Preliminary Neutronics optimization on the concept of Multi-Beam Accelerator Driven System

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Abstract

A new sub-critical reactor concept is proposed as one accelerator splitting into multiple beams to drive the subcritical reactor in this work, which is so called Multi-Beam Accelerator Driven System (MB-ADS). The spallation target is designed as a unit similar to the fuel assembly. The high current proton beam is divided into multiple parts and injected into different targets located in the core to improve beam efficiency and flatten the spatial power distribution of the core. Based on different MB-ADS schemes, neutronics were conducted on the effects of beam splitting number, target assembly arrangements, fuel partitioning, and neutron data libraries. The results show that a reasonable multi-beam scheme can significantly improve the efficiency of the proton beam and flatten the power distribution of the reactor compared to the one target ADS scheme. Due to the improved beam efficiency, the beam density on the target window is greatly reduced.

Full Text

Preamble

Preliminary Neutronics Optimization on the Concept of Multi-Beam Accelerator Driven System

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Abstract

A new subcritical reactor concept is proposed in this work, featuring a single accelerator splitting into multiple beams to drive the subcritical reactor, designated as the Multi-Beam Accelerator Driven System (MB-ADS). The spallation target is designed as a unit similar to a fuel assembly. The high-current proton beam is divided into multiple parts and injected into different targets located throughout the core to improve beam efficiency and flatten the spatial power distribution. Based on various MB-ADS configurations, neutronics analyses were conducted to investigate the effects of beam splitting number, target assembly arrangements, fuel partitioning, and neutron data libraries. The results demonstrate that a reasonable multi-beam scheme can significantly improve proton beam efficiency and flatten the reactor power distribution compared to the conventional single-target ADS scheme. Due to the improved beam efficiency, the beam density on the target window is greatly reduced.

1. Introduction

Accelerator Driven Systems (ADS) are designed to transmute long-lived radioactive isotopes in spent nuclear fuel into fission products with shorter half-lives. The power level of industrial-scale subcritical reactors typically exceeds hundreds of megawatts for efficient transmutation, with corresponding proton beam power reaching tens of megawatts. For instance, the European Facility for Industrial-scale Transmutation (EFIT) concept features a thermal power of 400 MW with a proton beam power of 16 MW [1,2], while the ADS investigated by JAEA is a Lead-Bismuth Eutectic (LBE) cooled subcritical reactor with 800 MW thermal power and 22.5 MW proton beam power [3]. In single-target ADS designs, high-intensity external neutrons are concentrated at the core center, resulting in a high power peaking factor.

The power peaking factor can be reduced by increasing the target diameter or adopting internal-external fuel partitioning arrangements. However, these approaches decrease neutron efficiency and increase engineering challenges for the spallation target. Simultaneously, increasing the proton beam power reduces ADS economic viability.

The Energy Amplification Factor (EAF) is defined as the ratio of core thermal power to beam power, expressed as:

$$\mathrm{EAF} = \frac{P_{\mathrm{core}}}{P_{\mathrm{beam}}}$$

EAF serves as a crucial indicator for evaluating beam efficiency in ADS design. Accelerator costs and operation and maintenance expenses depend on beam power, so a low EAF inevitably increases ADS costs. Appropriately increasing the subcritical reactor's k_{eff} is one method to increase EAF. In the JAEA-ADS and ANL-ADS designs, the reactor k_{eff} is 0.98 [4,5].

The JAEA-ADS and MYRRHA spallation target designs adopt a scheme where the beam pipe is directly inserted into the core, as LBE serves as both coolant and target material [5,6,7]. The front end of the beam pipe forms the target window. The proton beam passes through this window and directly bombards the LBE coolant in the core to generate spallation neutrons. The beam heat deposited on the target window and coolant can be removed by the reactor's heat removal system. This design integrates the spallation target with the reactor heat removal system, eliminating most conventional target equipment and simplifying the ADS.

