Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 27-28, 2011

Sub-Critical Nuclear Reactor Based on FFAG-Accelerator

Hee Seok Lee*, Hung-Sik Kang, Tae-Yeon Lee
Pohang Accelerator Laboratory, San 31, Hyoja-dong, Pohang, Kyungbuk 790-784
**Corresponding author:lee@postech.ac.kr*

1. Introduction

After the East-Japan earthquake and the subsequent nuclear disaster, the anti-nuclear mood has been wide spread. It is very unfortunate both for nuclear science community and for the future of mankind, which is threatened by two serious challenges, the global warming caused by the greenhouse effect and the shortage of energy cause by the petroleum exhaustion. While the nuclear energy seemed to be the only solution to these problems, it is clear that it has its own problems, one of which broke out so strikingly in Japan. There are also other problems such as the radiotoxic nuclear wastes that survive up to even tens of thousands years and the limited reserves of Uranium.

To solve these problems of nuclear fission energy, accelerator-based sub-critical nuclear reactor was once proposed [1-4]. (Its details will be explained below.) First of all, it is safe in a disaster such as an earthquake, because the deriving accelerator stops immediately by the earthquake. It also minimizes the nuclear waste problem by reducing the amount of the toxic waste and shortening their half lifetime to only a few hundred years. Finally, it solves the Uranium reserve problem because it can use Thorium as its fuel. The Thorium reserve is much larger than that of Uranium.

Although the idea of the accelerator-driven nuclear reactor was proposed long time ago, it has not been utilized yet first by technical difficulty and economical reasons. The accelerator-based system needs 1 GeV, 10 MW power proton accelerator. A conventional linear accelerator would need several hundred m length, which is highly costly particularly in Korea because of the high land cost. However, recent technologies make it possible to realize that scale accelerator by a reasonable size. That is the fixed-field alternating gradient (FFAG) accelerator that is described in this article.

2. Accelerator-based sub-critical nuclear reactor

2.1 Sub-critical reactor

The conventional nuclear reactors operate at critical condition. The criticality of a nuclear assembly is determined by the effective neutron multiplication coefficient k_{eff} which is defined as

$$k_{eff} = \frac{\text{Numbner of fissions in any one generation}}{\text{Numbner of fissions in immediately preceding generation}} \qquad (1)$$

When $k_{eff} = 1$, number of fissions in each succeeding generation is a constant and the chain fission reaction initiated in the system will continue at a constant rate. Such a system is said to be at a critical conditions. If $k_{eff} > 1$ the number of fission in the system increases with each succeeding generation and the chain reaction diverges; the corresponding condition is referred to as supercritical. On the other hand, if $k_{eff} < 1$ the chain reaction will eventually die out and the system is called subcritical. Since number fissions is proportional to the number of neutrons absorbed in the system, in relation 1 the number of fissions can be replaced by the number of the absorbed neutrons.

The conventional nuclear reactors operate in a very narrow range of the neutron multiplication coefficient ($0.994 < k_{eff} < 1.006$). Outside of this range either the reactor fades out or becomes supercritical and overheats.

In a subcritical reactor, the number of neutrons originating from fission is not sufficient to overcome the neutron losses (due to leaks and absorption of neutrons by materials within the reactor). Therefore, under no circumstances a chain reaction can be self-sustaining. In order for the fission reaction to proceed, the system must be fed continuously with neutrons from an external source.

In irradiation of a heavy metallic target (such as lead) with relativistic ions (such as proton, deuteron, helium, carbon ...) neutrons are produced by spallation of the target nuclei. Figure 1 shows the neutron yield as a function of the incident proton energy. It shows that 1 GeV proton is adequate to achieve maximum number of neutrons.

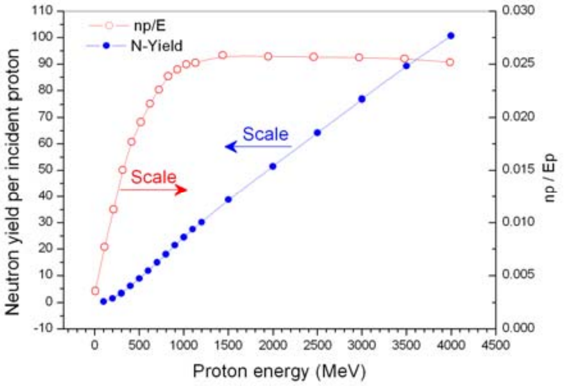

Fig. 1. Variations of the neutron multiplicity *np*, and neutron yield per unit energy of the incident proton (np/E_p) as a function of incident proton energy. The energy gain of an accelerator-based reactor is directly

proportional to np/E_p.[8]

