Research and Development Programme on ADS in JAEA

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Abstract. JAEA has been promoting the research and development (R&D) on accelerator-driven subcritical system (ADS) as a dedicated system for the transmutation of long-lived radioactive nuclides. The ADS proposed by JAEA is a lead-bismuth eutectic (LBE) cooled, tank-type subcritical reactor with a thermal power of 800 MW driven by a superconducting linac. The R&D activities can be divided into two categories: one is the design study and technical development for a future large-scale ADS, and the other is the experimental programme at the Transmutation Experimental Facility (TEF) under the J-PARC (Japan Proton Accelerator Research Complex) project. As for the design study of the future ADS, the reliability of the accelerator is being investigated based on the data analysis of existing linac facilities. As for the technical development of the superconducting linac, fabrication and tests of prototype cryomodule were carried out, and its good performance was demonstrated. As for the TEF development, design study including experimental device to handle minor actinide fuels is being conducted.

1. Introduction

To continue the utilization of the nuclear fission energy, the management of the high-level radioactive wastes (HLW) is one of the most important issues to be solved. The difficulty of the HLW management exists in its long-term radiological toxicity which has to be isolated from human environment more than thousands of years and heat generation which may deteriorate the enclosure performance of the geological repository. Regarding both the toxicity and the heat removal, minor actinides (MA) such as Np, Am and Cm play a significant role in the HLW disposal, though their mass content in the HLW is much lower than fission products. Especially when we utilize Pu in the nuclear reactors, MA will dominate the repository area required to dispose of HLW owing to the heat generation of ^{241}Am [1]. The necessity of MA transmutation is, therefore, widely recognized nowadays.

The Japan Atomic Energy Agency (JAEA) is kept implementing research and development (R&D) on Partitioning and Transmutation (P&T) technology to reduce the burden for the management of HLW [2, 3]. The R&D on P&T in JAEA are basing on two series of concepts: one is the homogeneous recycling of MA in commercial fast breeder reactors (FBR) and the other is the dedicated MA transmutation, so-called double-strata strategy, using accelerator-driven system (ADS). Both concepts have their own merits and can co-exist symbiotically and complementarily.

The R&D activities on ADS in JAEA are divided into two categories: one is design study and basic technical development for a future large-scale ADS, and the other is the planning of experimental program at the Transmutation Experimental Facility (TEF) under the J-PARC (Japan Proton Accelerator Research Complex) project. The present status and future perspectives of these activities are described in this report.

FIG. 1. Concept of 800 MWth, LBE-cooled, tank-type ADS

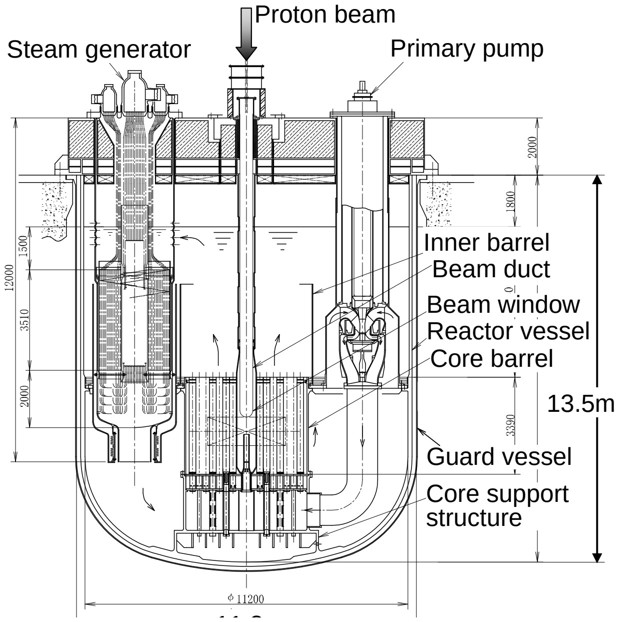


TABLE I: BASIC DESIGN PARAMETERS OF 800 MWth, LBE-COOLED ADS

Parameters	Specification
Thermal power	800 MW
Coolant	LBE
Spallation target	LBE (window-type)
Accelerator	Superconducting Linac
Proton beam energy	1.5 GeV
Active core diameter	234 cm
Active core height	100 cm
Fuel	(MA, Pu)N
Inert matrix	ZrN
Effective multiplication factor (k_{eff})	Max. : 0.970
Cycle length	600 EFPD
Transmutation rate	500 kgMA/cycle