In the MYRRHA design, the spallation target is configured as a target assembly that can be conveniently placed at different positions in the core [7]. The concept of multiple spallation target-driven ADS was proposed years ago to flatten core power distribution and reduce the probability of long beam interruptions [8,9]. Previous studies adopted a three-target, three-accelerator scheme, where each spallation target had independent equipment systems. While this approach somewhat flattened core power, it introduced complex system challenges.

To further improve beam efficiency, flatten core power, and reduce spallation target complexity, this work considers splitting a single proton beam into multiple sub-beams and employing more compact target assemblies to drive the subcritical reactor. The Beam Splitting System (BSS) includes RF cavity deflecting, quadrupole focusing, septum magnets for bending, double-circle scanning, and superconducting bending. A Direct Current (DC) proton beam is bunched by a 162.5 MHz Radio Frequency Quadrupole (RFQ), with the period between adjacent bunches being 6.15 ns. The RMS phase length of the bunch naturally extends from 0.2° to 5° in the High-Energy Beam Transport (HEBT) line, which is sufficiently short for beam splitting with RF cavities without significant beam quality loss. This strategy enables finer and more uniform proton beam injection into the core. The present work seeks to optimize the number of sub-beams and target assembly layout through simulations.

2.1 Simulation Codes and Neutron Libraries

A two-step method is adopted for ADS neutronics calculations [10]. In the first step, PHITS (Particle and Heavy Ion Transport code System) simulates the proton beam transport process in LBE coolant to generate external neutron source information for subcritical reactor neutronics calculations. PHITS can handle the transport of most particles across wide energy ranges using several nuclear reaction models and nuclear data libraries [11]. In the second step, OpenMC-0.13.0 simulates the neutronics of the subcritical reactor driven by the external neutron source generated from PHITS. OpenMC is a community-developed Monte Carlo neutron and photon transport simulation code [12] capable of performing fixed-source, k-eigenvalue, and subcritical multiplication calculations.

Neutron cross sections play a crucial role in ADS neutronics calculations, particularly the high-energy neutron (>20 MeV) cross sections, which significantly influence beam driving efficiency [10]. NJOY21 [13] and OpenMC were used to process a continuous-energy neutron HDF5 format library with an energy upper limit of 200 MeV for OpenMC, based on JENDL-5 [14] and TENDL-2021 [15]. JENDL-5 expands neutron reaction data to 795 nuclides and extends the energy region for some nuclides to 200 MeV. Since JENDL-5 lacks sufficient nuclides with 200 MeV data, the remainder was supplemented by nuclides from TENDL-2021, as shown in Table 1 . This work primarily investigates the neutronics at the initial stage of the subcritical reactor, so only the neutron data energy of nuclides in the model is ensured up to 200 MeV. To compare preliminary differences between high-energy neutron effects and cross-section libraries, ENDF/B-VII.1, ENDF/B-VIII.0, and JEFF-3.3 were also used in calculations for selected optimization schemes.

2.2 Subcritical Reactor Model

A Multi-Beam Accelerator Driven Subcritical conceptual Reactor (MB-ADS) was established, as shown in Fig. 1 [Figure 1: see original paper]. The core is an LBE-cooled fast reactor with a thermal power of 1500 MW, and detailed parameters are provided in Table 2 . The conceptual design references the Russian lead-cooled reactor BREST-OD-1200 [16] and JAEA-ADS, with the core filled with transmutation fuel. The fuel active zone height is set to 150 cm to improve external neutron efficiency. The long fuel region reduces the leakage rate of external neutrons from both ends of the target.

The proton beam energy is 1.0 GeV. The proton beam generated by a single accelerator is divided into multiple beams and injected into the core along each beam pipe. The spallation target in this scheme differs from conventional ADS spallation targets. It is designed as a target assembly similar to a fuel assembly, with the front end of the beam pipe connected to the target window and penetrating into the target assembly, as shown in Fig. 1. Similar to a fuel assembly, the target assembly is fixed on the grid plate at the lower end of the core.

