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Application of High Intensity Accelerator to Nuclear Engineering

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Abstract

Many advances have been made in accelerator technology during the past decade such as intense beam acceleration, high efficiency accelerating structure and RF source, improved beam handling technique and so on. These progresses will make it possible to apply the accelerator technology for new applications in various nuclear engineering fields. The objective of this talk is to present new nuclear energy researches by use of the accelerators, which can be realized only through the close cooperation between experts of nuclear engineering and accelerator technology.

I. Introduction

In nuclear engineering, almost all the types of accelerators such as linear accelerator, Van de Graaff, cyclotron and synchrotron have been extensively used to build up the data bases for the nuclear data measurements, material sciences and isotope productions. In addition to the handling of radiation and radioactive material, accelerators have many common technologies to the nuclear engineering including precision machinery, computer control, beam diagnostics, high voltage power supply, radio frequency source, high vacuum and so on. The technologies related to the target which is bombarded by intense beam such as heat transfer and fluid, radiation shielding, neutronics calculation and radiation damage are of particular importance in both fields. The relationship of these technologies is shown in Fig. 1.

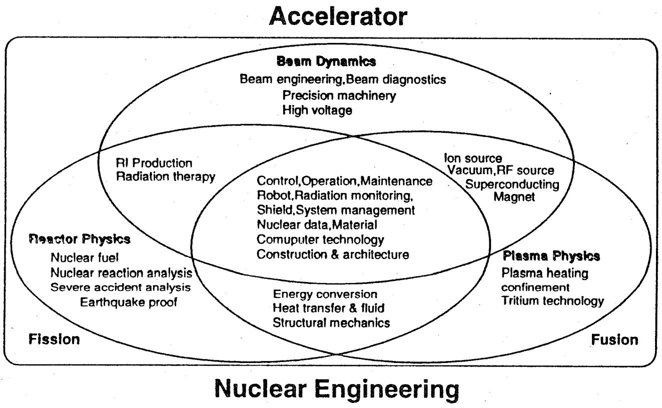

Fig. 1 Common Technologies for Accelerator and Nuclear Engineering

In order to make nuclear technologies steady progress in power generation and utilization of radiation, the effort has been directed toward the following two major targets. One is the development of safer nuclear reactor and new alternative energy resources. The other important aspect is to establish the radioactive waste management technology. In the spent fuel of the nuclear power reactor, minor actinides (MA: Np, Am and Cm) must be isolated from the human living area for long period, because some MA have long half lives exceeding 10^4 years. If the MAs are transmuted to stable or short life nuclides, the technological burden placed on the waste depository can be substantially moderated.

The Japanese Atomic Energy Commission concluded in 1988 to strengthen the research and development on partitioning and transmutation of nuclear wastes of minor actinides and long-lived fission products. The Science and Technology Agency formulated a national program called OMEGA (Options Making Extra Gains of Actinides and Fission Products). The accelerator based transmutation system using the spallation reaction by high energy proton beam is one of the options in the studies[1]. As compared with usual nuclear reactors, an accelerator based system does not require a critical condition, and therefore it has the significant advantage of large criticality safety margin. The thermal power of the subcritical core can be easily controlled by adjusting the power of accelerated beam.

The technical and economic success of future fusion reactors will depend on the endurance and availability of materials suitable for the severe radiation environment. It is important to estimate the mechanical properties of material under high intensity radiation fields, particularly, neutron field. It is, however, difficult to extrapolate from low dose irradiation, due to non-linear effects in the evolution towards end-of-life conditions and due to the absence of a guide line theory. Irradiations in high flux reactors and fast reactors are not valid for fusion conditions. It is generally understood that only accelerator based neutron source can provide the necessary source strength with the required neutron energy distribution. Therefore, the availability of an accelerator based neutron source is mandatory for a reliable prediction of the technical and economical feasibility for fusion reactor.

One of the most important devices, which contribute to the production of high temperature plasma in the tokamak type fusion, is the neutral beam injection (NBI) heating system. It should deliver high power hydrogen or deuterium neutral beams to the plasma. The performances of the system are dependent on the development of positive ion source/accelerator which can produce an ion beam current of tens of amperes at the beam energy of the order of 100 keV

These three fields (nuclear transmutation, intense neutron source and neutral beam injection) will be discussed in this presentation as the examples where accelerator technologies will be used for the nuclear engineering.