2. Design Study of Future ADS

2.1. General Scheme

JAEA's reference design of ADS is a tank-type subcritical reactor, where lead-bismuth eutectic (LBE) is used as both the primary coolant and the spallation target, as shown in *FIG. 1*. The basic design parameters are summarized in Table I.

In JAEA, a comprehensive R&D program has been started since the fiscal year of 2002 to acquire knowledge and elemental technologies that are necessary for the validation of engineering feasibility of ADS. Items of R&D were concentrated on the three technical areas peculiar to the ADS: (1) a superconducting linear accelerator (SC-Linac), (2) the LBE as a spallation target and subcritical core coolant, and (3) subcritical core design and neutronics of the ADS, where the second and third issue are discussed in other report [4]. In following section, R&D on SC-Linac is discussed.

2.2. R&D on SC-Linac

The proton accelerator for the ADS must have high power intensity, more than 20 MW, with good economic efficiency and reliability. To realize such an accelerator, energy efficiency must be enhanced to assure the self-sustainability for electricity of the whole system. Taking into account of these requirements, the SC-Linac is regarded as the most promising choice. Considering the production efficiency of the spallation neutrons in LBE, the accelerated energy of the SC-Linac was set to 1.5 GeV. This value will be optimized in the future taking into account the trade-off between the cost of the accelerator for higher energy and the engineering difficulty associated with higher current. In order to keep the thermal power at 800 MW, the beam current was adjusted from 8 to 18 mA (i.e. 12 to 27 MW) depending on the effective multiplication factor (k_{eff}) of subcritical core. Taking into account these requirements, the maximum beam current of the SC-Linac was set at 20 mA.

2.2.1. Manufacturing of a Prototype Cryomodule

The SC-Linac consists of a series of cryomodules, where each of them contains two units of superconducting cavities made of high-purity niobium [5]. In the present study, a prototype cryomodule was built, and its performance in formation of electric field and cooling by liquid helium was examined. *FIG. 2* shows a 9-cell superconducting cavity and the prototype cryomodule installing two 9-cell cavities. The cryomodule manufactured in this study was designed to accept 972 MHz radio frequency (RF) wave and to be suitable for the acceleration of 424 MeV proton (β = 0.725), though actual acceleration of proton was outside the scope of this study. Before the fabrication of the 9-cell superconducting cavity, R&D for optimization of the manufacturing precision of the cavities and their surface condition were carried out. Two superconducting cavities were installed in the prototype cryomodule and they were cooled down to 4.2 and 2.1 K, and the maximum surface electric field (MSEF) was measured. The experimental results at 2.1K are shown in *FIG. 3*. The resulting MSEF values for both cavities were 42 and 40 MV/m at 4.2 K and 37 and 35 MV/m at 2.1 K, respectively. These values exceeded the target value of 30 MV/m. These results provided prospects for realization of practical cryomodules.

2.2.2. System Design of SC-Linac

Basic parameters of the SC-Linac for ADS, such as the numbers of acceleration sections and

FIG. 2. (a) Super conducting cavity and (b) prototype cryomodule installing two cavities