A mixture of mono-nitride of minor actinides (MAs, including neptunium, americium, and curium) and plutonium (Pu) was used as fuel, with isotopic compositions of MAs and Pu recovered from light water reactor (LWR) spent fuel. Zirconium-nitride (ZrN) was used as an inert matrix for the fuel. Nitrogen enriched to 100% 15N was assumed for both (MAs, Pu)-nitride and ZrN.

Table 3 shows the mass ratio of transuranic (TRU) nuclides, with the Pu to MAs mass ratio being approximately 4:6. Zirconium nitride accounts for 68.8% of the mass fraction in the fuel.

2.3 Compact Spallation Target Assembly

The concept of the Compact Spallation Target Assembly (CSTA) is shown in Figure 2 Figure 2: see original paper. The shell structure of CSTA is identical to that of a fuel assembly. The side length of CSTA is 10.85 cm, and the beam pipe diameter is 15.0 cm. The beam pipe is inserted into the CSTA from above the core, with the target window located near the center of the active region.

Compared to the Traditional ADS Spallation Target (TST), CSTA does not have an independent heat exchange circuit, and the target diameter is smaller (<20 cm). The target and core share the same heat exchange system. After passing through the target window, high-energy protons bombard lead and bismuth nuclei to generate spallation neutrons, and the beam power is deposited and removed within the core coolant. Simultaneously, heat deposited in the target window is carried away by the flowing coolant.

This work seeks to determine a reasonable number and arrangement of CSTAs in the core through simulations to achieve high beam efficiency and low reactor power peaking factor.

2.4 Calculation of Neutronic Parameters

OpenMC features a flexible, low-overhead tally system that enables users to obtain physical results of interest. The external neutron efficiency, denoted as ϕ^*, represents the relative efficiency of one external neutron and is defined as the ratio of the average importance of one external neutron to that of one fission neutron. The external neutron efficiency can be expressed as:

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

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 leakage yield of neutrons from the target.

The incident current of beam particles can be expressed as:

$$I_{\text{beam}} = \frac{P_{\text{fission}}}{Q \cdot \nu \cdot \phi^* \cdot Y_{n/p}}$$

where P_{fission} is the fission power of the reactor, Q is the average energy released per fission, ν is the average number of fission neutrons per fission event, and $Y_{n/p}$ is the leaked neutron yield from one proton injection in the spallation target simulated by PHITS.

Thus, the EAF can be obtained from:

$$\mathrm{EAF} = \frac{\nu \cdot \phi^* \cdot Y_{n/p}}{1 - k_{\mathrm{eff}}}$$

In the neutronics simulations, $\langle F\Phi \rangle$ can be obtained using the Nu-Fission Rate tally filter, and the fission power induced by external neutrons can be determined from the Kappa-Fission Rate provided by OpenMC.

3. Results and Discussion

3.1 External Neutron Source

First, the PHITS code was used to simulate the proton transport process in the spallation target to obtain external neutron source information. The target is a cylinder with a length of 100 cm, and radii of 15 cm, 20 cm, 30 cm, 45 cm, 50 cm, and 60 cm with hemispherical beam windows were studied to investigate the relationship between neutron yield and target size. The neutron source generated by a target diameter of 15 cm was used in the MB-ADS simulations. Information on leakage neutrons from the spallation target, including position coordinates, energy, and direction vectors, was recorded and saved in HDF5 files for coupling with OpenMC calculations. Figure 3 [Figure 3: see original paper] shows the variations of the external neutron energy spectrum with target diameter, demonstrating that smaller target diameters produce harder leaked neutron spectra.

