STATUS OF THE IFMIF-EVEDA 9 MeV 125 MA DEUTERON LINAC

A. Mosnier, Fusion for Energy, BFD Department, Garching, Germany

Abstract

The scope of IFMIF/EVEDA has been recently revised to set priority on the validation activities, especially on the Accelerator Prototype (LIPAc) extending the duration up to mid 2017 in order to better fit the development of the challenging components and the commissioning of the whole accelerator. The present status of LIPAc, currently under construction at Rokkasho in Japan, outlines of the engineering design and of the developments of the major components will be reported. In conclusion, the expected outcomes of the engineering work, associated with the experimental program will be presented.

INTRODUCTION

The International Fusion Materials Irradiation Facility (IFMIF) aiming at generating materials irradiation test data for DEMO and future fusion power plants is based on an accelerator-driven, D-Li neutron source to produce high energy neutrons at sufficient intensity and irradiation volume. IFMIF Engineering Validation and Engineering Design Activities (EVEDA) have been conducted since mid 2007 in the framework of the Broader Approach Agreement.

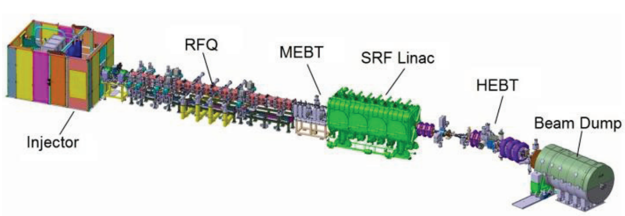

Figure 1: LIPAc layout

In order to demonstrate the feasibility and to develop the technology, a representative portion of one of the two IFMIF accelerators, up to the first section of the SRF Linac, is being designed and built. This high intensity linear accelerator prototype, called LIPAc (Fig. 1), will be assembled and commissioned at Rokkasho in Japan, with the objective to reach a stable 125 mA, 9 MeV continuous deuteron beam. These engineering validation activities are conducted since mid-2007 under the framework of the Broader Approach Agreement and are shared as follows:

- The accelerator components are designed, manufactured and tested by European institutions (CEA, CIEMAT, INFN, SCK-CEN): Injector, Radio Frequency Quadrupole (RFQ), Medium and High Energy Beam Transport lines, Superconducting RF Linac, Beam Dump, 175 MHz RF Systems, Local Control Systems, Beam Instrumentation;
- The conventional facilities (building and auxiliaries), the Central Control System, as well as the RFQ couplers, are provided by JAEA;
- The design integration and the interface management are coordinated by Fusion for Energy (F4E);
- The coordination and the integration on site are provided by the Project Team hosted in Rokkasho.

In 2010, the priority was set on the validation of the Accelerator Prototype [1] extending the duration up to mid 2017 in order to better fit the time required for the development of the challenging components and for the installation and sequential commissioning of the accelerator at Rokkasho.

ACCELERATOR COMPONENTS

Accelerator components [2] are designed, manufactured and individually tested in Europe, and then transported to Rokkasho for installation in the accelerator building.

Injector

The injector has to deliver a continuous low emittance deuteron beam (140 mA, 100 keV) with high reliability. The ion source is based on an electron cyclotron resonance cavity, excited by a 2.45 GHz magnetron [3]. The extracted beam is matched to the RFQ entrance by means of a dual solenoid focusing scheme in the LEBT. In order to meet emittance and matching requirements, the space charge must be highly compensated by injection of krypton gas and up to the RFQ entrance thanks to an electron repeller electrode. In addition, an electrostatic chopper will be implemented between the two solenoids to enable the operation of LIPAc with short pulses of very sharp rise/fall times.

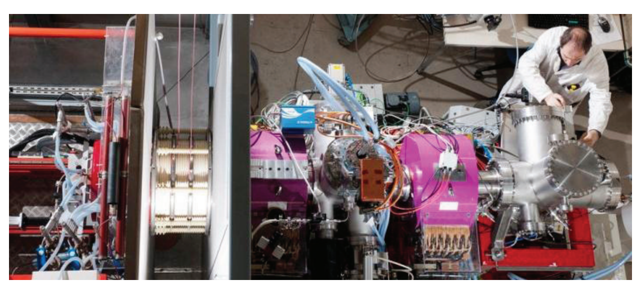

Figure 2: Top view of the Injector (P. Stroppa/cea credit).