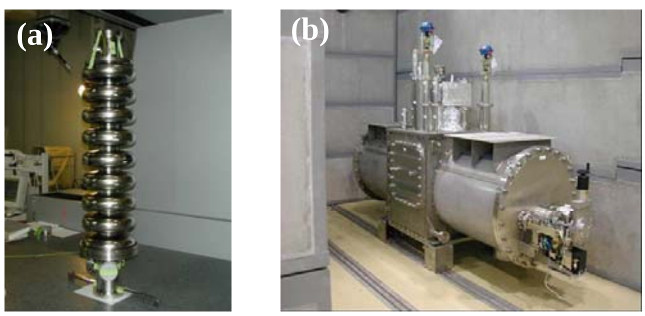
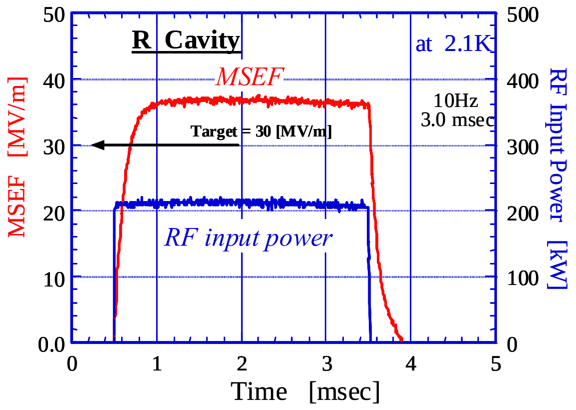


FIG. 3. The experimental results of maximum surface electric filed for superconducting cavity installed in the prototype cryomodule



cryomodules, the strength of magnetic field of focusing magnet and the total length, were determined for the acceleration energy from 100 MeV to 1.5 GeV [6]. Ten acceleration sections were selected by the optimization study considering superconducting cavity of each section and phase slip of the cavity. The superconducting cavity for each section was designed based on cell length for decided each acceleration section. In a lattice design, the MSEF of 30 MV/m was adopted from the experimental results for the prototype cryomodule. The final design provided that the SC-Linac consisted of 89 cryomodules. One klystron was provided for each cryomodule giving a total of 89 klystrons. These klystrons were classified into three categories, according to rated output power: 197, 425, and 750 kW. The beam dynamics analysis showed that it was able to supply a stable proton beam. The total length of the SC-Linac was estimated as 472 m, using the effective length of equipment, such as the quadrupole magnet and the cryomodule, for the SC-Linac of the J-PARC project [6] as reference.

2.2.3. Reliability of SC-Linac

The reliability of the SC-Linac, especially the management of frequent beam trip transients, is one of the critical issues for ADS. Thermal shock damage on the reactor structure is the most important influence caused by the beam trips. Before tackling the reduction of the beam trip frequency, it seems important to know the current level of the technology and to plan the strategy to overcome the problems.

Thermal transient analyses are underway to investigate the effects of beam trips on the reactor components. As a result, the acceptable frequency of beam trips ranged from 43 to 2.5 × 10^4 times per year, depending on the beam trip duration as shown in *FIG. 4*. Further, the down time distribution of the SC-Linac

FIG. 4. Comparison of the acceptable frequency of beam trips and the estimated frequency of the SC-linac

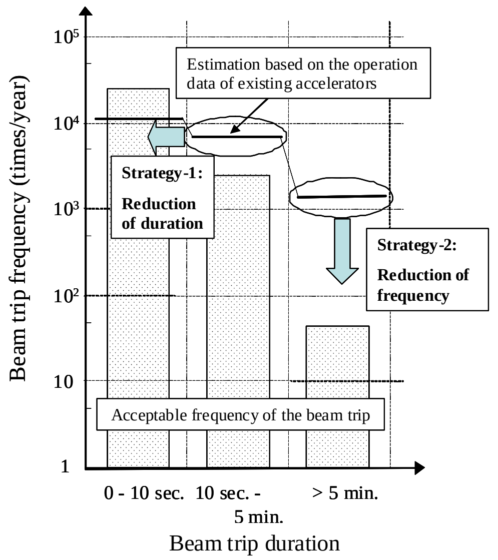


FIG. 5. Conceptual view of J-PARC accelerators and facilities [9]

