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Towards Next Generation Accelerator Driven Subcritical System

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Abstract

Accelerator Driven sub-critical System (ADS) is considered the most important candidate for nuclear waste transmutation. We propose a Multi-Target Accelerator Driven System (MTADS) to resolve two longstanding challenges of ADS, namely heat removal and the associated target lifetime, and inhomogeneous power distribution that affects reactor burn-up. An 18 mA, 1 GeV proton beam is split into 12 beams by radio frequency cavities and injected into 12 compact targets inside the reactor. With a beam power of 18 MW, the sub-critical reactor is driven to 1500 MW thermal power. The peaking factor of the reactor is reduced to 1.7 by optimization of target number and position for the MTADS. The maximum beam current density is also reduced to 18.5 A/cm², which prolongs the beam window lifetime to 12 months with T91 steel. For next-generation ADS, the concept of MTADS simplifies the sub-critical system and increases the transmutation efficiency.

Full Text

Preamble

Towards Next Generation Accelerator Driven Subcritical System

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Abstract

Accelerator Driven sub-critical System (ADS) is considered the most promising candidate for nuclear waste transmutation. We propose a Multi-Target Accelerator Driven System (MTADS) to address two longstanding challenges of ADS: heat removal and the associated target lifetime, and inhomogeneous power distribution that affects reactor burn-up. An 18 mA, 1 GeV proton beam is split into 12 beams by radio frequency cavities and injected into 12 compact targets inside the reactor. With a beam power of 18 MW, the sub-critical reactor is driven to 1500 MW thermal power.

Through optimization of target number and position, the peaking factor of the reactor is reduced to 1.7 for the Multi-Beam Accelerator Driven System. The maximum beam current density is also reduced to 18.5 A/cm², which prolongs the beam window lifetime to 12 months when using T91 steel. As a next-generation ADS concept, MTADS simplifies the sub-critical system and enhances transmutation efficiency.

Introduction

In humanity's quest for carbon neutrality in the 21st century, nuclear power—with its low carbon emissions—is expected to play a vital role in the energy system. Because power output from nuclear energy is more stable and reliable than renewable sources like solar and wind, it is well-suited to serve as base-load energy in a low-carbon energy system [1]. Following seven decades of development since humankind first harnessed energy from uranium fission, approximately 440 nuclear reactors worldwide currently generate around 10% of global electricity. Nuclear power constitutes the second-largest low-carbon energy source, accounting for about 26% of the total by 2020. More than 95% of the world's commercial nuclear power plants are thermal reactors moderated by light water, heavy water, or graphite [2]. In recent years, public acceptance of and advocacy for nuclear energy have been rising again [1], with over 50 reactors under construction and about 30 new countries considering nuclear energy to meet their energy needs and climate goals [3]. However, the perennial challenge of nuclear fission energy—the spent fuel problem—remains, as nuclear waste is generated concomitantly with fuel burn-up.

In fact, the current nuclear energy system utilizes less than 1% of fission resources, leading to the accumulation of vast quantities of spent fuel. By the end of 2019, approximately 433,000 tons of spent fuel had been discharged globally, with an average of about 11,300 tons discharged annually from nuclear power plants worldwide. By 2035, spent fuel discharges are estimated to reach

nearly 618,000 tons, with stockpiles approaching 450,000 tons [4]. Minor Actinides (MAs) and long-lived fission products (LLFPs) have long half-lives and high radiotoxicity, posing long-term threats to the environment and human society. Deep geological disposal of spent fuel has been proposed as a solution for long-lived high-level nuclear waste (HLW), but such an option would threaten the environment for hundreds of thousands of years—a timescale far exceeding the history of agriculture. To date, all spent fuel is stored on-site or off-site in engineered storage facilities, awaiting final disposition decisions.

