Present Status of the Accelerator System in the IFMIF/EVEDA Project

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(Received: 20 November 2009 / Accepted: 18 January 2010)

The IFMIF/EVEDA project, one of the three projects under contract with the BA agreement between EU and Japan, was started in the middle of 2007. During these two years, the design of an accelerator prototype has been progressed as the engineering validation activity and the base point of the engineering design activity for the IFMIF. The accelerator components for the prototype are being shifted to the manufacturing phase through the design reviews. In this article, the summary of the design of the prototype and the beam test plan of the prototype at Rokkasho BA site are described.

Keywords: IFMIF/EVEDA, fusion materials irradiation, accelerator-driven neutron source, D^+ beam, CW linac, BA projects

1. Introduction

In order to realize energy production using nuclear fusion reactors, selection of plasma facing materials to endure neutron fluxes with the energies of 14 MeV produced by D-T nuclear reactions is one of the most important issues. ITER will be employed as the physical properties of thermonuclear plasmas and some key technologies. However, the amount of neutrons produced in the ITER will be two orders smaller than that produced in the next stage of fusion demonstrator called DEMO. IFMIF (International Fusion Materials Irradiation Facility) should be in charge of an investigation of materials under a high flux of energetic neutrons in order to design the DEMO.

The IFMIF is an accelerator driven neutron source consisting of two RF linear accelerators (linacs) each of which provides a continuous-wave (CW) positive deuteron ion (D^+) beam with the intensity of 125 mA (total 250 mA by two linacs) at the beam energy of 40 MeV. Production of such a CW beam with the beam energy of MeV region accelerated by a linac is one of the most challenging accelerator technologies. The CW beams accelerated by the linacs are required not only for the fusion materials R&D but also for the plasma heating or the plasma diagnostics in the future fusion devices [1-3]. The two D^+ beams are injected into a 25 mm-thick Li jet flowing at a speed of nominally 15 m/s and produce an intense flux of neutrons with the energy spectrum which is able to simulate the irradiation effects encountered in DEMO. The IFMIF is constituted by the following three systems;

- the accelerator system,
- the lithium target system, and
- the materials irradiation test system.

A joint implementation of the Broader Approach (BA) activities in the field of fusion energy research and development has been agreed between the European Atomic Energy Community (EURATOM) and the Government of Japan in February 2007. Engineering Validation and Engineering Design Activities for the IFMIF (IFMIF/EVEDA) which is one of the three BA projects was initiated in the middle of 2007.

In this project, design, construction operation and maintenance of prototypes for the three systems as an Engineering Validation Activity (EVA) and the Engineering Design Activity (EDA) for the IFMIF including the interfaces between systems will be performed.

In this paper, the progress of the accelerator system in the BA IFMIF/EVEDA project for these two years and the commissioning schedule of the prototype in Rokkasho are described. An overview of the IFMIF/EVEDA project and the progress of other systems will be described elsewhere [4-6].

2. IFMIF Accelerators and its prototype

In the IFMIF, two linacs will be employed to supply D^+ beams with the beam power of 10 MW, which is one order higher power than the existing accelerators such as J-PARC in Japan [7] and SNS in the United States [8]. A beam power chart of the proton/deuteron accelerators in the world is shown in Fig. 1. In the figure, most of the accelerators are high energy (GeV region for nuclear and particle physics and several hundred MeV regions for life and material science) and low average beam current. On the other hand, the IFMIF accelerators and its prototype are in several ten MeV regions and the average beam current of several hundred mA region, which means a challenging machine for the accelerator science and

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technology. In these cases, the beam divergence due to space-charge effects may be one of the serious problems to deliver the beam to the downstream. In the LEDA (Low Energy Demonstration Accelerator) project performed at Los Alamos National Laboratory, the similar continuous-wave (CW) proton beam current and beam energy to the IFMIF accelerator prototype was accomplished [9]. However, in the case of the IFMIF accelerators and the prototype, because the accelerated ion species is D^+ and the operation is also CW mode, only a few losses may cause the serious radio-activation of the accelerator devices.