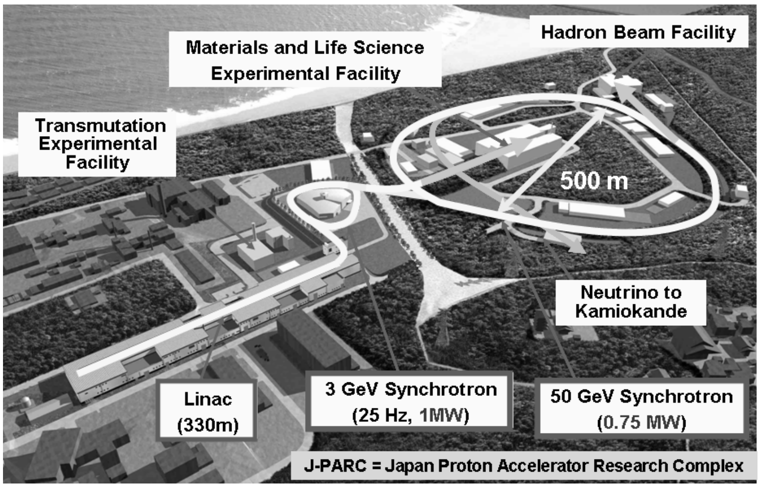
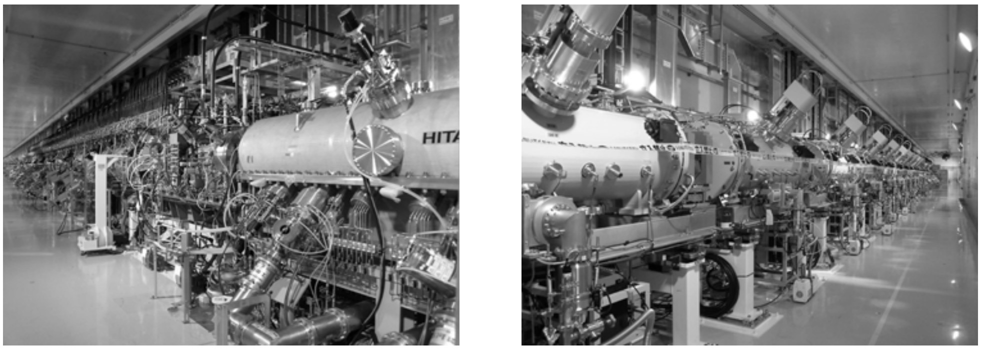


FIG. 6. J-PARC LINAC

(a) Low energy part (RFQ and DTL) and (b) Medium energy part (SDTL up to 181 MeV)



(a) (b)

estimated by the operation data of existing accelerators is a straight line as shown in this figure, where the details are discussed in another report in this Meeting [7]. Two strategies are now being considered to overcome this trip problem on ADS: (1) Reduction of the beam trip duration down to 10 sec., (2) Reduction of frequency for relatively long beam trips.

3. J-PARC Project

JAEA is conducting a multi-purpose high-intensity proton accelerator program called J-PARC collaborating with the High Energy Accelerator Research Organization (KEK) [8, 9]. The conceptual view of the accelerators and the facilities is shown in *FIG. 5*.
The proton accelerators consist of three stages, the linac, 3 GeV Synchrotron (Rapid Cycling Synchrotron, RCS) and 50 GeV Synchrotron (Main Ring, MR). The proton energy of the linac is 400 MeV in Phase-I of the project and will be upgraded to 600 MeV in Phase-II. The experimental facilities consist of the Materials and Life Science Experimental Facility (MLF), the Nuclear and Particle Physics Facility and the Neutrino Facility in Phase-I, and the TEF in Phase-II.