The Accelerator Driven System (ADS), with its high neutron surplus and enhanced safety, was proposed to incinerate nuclear waste, particularly MAs and LLFPs [5][6]. The ADS concept was first proposed by Ernest Lawrence in 1950, who suggested breeding fissionable fuels by bombarding uranium with accelerated protons/deuterons [7]. The Material Test Accelerator (MTA) project was initiated in 1950 to conduct R&D on ADS but was terminated in 1960 following the discovery of uranium ores in the USA that met fuel demands [7].

Since then, the ADS concept has been widely studied worldwide. In 1990, Takahashi proposed placing the spallation target inside the reactor to leverage both the high neutron yield of spallation reactions and low neutron spatial leakage [8]. This concept reduced the proton beam current requirement from 100–250 mA to 10–30 mA at GeV-level energies. In 1991, Charles Bowman proposed the first engineering design of ADS [9], and in 1992, Carlo Rubbia introduced the Energy Amplifier concept [10]. From the 1990s to the 2010s, several conceptual ADS designs at the hundreds-to-thousands of megawatt scale were developed, including EFIT, JAEA ADS, ANL ADS, and MYRRHA [11–14]. The ADS concept involves protons bombarding a spallation target inside the reactor to generate spallation neutrons, which then enter the sub-critical blanket to trigger a chain reaction in nuclear fuel, releasing substantial fission energy.

To maintain reactor operation at the hundreds-of-MW or GW thermal power level, proton energies of 500 MeV to 3 GeV are required, with beam powers in the tens of megawatts. This necessitates a proton beam current of 10 mA or higher and a target power level of 10–30 MW. Industrial-scale ADS faces enormous design challenges for both target and reactor, including target heat removal, cooling and lifetime of the proton beam window, complexity of the target loop, inhomogeneous reactor power distribution, fuel pin power limits, and inhomogeneous fuel burn-up.

Various attempts have been made to overcome these challenges. In the JAEA-ADS and MYRRHA designs, the proton beam directly strikes liquid lead-bismuth (LBE) coolant in the reactor to avoid target loop complexity and reduce target radius [14]. In the ANL ADS, fuel consists of small particles suspended in LBE within long tubes to reduce neutron leakage and enhance fuel burn-up [13]. However, these attempts have not resolved all ADS challenges. Experience from MEGAPIE, with a beam current density of 35 A/cm² and energy of 580 MeV, demonstrated a beam window lifetime of only 3 months

[15]—far shorter than the typical reactor fuel exchange period of 18 months or more. In JAEA and EFIT designs, a two-domain enrichment fuel arrangement is adopted to limit the reactor peaking factor, which constrains total reactor power. The fundamental problem with existing ADS designs is that excessively concentrated power density in and around the target does not match the requirements of energy generation systems.

In 1999, R. Pagan and C. Breeders proposed the concept of a multi-target accelerator driven system, where six or twelve beams are injected into the reactor to reduce the power limit per target and the power peaking factor [16]. The power peaking factor (PPF) is defined as the ratio of maximum local power density to average power density in the reactor core [Appendix]. In ADS reactor design, the magnitude of PPF affects reactor output power due to temperature limits of fuel pellets. An excessive PPF may cause the hottest point temperature to exceed limits, thereby restricting the entire reactor's output power. Excessive PPF can also lead to local fuel overpower, potentially causing severe accidents such as fuel rod damage and radioactive release. Since then, several studies on multi-beam accelerator driven systems have been published worldwide, most focusing on reactor design [17-18].

The initial purpose of the multi-beam and corresponding spallation target was to flatten the radial power distribution in the subcritical reactor, while the multi-accelerator-driven scheme aimed to reduce the probability of long-term beam interruption and increase subcritical reactor operational reliability. However, the multi-accelerator and multi-target scheme adds complexity to system design, particularly in the coupling area of target devices at the reactor top. Consequently, multi-target schemes are currently not employed in industrial ADS designs in many countries.

