CYCLOTRONS FOR ACCELERATOR-DRIVEN SYSTEMS*

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Abstract

Accelerator-Driven system (ADS) can transmute long lived nuclear waste to short lived species. For this system to be fully realizable, a very stable high energy and high power proton beam (typically, 1 GeV beam energy and 10 MW beam power) is required, and preparing such a powerful and stable proton beam is very costly. Currently, the most promising candidate is superconducting linear accelerators. However, high power cyclotrons may be used for ADS particularly at the stage of demonstrating proof of principle of ADS. This paper discusses how cyclotrons can be used to demonstrate ADS.

INTRODUCTION

The accelerator-driven system (ADS) [1][2][3] in which a nuclear reactor is set up sub-critical and extra neutrons required for sustainable power generation is provided by neutrons emitted from high energy proton beam hitting a heavy metal target had long been considered to be a safe nuclear power generation system. In this scheme, the accelerator plays the role of safety key, turning off the accelerator which is very sensitive to perturbations and leaving the reactor in shortage of neutrons, so that the nuclear chain reaction can immediately stop. However, the nuclear disaster of Fukushima demonstrated that even ADS would not have avoided the Fukushima accident which occurred due to failure of cooling system after the reactor became subcritical. The status of ADS as a safe power generation system was shaken just as much as the conventional reactor was. In this regard, the idea that the thorium molten salt reactor adopts air cooling and, therefore, there will be no chance of Fukushima-type accident has been suggested. Although this ADS-based thorium reactor is promising, it is still in the early stage of development and the realization will take long time. We may have to wait for quite some time until the ADS-based thorium reactor will be fully developed, if we want to use fully safe nuclear power generation. In other words, power generation using the uranium-based ADS, let alone nuclear power in general, may not be highly supported by the public.

However, in spite of being unable to provide perfect safety against Fukushima-type accidents, nuclear energy has a strong advantage to protect environment that it is the only base load energy from emitting negligible amount of carbon dioxide, the greenhouse gas. Such renewable energy forms such as solar photovoltaic and wind energy cannot play the role of base load energy because these energy forms vary sensitively in large scale to the weather condition. These renewable energy forms cannot be a serious candidate for the base load power until a huge scale of energy storage system is developed. It is important to note that the global warming due to the greenhouse effect is on-going right now and we have to try to stop it promptly. One of the methods is to construct nuclear power plants instead of coal power plants, and perhaps that is why nuclear power plants are still being constructed as several countries including Vietnam, Bangladesh, United Arab Emirates, Turkey and Belarus began to build the first nuclear power plant (NPP) of each country in 2012 while Jordan and Saudi Arabia began in 2013. Regarding this, ADS has a very helpful function, besides safe power generation, which is transmutation of spent fuel from long-lived materials (of the order of tens of thousands years) such as actinides to short lived materials (of the order of few hundred years). How to dispose or process nuclear spent fuel is a still unsolved problem of all countries with nuclear reactors. ADS proposes so far the best method of disposal, transmutation of minor actinides having hundred thousand year level half lifetime to nuclear species having 2~3 hundred year half lifetime. The critical fast reactors are also capable of transmuting minor actinides while generating power. Compared to critical fast reactors that incorporate uranium in the fuel, ADS can in principle operate on pure minor actinides (MA) feed as a dedicated transmutation system and thus is safer and can transmute more MA in a given time. The power required for the transmutation-dedicated ADS can be provided by making use of the massive heat generated from transmuting MA for electricity generation, although it may not be enough for commercial purpose.

With the current technology level, transmutation of spent fuel by ADS seems more feasible than power generation by ADS. Korea is one of the countries that face impeding spent fuel problem and ADS can be a serious candidate for solving the problem. Although this transmutation dedicated ADS cannot provide perfect safety against the Fukushima-type cooling accidents, this may still be studied and built extensively because the primary purpose of the transmutation-dedicated ADS is not the safety but removal of the toxic long-lived nuclear waste. This paper discusses possible schemes of ADS for transmutation of spent fuel. Focus will be put on economic aspect and currently available technologies.

ADS AND CYCLOTRONS

The ADS scheme adopts a sub-critically designed reactor and a target system which is designed to emit many neutrons when hit by protons. As it requires fast neutrons not thermal neutrons, the ADS does not use moderator including water. With the neutrons from the target added, the reactor can maintain criticality necessary for sustaining the reactor. The ADS scheme was proposed long time

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ago, but has not been realized yet mainly because the accelerator technology has not sufficiently been developed. Realization of the ultimate goal of ADS, industrial scale electricity generation with the transmutation function in parallel, requires an unprecedented proton beam power in CW (up to several tens of MW while the highest proton beam power achieved so far is only 1.3 MW) and unprecedented accelerator operation stability. These difficult requirements determined by the condition to create required number of neutrons have not been realized, yet. The important milestones of the road to the ultimate goal have been classified by researchers to the 4 phases shown below in Table 1 [4] and the corresponding technical requirements were specified through studies. In particular, the accelerator stability requirement is the most difficult to achieve and such a challenge that its achievability is unclear even in the near future. The primary purpose of these stability requirements is not to secure the availability of electricity transmission but rather to prevent components of ADS, such as proton beam window and reactor vessel, from being damaged by frequent interruptions. The availability can be secured by energy storage system as specified in stage 3 in the table below.