In the IFMIF/EVEDA project, the prototype will be designed, constructed and tested for the engineering validation and the results will reflect the engineering design for the IFMIF accelerators. It consists of a 100 keV injector equipped with an ECR (electron cyclotron resonance) type ion source and an LEBT (low energy beam transport line), an RFQ (radio-frequency quadrupole linac) accelerating up to 5 MeV, an MEBT (medium energy beam transport line), the 1st section of HWR type SC linac (half-wave-resonator type super-conducting linac) up to 9 MeV, an HEBT (high energy beam transport line) equipped with a beam diagnostics to investigate the beam quality, a beam dump to endure the beam power up to 1.2 MW in CW operation, RF power sources supplying to the RF cavities in the RFQ and SC linac, accelerator control system and auxiliary systems. A schematic drawing of the IFMIF accelerator prototype with institutes in charge with the specifications of the subsystems is shown Fig. 2. And the accelerator specifications and beam parameters for the IFMIF accelerators and the prototype are listed in Table 1.

Most of the accelerator subsystems will be provided by European institutes (CEA-Saclay in France, CIEMAT in Spain, INFN/LNL in Italy and SCK•CEN in Belgium), while the RF couplers for the RFQ, the supervision of the accelerator control system and the accelerator prototype building for the beam tests constructed at the International Fusion Energy Research Centre (IFERC) in Rokkasho village will be provided by JAEA in Japan. Each accelerator subsystem is designed, manufactured and individual tested in each institute, and then all the subsystems will be transported to the IFERC in order to integrate and operate the prototype systematically [10].

2.1 Beam Dynamics

Beam dynamics study is the basis of the accelerator design and optimization from the ion source to the target. For the beam dynamics studies of the prototype and IFMIF accelerators, a beam simulation package code, *TraceWin*, which has been developed for the high intensity linac design, is employed. A feasibility study has been carried out and the preliminary specifications of all the accelerator devices along the beam line were chosen [11].

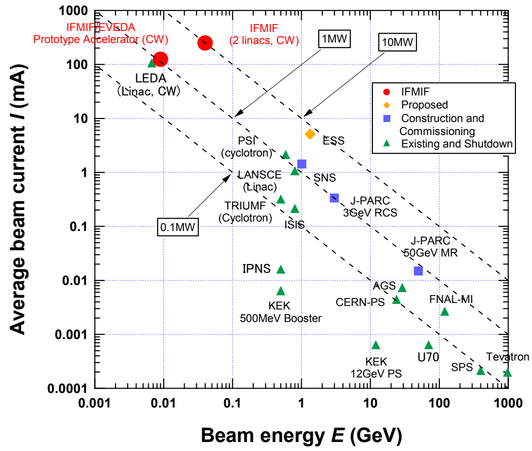

Fig. 1 Average beam power chart of the proton/deuteron accelerators in the world.

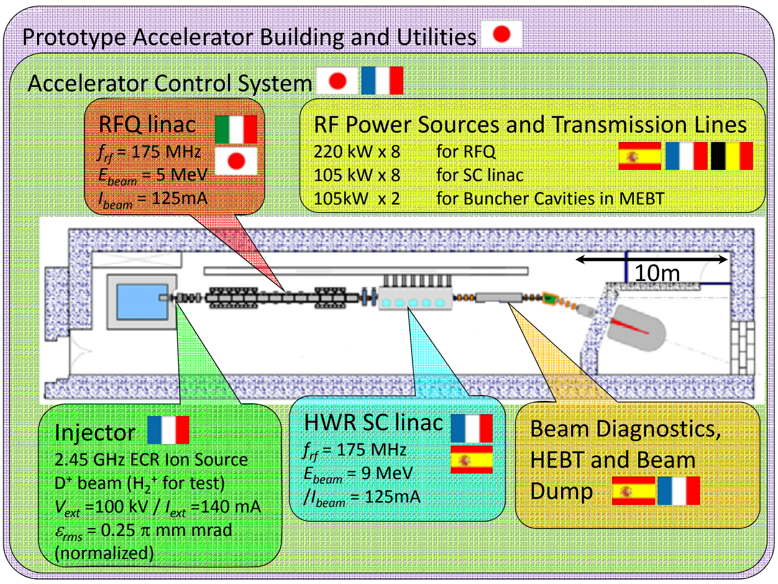

Fig. 2 Schematic drawing of the accelerator prototype with institutes (national flags) in charges.

Table 1 Specifications and beam parameters for the IFMIF accelerators and its prototype.