2.2 Fixed-field alternating gradient(FFAG) accelerator

Like the synchrotrons and cyclotrons familiar to today's scientists, FFAG use electric fields to accelerate bunches of protons (or electrons, ions) around a ring at close to the speed of light. But they differ in the way they guide the particles around the circuit. In cyclotrons, a fixed magnetic field forces a beam of charged particles to move in a circle, but regular voltage "kicks" boost the particles' speed and make them spiral outward. The size of the huge magnets needed to keep the particles inside the machine limits the energy of the beam. Synchrotrons overcome that problem by using variable magnetic fields that ramp up as the particles increase in energy. But once the field is geared up for high-energy particles, you cannot inject more, low-energy particles into the accelerator. That cutoff puts a ceiling on the beam's intensity. FFAG solve those problems by using a magnetic field that stays fixed in time but that grows stronger toward the outside of the ring. As particles gain energy and drift outward, the strong field keeps them on track. As a result, particles with a range of energies can all orbit at the same time, enabling FFAG to produce particle beams more energetic than a cyclotron's and more intense than a synchrotron's.

The idea first came in 1953 [5-7]. Researchers in the United States built three small FFAGs in the late 1950s and early 1960s. But the difficulty of creating the carefully shaped magnetic fields made larger devices impractical. However, better magnets and computer simulations of three-dimensional magnetic fields have renewed an interest in FFAG. Currently 6 FFAG accelerators are operational but most of them are designed for cancer therapy. Recently, in US, a 1 GeV, 10 MW FFAG accelerator was planned for the sub-critical nuclear reactor, which has only a circumference of 200 m. This is a very compact size for a 1 GeV 10 MW proton accelerator. That is why FFAG accelerator is considered for the accelerator-based nuclear reactor. Figure 2 shows a schematic diagram of a sub-critical nuclear reactor.

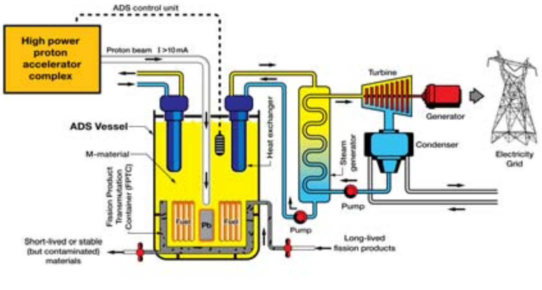

Fig. 2. An example idea of accelerator-based nuclear reactor.[9]

3. Summary

Sub-critical nuclear reactor can be realized by use of the fixed-field alternating gradient accelerator. Especially, thorium based nuclear reaction is best choice to overcome the current problems induced from the current nuclear reactor. In this paper, the conceptual ideas including hot issues of accelerator-based reactor are proposed.

REFERENCES

[1] K. D. Tolstov, Some aspects of accelerator breeding, Preprint 18 - 89 - 778, Joint Institute for Nuclear Research, Dubna, Russia, 1989.

[2] K. D. Tolstov, The modeling of electro-nuclear method of atomic energy production and radioactive waste transmutation, Preprint 18 - 92 - 303, Joint Institute for Nuclear Research, Dubna, Russia, 1992.

[3] C. D. Bowman, E. D. Arthur, P. W. Lisowski, G. P. Lawrence, R. J. Jensen, J. L. Anderson, B. Blind, M. Cappiello, J. W. Davidson, T. R. England, L. N. Engel, R. C. Haight, H. G. Hughes, J. R. I. III , R. A. Krakowski, R. J. LaBauve, B. C. Letellier, R. T. Perry, G. J. Russell, K. P. Staudhammer, G. Versamis, and W. B. Wilson, Nucl. Instr. and Meth. A 320 (1992) 336.

[4] F. Carminati, R. Klapisch, J. P. Revol, C. Roche, J. A. Rubio, and C. Rubbia, An energy amplifier for cleaner and inexhaustible nuclear energy production driven by a particle beam accelerator, Preprint, CERN/AT/93-47-ET, 1993.

[5] T. Ohkawa: Proc. of Annual Meeting of JPS (1953).

[6] A. A. Kolomensky Zh. Eksp. Teor. Fiz. 33 (1957) 298.

[7] K. T. Symon, D. W. Kerst, L. W. Jones, L. J. Laslett, and K. M. Terwilliger: Phys. Rev. 103 (1956) 1837.

[8] S.R. Hashemi-Nezhad, Australian Physics, Vol.43, No.3,(2006),90-96.

[9] B. Cywinski, BASROC CONFORM Open-day 2008.