ACCELERATORS FOR NUCLEAR WASTE TRANSMUTATION

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Abstract

Development of accelerator technology has been significant for last decade so that very efficient and high intensity linear accelerators can be designed and built for various energy–related applications. In particular, accelerator–based nuclear waste transmutation system has attracted considerable attention because to eliminate long lived actinides and fission products from nuclear power plants is most important issues in the nuclear technology. Several concepts have been proposed in the combination of the accelerator configurations and target/core systems. The present typical concepts consider high–intensity proton linear accelerator for the energies of 800 to 1600 MeV and beam current ranges from several mA to a few hundred mA. In the paper, major problems related to high–intensity linear accelerator for the transmutation system will be summarized.

Introduction

The electric power of 400GWe, corresponding to about 17% of the world consumption, is generated by nuclear power reactors. The high–level radioactive waste (HLW) from this power source is one of the serious problems of the nuclear technology. The HLW is currently confined in the spent fuel assemblies or stored temporarily for the further plutonium recycling. The general policy of managing the HLW is based on the disposal into deep geological depositories after solidification into a chemically stable form. These repositories must confine the waste for tens of thousands of years. Even though geological storage should be quite safe and effective, the concern for public acceptance might still remain.

To widen options of future waste management and to explore the possibility to utilize this HLW as useful resource are worthwhile. It is also important to reduce the long–term radioactivity of nuclear waste sufficiently so that it may be possible to be buried safely in the near–surface storage.

One technology which might achieve the required transmutation in waste radioactivity is accelerator–based transmutation. The system consists of a high intensity proton accelerator and a subcritical target/core with the HLW. It uses neutron absorption reaction (fission and capture) to transmute materials with long–lived radioactivity into short–lived or stable materials. The accelerator provides intense neutrons which subsequently cause the fission reaction chain in the subcritical core. The design values of neutron multiplication factor k_{eff} in the core ranges from 0.8 to 0.99. Because the accelerator provides the neutrons required to maintain the chain reaction, the safety margin may be increased due to the fact that the chain reaction ceases when the accelerator stops. A large amount of energies is in turn released in the fission chain of these wastes. The proposed concepts allow this energy to be converted to electric power. These accelerator–based systems also have the capacity to destroy the large plutonium stockpiles which become one of the world serious problems. For further application, it is also proposed that this technology be used to produce nuclear electricity from the natural thorium without a long term high–level radioactive waste.

Table 1 gives the general feature of the transmutation system with objectives and methods. This accelerator–based transmutation systems using high intensity linear accelerator have been studied

TABLE 1
Accelerator–Based Transmutation Objectives and Methods

Objectives

Transmutation of Long Lived Nuclei	Minor Actinide (MA: Np, Am, Cm) Fission Product (FP: ^{99}Tc, ^{129}I) Plutonium

Methods

Accelerated Particle	Emitted Particle	Reactions	Transmuted Material
Proton	Spallation	Neutron	
	Neutron Multiplication		
		Fast Fission	MA
	& Moderation		
		Thermal Capture	MA and FP
		Thermal Fission	
Electron	Gamma–rays		
		Photo Reaction	FP

intensively for last several years in Japan, U.S. and Russia and recently interested some of European countries. Several summary reports have been published elsewhere[1–4].

Transmutation of Actinides and Fission Products

The HLW from nuclear reactors can be classified into two categories: minor actinides (MA) and fission products (FP). The MAs are heavy elements, which include isotopes of neptunium, americium and curium. A typical light water reactor (LWR) produces about 25kg of MA per year. These wastes are produced in LWRs while burning the nuclear fuels of ^{235}U. These MA nuclei undergo fission when they are struck by a fast neutron. The thermal power of about 80MW is generated from 25kg MAs transmutation by fission.

The transmutation rate of the MA is dependent on the values of their fission and capture cross sections. The capture–to–fission ratio is usually smaller at high energy even though the cross section magnitudes become small. The transmutation concepts have, in general, concentrated on designing systems which provide higher energy (fast) neutrons because actinide can be transmuted in a fast neutron system. The fast neutron system has high efficiency but have a large inventory, frequent fuel reprocessing and refabrication. On the other hand, LANL has proposed recently the attractive system called ATW which uses thermal neutron system. The ATW system requires small inventory and no reprocessing or refabrication, although it has somewhat lower neutron economy.