3.1. Present Status of J-PARC

The proton-beam tests started in November 2006. Protons were successfully accelerated to the first candidate energy (181 MeV) of the linac in January 2007, to the designed energy of the RCS in October 2007, and to the initial goal in the MR of 30 GeV by December 2008. Then in January 2009, 30 GeV protons were successfully extracted from the MR to the Hadron Experimental Hall in the Nuclear and Particle Physics Facility. On the other hand, the RCS officially started supplying the proton beams to the MLF on December 23, 2008 and the user operation with neutron and muon beams was started from that day.
FIG. 6 shows the photos of linac part. It consists of an ion source, RFQ (Radio Frequency Quadrapole), DTL (Drift Tube Linac), and SDTL (Separated-type DTL) up to 181 MeV which is the incident energy for the RCS at the beginning of the Phase-I operation. The ACS (Annular-ring Coupled Structure) linac has being prepared for the energy range from 181 MeV to 400 MeV which is the design energy for Phase-I. The beam current of linac will be 0.33 mA in average, and operated in pulsed mode with 25 Hz in the final stage of Phase-I. Then it will be upgraded in Phase-II to 50 Hz, half of which will be supplied to TEF.

3.2. Transmutation Experimental Facility

The original design of TEF consists of two buildings: the Transmutation Physics Experimental Facility (TEF-P) and the ADS Target Test Facility (TEF-T) [10]. TEF-P is a zero-power critical assembly where a low power proton beam is available to study the neutronics and the controllability of the ADS. TEF-T is a facility which can accept a maximum 200 kW-600 MeV proton beam into the spallation target of LBE to conduct the material irradiation and target engineering tests as shown in *FIG. 7*.

3.2.1. Step-wise Construction of TEF

Although the original concept of TEF is to construct both TEF-P and TEF-T simultaneously at the adjacent areas, the separation of TEF into two parts is now discussed to start basic experiment as early as possible, considering the shortage of construction budget. The basic idea is to separate TEF into

FIG. 7. Transmutation Experimental Facility (TEF)

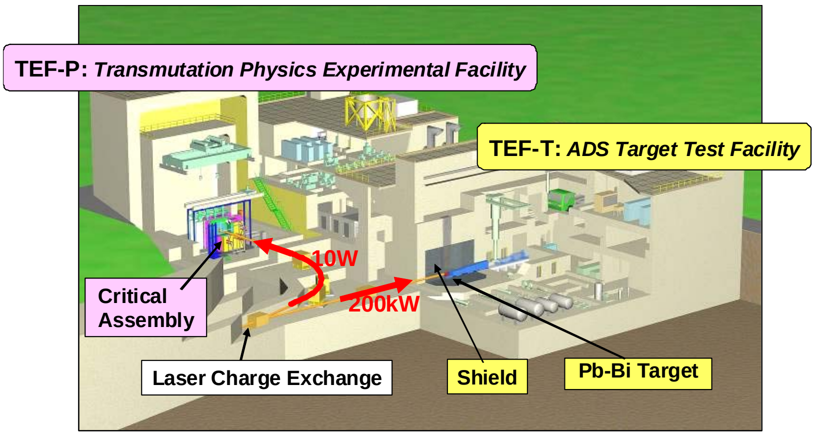
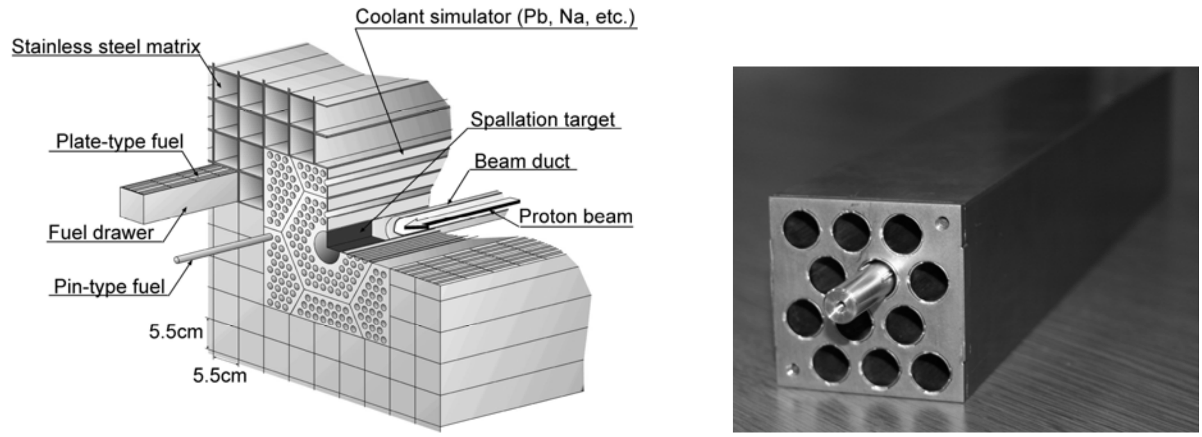


