HIGH INTENSITY PROTON ACCELERATOR FOR NUCLEAR WASTE TRANSMUTATION

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Abstract

A conceptual design study has been carried out for an accelerator-driven actinide (TRU) transmutation system with sodium-cooled subcritical reactor using spallation reactions. In the present calculations, annual transmutation rate of about 250 kg of actinides and production of 820 MW thermal power are obtained by using a 1.5 GeV proton beam with a current of 39 mA. The plant generates electric power of 246 MW with a conventional steam turbine, and supplies sufficient electricity to the accelerator.

The high intensity proton linear accelerator (ETA: Engineering Test Accelerator) with an energy of 1.5 GeV and an average current of 10 mA has been proposed by Japan Atomic Energy Research Institute, JAERI. In a course of the development, the R&D works for the low energy portion of the linear accelerator (BTA: Basic Technology Accelerator) with an energy of 10 MeV and a current of 10 mA are carried out.

Introduction

The Japanese national program called OMEGA (Options Making Extra Gains of Actinides and Fission Products) has started in 1989 by aiming at promoting the research and development of the nuclear waste partitioning and transmutation technologies. As a part of the program, JAERI has laid out several R&D plans for accelerator-based actinide transmutation system.

In this proposal, nuclear spallation reactions with high energy proton beams are taken to be one of the effective transmutation processes. The basic concept of the transmutation system with proton spallation reactions has been studied at JAERI. The main goal of this program is to process the TRU of which the yearly production rate is typically 25 kg for a 1000 MWe LWR. Various engineering tests have to be performed using a high intensity (high-energy and high current) 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 nuclear data measurements, material sciences, radio isotope productions and other basic sciences with the proton, neutron and other secondary beams[1] in addition to nuclear waste incineration.

A study of the transmutation system

The detailed description of a transmutation target, neutronics calculation and power dissipation calculation has been published elsewhere[2]. Only the essential part of the scheme is described in the paper. Fig. 1 shows a conceptual flow diagram for an accelerator driven target system in combination with a subcritical reactor.

The target and fuel assembly in the reactor proposed here are similar to that used for the common fast breeder reactor with the Na coolant. Primary nuclear spallation reactions and the subsequent particle transport processes were simulated using the NMTC/JAERI code[3] for the neutron energy range above the cutoff energy of 15 MeV. Below this energy, a three dimensional Monte Carlo transport code was used.

The maximum power densities in the fuel and target regions are about 920 MW/m^3 and 360 MW/m^3, respectively. Thermal hydraulics calculations were performed to assure that the fuel and the cladding temperature stay below the maximum allowable temperature (900 °C in actinide fuel and 725 °C in cladding). The calculated maximum thermal output powers were 820 MW. Accordingly, the averaged power densities were 400 W/cc for the incident proton beam current of 39 mA. Table 1 summarizes the operating conditions and characteristics of this accelerator transmutation system.

Table 1. Operating condition of the accelerator-based transmutation 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	4x10^{15} n/cm^{2}s
Mean neutron energy	690 keV
Burn up	250 kg/y
Thermal output	820 MW
Power density(max)	930MW/cm^3
(ave)	400MW/cm^3
Maximum temperature	
Output coolant	473 °C
Fuel	890° C
Clad	528° C
Electric output	246 MW

From these calculations, the spallation neutrons and the subsequent induced fission neutrons can transmute the TRU produced by nearly ten LWR in a Na cooled subcritical assembly. As a by-product, this system can be used to produce excess electric power of about 246 MW, a part of which can be used to operate the proton accelerator.

Accelerator development

As a first step in the ETA development, the low energy portion of the accelerator (BTA) is studied, since beam current and quality are mainly determined by this low energy portion. The basic specification of BTA is given in Table 2 and the conceptual layout is shown in Fig. 2. Because of the high beam current and duty factor, heat removal problem from the accelerator structures is an important issue for the mechanical design. Temperature distribution and thermal stresses are carefully studied with the three dimensional modeling codes. The beam energy for the BTA is chosen to be 10 MeV in order to avoid proton induced reactions in accelerator structural materials where the Coulomb barriers are barely exceeded. The acceleration frequency of 200 MHz is selected both for RFQ and DTL mainly due to the availability of RF source and relatively manageable heat removal problem.