II. Nuclear Transmutation System

A. Solid Target/Core System

Fig. 2 shows a conceptual flow diagram for an accelerator based solid target transmutation system in combination with a subcritical reactor[2]. The high energy proton beam of 1 GeV class and several tens of mA bombards the tungsten target and produces intense neutrons caused by spallation reaction and subsequent fission. The target and fuel assembly in the reactor are similar to that used for the common fast breeder reactor with the sodium coolant. Nuclear spallation reactions and the following particle transport processes are simulated using the intra-nuclear cascade code and a three dimensional Monte Carlo transport codes. This concept makes use of fast neutron flux, because most of MA nuclides are only fissionable above the several hundred keV region. Thermal hydraulics calculations are also performed to assure that the fuel and the cladding temperature stay below the maximum allowable temperature.

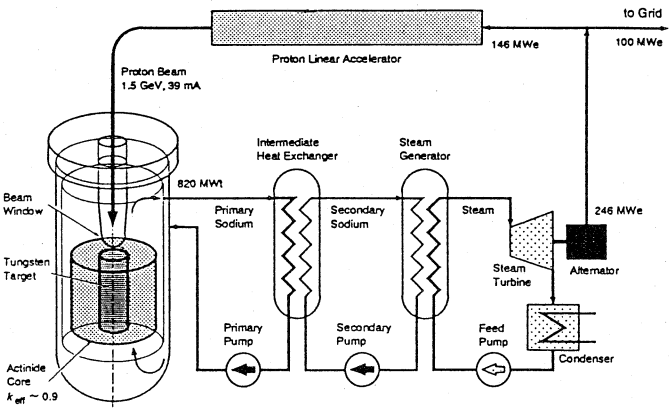

Fig.2 A Concept of Accelerator–Driven Actinide Transmutation Solid Target/Core System

From the calculations for the proton beam with an energy of 1.5 GeV and a beam current of 39 mA, the system can transmute the MAs produced by nearly ten LWR (Liquid Water Reactor). As a by-product, the maximum thermal output powers of 820 MW are obtained. This system also produces excess electric power of about 246 MW, a part of which can be used to operate the proton accelerator. Table 1 summarizes the operating conditions and characteristics of this accelerator transmutation system.

Table 1. Operating Conditions of the Accelerator–Driven Transmutation Solid Target/Core System

Proton beam energy	1.5 GeV
Proton beam current	39 mA
Actinide inventory	3160 kg
k_{eff}	0.89
No. of neutrons	40 n/p
No. of fission (>15MeV)	0.45 f/p
(<15MeV)	100 f/p
Neutron flux:	4×10^{15} n/cm^{2}s
Mean neutron energy	690 keV
Burnup	250 kg/y(8%/y)
Maximum temperature	
Output	473 °C
Fuel	890 °C
Clad	528 °C

B. Molten–Salt Target/Core System

Another advanced option for an accelerator-based nuclear waste transmutation system[3] is molten–salt target system. The main advantage of molten–salt system is the capability of the continuous on–line separation of fission products and spallation products from the fuel. Furthermore, process of actinide fuel fabrication is not required. Although this system offers several attractive features for the design of transmutation system, the actinide in the primary molten–salt loops other than the core region occupies a considerably large amount of the total inventory compared to the solid system.

A preliminary conceptual design study is performed on an 800 MWt chloride molten–salt core/target which is chosen for the system based on the consideration about actinide solubility. The system is calculated to have a power output of 1660 MW. In the molten–salt system, the most difficult heat removal problem appears in heat exchanger. If the design condition had followed a conventional approach with external type heat exchanger, removal of 800 MW thermal power would require the total fuel volume much larger than >10 t of actinides. Highly efficient heat exchangers are essential in the molten–salt system to reduce the total volume of the primary loops.