Table 4 presents the distribution information of leakage neutrons across different energy groups. The leakage neutron yield increases with target diameter. Most leaked neutrons are concentrated between 0.1 MeV and 5 MeV, and the fraction of high-energy neutrons (>20 MeV) decreases significantly with increasing target diameter. When the target diameter is less than 20 cm, the proportion of high-energy neutrons even exceeds 6%, with neutrons above 200 MeV accounting for 1%.

Many studies have shown that the efficiency of high-energy neutrons, particularly those above 100 MeV, is much higher than that of fission neutrons [17,18]. Based on current neutron data libraries, the upper energy limit can only reach 200 MeV. For neutrons above 200 MeV, their energy is uniformly set to 200 MeV in simulations.

3.2 Neutronics Characteristics of Single-Target ADS

In conventional ADS, the spallation target is located at the core center. This section discusses the neutronics characteristics of subcritical reactors driven by a single target, including the effects of target diameter on beam efficiency and core power distribution.

Four subcritical reactor configurations are shown in Figure 4 [Figure 4: see original paper]. CSTA-1 is a single CSTA scheme, while TST-1, TST-2-a, and

TST-2-b are traditional target schemes with different target diameters. In TST-1 and TST-2 schemes, 7 and 19 fuel assemblies (FA) are removed from the core center, respectively. In the TST-2 scheme, the a-core features uniformly arranged fuel, while the b-core employs inner and outer zones with different FAs. The fuel rod diameter in the outer zone is larger than in the inner zone for power flattening. Reflector assemblies (RA) are arranged outside the FA region.

Table 5 presents the main neutronics results for the four schemes. The k_{eff} of these subcritical reactors is set between 0.978 and 0.979, with statistical errors of approximately 20 pcm. The results show that external neutron efficiency decreases with increasing target diameter, indicating that the neutron energy spectrum is the dominant factor affecting neutron efficiency, as mentioned in Section 3.1. Normalized to a fixed fission power, the proton beam current increases as leakage neutron efficiency decreases.

The beam density can be obtained by dividing the beam current by the beam spot area. Calculated beam densities are also provided in Table 5, based on the assumption of a circular uniform proton beam. The ratio of beam pipe to target diameter follows the ADTF design proposed by ANL [19]. In this work, proton beam density is used as a criterion for target design challenges, as it affects the thermal-hydraulic design and radiation damage evaluation of the target window. In many ADS designs with window targets, beam density is generally limited to 20–40 µA/cm^2 [4,5,7,19], constrained by LBE/lead coolant velocity and radiation damage to window materials from the proton beam. Although beam currents in CSTA and TST-1 schemes are low, the small beam pipe diameter results in beam densities of 119.96 µA/cm^2 and 54.02 µA/cm^2, respectively. In contrast, using larger diameter targets in the TST-2 scheme increases beam current but reduces beam density to approximately 23 µA/cm^2 due to the larger beam pipe.

Fuel zoning strategies are often employed to flatten core power and enable FAs near the spallation target to meet thermal-hydraulic limits. The beam current in the TST-2-b scheme with fuel zoning is higher than in the TST-2-a scheme. Figure 5 [Figure 5: see original paper] shows the radial power density distributions of fuel pins at the axial center of FAs for different schemes. Based on the symmetry of FAs near the target, horizontal and vertical directions were selected for heat deposition tallying. A small-diameter spallation target produces high neutron emission density, resulting in high power density around the target. The peak power density in CSTA-1 exceeds 1500 W/cm^3. The maximum power density in fuel pins decreases to 1200 W/cm^3 and 1000 W/cm^3 from the TST-1 scheme to the TST-2-a scheme as target diameter increases. Figure 5 shows that radial power density is slightly flattened after TST-2-b adopts fuel zoning, with the maximum fuel pin power density decreasing by approximately 100 W/cm^3 compared to TST-2-a.

In industrial ADS design, radiation damage to the target window and thermal-hydraulic limitations of FAs near the target are critical issues. Although fuel zoning strategies help flatten core power peaks, they also increase beam current.