FIG. 8. Conceptual view of assembly of TEF-P and Pb block for pin fuel loading

(a) Conceptual view of assembly and (b) Pb block for pin fuel loading



(a) (b)

Part-1 : TEF-P (with 400 MeV proton beam) and a beam dump
Part-2 : TEF-T and a 600 MeV SC-Linac

In the first part (Part-1), about 30 kW (maximum) proton beam with 400 MeV will be available. Because the power of proton beam is too large to introduce it directly into TEF-P, a beam dump to accept the full power proton beam must be installed. Laser charge exchange device will be used to extract a 400 MeV, 10 W beam which is transported to TEF-P. The beam dump as well as TEF-P can be used for various experimental purposes.
In the second part (Part-2), a 600 MeV, 200 kW (maximum) proton beam accelerated by SC-Linac will be introduced into TEF-T. Laser charge exchange device will extract a 600 MeV, 10 W beam for TEF-P.

3.2.2. Specification of Beam Dump

The low power proton beam should be extracted from kW-order proton beam, most of which must be absorbed by a beam dump located near TEF-P. The beam power will be set at about 30 kW considering the stable operation of linac. The beam dump is made from copper plates cooled by water. The thickness of the disks was optimized to equalize the heat deposition of proton beam. Dimension of the dump unit is about 1 m in diameter and 2 m in length. The application of beam dump such as short-lived nuclide measurements, particle physics, cross section measurements and epithermal neutron generation are now under investigation.

3.2.3. Specification of TEF-P

TEF-P is designed as the facility including horizontal table-split type critical assembly with rectangular lattice matrix, referring to Fast Critical Assembly (FCA) in JAEA/Tokai. Although the regular fuels of TEF will be plate-type, a partial mock-up region using pin-type fuels will also be available. *FIG. 8* shows a schematic view of the partial loading of pin-type Minor Actinide (MA) fuels around spallation target. The central rectangular region (28 cm × 28 cm × 60 cm) will be replaced with hexagonal subassemblies. To measure the physical parameters of the MA transmutation systems including MA-loaded fast reactors, the pin-type fuel containing MA is indispensable. To manage the decay heat and radiations from MA fuels, TEF-P will be equipped with air-cooling systems and remote handling systems. The power level of TEF-P is usually in the order of 10-100 W from viewpoints of the quality of experimental data and accessibility to the core. The maximum thermal power is temporarily fixed as 500 W. TEF-P is designed to contribute not only to the ADS development but also to the fast reactor development by the experiments in critical state.

In the experiment with the proton beam, k_{eff} of the assembly will be kept less than 0.98. The proton beam is introduced horizontally from the center of the fixed half assembly. For spallation target, solid materials, such as lead and tungsten, will be used. In TEF-P, it is also available to perform the spallation target neutronic experiments without nuclear fuels.

A low current proton beam is extracted by a laser charge exchange technique from high-intensity beam line of 30 kW (0.075 mA, 400 MeV) in Part-1 and 200 kW (0.33 mA, 600 MeV) in Part-2, most protons are introduced into the beam dump or TEF-T. A pulse width of the proton beam delivered to the TEF-P will be varied from 1 ns to 0.5 ms in accordance with a requirement of experiments. The proton beam intensity can be controlled by a collimator device which will be installed in beam control area of TEF-P. This area can be used for various experiments that require the low power proton beam or very short pulse beam such as the time-of-flight measurement.