Multi-Target Accelerator Driven System

Here, we propose a new design for a Multi-target Accelerator Driven System (MTADS). The proton beam is accelerated by a superconducting proton linear accelerator and then evenly split into 12 beam lines, bent downward, and directly injected into 12 targets inside the reactor. No isolated loop exists for each target, which simplifies the target structure. Each target consists solely of a beam tube inserted into the reactor through which liquid lead-bismuth eutectic (LBE) from the reactor flows.

The beam travels through the tube and bombards the LBE coolant to generate neutrons. A beam window separates the vacuum from the LBE at the beam-target interface. Neutrons from the targets are amplified by the sub-critical reactor. Fig 1 [Figure 1: see original paper] shows the layout of the multi-target accelerator driven system. The proton beam energy is 1 GeV with a current of 18 mA, corresponding to a beam power of 18 MW. The reactor thermal power is 1.5 GW. The parameters of MTADS and Single-Target ADS (STADS) are listed in Table 1. Based on the same fuel assembly in the subcritical core,

the multi-target scheme reduces proton beam demand by 26%, decreases the power peaking factor by 32%, and improves electrical efficiency compared to the single-target scheme.

Beam Splitting and Transport

Using a transverse RF electromagnetic field, the beam can be split into multiple branches. With a 90-degree phase difference in horizontal and vertical planes, micro beam bunches are scanned to 12 points on a circle. If the RF cavity frequency is properly selected, the beam can be split into 12 beams. The beam splitting concept is shown in Fig 2 [Figure 2: see original paper]. The spacing between neighboring beams is further enlarged by a duodecuple magnet and separated into independent beam lines for parallel transport. A multi-channel superconducting magnet with 12 beam channels bends the beams 90 degrees downward into the reactor. Each bending channel contains two 45-degree dipole coils and a quadrupole coil made of Canted-Cosine-Theta (CCT) for beam bending and local achromatic compensation. At the exit of the multi-channel magnet, space is provided for 12 beam lines to transport the beam down to the 12 targets inside the reactor. Each beam line includes scanning magnets to create a uniform beam distribution on the beam window. The detailed design of the beam splitting system will be described in an upcoming publication.

Compact Spallation Target Assembly

Each target inside the reactor can be considered a Compact Spallation Target Assembly (CSTA). It comprises a beam tube inserted from above into the reactor and surrounded by LBE coolant. CSTA utilizes LBE coolant as the target material, with a T91 beam window separating the LBE from the accelerator vacuum. The CSTA concept is shown in Figure 3 [Figure 3: see original paper]. The shell structure of CSTA is identical to that of the fuel assembly, and the beam pipe is inserted into the CSTA interior from above. The beam window is located near the center of the fuel pins' active region. Each target receives 1.5 MW of beam power. The CSTA side width is 108.5 mm, and the beam tube diameter is 150 mm. The beam window is positioned 100 mm above the center of the fuel pins' active region, with a thickness of 2 mm. The detailed CSTA design will be published separately.

Compared to traditional ADS spallation targets, CSTA has no independent heat circulation loop, reducing the target outer diameter to less than 200 mm. The target and core share the LBE fluid and heat exchange system. High-energy protons pass through the beam window and bombard lead and bismuth nuclei to generate spallation neutrons. Beam power deposited in the LBE and beam window is removed by LBE flow. The LBE coolant temperature at the CSTA inlet is 300°C, and the maximum LBE flow velocity is limited to less than 2 m/s to control material corrosion.

Beam Distribution and Temperature

The beam distribution on the target is uniformized by scanning magnets in the beam line. Without scanning, a Gaussian-distributed beam with an RMS size (σ) of 7 mm would have a peak current density of 487.2 A/cm^2 —far exceeding the reasonable thermal limit of the beam window. Through waveform modulation of the scanning magnets, a double-ring beam distribution is formed on the beam window, as shown in Fig 4 [Figure 4: see original paper]. After scanning, the maximum beam current density on the target is reduced to 18.5 A/cm^2 , approximately only 4% of the unscanned value. This beam current density at the beam window is much lower than that in MEGAPIE. The density variation is a function of radius with a hollow near the center.

