the A-core (Fig. 1.2) and the pulsed-neutron generator (Fig. 1.4) of KUCA. Then, neutron characteristics of statics and kinetics parameters in reactor physics were experimentally investigated through the development of measurement methodologies and numerically examined through the confirmation of calculation precision by the Monte Carlo calculations. After the first injection of 100 MeV protons, the next campaign of ADS experiments was devoted to basic research (feasibility study) on ADS coupling with the FFAG accelerator (a tungsten or lead-bismuth: Pb–Bi target) and the A-core, by varying external neutron source (14 MeV neutrons or 100 MeV protons), neutron spectrum of reactor core combined with nuclear fuel (uranium-235, thorium-232, and natural uranium), moderators (polyethylene and graphite) and reflectors (polyethylene, graphite, beryllium, aluminum, iron, lead, and bismuth), and subcriticality. Significantly, in 2019, the world's first nuclear transmutation of MA by ADS [66] was accomplished at the condition that the spallation neutrons were supplied to a subcritical core through the injection of 100 MeV protons onto a Pb–Bi target, demonstrating fission and capture reactions of neptunium-237 and americium-241.

All experimental data of ADS were compiled as “ADS experimental benchmarks at KUCA,” publishing the KURNS technical reports [81–85], and employed as “Coordinated (Collaborative) Research Projects (CRP) of Accelerator-Driven System and Low-Enriched Uranium Cores in ADS” organized by the International Atomic Energy Agency (IAEA). Through the CRP programs of ADS by IAEA ranging between 2007 and 2018, experimental data of ADS at KUCA were shared with all IAEA state members and used for conducting the validation and verification of nuclear calculation codes and major nuclear data libraries.

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