The by–products from the fission of fuel material are called fission products. Short–life fission products (<10years) can be left to decay naturally. Those which have a longer half life can be transmuted into non–radioactive or short lived nuclei through neutron capture. At high neutron energies, this process is ineffective, because the capture cross section are small. At thermal neutron energies, however, capture cross sections are larger. In the geological storage, some of the FP have the possibility to migrate out of the depository. In this regard, ^{99}Tc and ^{129}I are considered to be the most troublesome materials. Fortunately, these isotopes have high thermal capture cross sections and are easily transmuted to stable isotopes. Thermal neutron system can be used to transmute FPs much easier than the fast neutron system in this regard.

A list of the currently proposed various concepts [5–12] made by several research groups is given in Table 2. From this table, it can be seen that the required accelerator size is very much dependent on the neutron multiplication factor k_{eff}. The electron linac concept has been also proposed for the FP transmutation by using the (γ,n) reaction[13].

TABLE 2
Accelerator Transmutation System

System: Accelerator Sub–critical Hybrid System

Fast Reactor Type System

Lab.	Target/Core	k_{eff}	Accelerator Power
JAERI	W Target, MA Metallic Fuel	0.89	1.5GeV,39mA[5]
	MA Molten Salt Fuel	0.92	1.5GeV,25mA[6,7]
BNL	Pb Target, MA MOX Fuel	0.98–0.99	1.5GeV,2–5mA[8]
	Pb Target, MA Particle Fuel	0.98–0.99	1.5GeV,4–8mA[8]
	MA Oxide Fuel Lattice (PHOENIX:8 Modules)	0.90	1.6GeV,104mA[9]
CEA	MA Molten Salt Fuel	>0.95	1.5GeV,75mA[10]
	Pu Molten Salt Fuel	>0.85	1.5GeV,270mA[10]

Thermal Reactor Type System

LANL	Solid Target,Slurry Fuel D_2O Blanket (4 Modules)	0.95	1.6GeV,250mA[11]
	Pb target Molten Salt Fuel Graphite Blanket (8 Modules)	0.95	0.8GeV,90mA[12]
RIT	Pb/Th/^{7}Li Molten Salt Fuel	–	1GeV,5–100mA[8]
ENEA	Pb Target Molten Salt		1.6GeV,200mA[8]
ITEP	W/Pb–Bi Target, Molten Salt H_2O Blanket	0.97	1GeV,100mA[8]

High–Power Proton Accelerator

The present typical concepts consider high–intensity proton linear accelerator for the energies of 800 to 1600 MeV and beam currents of several mA to a few hundred mA as indicated in the table. For those high intensity accelerators, low beam loss and very high efficiency are important. Optimization should be made with the complex combination of RF frequency, aperture size, focusing, injection condition and so on to maintain the low beam loss, high efficiency, low cost and other criteria. The detailed beam dynamics calculation has to be made using various particle simulation code with numbers of particle.

Efficiency

A high efficiency for converting AC power into beam power is most important for an accelerator, because an electric input power becomes several tens to hundreds of MW. Most efficient RF power can be generated by MW klystrons similar to the ones used in large storage rings where efficiencies up to 70% are reached. As the investment and operating costs will be dominated by the costs of the RF system, the choice of frequency are influenced by availability and potentiality of adequate RF generators. The economic consideration between linac length and gradient is also important aspect. The present RF cost so far gives the constant accelerating gradient of about 1MV/m.

Beam Loss

The most important design consideration for the high–intensity linacs is to insure that beam losses along the linac are kept low enough to insure hands–on maintenance. Non–linear space–charge force makes the beam dynamics complicated significantly. If the beam is mismatched or misaligned at injection, transverse beam size increases due to equipartitioning process. To keep the beam matched for whole accelerator, abrupt change of the transition such as accelerating frequency and focusing condition change should be minimized. It is also important to maintain the large ratio of transverse aperture to rms beam size and longitudinal bucket width to rms beam length.

The beam dynamics in the simulation codes have been conventionally evaluated in the ordinal rms prescription of the beam behavior. However, it is realized that the rms condition is not sufficient for the linac design with low beam loss requirement. Low density long–extended halo must be also accurately predicted. Only fractional losses of the order of 10^{-5} to 10^{-8}/m cause the serious activation especially in the high energy part.

At ordinary accelerator, beam halo patterns are different depending on the operating condition. The best way to predict beam loss is to compare residual activity pattern along the existing accelerator. Accumulated data over long time operation at LAMPF was used to compare the beam spill prediction using the simulation code with a large number of particles[14]. Loss patterns at the spill area where abrupt machine transitions occurs were predicted with the good accuracy. The present simulations seems to predict measured quantities to 10–15%. It is believed that the present code allow qualitative assessment and rough quantitative assessment to fractional losses of 10^{-3} and 10^{-4}.