The temperature distribution in the target and beam window was calculated using the ANSYS-FLUENT software package [22], with results shown in Fig 5 [Figure 5: see original paper]. The maximum temperature inside the LBE target is 384.0°C . The maximum beam window temperature is 364.7°C on the LBE side and 378.9°C on the vacuum side. All these parameters fall within the operational domain of T91 steel with LBE, with adequate safety margins.

Subcritical Reactor

The subcritical reactor is an LBE-cooled fast reactor with 1500 MW thermal power. The conceptual design draws from the Russian lead-cooled reactor BREST-OD-1200 and the Japanese JAEA-ADS [23, 12]. The fuel rod diameter is 10 mm, and the fuel rod pitch is 15.6 mm. The LBE coolant inlet temperature is 300°C .

The core is loaded with transuranium fuels. The height of the fuel active zone is set to 1500 mm to reduce the spatial angle from the upper and lower directions, thereby improving the utilization efficiency of external neutrons for reactor fuel. The fuel consists of a mixture of mono-nitrides of Minor Actinides (MAs, including Neptunium, Americium, and Curium) and Plutonium (Pu), recovered from spent fuel of light water reactors (LWR). Zirconium-nitride (ZrN) is selected as the inert matrix within the fuel. Enriched ^{15}N (100%) is assumed for both (MAs, Pu)-nitride and ZrN. The mass ratio of Pu to MAs is approximately 4:6, and Zirconium Nitride accounts for 68.8% of the fuel mass fraction.

The optimization of CSTA number and position fully considers the principles of minimizing proton beam demand and minimizing core power peaking factor. After optimization, 12 CSTA targets are placed inside the reactor to drive neutron multiplication. The reactor layout is shown in Fig 6 [Figure 6: see original paper]. The reactor keff is 0.975, with an energy amplification factor of 83. The reactor thermal power is 1.5 GW. The power peaking factor is reduced to 1.7 by uniformly distributing targets throughout the reactor. The power density at the reactor mid-plane is shown in Fig 7 [Figure 7: see original paper]. The maximum power density in a fuel assembly is about 100 W/cm^3 , much lower than that of JAEA-ADS [12]. The radial and axial power distributions are shown in

Fig 8 [Figure 8: see original paper]. The fuel assemblies with maximum power density are those surrounding each CSTA target.

The temperature distribution of the fuel assembly surrounding the CSTA target was calculated using ANSYS-FLUENT [22], with results shown in Fig 9 [Figure 9: see original paper]. The maximum fuel cladding temperature is 528°C, and the maximum fuel pellet temperature is 1064°C. All these parameters fall within the operational domain of T91 steel with LBE, with adequate safety margins.

Discussion

By adopting the RF splitting method, the beam traverse period is 73.8 ns for 12 targets, which is 12 times the beam period of the linear accelerator. This beam traverse period is much shorter than the neutron generation time of 434 ns for the reactor, meaning that power density oscillations caused by the traversing beam can be neglected.

By splitting the proton beam into 12 beams and injecting them into 12 CSTA targets in the reactor, MTADS significantly reduces target challenges. With a beam energy of 1 GeV and current density of 18.5 A/cm², the target window lifetime is extended from 3 months to 12 months. This means only beam tubes and windows need replacement annually, which aligns with the refueling period. CSTA target replacement is much simpler than for targets with independent loops, as there is no need to disconnect and reconnect cooling loops—important because LBE coolant becomes highly activated under proton and neutron irradiation.

Reactor power density is also uniformed in MTADS, which increases reactor power. This is beneficial for energy production with high beam utilization efficiency and for nuclear waste transmutation across a large homogenized area with high neutron flux. The annual minor actinide burning rate in MTADS is 520 kg/year, four times that of EFIT and twice that of JAEA-ADS.