Table 2. Basic specification of BTA

Operation mode	pulse
Duty factor	10 %
Output energy	10 MeV
Average beam current	10 mA
Peak beam current	100 mA

Ion source A prototype of multi-cusp ion source[4] was constructed in collaboration with the group of the NBI (neutral beam injectors) Heating Laboratory. The well collimated hydrogen ion of 56 mA was obtained using the 60 kV Test Facility with the observed normalized emittance of about 0.45 πmm.mrad (90%) and proton ratio of 80 %. The high voltage power supply of 100 keV is being constructed and will be tested in October.

RFQ The design study for the RFQ has been progressed. Two dimensional machining of the vane (circular cross section of the tip) for the RFQ was examined and its effects were estimated with the modified PARMTEQ code. The undercutting of the vanes and power losses at the end region were studied with the MAFIA codes. The temperature distribution and thermal displacement were studied[5].

DTL A drift tube structure, magnetic field strength and heat removal problem were investigated under the various mechanical constraints. A hollow conductor type coil with 5x5 mm^2 was chosen for focussing magnet. Configuration of quadrupole magnet is optimized under the condition on the coolant water (temperature rise 25 °C in the coil, pressure drop 5 kgf/cm^2 and velocity 3.4 m/s). The beam dynamics design calculations for the DTL have been made using the computer code PARMILA[6]. The MEBT consisting of four quadrupole magnets and one buncher is preliminary considered between RFQ and DTL to obtain matching. The DTL parameters are given in Table 3. The hot test model with 9 cells, among which the #1 drift tube and the one at the front end plate are installed with actual quadrupole magnets, is designed and will be fabricated and tested for solving the problems in high power operation.

Table 3. DTL parameters

Frequency	201.25 MHz
Energy	2 - 10 MeV
Current	100 mA
Average field	2.0 MV/m
Tank diameter	89.3 cm
Tank length	564.9 cm
Cell length	9.86 - 21.55 cm
g/L	0.234 - 0.293
DT outer diameter	20 cm
DT inner diameter	2 cm
Synchronous phase	-30°
DT cell number	36
Focus magnetic field	80 - 35 T/m
Q	69800
Wall loss	720 kW
Beam power	800 kW
Emittance	
x(rms)	0.048 πcm.mrad
y(rms)	0.035 πcm.mrad
z(rms)	0.0053πMeV.rad

RF source Three sets of RF sources with 1 MW peak class amplifier are necessary (641 kW for RFQ and two 760 kW for DTL). The tetrode tube 4CM2500KG (EIMAC), which was originally developed for fusion plasma heating, will be used with multistage amplifier configuration.

High β linac 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 investigated.

Summary

The R&D works with the design and construction of prototype accelerator structures for cold model (low power) test and hot model (high power) test are in progress. For hot model test, measurements of the electric and magnetic characteristics of the accelerator structure will be conducted with the single unit of high power RF source prepared. Problems of heat dissipation and heat removal in the structure are also emphasized. The detailed design works for BTA construction are followed in the next stage based on the results of the R&D works.

