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OVERVIEW OF ADS PROJECTS IN THE WORLD

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Abstract

Accelerator-driven subcritical systems (ADS) offer an advantageous option for the transmutation of nuclear waste. ADS employs high-intensity proton linear accelerators (linacs) to produce spallation neutrons for a subcritical reactor. Besides the challenges of any megawatt (MW) proton machine, ADS accelerator must operate with stringent reliability to avoid thermal stress in the reactor structures. Thus, ADS linacs have adopted a reliability-oriented design to satisfy the operation requirements. This work provides a review and the present status of the ADS linacs in the world.

INTRODUCTION

With the increase in the necessity for a safe, sustainable, and zero-emission energy source, nuclear energy represents a suitable option [1]. However, society has concerns about nuclear safety and the long-time residual waste it produces. The partitioning and transmutation strategy offers an effective way to reduce the burden of geological storage, as shown in Fig. 1. Partitioning comprises the selective separation of radioactive isotopes of the spent fuel, where some of them are reused as a fuel, and the other part, the so-called nuclear waste, is transmuted to reduce the radiotoxicity level. Accelerator-driven subcritical system (ADS) is an advanced nuclear system that could be used for the transmutation of minor actinides, therefore reducing the burden of geological disposal. Additionally, it can produce electricity, as the energy amplifier proposed by Rubbia [3], and fissile material, known as Accelerator- Breeding [4].

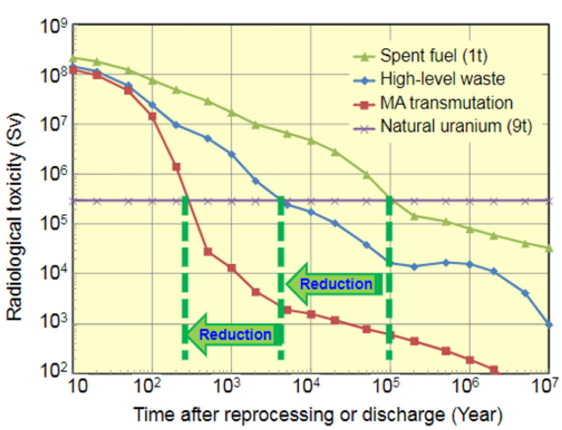

Figure 1: Reduction of radiotoxicity by applying partitioning and transmutation strategy [2].

ADS is composed of a high-power accelerator, a spallation target, and a subcritical reactor [1]. Figure 2 shows the design of the JAEA-ADS. The accelerator drives the beam, usually protons, to a spallation target to produce neutrons for the subcritical reactor. Because the reactor is subcritical, it requires an external source of neutron to sustain the nuclear fission. Thus, if the accelerator is stopped, the fission process is also stopped. This feature enhanced the safety of these nuclear reactors. In addition, the ADS provides greater flexibility concerning the fuel composition.

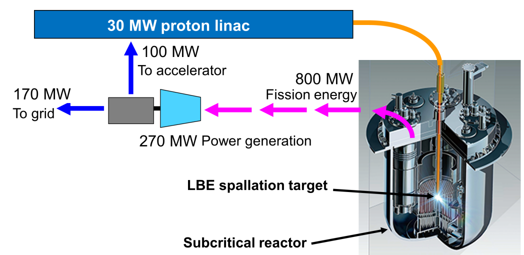

Figure 2: JAEA-ADS design.

With the advancement of high-power accelerators, especially superconducting radio frequency (SRF) technology, ADS accelerators have benefited from those developments. However, the ADS accelerator is expanding the intensity frontier to operate with high reliability and stability in the MW beam power regime. This work provides a review of the key features of the ADS accelerators and presents a summary of ADS activities around the world.

ADS ACCELERATOR FEATURES

The ADS accelerator must meet specific requirements to make the ADS technology suitable:

- Stable and efficient continuous wave (cw) operation of a beam power of few to tens of MW, which is defined by the thermal power and subcritical of the reactor [5, 6].
- Final beam energy is about 1 to 2 GeV for efficient neutron production through a spallation process.
- Beam current of few to tens of mA.
- Operating with beam loss less than 1 W/m to facilitate maintenance.
- High reliability to avoid thermal stress in the reactor structures. The number of allowing beam trips is more strict than other high-power accelerators, as shown in Fig. 3.
- High beam stability is necessary to ensure the integrity of the beam window.

To this end, a reliability-oriented design based on a robust lattice design, fault tolerance, and easy repairability is pursued [10].