The injector was assembled at CEA-Saclay in order to test the components in Europe before the shipment to Japan scheduled at the beginning of 2013 (Fig. 2). After the first H+ beam produced in May 2011, a test campaign was carried out in pulsed and continuous operation. Pulsed beams of 150 mA at 100 kV and continuous beams of 100 mA at 75 kV were routinely produced. The first D+ beam was extracted in April 2012, first in pulsed mode and then in continuous mode for a short period in order to limit the activation of the elements. However, as the continuous operation at 100 kV was limited by HV discharges in the extraction system, a new 5 electrode

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system (instead of the former 4 electrode system) is being installed and injector tests will start gain at the end of September 2012 to complete the optimization (ion source plasma, krypton pressure, solenoid setting) and characterize the beam emittance which should be lower than 0.25 π mm mrad.

Radiofrequency Quadrupole

The 4-vane RFQ, under development by INFN, has to bunch the DC beam from the injector and to accelerate the beam from 0.1 to 5 MeV. The 10 m long cavity is composed of 18 x 0.54 m long modules flanged together (Fig. 3). The peak surface electric field is limited to a maximum value of 1.8 x Kilpatrick's criterion.

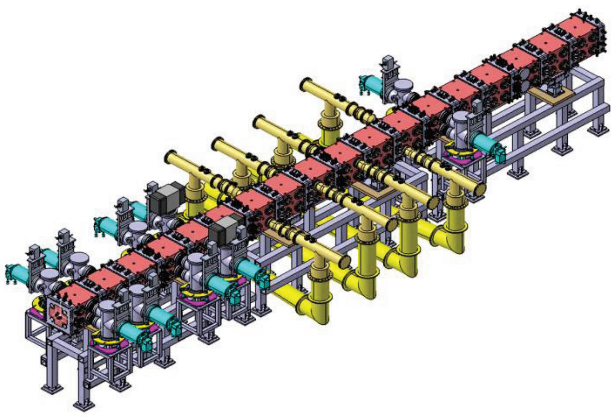

Figure 3: 3D mock-up of the RFQ equipped with RF couplers, cryo-pumps, slug tuners and cooling channels.

The RF power (about 1300 kW) is injected by 8 loop couplers, using 6 1/8" RF windows. High power tests have been performed with a high-Q load circuit at JAEA-Tokai. Final acceptance tests and RF conditioning in TW mode of two complete couplers (waveguide, window and tip modules) will be performed at INFN-Legnaro at the beginning of 2013 on a specific test bench [4] including a coupling cavity. The manufacturing of the other couplers will start just after approval of the acceptance tests.

The RF tuning of the RFQ is ensured by 22 slug tuners per quadrant. An aluminium full scale RFQ model has been built to validate the tuning procedures and the mode stabilization by means of bead-pull measurements. The tuning algorithm allowed reaching voltage errors of ±1% in 4 iterations only.

The cooling system is able to remove the dissipated power in the structure (more than 700 kW assuming 10% extra field) but also to regulate the resonance frequency and to keep the correct field profile, thanks to four independent circuits, enabling the temperature difference between the vane and the outer walls to be independently adjusted in the 3 super-modules.

A vacuum system, composed of dry primary and 10 cryogenic pumps, provides a high pumping speed to balance the gas load (dominated by beam losses), resulting in a pressure profile below 5 10^{-7} mbar all along the RFQ.

In order to test the production procedure, a full scale technological prototype (30% shorter) has been machined in INFN and brazed at CERN in two steps (1st horizontal, 2nd vertical). Leak tests and dimensional checks have been passed successfully (average vane displacement close to the target of 50 μm).