Requirements for Accelerators

On the other hand, the required proton energy and beam power are determined by the required number of neutrons coming from the spallation target, and this number is determined by the neutron multiplication factor k of the reactor. The closer to 1 k is, the smaller number of neutrons are required. But, to generate a given number of neutrons (a given k), infinitely many combinations of the proton energy and beam power are possible and once the proton energy is chosen, the beam power is determined. Hence, the most (cost) effective combination should be chosen. As shown in Fig. 1, the most effective proton energy to generate the highest number of neutrons per proton is around 1 GeV and this energy has already been achieved by a few accelerators. Required proton beam power depends heavily on the neutron multiplication factor k and varies from 10 MW to 75 MW depending on k. In principle, this high power can be delivered by proton beam. For example, linear accelerators based on superconductor technology can deliver even 100 MW proton beam. The necessary technology is practically secured. However, as building this high power accelerator cost very high, choosing appropriate multiplication factor is important in saving ADS cost. The lower k is, the higher beam power and cost are required with higher safety. By contrast, the higher k is (but lower than 1), the lower beam power and cost are required but the safety is lower, too. In the case of dedicated transmutation operating on pure MA, k may be able to get closer to 1 than power generation without higher risk. Anyway, the currently achievable goal is certainly the first phase, transmutation demonstration, and possibly the second phase, industrial scale transmutation. Hence, the goal right now should be transmutation of long-lived nuclear waste.

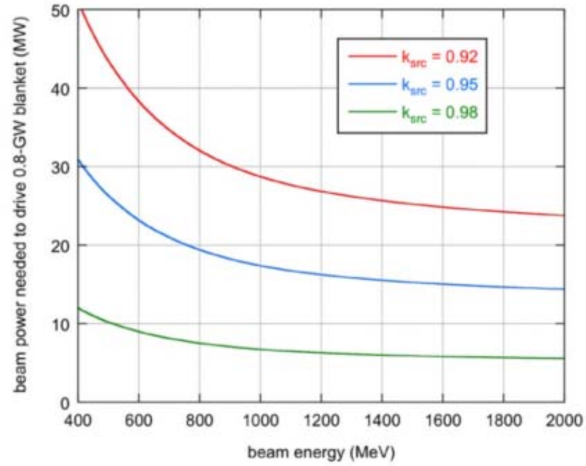

Figure 1: Beam power needed to drive a 0.8-GW ADS sub-critical core as a function of beam energy, for several values of k. [4].

Accelerator Types for ADS

The issue for accelerators in ADS is proton energy and beam power. As is well known from simulation, 1.2 GeV proton energy is most effective for producing neutrons. However, the figure also shows that proton energy above 0.5 GeV can fairly be effective for neutron production. A few accelerator types, such as the linear accelerator, cyclotron or FFAG, have been studied as a candidate for the ADS accelerator. But, considering that the FFAG is still an accelerator being studied rather than a matured type widely used, the linear accelerator and cyclotron are the two accelerator types that can be used. Synchrotrons cannot supply sufficiently high beam power. The advantage of using the linear accelerator is its directness in upgrading the proton energy and beam power. This is particularly so for the superconducting linear accelerator. The superconducting linear accelerator seems to be the only viable accelerator for producing 100 MW level beam power which may be required in the future for industrial scale power generation. But, the disadvantage of using a high power superconducting CW linear accelerator is its huge cost in construction and maintenance, and this is particularly so in Korea where land costs high. Note that a typical GeV-scale linear accelerator is longer than 300 m.

By contrast, designing a 1 GeV cyclotron is very difficult. However, note that the highest beam power in the world is delivered by the 590 MeV cyclotron at Paul Scherrer Institute (PSI), Switzerland which boasts 1.3 MW beam power. This cyclotron has a plan to be upgraded to 1.8 MW [5]. Note that the PSI cyclotron can certainly take responsibility for at least the first stage of demonstrating nuclear transmutation, even now. Also, higher proton energy and higher power cyclotrons have been proposed such as an 800 MeV and 2.4 MW cyclotron [6] or even a 1 GeV and 10 MW cyclotron [7]. That is why this article proposes the cyclotron as the ADS accelerator particularly in Korea. Authors of this article will design a cyclotron for ADS in the energy range of 0.5~1.0 GeV and beam power range of 2 ± 0.5 MW.

Table 1: Range of Parameters for Accelerator-Driven Systems for the Following Four Missions [4]

	Transmutation Demonstration	Industrial Scale Transmutation	Industrial Scale Power Generation with Energy Storage	Industrial Scale Power Generation without Energy Storage
Beam Power	1 – 2 MW	10 – 75 MW	10 – 75 MW	10 – 75 MW
Beam Energy	0.5 – 3 GeV	1 – 2 GeV	1 – 2 GeV	1 – 2 GeV
Beam Time Structure	CW/pulsed (?)	CW	CW	CW
Beam Time (t<1 sec)	N/A	<25000/year	<25000/year	<25000/year
Beam Time (1<t<10 sec)	<2500/year	<2500/year	<2500/year	<2500/year
Beam Time (10 s<t<5 min)	<2500/year	<2500/year	<2500/year	<250/year
Beam Time (t>5 min)	<50/year	<50/year	<50/year	<3/year
Availability	>50%	>70%	>80%	>85%

Multi-beam Scheme

Even though is not easy to construct a high energy (around 1 GeV) cyclotron, a CW cyclotron with the energy and beam power of PSI cyclotron can be used for industrial transmutation by forming a cyclotron complex of 5-6 identical cyclotrons. This multi-beam ADS scheme [8], can be not only economical but also realizable with current technology.

CONCLUSION

ADS is a very important tool to fight against the greenhouse gas effect. The currently available high energy and high power cyclotron of the PSI cyclotron level can be used for ADS particularly at the stage of demonstrating the transmutation. If multi-beam scheme is used in the future, a CW cyclotron of the PSI cyclotron level will be able to be used in a complex of 5-6 identical cyclotrons.

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