Primary Parameters	EVEDA	IFMIF	Unit
Number of linacs	1	2	
Duty cycle	CW	CW	
Ion species	D^+	D^+	
Beam intensity	125	2x125	mA
Beam energy	9	40	MeV
Beam power	1.125	2x5	MW
Beam emittance (vertical)	0.35	0.40	π mm mrad
Beam emittance (horizontal)	0.35	0.40	π mm mrad
Beam emittance (longitudinal)	0.55		π mm mrad
RF frequnecy	175	175	MHz
Total length	34	85	m

2.2 Injector

The aims of the injector are to produce a D^+ beam and to deliver the beam with sufficient quality to the RFQ. The extraction system of the ECR-IS has been optimized for this purpose. As a simulation result, it is found that 4-electrode configuration with the maximum electric field about 100 kV/cm is satisfied to produce a 140 mA D^+ beam with the beam energy of 100 keV with the appropriate beam quality [12].

In the LEBT, a configuration of two solenoid magnets is designed to be employed for the beam transportation to the entrance of the RFQ with optimum matching parameters. Moreover, in order to compensate the space charge effect caused by the high current density in the LEBT, a small amount of krypton gas will be introduced into the LEBT region [13].

2.3 RFQ

RFQ accelerators are widely used in place of electrostatic accelerators with several hundred kV, recently. For the IFMIF, a four-vane type RFQ is used with the following characteristics shown in Table 2 [14].

Table 2: Design values of the IFMIF RFQ

Specifications		Value	Unit
Beam energy	(input)	100	keV
	(output)	5	MeV
Beam current		125	mA
Output beam power		625	kW
Beam power loss		522	W
Frequency		175	MHz
RFQ length		9.78	m
		5.7	λ
Vane voltage	(min.)	79.29	kV
	(max.)	132	kV
Radius of the aperture	(min.)	4.1	mm
	(max.)	7.1	mm
Max. surface electric field		1.8	Kp

In order to minimize the activation caused by beam losses in the RFQ, transport the high quality beam to the SC linac, and avoid the sparking risks, the structural design study has been intensively concentrated [15]. Finally some notable results are obtained. The RFQ length, the radius of the minimum beam aperture, and the maximum surface electric field are 9.78 m, 3.48 mm and 24.7 MV/m, respectively.

A detailed beam dynamics study has been also undertaken to optimize the beam optics matched with the parameters of the beam coming from the LEBT. In the ideal condition with a Gaussian phase-space distribution in the beam, the beam transmission of the RFQ will be 95.7 % and the most of particles will be lost in the 1/3 upstream section of the RFQ, where the ions have the beam energy less than 1 MeV.

2.4 MEBT

The MEBT plays a role to match the D^+ beam from the RFQ to the SC linac with acceptable beam parameters. It consists of two buncher cavities for the longitudinal phase-space matching and five quadrupoles for the transverse phase-space matching with some flexibility. The final configuration with the electric and magnetic parameters of the equipments will be decided and reported before long.

2.5 1st section of HWR SC linac

As an alternative solution of the IFMIF accelerator, a super-conducting structure based on a half-wave-resonator type was selected. The SC linac has many technological and financial advantages as shown below,

- the RF power reduction is substantial, leading to large economies for IFMIF operation (6 MW on the grid),
- the scheme is intrinsically suitable for CW operation (low losses, no heat exchange etc.),
- the technology involved is less sensitive to all machining and assembly errors, and
- the RF power system is simpler and more reliable, because based on smaller and more conventional power units.

The proposal of the HWR SC linac was approved by the BA Steering Committee meeting in May 2008. The specifications of the SC linac for the IFMIF accelerators are listed in Table 3.

Table 3: Design values of the HWR SC linac for IFMIF ("1" for the prototype)

Specifications		1	2	3	4
Cavity β		0.094	0.094	0.166	0.166
Cavity length	(mm)	180	180	280	280
Beam aperture	(mm)	40	40	48	48
Nb cavities/period		1	2	3	3
Nb cavities/cryostat		1x8	2x5	3x4	3x4
Nb solenoids		8	5	4	4
Cryostat length	(mm)	4.64	4.3	6.03	6.03
Output energy	(MeV)	9	14.5	26	40

In the IFMIF/EVEDA project, the first section of the SC linac will be designed, manufactured, assembled and tested. The activities have started in October 2008 and were mainly focused on the preliminary design of the super-conducting resonators with the cavity tuning system and the couplers.

The first cryomodule for the IFMIF accelerators or the prototype consists of 8 HWR cavities with the power couplers, 8 solenoid packages, RF pick-up antennas, a support frame, a magnetic shield, a thermal shield, cryogenic pipes, pumping pipes, instrumentation and vacuum tank equipped with access traps.