The module production [5] has been split into 3 super-modules (SM), composed of 6 modules each:

- high energy SM with homogenous aperture
- intermediate energy SM with z-dependent aperture
- low energy SM

One module of the high energy SM has been machined and brazed (Fig. 4). A maximum deformation of 100 μm has been measured, still acceptable but at the limit of the specification, and might be corrected for the next modules by using the appropriate annealing cycle and improved fixation tooling. Three modules (plus the RF plug) will be completed in November 2012 for high power tests, planned at the beginning of 2013 at INFN-Legnaro.

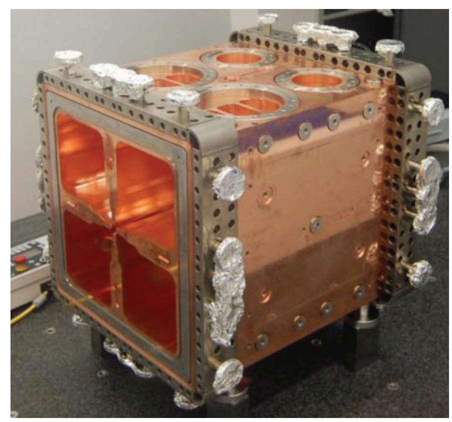

Figure 4: First RFQ module completed

SRF Linac

The high-energy section of LIPAc accelerates the beam to 9 MeV and consists of the first cryomodule (Fig. 5) of the IFMIF SRF Linac, housing eight superconducting half-wave resonators (HWR) and eight solenoid packages. The main cavity and magnet parameters are listed in Table 1.

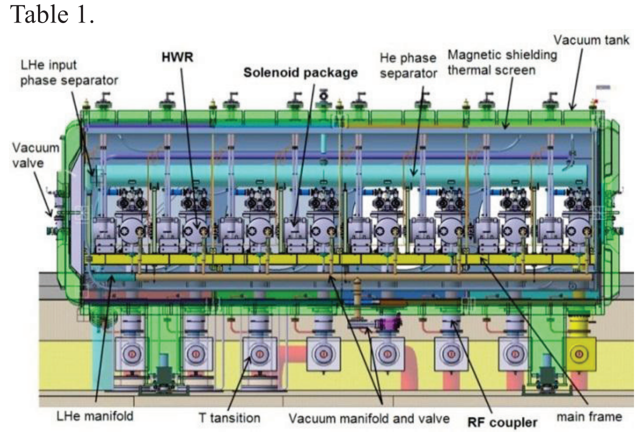

Figure 5: 3D mock-up of the LIPAc Cryomodule

RF optimisation of the HWR geometry lowered the electric and magnetic peak surface fields down to E_p/E_{acc}=4.4 and B_p/E_{acc}=10.1 mT/MV/m.

Table 1: Main Parameters of Cavity and Solenoid

Frequency	175	MHz
Cavity β	0.094	
Accelerating field Eacc	4.5	MV/m
Quality factor Qo	$1.4\ 10^9$	
Max. forward Power / coupler	200	kW
Max. Tuning range	± 50	kHz
Beam aperture cavity/solenoid	40 / 50	mm
Magnetic field Bz on axis	6	T
Field at cavity flange	≤ 20	mT

The original design of the tuner relied on a capacitive plunger with a large membrane to allow an elastic deformation of ±1 mm. Two prototype cavities have been fabricated (Fig. 6) and tested at cold temperature. Unfortunately, results showed a low Qo, as well as a quench at low field, pointing to a suspect plunger. In addition, potential problems occurring in the main cavity body cannot be also ruled out [6]. Following up the recommendations of a Review Panel, a new design based on a conventional compression tuner principle is under development [7]. Given the rigidity of the present resonator design, this solution implies a lengthening of the cryomodule lattice (about 10 cm) to ease the integration of the tuner between the HWR tank and the solenoid package.

Figure 6: HWR prototype.