The spallation target must increase its diameter to meet thermal and material constraints, which further increases beam current, leading to higher accelerator costs and reduced system productivity efficiency.

3.3 Neutronic Optimization of MB-ADS

Based on the discussion in Section 3.2, CSTA with smaller diameters exhibits higher proton efficiency. We aim to arrange a reasonable number of CSTAs at optimal core positions to improve beam efficiency and flatten core power.

3.3.1 Effect of CSTA Position on Neutron Efficiency The correlation between CSTA position and external neutron efficiency depends on its location in the core. For this study, two core arrangements were selected, as shown in Figure 6 [Figure 6: see original paper]: one with uniform fuel arrangement (Case-1) and another with fuel zoning arrangement (Case-2). Ten CSTA positions from the core interior to exterior were evaluated. In simulations, the external neutron source was adjusted according to CSTA position to ensure accurate beam injection into the target. The k_{eff} values for Case-1 and Case-2 cores without CSTAs are 0.97943 and 0.97852, respectively.

Figure 7 [Figure 7: see original paper] shows simulation results for external neutron efficiency (ϕ^*) at different CSTA positions. In Case-1, ϕ^* is highest when the target is located at the core center and gradually decreases as the target position moves outward. In Case-2, ϕ^* is significantly reduced in the central region but improved in the outer fuel region. This explains why placing the target at the core center yields the highest neutron efficiency in single-target ADS. After power flattening through fuel zoning, proton beam current increases due to decreased neutron efficiency. Therefore, CSTAs should be placed as close as possible to the core center.

3.3.2 Six-CSTA Schemes First, we investigate the impact of distance between CSTAs on neutronics. Based on the geometric symmetry of the hexagonal FA core arrangement, a six-CSTA scheme was studied to understand the neutronic influence of CSTA spacing and positioning. As shown in Figure 8 [Figure 8: see original paper], six CSTAs are arranged along three diagonals of the core hexagon to vary their distance from the core center.

The core k_{eff} is maintained between 0.978 and 0.979 across different schemes, with a statistical error of 20 pcm. Table 6 presents the calculated neutronics parameters for these schemes. The external neutron efficiencies are all higher than that of TST-2 due to high leaked neutron energy in CSTA. Beam currents are lower than TST-2 in schemes CSTA-6-1 through CSTA-6-4, where CSTAs are close to the core center. In schemes CSTA-6-5 and CSTA-6-6, beam demand is high due to placement of CSTAs in low neutron efficiency areas. After adopting the multi-beam strategy, beam density in schemes CSTA-6-1 through CSTA-6-4 is significantly reduced compared to TST-1. Under CSTA-6-1 and CSTA-6-2 schemes, beam density decreased from 110 $\mu\text{A/cm}^2$ to approximately

20 µA/cm^2 compared to the CSTA-1 scheme, without significant beam current increase.

Fuel pins with a length of 1 cm at the axial center of FAs were selected for heat deposition tallying to study radial distribution. The highest fuel power density and beam density across different schemes are shown in Figure 11 [Figure 11: see original paper]. The highest fuel power density shows an opposite trend to beam intensity, making it difficult to simultaneously reduce maximum power density and beam density. The more reasonable scheme appears to be CSTA-6-4. Compared with the TST-2-b scheme, beam current is reduced by 28.6%, maximum pin power density is reduced by approximately 18.8%, and beam density increases by only 2 µA/cm^2. This demonstrates that a reasonable CSTA layout can simultaneously reduce beam current and fuel pin power density. However, due to the relatively small beam irradiation area in six-beam schemes, beam density improvement is not significant.

3.3.3 Twelve-CSTA Schemes This section discusses optimization with twelve beams injected into 12 targets (CSTA-12) in the core. The twelve CSTAs are divided into two groups of six each, arranged in symmetrical positions inside and outside the core. The inner ring CSTA layout follows the CSTA-6-2, CSTA-6-3, and CSTA-6-4 schemes from Figure 8 [Figure 8: see original paper], while outer ring CSTAs are placed at fixed positions. This yields three schemes for uniform fuel arrangement. Based on the CSTA-12 scheme, the core is divided into internal and external zones to obtain an additional comparative scheme.