D^+ ions are accelerated by the independently phased neighbor 2-gap resonators equipped with short focusing lattice. Each cavity has a tuning system for compensation of the frequency shift and variation. The tuning system has a plunger located at the opposite side of the coupler port.

2.6 RF Power Sources

Continuous RF powers have to be supplied to the RFQ, the buncher cavities in the MEBT and the HWR SC linac [16]. The RF power system consists of 8 power amplifiers of 220kW for the RFQ and 10 power amplifiers of 105 kW for the buncher cavities and the SC linac in the prototype. Each chain is composed an LLRF (Low Level Radio Frequency) system managing the RF driver signals to following RF amplifiers, three amplification stages, transmission lines, a circulator and a water-cooled dummy load.

2.7 HEBT with Beam Diagnostics

For the prototype, a diagnostic plate (D-plate) is installed downstream of the RFQ or the SC linac. The main diagnostic devices are listed in Table 4 [17].

Table 4: Diagnostics for beam parameter measurement

Parameters to be measured	Monitor/ Method
Beam current (DC component)	DC current transformer (DCCT)
Beam current (AC component)	AC current transformer (ACCT)
Beam position	Short-stripline type monitor (SBPM)
Transverse beam profile	Gas-fluorescence type monitor (FPM)
	Gas-ionization type monitor (BTPM)
Transverse beam halo	Segmented-ring type monitor (SHM)
Transverse emittance	Quadrupole scan method
Longitudinal emittance	Buncher scan method
Average beam energy	Time-of-flight method
Energy spread	Magnetic dipole method (MD)

In order to monitor the beam current for both the CW mode and pulse mode, two types of the current transformer will be prepared and used. The transverse beam position monitor will play an important in order to transport the beam properly to the beam dump through the ideal beam orbit. Two non-beam-destructive profile monitors based on interaction of the beam with the residual gas will be tested in the D-plate. In high current hadron linacs, the beam halo has to be monitored to minimize the beam losses and ensure a safe operation. In the prototype, segmented rings will be installed at the outer region of the beam pipe in the D-plate to monitor the halo growth and to serve a fast interlock signal in case of detection of anomalous beam losses. Quadrupole and buncher scan methods will be used to monitor the transverse and longitudinal emittance of the beam respectively. The results obtained from these monitors with certain accuracy will bring information to handle better beam operations by combining with the beam simulation code. The average beam energy will be determined by the TOF (time of flight) method using three beam position monitors with sufficient phase accuracy. A dipole magnet installed between the SC linac and the beam dump will be employed to measure the beam energy spread.

2.8 Beam Dump

In the prototype, a beam dump is required in place of the Li jet target in the IFMIF to stop the D^+ beam accelerated up to the power of 1.125 MW. Because the beam ejected from the SC linac seems to be extremely high current density, it will be expanded by the quadrupoles installed in the HEBT and then absorbed safely at the beam dump. The beam dump and its surroundings will become activated due to neutron irradiation by interaction of the D^+ beam with the materials of the beam dump.

The beam dump is made of OFE copper and its geometry is based on conical shape with 2.5 m in length and 30 cm in diameter and the mechanical design of the beam dump with the cooling system is performed [18]. Analysis of the beam dump for the radioprotection and a preliminary calculation of the neutron effective dose rates in the accelerator vault are also examined [19, 20].

2.9 Control System

In order to keep safety with satisfying the laws and regulations in Japan and to operate the prototype properly, the accelerator control system comprises of six control subsystems;

- Central Control System (CCS),
- Local Area Network system (LAN),
- Local Control System (LCS),
- Personnel Protection System (PPS),
- Machine Protection System (MPS), and
- Timing System (TS).

An overview of the control system architecture including the subsystems for the prototype is shown in Fig. 3.

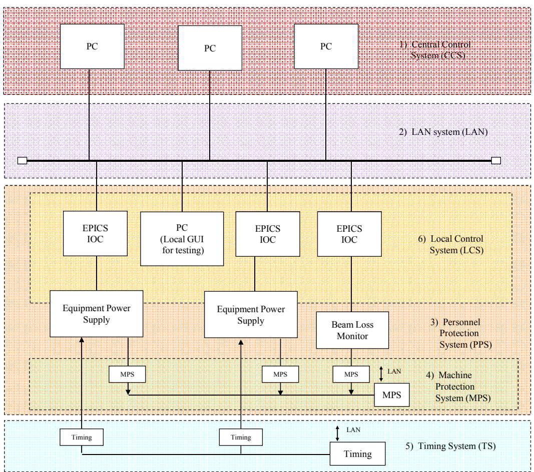

Fig. 3 An overview of the control system archtecture for the prototype accelerator.