The RF coupler [8] is composed of a water-cooled Cu antenna, a disk ceramic window, an external conductor made of helium cooled double wall tube and a tee transition between the input coaxial line and the coupler, including a duct for the cooling water. Pairs of couplers will be tested and conditioned at room temperature by means of a coupling box, especially developed to achieve large bandwidth and low losses. Two prototype couplers have been fabricated (Fig.7, left) and will be tested when the 200 kW RF source will be available, planned at the end of 2012.

The beam focussing and orbit corrections are performed by 8 sets of superconducting solenoids/steerers and beam position monitors, located before each HWR. The NbTi solenoid includes an active shielding made of a concentric outer solenoid in antiparallel configuration to lower the stray field below 20 mT at the cavity flanges. During the cold tests at 4.2K performed in a vertical cryostat (Fig. 7, right), the theoretical critical current of the magnet was reached (at about 260 A, well above the nominal current of 210 A) with a very short training [9].

The design of the cryomodule is now almost completed: cavity vacuum and cryostat insulation vacuum are separated in order to ensure a good vacuum quality. The 5-m long cryostat includes the magnetic shielding to protect the HWR from the earth magnetic field, two independent 4.5K helium circuits to cool down the cavities and the magnets, a helium phase separator and a thermal shield cooled at 60K by GHe.

Figure 7: coupler prototype (left) solenoid test (right).

MEBT, HEBT and Beam Dump

Five quadrupoles and two bunchers in the MEBT [10] fulfil the transverse and longitudinal matching conditions of the RFQ output beam to the SRF input (Fig. 8). A prototype magnet has been fabricated and validated in a magnetic test bench. A 5-gap IH buncher meets the voltage requirement (350 kV) with a minimum RF power dissipation. A prototype buncher is under fabrication and power tests are planned at mid-2013. The beam halo and out-of-energy particles coming from the RFQ are stopped in two movable scrapers, designed for a maximum 500 W

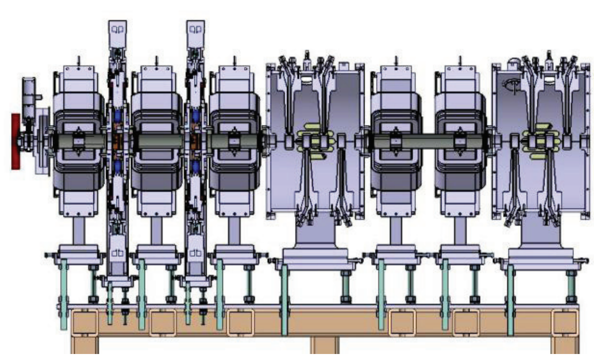

Figure 8: Medium Energy Beam Transport line.

The HEBT (Fig. 9) which transports the beam from the Linac to the beam dump includes the following elements:

- a Diagnostics Plate for the beam characterization
- a bending magnet to reduce the neutron radiation from beam dump towards upstream components
- a magnetic beam expander to limit the power density on the beam dump (< 200 kW/cm^2)
- a lead shutter, closed during beam shutdown to act as a gamma shield from the activated beam dump
- a beam scraper to protect the last portion of the vacuum pipe in front of the beam dump.

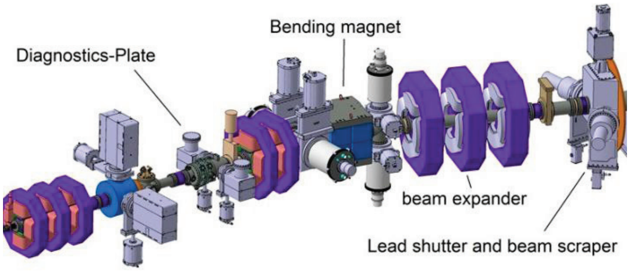

Figure 9: High Energy Beam Transport line.