Neutronics parameters for the CSTA-12 schemes were obtained through simulations, as shown in Table 7 . The core k_{eff} is maintained near 0.9785, with a statistical error of 20 pcm. Proton beam currents in CSTA-12 schemes increased by approximately 4 mA compared to CSTA-6 schemes because six CSTAs are arranged in the core edge region where external neutron efficiency is reduced. Notably, beam currents under fuel zoning arrangements are smaller than under uniform fuel arrangements. As shown in Figure 7, fuel zoning decreases neutron efficiency at the core central position, shows smaller changes in the transition region, and increases neutron efficiency overall in the outer region.

The external neutron efficiency of CSTAs in the inner circle remains essentially unchanged due to their departure from the core center. In fuel zoning schemes, the external neutron efficiency of CSTAs arranged in the outer region improves, as shown in Figure 7. This differs significantly from the TST-2 ADS mentioned in Section 3.2. Therefore, beam current in schemes using fuel zoning is reduced compared to corresponding uniform fuel loading schemes.

As shown in Tables 6 and 7, proton beam current increased by 5–20% in 12-beam schemes compared to the CSTA-6-4 scheme, while beam density decreased by nearly 50%. Compared with TST-2-a and TST-2-b, the CSTA-12-F scheme reduces proton beam intensity by 14.9% and 22.7%, increases the energy amplification factor (EAF) by 17.5% and 29.5%, and reduces beam density on the target window by 33.6% and 39.8%, respectively. The multi-beam driven subcritical reactor scheme demonstrates significant neutronic advantages over the single-target ADS scheme.

The spatial distribution of pin power density in CSTA-12 schemes is discussed below. The geometric spatial tally diagram is shown in Figure 14 [Figure 14: see original paper]. Based on CSTA layout symmetry, radial power distribution was selected in both horizontal and vertical directions, with tally fuel pins located at the axial center of each fuel rod. Two fuel assemblies were selected for axial power distribution tallying: location A at the core center and location B adjacent to the CSTA.

Figure 15 [Figure 15: see original paper] shows axial power density distributions of pins in FAs for CSTA-12 schemes. Here, power densities of pins in the same FA are averaged at each axial position. The fuel power is symmetrically distributed in the axial direction, with the highest power density located at the fuel region center. The maximum power density exceeds 750 W/cm^3 in the CSTA-12-A scheme where CSTAs are close to the core center. In the CSTA-12-F scheme, the maximum power density is the lowest, at approximately 550 W/cm^3.

Figure 16 [Figure 16: see original paper] shows radial power density distributions in fuel pins. In uniform fuel schemes, the highest pin power density appears in the central FA. In fuel zoning schemes, the highest fuel pin power occurs in pins close to inner CSTAs. Compared to uniform fuel schemes, power density in the central area decreases by approximately 70–100 W/cm^3, and pin power density near CSTAs decreases by 50 W/cm^3 in fuel zoning schemes.

Maximum power densities and beam densities for different schemes are shown in Figure 17 [Figure 17: see original paper]. Beam density shows slight variation across all CSTA-12 schemes, with the highest being 15.42 μA/cm^2 in CSTA-12-C and the lowest being 13.02 μA/cm^2 in CSTA-12-D. However, significant differences exist in maximum power density among CSTA-12 schemes, with CSTA-12-A reaching 770 W/cm^3 and CSTA-12-F achieving the lowest fuel power density at 601 W/cm^3—a difference of 170 W/cm^3. Considering both maximum power density and beam density, the CSTA-12-F scheme is more reasonable.