A number of extensive researches have been made to study this beam halo formation phenomena[15]. This study area has been a very active field at present though it is still very complicated. These studies eventually will result in optimization of the combination of the bore diameter and focusing strength.

Reliability

The reliability, availability, maintenability and inspectability are important issues for the accelerator for the plant operation. The availability for the transmutation system is requested to be more than 75 %. The transmutation system is composed of two subsystems, the accelerator and the target. The accelerator subsystem can be classified into three major part: the accelerator structure or mechanical parts, the injector and the RF system. These three systems are independent with respect to the any break downs. The extremely high reliability for the each subsystem component must be necessary.

TABLE 3
Major Development Items

High Intensity	Several mA – 300mA
	Ion Source:High Brightness, Long Life
	RFQ:Low Emittance Growth
	Heat Deposition, Funneling
Efficiency	
	RF Source:High Power and High Efficiency
	CCL Design: High Impedance and Easy Manufacturing
	Accelerator Gradient: Optimization
	Energy Balance,Cost
Beam Loss	<1nA/m
	Understanding of Formation Mechanism
	BeamLoss Rate :$<10^{-5}$–10^{-8}
Reliability and Safety	Reliability :>70%
	Reliability, Availability, Maintenability, Inspectability

Plans for High–Intensity Linacs

Several laboratories have been proposing the accelerator concepts for the transmutation and development steps. In the following, some typical examples will be described.

LANL The LANL is proposing the several concepts of ATW which uses the thermal neutron concept[16]. The beam energy and current for each concept depends on the objectives of the transmuted material ranging 800MeV to 1600MeV and 90mA to 250mA, respectively. As one of the concepts[12], the beam energy is 800MeV with a CW current of 100mA for protons. The beam is originated in two low energy beam launches each consisting of a proton injector with a 350 kHz RFQ and DTL. The 50mA output beams from the low energy launches are funneled together into an intermediate energy bridge coupled drift tube linac (BCDTL). The final accelerator structure, a couple cavity linac (CCL), takes the beam to 800MeV. The beam is then split in two before hitting the targets. The power required to operate the accelerator is 170MW.

A small scale target-blanket experiment using LAMPF is proposed to demonstrate the many important aspects of the transmutation system. The experiment is planned with the either molten salt lead or lead-bismuth eutectic to stop 800MW and 1mA beam. This target design will provide beam power capacities on the several MWs.

MRTI The accelerator concept which the MRTI is proposing consists of the three parts[17]. In the initial part called HILBILAC (High Intensity Low Beta Ion Linac), the strong superconducting magnetic field focusing is used. Operating frequency is 350MHz and output energy is 3MeV. The next part is a DTL with the same operational frequency and the output energy of 100MeV. All DTL tanks are also housed in a system of periodically arranged superconducting solenoids. In the high energy part, the disk and washer accelerating structure (DAW) is used. Its operating frequency is 1050MHz with the accelerating field gradient of 1MV/m. The odd frequency ratio three between DTL and DAW allows the simultaneous acceleration of H^+ and H^-.

An RF generator, Regotron, will be used as a powerful relativistic electron beam device with a low perveance and a distributed power take-off system, consisting of a number of uncoupled resonators. The principle of autophasing is used.

JAERI The JAERI is proposing to build the accelerator called Engineering Test Accelerator (ETA, 1.5GeV,10mA) for the purpose of performing various tests for accelerator-based transmutation[18]. The main accelerator components for the low energy parts such as ion source, RFQ, DTL and RF source have been developed. The ETA will be operated with pulsed mode, so that various experiments can be performed simultaneously. In the ETA development, the stepwise approach will be taken with modest average beam intensity compared to the actual plant-type accelerator. The size of its beam power will, however, be still 10 to 100 times larger than the existing machines and expensive. The ETA will be also used for other basic researches as neutron and muon sources.

ITEP The ITEP has been proposing to combine the original Be target and subcritical blanket in new test facility 36MeV Linac ISTRA, which will be mounted on the place of partly disassembled heavy water ITEP experimental reactor. This can be considered as prototype linac driven high power facilities. Presently, 150mA beam has been accelerated in RFQ and first DTL resonator up to 10MeV at low duty cycle. The linac average current can be raised up to 1mA by increasing of duty factor after assembling the second DTL and upgrading RF system[19]

Engineering Development

Several major issues exist for the development for the accelerator.

Construction of Low Energy Accelerator Part

An integrated "front-end" system up to several tens of MeV machine should be constructed and operated as a first step to test entire injection system on engineering issue and reliability/availability problem. To demonstrate the soundness of the whole injection system consisting of ion source, LEBT, RFQ and DTL (funneling if necessary) to show good beam profile, bunching condition and emittance preservation is important before actual construction of the whole accelerator system will be started.