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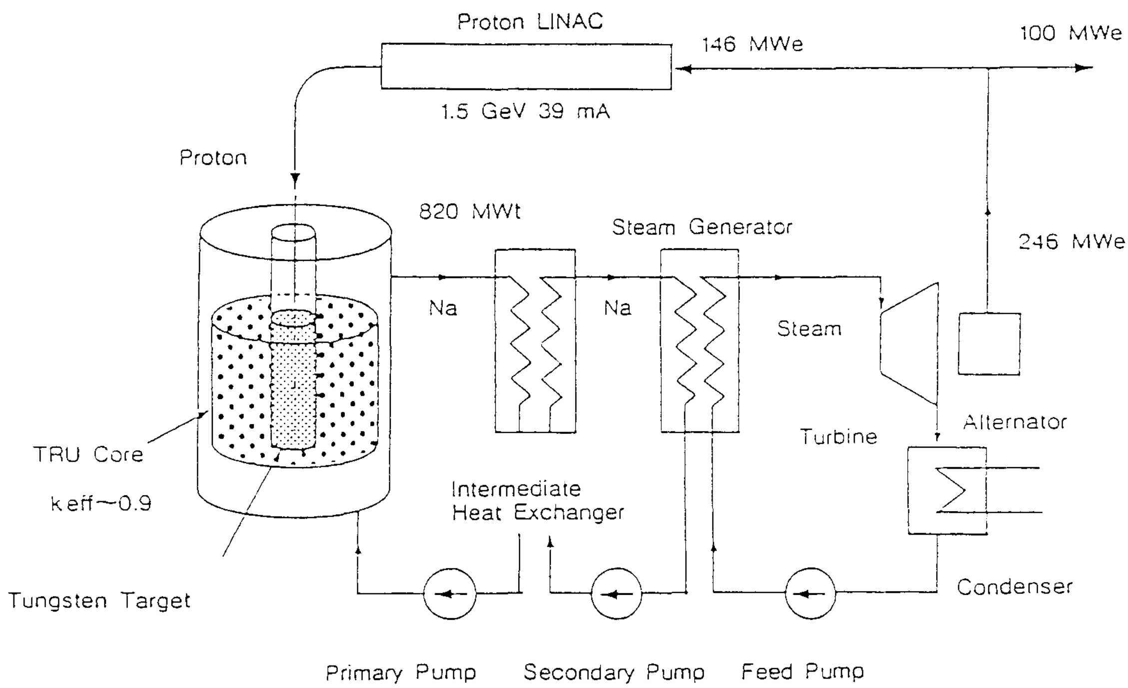

Fig. 1 A conceptual flow diagram for an accelerator-driven target system

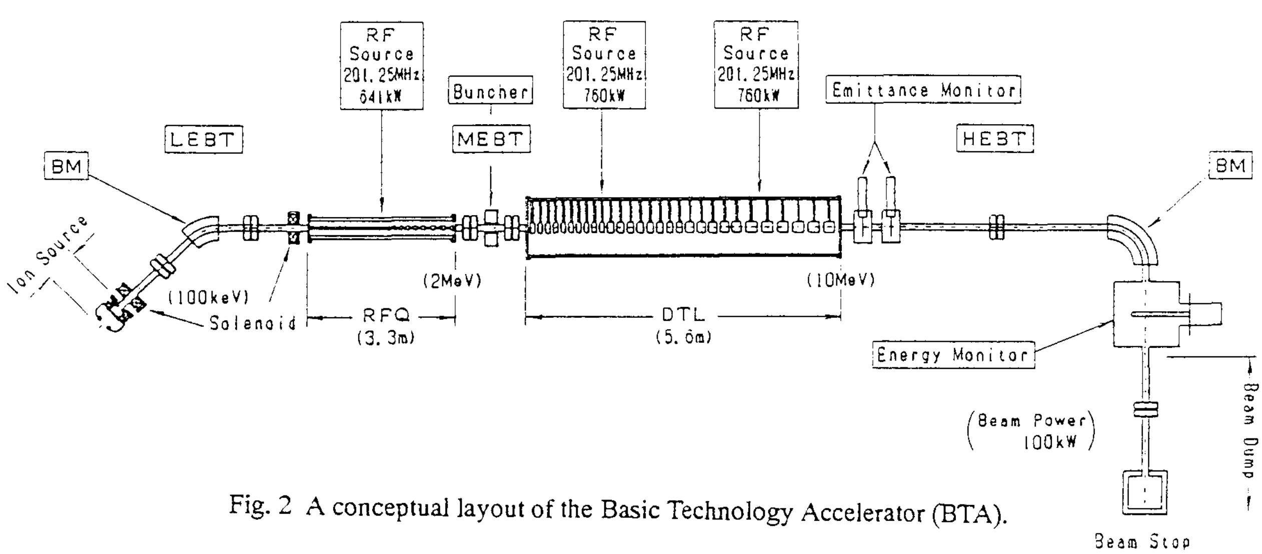

Fig. 2 A conceptual layout of the Basic Technology Accelerator (BTA).