3.2.4. Experiments Using MA fuels

To make meaningful experiments using MA fuels, a certain amount of MA fuels are necessary. For example, if a central test region of 28 cm × 28 cm × 60 cm (about 50 litters) is loaded with MA fuel, about 10 kg of MA is necessary to simulate 5 % MA-added MOX fuels for fast reactors and about 40 kg of MA for ADS dedicated fuels.

The effect of the experiment was roughly estimated by coupling the covariance of nuclear data and the sensitivity analyses [11]. Nevertheless, this estimation does not correctly represent the usefulness of the experimental data because the current covariance data of MA nuclides are not fully provided and some data seem to have too small errors. It is, therefore, necessary to improve the covariance data as well as the cross section data so as to discuss the necessity of the integral validation of the MA nuclear data.

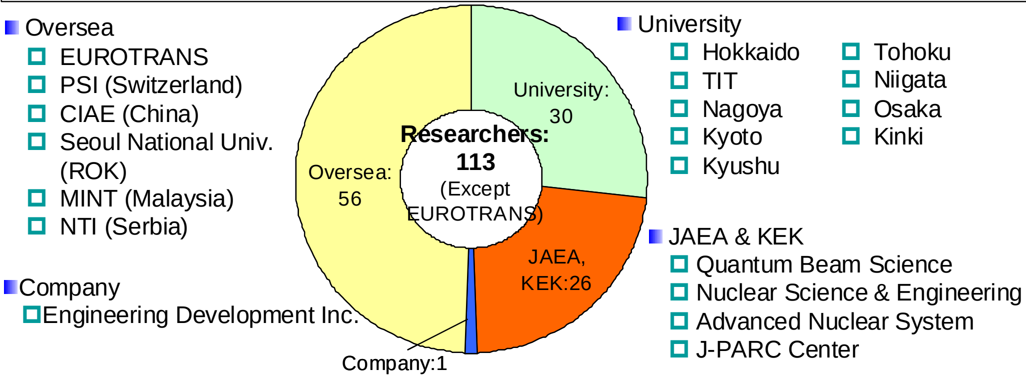
3.2.5. Specification of TEF-T

TEF-T mainly consists of an LBE spallation target, an LBE cooling system (primary loop), a helium gas cooling system (secondary loop) and an access cell to handle irradiation samples. The LBE is filled into a cylindrical sealed double-layer tube target. An effective size of the target is about 15 cm in diameter and 60 cm in length. Several kinds of target are planned and designed according to the objectives of the experiments. One of the target vessels is designed to irradiate ten or more irradiation samples in the flowing LBE environment.

A primary LBE loop is designed to allow the maximum velocity of 2 m/s and maximum temperature of 723 K. These conditions are similar to those of the large-scale ADS. The outstanding point of TEF-T is that it is a dedicated facility for the R&D of structural materials of ADS, and hence experiments under various conditions can be conducted.

FIG. 9. Results of preliminary LOI

- **Total number of received Pre-LOI : 38**
- Areas
  1. Reactor physics of ADS: 11
  2. Reactor physics of advances nuclear system including MA-loaded experiments: 10
  3. Nuclear data and neutron spectrum measurements: 6
  4. High-energy physics, shielding: 5
  5. Nuclear physics (neutrino measurement, ultra cold neutron, short-lived RI beam): 3
  6. Pb-Bi spallation target: 2
  7. Boron Neutron Capture Therapy: 1



3.3. Preliminary Letters of Intent

Although the TEF program is not yet funded officially, the Project Team called for preliminary Letters of Intent (LOI) for experiments at the TEF in the year of 2006. The purposes of the preliminary LOI are: (1) to know which groups have an interest in this activity and what contributions from them can be expected, (2) to reflect new ideas and proposals on the specifications and the layout of TEF including the beam dump, and, (3) to establish an appropriate collaboration scheme between J-PARC and the anticipated outside users.
FIG. 9 shows the results of the preliminary LOI. Thirty eight proposals were received in total. The experiments for both ADS and MA-loaded FBR were mainly proposed. In other fields, proposals were for nuclear data measurement, high energy physics, LBE spallation target technology, and miscellaneous researches including medical applications using protons and neutrons at the beam dump were received. Although the detailed discussions for the proposals have not been started yet, it is clear that TEF can serve as a basic experimental platform for the nuclear science, engineering, and applications. The project is still open to accept other proposals.