Conclusion

This paper proposes a new design for a Multi-Target Accelerator Driven System. MTADS can increase both system efficiency and ADS thermal power while reducing beam power. The accelerator, target, and reactor are well-coupled in the MTADS design. The MA transmutation efficiency of MTADS can reach 520 kg/year, which is beneficial for reducing nuclear waste.

Methods

The beam splitting system was simulated using TraceWin [24], with electromagnetic fields of RF cavities obtained from CST Studio. The simulation ran from the beginning of the High-Energy Beam Transport (HEBT) line to the CSTA. The initial 6D beam distribution is a truncated Gaussian distribution

generated from simulations of the superconducting linac. Multiparticle simulation was conducted with space charge consideration based on Particle-In-Cell simulation.

A two-step method was adopted for neutronics calculations of MTADS [25]. In the first step, PHITS (Particle and Heavy Ion Transport code System) was used to simulate proton beam transport in LBE coolant to generate the external neutron source [26]. In the second step, OpenMC-0.13.0 was used to simulate neutronics of the subcritical reactor driven by the external neutron source from PHITS [27].

PHITS can handle transport of most particles over a wide energy range using several nuclear reaction models and nuclear data libraries. OpenMC is a community-developed Monte Carlo neutron and photon transport code capable of performing fixed source, k-eigenvalue, and sub-critical multiplication calculations. A calculation benchmark of MCNP, PHITS, and OpenMC has been performed with good agreement [25]. The JENDL-5 and TENDL-2021 mixed neutron library was used in neutron calculations, with neutron energies up to 200 MeV.

Appendix: Formula of Beam Importance and Peaking Factor

The external neutron efficiency, denoted as ϕ^* , represents the efficiency of converting one external neutron into reactor fission neutrons:

$$\phi^* = \frac{\langle F\Phi \rangle}{\langle S \rangle} \left(\frac{k_{\text{eff}}}{1 - k_{\text{eff}}} \right) \quad (1)$$

where k_{eff} is the effective multiplication factor of the reactor, $\langle F\Phi \rangle$ is the total neutron production by fission, and $\langle S \rangle$ is the neutron leakage yield from the target.

The beam current $\langle S_p \rangle$ can be expressed as:

$$\langle S_p \rangle = \frac{\nu P_{\text{sub}}}{Qz} \left(\frac{k_{\text{eff}}}{1 - k_{\text{eff}}} \right) \quad (2)$$

where P_{sub} is the reactor fission power, Q is the average energy released per fission, ν is the average number of neutrons released per fission, and z is the leaked neutron yield from one proton injection in the spallation target calculated by PHITS. In simulations, $\langle F\Phi \rangle$ can be obtained by the Nu-Fission Rate tally filter, and the fission power induced by external neutrons can be given by the Kappa-Fission Rate provided by OpenMC.

The Energy Amplification Factor (EAF) is defined as the ratio of core thermal power (P_{sub}) to beam power (P_{beam}):

$$\text{EAF} = \frac{P_{\text{sub}}}{P_{\text{beam}}}$$

The EAF is an important indicator for evaluating beam efficiency in ADS design and can be expressed as:

$$\text{EAF} = \frac{E_b \nu}{Qz} \left(\frac{k_{\text{eff}}}{1 - k_{\text{eff}}} \right) \quad (3)$$

where E_b is the beam energy.

Power Peaking Factor (PPF) is a critical parameter for efficient and safe reactor operation in ADS. Here we define PPF as:

$$\text{PPF} = \frac{P_{\text{max}}}{P_{\text{av}}}$$

where P_{max} is the maximum power density in a fuel pin, P_{av} is the average power density in a fuel pin, P_{tot} is the thermal power of the reactor core, and V is the fuel volume.

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Data availability: Data will be made available on request.

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