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Table 1: Summary of the Worldwide ADS Activities

	Accelerator	Purpose	Status
CiADS (China) [11]	2.5 (10)-MW SRF proton linac	ADS demo	Commissioning
MYRRHA (Europe/Belgium) [12]	2.4-MW SRF proton linac	ADS demo	Construction
JAEA-ADS (Japan) [13]	30-MW SRF proton linac	Transmutation of nuclear waste	Design
SKKU-ADS (Korea) [14]	5-MW SRF proton cyclotron	ADS Th based nuclear reactor	Design
KIPT (Ukraine) [15]	0.1-MW electron linac	ADS demo	Scientific program under develop
IFSR (India) [16]	1-MW SRF proton linac	Energy production	Design
ADS-Troitsk (Russia) [17]	0.75-MW proton linac	ADS demo	Design (using the existing Troitsk facility)
Mu*STAR (USA/Muons, Inc.) [18]	2.5-MW SRF proton linac	Transmutation of nuclear waste	Design
CYCLADS (Europe/Consortium) [19]	5-10-MW proton cyclotron	Transmutation of nuclear waste	Design

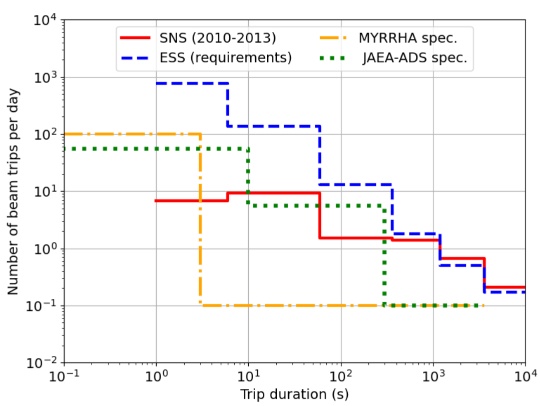

Figure 3: Beam trips frequencies [5, 7–9].

WORDWILDE ADS ACCELERATOR ACTIVITIES

ADS R&D is taking place around the world, and the particle accelerator community is pursuing a high-reliability MW cw proton operation. Table 1 represents a partial summary of worldwide ADS activities. It is worth mentioning that even though the mainstream is the use of a proton linac, there are proposals to consider electron beams (KIPT) and cyclotrons (SKKU-ADS and CYCLADS). A summary of the principal features and the current statutes of the CiADS, MYRRHA, and JAEA-ADS programs will be presented next.

CiADS

China Initiative Accelerator Driven System (CiADS) is phase II of the Chinese ADS program [11, 20, 21]. CiADS will employ a superconducting cw linac to accelerator 5 mA proton beam to a final energy of 500 MeV, as shown in Fig. 4 (a). Table 2 provides the details of the CiADS project. CiADS is led by the Institute of Modern Physics (IMP) in collaboration with the Institute of High Energy Physics (IHEP), China National Nuclear Corporation (CNCC), and China General Nuclear Power Group (CGN) and will be located in Huizhou, China.

IMP is currently commissioning the ADS Front-end Demo Facility (CAFe), which was constructed together with IHEP. The CAFe aims to demonstrate the superconducting front-end linac 10 mA cw beam for CiADS. A high beam power test was conducted from January to March 2021, achieving a beam power of 205.5-kW with a 10.2 mA cw proton beam. CiADS works on various activities: RFQ manufacturing, SRF, solid-state amplifiers, superconducting solenoids, and LBE target, among others.

MYRRHA

The Multipurpose Hybrid Research Reactor for High Technology Applications (MYRRHA) is a European project managed by the Belgian Center for Nuclear Research (SCK CEN) [12]. MYRRHA will accelerate a 4 mA cw proton beam to a final energy of 600 MeV. Figure 4 (b) shows the design of the MYRRHA and Table 2 summarizes the most relevant parameters of it.

MYRRHA will be developed in phases. Currently, the project is in phase I, also called MINERVA. MINERVA is under construction at MOL in Belgium and aims the operation of a 4 mA cw beam to a final energy of 100 MeV. MYRRHA and its collaborators also work on other activities, including SRF prototyping, cryomodule development, fault-recovery scenarios, and solid-state amplifiers [9, 22].