A conical dump [11] made of copper has been designed to stop the 1.125 MW deuteron beam (Fig. 10). It is cooled by a high velocity water flow that circulates through an annular channel along the outer surface of the cone. Thermo-mechanical studies showed a high robustness to beam errors, CW and pulsed mode operation, buckling and high velocity coolant flow effects. A local shielding made of water tanks and polyethylene against neutrons and iron blocks against gamma rays associated with an extra frontal shielding made of a 70 cm thick concrete wall to fulfil the radiological protection requirements: low dose rates outside the accelerator vault during accelerator operation and manual maintenance inside the accelerator vault possible during beam-off phases. The HEBT and the beam dump are in the final stage of detailed design, and cartridge prototypes have been built. Hydraulic test of a full scale cartridge is on-going. Integration and test of the complete beam dump is planned at mid-2013.

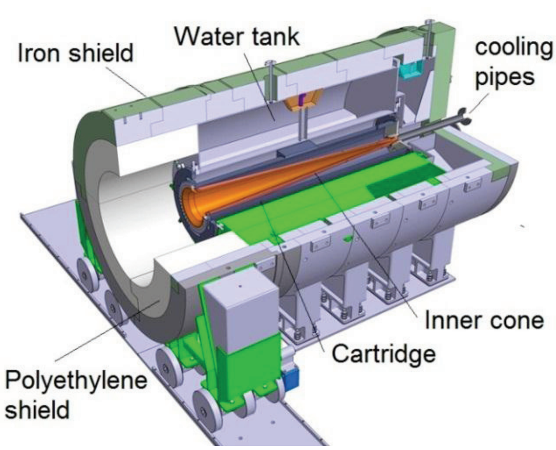

Figure 10: Beam Dump.

RF Power Systems

The RF Power System [12] is composed of 18 RF power generators to feed the 8 RFQ couplers (200 kW), the 8 superconducting half wave resonators of the SRF Linac (105 kW) and the 2 buncher cavities (16 kW). Except for the buncher cavities, which are fed by full solid-state amplifiers, the same topology has been chosen for all the power chains for standardization and scale economy reasons: they use the same main components (solid-state pre-driver and tetrodes for driver and final amplifier) which can be individually tuned to provide different RF output powers up to 200 kW (Fig. 11). The first prototype 200 kW RF source will be ready by the end of 2012 and will be used for the testing and conditioning of the HWR couplers while the first 2 x 100 kW RF module is expected at the beginning of 2013. The 16 kW solid-state amplifier should be ready for the high power tests of the buncher cavities at mid-2013.

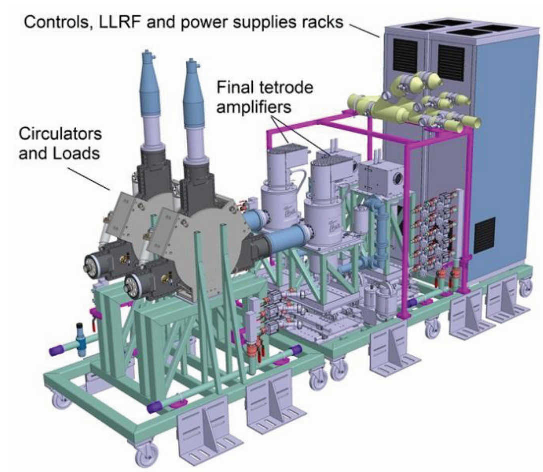

Figure 11: RF module with two 100 kW amplifiers.

Beam Diagnostics

A full set of non-interceptive diagnostics [13] to monitor and to characterize the beam all along the accelerator has been developed (Fig. 12): current monitors of various types (ACCT, DCCT, FCT), 20 beam position monitors (8 of them at cryogenic temperature), beam profile monitors (based on ionization and fluorescence of the residual gas), about 40 beam loss monitors (ion chamber LHC type), micro-loss monitors (based on CVD diamond operating at cryogenic temperature) and a bunch length monitor (residual gas). For short chopped beam pulses, SEM grids and slits will be used for emittance and energy spread measurement.

In addition, a Diagnostic plate (D-Plate) combines specific diagnostics to characterize the beam during commissioning with the beam, and will be located first at the exit of the RFQ and MEBT and second at the exit of the SRF Linac during LIPAc normal operation (Fig. 13).

The Control System (including Central Control System, Local Area Network, Personnel Protection System, Machine Protection System, Timing System, Local Control System) based on EPICS, is in progress [14].