Manufacturing of a PLC sequence for the MPS monitoring and operation, development of the test module for the TS and development of the EPICS drivers for the SIMENS S7 PLC and for TS are carried out at Rokkasho in 2009 for the preparation of the injector tested in EU in 2010 [21].

3. Beam Test Plan of the IFMIF Accelerator Prototype

In the beam tests of the prototype at IFERC, even a small amount of the beam loss will cause radio-activation or damage of the accelerator devices due to the generation of D^+ beams with the maximum beam energy and current of 9 MeV and 125 mA. And the engineering validation of the IFMIF accelerator must be carried out efficiently under the limited time and budget. In consideration with these requirements and constraints, it is necessary to have a prospect of the steady operation for the future IFMIF accelerators by having a clear view of the allowable radiation level and clarifying the experimental data to be obtained. A commissioning scenario to progress the prototype is proposed step by step as shown below,

1. Injector only,
2. Injector + RFQ + MEBT, and
3. Whole accelerator prototype.

Because the prototype is tested step by step while the post-accelerators are installed as shown in Fig. 4, usage of an H_2^+ beam is considered to be employed as an accelerated ion species and not only a CW operation mode but also a pulse operation mode are prepared in order to avoid the severe activation.

The beam tests in Rokkasho are planned to be started in the middle of 2012 and finished in the end of 2014. In 2012, the behavior of the injector will be checked and the reproduction of the results tested in EU will be confirmed. After the installation of the RFQ in 2013, adjustment of the RF frequency and the magnetic fields will be performed sufficiently by using the H_2^+ beam. After the tuning, the beam quality of the D^+ beam will be investigated in a short term for activation as small as possible. In the final year, after the installation of the SC linac, the beam test of the whole accelerator prototype will be performed. Again, H_2^+ beam will be used for the tuning of the accelerator and the measurement of the beam quality. Finally, the D^+ beam will be accelerated in the CW mode for the engineering validation of the IFMIF accelerator system.

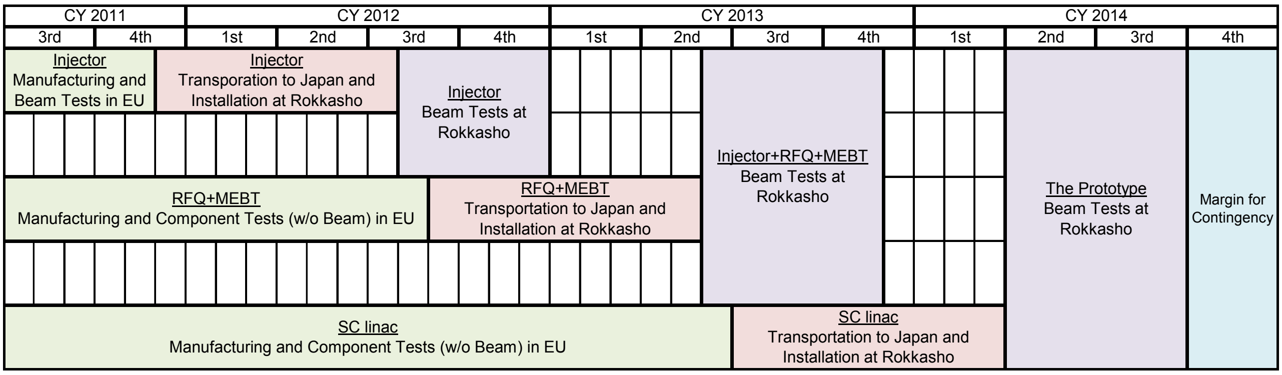

Fig.4 Schedule of the beam tests for the prototype at Rokkasho.

4. Summary

Progress of the accelerator system in the IFMIF/EVEDA project is described. Even the prototype which will be tested in Rokkasho is a challenging machine and world highest beam power same as J-PARC in Japan or SNS in US. All the subsystems of the prototype have started to be designed, settled the plan of the manufacturing and component tests and fixed the design parameters. The HWR SC linac in place of a normal-conductive Alvarez-type linac is decided to be employed as a post-accelerator of the RFQ because of some technical and financial advantages for the manufacturing and operation. As a result of the analysis of planning for the engineering validation of the IFMIF accelerator system, the project duration to be extended to the end of 2014 was approved by the 5th BA Steering Committee meeting held in May 2009.

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