Superconducting Cavities

Super-conducting (SC) cavity and RF technology may be appropriate in the longer time range for energy production systems where efficiency is important. The definite advantage of the SC system would be that much larger bore radius could be obtained as compared to normal conducting (NC) cavities of the same frequency. The cavity development, particularly in the region of low β is needed. The SC cavities for β=1 are now operated routinely and at increasing numbers in electron accelerators and large e^+ storage rings . An increasing use of the SC low β structures (β<0.2) is also made in heavy-ion accelerators for nuclear physics. SC cavities for the β range of 0.2 to 0.9 have not been developed but recently attempts have been started to develop them for high brightness beam[4].

Cooperation

The development for the transmutation system include many research field not only accelerator technology but also other related technology fields including target/blanket, material, chemistry, nuclear physics and manufacturing technology. The close cooperation among these various fields should be inevitable including laboratory, international and industry cooperation. In particular, the cooperation with the nuclear engineering should be emphasized. In addition to the handling of radiation and radioactive material, accelerators have many common technologies to the nuclear engineering including computer control, beam diagnostics, RF 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 field.

This transmutation system will be subject for the plant type application. The construction of the system for the validation of design and manufacturing procedures is also important beyond the individual research groups. Intercomparison system of the simulation codes, parameter data base, calculate results and experimental data should be organized under the international basis.

TABLE 4
Important Aspect for Technology Development

- Stepwise Development
  - Design, Manufacturing Method and Cost
    - Ion Source, RFQ, DTL, CCL, RF Source
    - Mock-up Test for Low Energy Part
- Validation of Design Procedure
  - Intercomparison of Simulation Codes, Parameter Data Base, Calculated Result and Experimental Data.
- Close Contact with Target/Core Design Teams
  - Mock-up Experiment Using Existing Accelerator Coupled with Small Scaled Target/Core System

Summary

No basic objections to construct high intensity linac have been identified but more study efforts for space-charge dominated beam transports will be needed. The large beam intensities will ask for detailed tests of all accelerator components. The existing linear accelerator for spallation source could be very useful as the intermediate step towards the goal for the various prototype experiments. Participation of a number of accelerator teams in this effort is important. A international and industrial collaboration not only in the field of accelerator but also for wastes targeting technology and safety aspects would be highly desirable.

References

[1] Specialist Meeting on Accelerator-Driven Transmutation Technology for Rad Waste and Other Applications, Stockholm 1991, ed. R.A.Jameson, Los Alamos report LA-12205-C

[2] Specialists Meeting on Accelerator Based Transmutation, PSI Villigen, Switzerland 1992, ed. H.W. Wenger, PSI Proc. 92-02, September 1992.

[3] R.A.Jameson, G.P.Lawrence and S.O.Schriber, 3rd European Acc.Conf. Berlin, (1992) 230

[4] H.Lengeler,CERN AT /93-02 (DI) 1993.

[5] T. Takizuka et al., NEA/P&T report n.7 (Argonne, 1993)

[6] Y.Kato et al., PSI Proc. 92-02 ISSN 1019-7477, p133 (1992)

[7] T.Nishida et al. Proc. ICENES'93, 0419(1993)

[8] H. Yoshida, NEA/NSC Questionnaire Report (1994)

[9] H.Takahashi PSI Proc. 92-02 ISSN 1019, p3 (1992)

[10] C. Giard Proc. 8 th Journees SATURNE(1994) to be published.

[11] J.R.Ireland, PSI Proc. 92-02 ISSN 1019-6477, p27 (1992)

[12] F. Venneri et al., Physics Worlds Vol.6 No.8 (1993) 40

[13] S. Toyama and S.Tani, PNC TN 9410 93-215 (1993)

[14] R.Garnett, R.S.Mills and T.P.Wangler, Proc. of 1990 Linear Accelerator Conf., Albuquerque, NM, September, 10-14, 1990, p347.

[15] R.A.Jameson, 1993 Particle Accelerator Conf. IEEE Catalog No. 93CH3279-7,3926

[16] G. Lawrence, 1990 Proc. Linac Conf., Los Alamos ReportLA-12004C,553 (1991)

[17] G.I.Batskikh et al. In. Conf. Accelerator-Driven Transmutation Technologies and Applications. to be published 1994

[18] M. Mizumoto, 2nd European Acc. Conf.(1990) Nice, June 12-16,1990, p346

[19] I.V.Chuvilo et al., In. Conf. Accelerator-Driven Transmutation Technologies and Applications. to be published