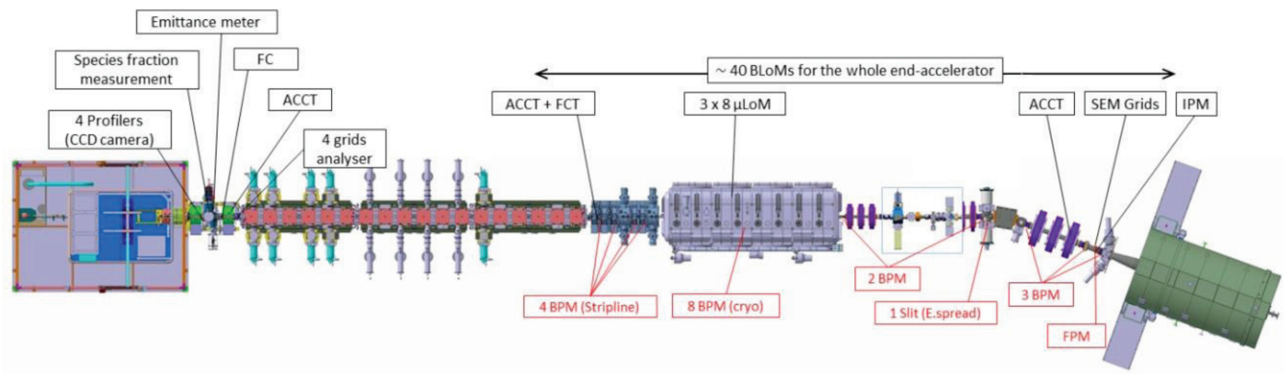

Figure 12: Beam instrumentation along the accelerator.

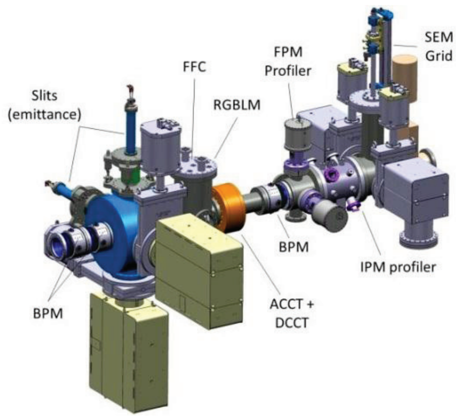

Figure 13: Diagnostics Plate.

ACCELERATOR BUILDING

The building (Fig. 14), completed in Rokkasho in March 2010, consists of an accelerator vault, a nuclear heating, ventilation and air conditioning (HVAC) area, a heat exchange and cooling water area for both radiation controlled and non-controlled areas, an access room, a control room, and a large hall for power racks, RF systems (HVPS and RF power chains) and the 4K refrigerator. The accelerator vault is surrounded by 1.5 m thick concrete walls and ceiling. The installation of the main auxiliaries has been completed and the first accelerator component, the injector, will be delivered and installed at the beginning of 2013.

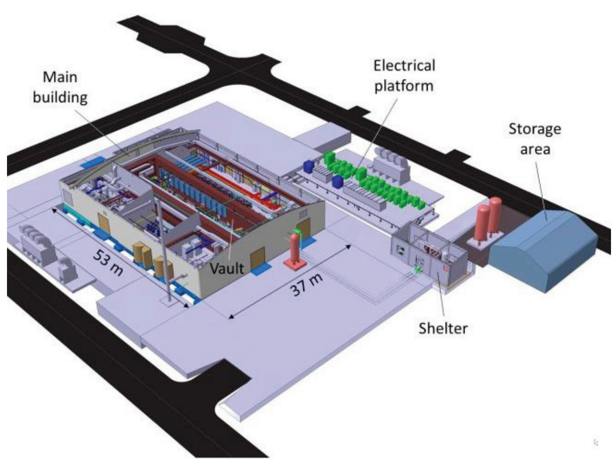

Figure 14: Building mock-up.

ACKNOWLEGMENT

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