Recently, the Los Alamos National Laboratory (LANL) has being proposing an another unique molten–salt system, called the Accelerator Transmutation of Nuclear Waste (ATW)[4]. The LANL concept uses the extremely high thermal neutron flux of the order of 10^{16} n/cm^{2}s. In such a high thermal flux, actinides can be transmuted effectively by so-called two-step reaction (Actinides capture neutrons and then fission with competition of short half-life β decay). Major advantages of this concept are that it can also transmute fission products effectively, and it can operate with a very small radioactive inventory. The system consists of a 150 mA class accelerator, a liquid lead (or lead-bismuth flowing target), and a surrounding heavy–water blanket. Actinide and fission products are loaded in the heavy–water blanket. Most difficult problems of the ATW system are radiation damage in target container material, processing and separation chemistry due to the extremely high neutron flux.

C. Accelerator Development

The high–intensity proton linear accelerator (ETA: Engineering Test Accelerator) with an energy of 1.5 GeV and average current of 10 mA has been proposed by JAERI[5]. Various engineering tests will be performed using a high intensity accelerator for the transmutation system before actual plant has been constructed. The need for the development of such a high intensity proton linear accelerator (ETA) should be stressed for that purpose. Nuclear spallation reactions with high energy proton beams will also produce various intense beams, that can be utilized for other nuclear engineering applications. Those include material sciences, radio isotope productions, nuclear data measurements and other basic sciences with proton, neutron and other secondary beams in addition to nuclear waste transmutation.

The conceptual layout of the Engineering Test Accelerator (ETA) is shown in Fig.3. In the case of high intensity accelerator, it is particularly important to minimize beam losses to avoid damage and activation of the accelerator structures. Because the beam quality and maximum current are mainly determined by the low energy portion of the accelerator, the accelerator (BTA) with an energy of 10 MeV and average current of 10 mA is designed and will be built as a first step in the ETA development[6,7].

The accelerator cavities and rf system for high β structures dominate the construction cost for ETA. The conceptual and optimization studies for the ETA are performed concerning proper choice of operating frequency, energy configuration, type of high β structure based on the beam dynamics and mechanical engineering considerations. RF source aspects on the trade-offs between large and small amplifiers are being investigated.

III. Intense Neutron Source for Fusion Material Test

A proposal is made on a version of the D + Li (the FMIT type) neutron source called ESNIT (Energy Selective Neutron Irradiation Test Facility) for resolving complex neutron energy dependence in irradiation effects on materials[8]. Attractive features of an accelerator-based source are the flexibility of controlling the quality and quantity of neutrons and the closer accessibility to in-situ type experiments, which are essential for the studies with specific neutron environments. The maximum fluence of about 0.5

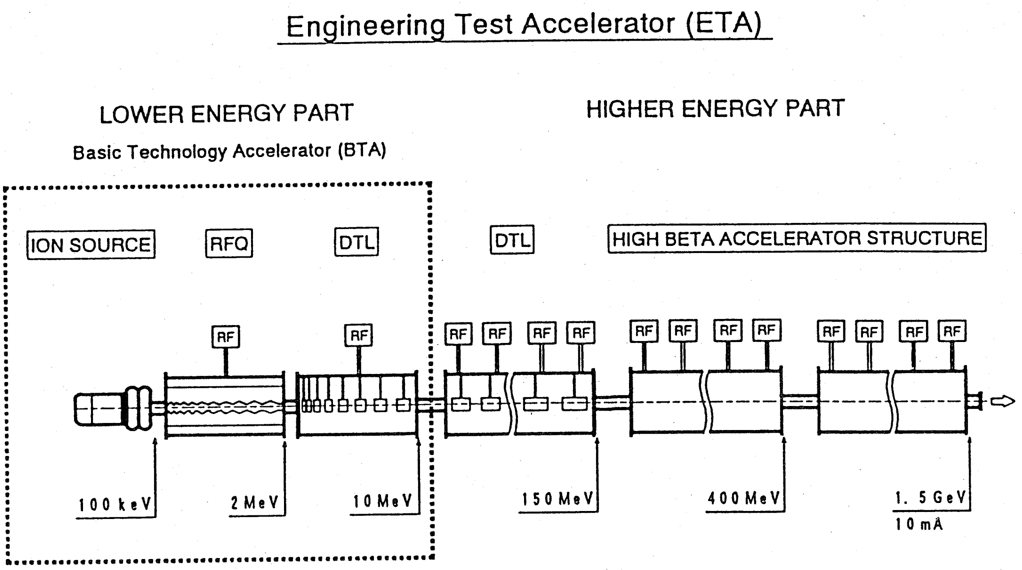

Fig.3 A Conceptual Layout of ETA and BTA

– 1 x10^{23} n/cm^2/year which can create damage of a typical candidate fusion reactor material by around 10 dpa (displacement per atom).