3.4 Influence of Neutron Libraries

Based on the CSTA-12-F scheme, the core k_{eff} was simulated using different neutron libraries. ENDF/B-VII.1, ENDF/B-VIII.0, JEFF-3.3, JENDL-5, and JENDL-5+TENDL-2021 were applied in simulations, with results shown in Figure 18 [Figure 18: see original paper]. The differences in simulated k_{eff} using ENDF/B-VII.1, ENDF/B-VIII.0, and JEFF-3.3 are less than 100 pcm. The simulated k_{eff} using JENDL-5 is approximately 500 pcm higher than that using ENDF/B-VIII.0. The simulated reactivity of the mixed library JENDL-

5+TENDL-2021 is 950 pcm higher than that of ENDF/B-VIII.0.

By adjusting the Pu and MAs ratio in the nuclear fuel, the k_{eff} of CSTA-12-F under different neutron libraries was adjusted to between 0.9780 and 0.9785. Since only a small number of nuclides in neutron libraries have energy upper limits up to 200 MeV (most have 20 MeV limits), leaked neutrons with energy above 20 MeV were set to 20 MeV to ensure OpenMC could perform simulations. In simulations using the mixed JENDL-5+TENDL-2021 library, the upper limits of the external neutron source were set to 200 MeV and 20 MeV, respectively. Basic neutronics parameters of CSTA-12-F under different libraries were obtained, as shown in Table 8 . In different sets with a neutron energy upper limit of 20 MeV, simulated neutron efficiency achieved good consistency, with ϕ^* values between 1.14 and 1.18. Consequently, beam current and EAF also showed consistent results across different nuclear libraries, with differences less than 5%. However, using the high-energy neutron library results in a 24% increase in EAF and a 20% decrease in beam current. High-energy neutrons from external sources cannot be ignored in ADS research.

Figure 18 shows pin power density distributions based on different nuclear libraries and neutron energy cutoffs, with the tally range referring to the vertical direction in Figure 14. The statistical error of power density calculated by OpenMC is less than 0.5%. Pin power density based on different neutron libraries is consistent, with numerical differences less than 4%. However, in simulations based on the JENDL-5+TENDL-2021 mixed library, pin power density in the core central region with a 200 MeV neutron energy cutoff is approximately 30 W/cm^3 higher than with a 20 MeV cutoff—a difference exceeding 5%. High-energy neutrons in the external source have a non-negligible impact on power distribution in subcritical reactors.

Conclusion

In single-target ADS schemes, proton beam efficiency decreases with increasing target diameter, while maximum fuel power density also decreases with target diameter. Using fuel zoning strategies in the core helps reduce maximum power density but also reduces beam efficiency. Therefore, simultaneously balancing beam efficiency and power flattening is difficult in single-target ADS schemes.

In the optimization strategy of proton beam splitting driven subcritical reactors, the spallation target is designed as a compact target assembly, and the proton beam is divided into a larger number of beamlets. Through optimization studies on 6-beam and 12-beam configurations, effective power flattening is only achieved when CSTAs are arranged far from the core center. Compared to single-target ADS results, reasonable MB-ADS schemes offer advantages in both beam efficiency and core power flattening. The 12-beam scheme significantly reduces beam density on the target window when using fuel zoning strategies—a characteristic unattainable in single-source ADS. High-energy neutrons in libraries significantly impact beam efficiency and power distribution.

Comprehensive high-energy neutron cross-section libraries are required for ADS research and design. MB-ADS uses multiple CSTAs to drive the subcritical reactor. Small target diameter reduces neutron leakage in the beam recoil direction and greatly increases the proportion of high-energy neutrons in the external source. With no dedicated loop or active components for targets, the accelerator is directly coupled with the subcritical reactor. Dispersing beam density through multiple CSTAs is expected to reduce target window heat transfer and material damage problems. CSTAs can be flexibly distributed at different core positions, allowing ADS designers to search for optimal numbers and positions of CSTAs to optimize system parameters.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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