4. Conclusion

JAEA has been promoting various R&D activities on ADS. As for the design study of the future ADS, the reliability of the accelerator is being investigated based on the data analysis of existing linac facilities. Reduction of frequency for relatively long beam trips is important to overcome this trip problem on ADS. As for the technical development of SC-Linac, fabrication and tests of prototype cryomodule were carried out, and its good performance was demonstrated.

Under the framework of the J-PARC project, the experimental program using TEF is being proposed as the second phase of the project. The step-wise construction is now considered for TEF; TEF-P and a beam dump as Part-1, and TEF-T and SC-Linac as Part-2. The preliminary LOI was called for and thirty eight proposals were received. The proposals were mainly in the fields of reactor physics experiments for ADS and MA-loaded FBR, and wide range of basic experiments were also proposed including LBE spallation target technology and nuclear science.

Reference

[1] OIGAWA, H., et al., “Parametric Survey on Possible Impact of Partitioning and Transmutation of High-level Radioactive Waste”, Proc. of GLOBAL2005, International Conference Nuclear Energy System for Future Generation and Global Sustainability, Tsukuba, Japan, October 9-13, 2005, (2005).

[2] MINATO, K., et al., “Research and Development Activities on Partitioning and Transmutation of Radioactive Nuclides in Japan”, OECD/NEA 9th. Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, September 25-29, 2006, Nimes, France, (2006).

[3] JAPAN ATOMIC ENERGY AGENCY, Present Status and Future Plan of Research and Development in JAEA on Partitioning and Transmutation Technology for Long-lived Nuclides, JAEA-Review 2008-074, Tokai, Japan (2009) (in Japanese).

[4] TSUJIMOTO, K., et al., “Feasibility of Lead-Bismuth-Cooled Accelerator-Driven System for Minor-Actinide Transmutation”, Nuclear Technology, **161**, (2008) 315-328.

[5] NOGUCHI, S., et al., “Prototype Cryomodule for the ADS LINAC”, Proc. of the 11th Workshop on RF Superconductivity, Travemünde/Lübeck, Germany (2003) MoP32 and http://srf2003.desy.de/.

[6] OUCHI, N., et al., “Development of a Superconducting Proton Linac for ADS”, Proc. of 4th Workshop on Utilization and Reliability of High Power Proton Accelerators, (2004) 175-183.

[7] TAKEI, H., et al., “Estimation of acceptable beam trip frequencies of accelerators for ADS and comparison with experimental data of accelerators”, International Topical Meeting on Nuclear Research Applications and Utilization of Accelerators, IAEA, Vienna (2009).

[8] The Joint Project Team of JAERI and KEK, “The Joint Project for High-Intensity Proton Accelerators”, JAERI-Tech 99-056 (KEK Report 99-4, JHF-99-3) (1999).

[9] http://j-parc.jp/index-e.html

[10] OIGAWA, H., et al., “Concept of Transmutation Experimental Facility”, OECD/NEA 4th. International Workshop on the Utilisation and Reliability of High Power Proton Accelerators, May 16-19, 2004, Daejeon, Republic of Korea, (2004).

[11] SUGAWARA, T., et al., “Improvement Effect of Neutronics Design Accuracy by Conducting MA-loaded Criticality Experiments in J-PARC”, Proc. of PHYSOR 2008, International Conference on the Physics of Reactors, Interlaken, Switzerland, September 14-19, 2008, (2008).