JAEA-ADS

The Japan Atomic Energy Agency (JAEA) is working on the design of a 30-MW cw proton linac for the ADS proposal [13, 23]. The JAEA-ADS linac will accelerate a 20 mA proton beam to a final energy of 1.5 GeV. Then, the

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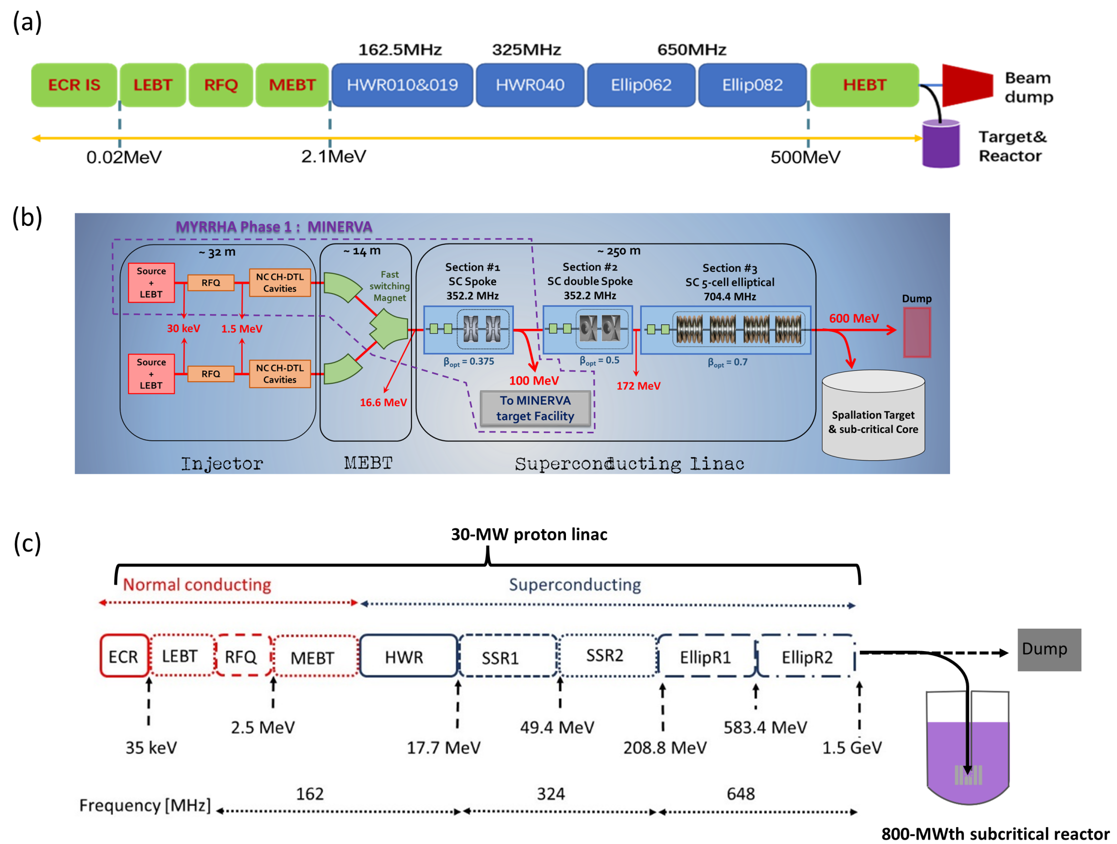

Figure 4: ADS designs: CiADS (a) [20] , MYRRHA (b) [12] , and JAEA-ADS (c).

Table 2: Summary of the ADS Design Parameters

	Parameter	CiADS	MYRRHA	JAEA-ADS
Proton linac	Energy (GeV)	0.5	0.6	1.5
	Beam current (mA)	5	4	20
	Operation mode	cw/pulse	cw	cw
	RF Frequency (MHz)	162.5/325/650	176.1/352.2/704.4	162/324/648
Target	Maximum beam power (MW)	2.5	2.4	30
	Material		lead-bismuth eutectic (LBE)	
Fast reactor	k_{eff}	~0.75/~0.96	0.95	0.97
	Thermal power (MW)	~7.5/~9.7	50-100	800

beam transport to the target will carry from the end of the linac to the spallation target inside the 800-MWth thermal power subcritical reactor. JAEA-ADS linac team is focusing on two topics: beam optics and SRF prototyping. In beam optics, the reference design and fast beam recovery scenarios have been developed [24, 25]. For SRF fabrication, the prototyping of the single spoke resonator is taking place [26]. JAEA has a plan to construct a transmutation experimental facility (TEF) and is working on the LBE target system, shielding calculations as well as reactor design [23].

CONCLUSIONS

ADS has become a promising choice to deal with the problem of nuclear waste storage and provide clean energy, thus, aiding the use of nuclear energy to achieve the zero-emission goal. Transmutation has been one of the earliest motivations for the development of particle accelerators. At the present, ADS accelerators have benefited from the current state-of-the-art of the present high-power accelerator. However, they will contribute to expanding the barrier of high intensity by operating in the MW range with acceptable beam loss, high reliability, stability, and cost-effectiveness. ADS will not only have an important impact on achieving a sustainable energy source, but it also will boost the high-power proton accelerator technology. Thus, for the development of ADS accelerators, it is necessary to close international cooperation between laboratories around the world.

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