Since the primary purpose for the ESNIT is the fusion reactor materials test, the peak energy of the neutron spectrum should be around 14 MeV. However, the neutron spectrum contains a broad, high energy tail, and the basic research in the effects of such components is the main object of the ESNIT. Thus, the deuteron energy is chosen 40 MeV to enhance the high energy tail component and can be varied and selective with the 5 MeV step.

The ESNIT injector section has three types of ion source, a low energy beam transport line and a radiofrequency quadrupole linear accelerator (RFQ). It supplies positive deuteron, negative deuteron and hydrogen molecular ion beam. Typically a dc D^+ beam and a low duty pulsed D^- beam are injected simultaneously. The most important issue for the accelerator system is to produce the well controlled and stable neutron field at the irradiation volume for a long period, several months to a year. Some of specifications of the preliminary design of the accelerator concept of the ESNIT are given in table 2[9].

Table 2. Preliminary ESNIT Specifications

Main characteristics	
Frequency	120MHz
Exit energy	10,15,20,25,30,25,30 MeV
Average current	50mA(cw)
Ion source	
$D^+/D^-/H^+_2$	60mA max
Output energy	75keV
Emittance(90%)	1πmmmrad
RFQ structure	
Exit energy	2MeV
Transmission	>90%
Max surface field	<1.5 kilpatrik
DTL	
Field gradient	1 – 1.5MeV/m
Beam spill	<0.01μA/m
RF source	
Power	1MW/unit x 9 set
Required power	4.35MW

The International Energy Agency (IEA) is also taking an initiative to evaluate the neutron source requirements and the technologies for the next step fusion reactor DEMO. The much intensive scheme called IFMIF (International Fusion Material Irradiation Facility) have been proposed with two deuteron beams. The beam would be generated by accelerator module capable of delivering up to 250 mA each with a total delivered current of 500 mA to 1A[10].

IV. Neutral Beam Injection for Fusion Reactor

In the fusion device, one MeV class NBI system plays an important role in the plasma heating and the plasma current drive for the steady state operation of the tokamak[11]. The role of the high energy and high power ion source/accelerator in the fusion research becomes much more important. Charged particle beams can not be injected into the plasma because of the strong magnetic field for plasma confinement. Hence, the ion beams must be converted into the plasma without being deflected by the magnetic fields. The high energy neutral particle H^0, D^0, T^0 injected into the plasma are ionized by the collisions with the plasma injection and electrons.

The NBI system for the existing large tokamak such as JT60 and the JET can deliver hydrogen or deuteron neutral beams with the energy of 50 – 140 keV and injection power of 10 – 30 MW and contribute to the increase of plasma temperature up to 10 –30 keV. These NBI systems utilize positive ion source which can produce 30 – 60 A of hydrogen or deuterium ion beams. The high energy ions contribute also to the direct fusion reaction whose effect improves the fusion gain. The neutral beams contribute to the supply of the fuel, the deuteron or tritons, in the core of the plasma.

V. Summary

Recent advances in the accelerator technology appear to make practical high intensity accelerators with the average beam current up to the range of 100 mA. Important applications of such accelerators include nuclear waste transmutation and high intensity neutron sources for material researches. The same technology can be applied to the Neutral Beam Injection for fusion plasma heating. The problems, which are still solved and developed, would be an activation by beam spill, stable and high current ion source development, high power RF source and heat removal in target and accelerator structure. The necessary technologies for these problems are common to those in nuclear engineering fields. High intensity accelerator will be realized in collaboration between accelerator and nuclear engineers and will open up various new practical and attractive research areas.

Acknowledgement

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