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CRYOMODULE DEVELOPMENT FOR MATERIALS IRRADIATION FACILITIES: FROM IFMIF/EVEDA TO IFMIF-DONES

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Abstract

For several years, CEA has been involved in the development of superconducting linac for high flux neutrons sources aiming at testing and qualifying specific materials to be used in fusion power plants. In the framework of the ITER Broader Approch, a prototype cryomodule is under construction in Japan for the IFMIF/EVEDA phase (Engineering Validation and Engineering Design Activities) and the construction of the Accelerator Prototype (LIPAc) at Rokkasho, fully representative of the IFMIF low energy (9 MeV) accelerator (125 mA of D+ beam in continuous wave). Meanwhile, the design studies of a plant called DONES (Demo Oriented Neutron Source, derived from IFMIF) started. The superconducting linac is based on the same principles as the one developed for IFMIF/EVEDA, but taking into account the lessons learnt from the accelerator prototype. This paper presents the similarities but also the differences between the linacs and cryomodules for IFMIF/EVEDA and IFMIF-DONES.

INTRODUCTION

The mission of International Fusion Materials Irradiation Facility IFMIF is to provide an accelerator-based, D-Li neutron source to produce high energy neutrons at sufficient intensity and irradiation volume to test samples of candidate materials up to about a full lifetime of anticipated use in fusion energy reactors.

Because of the challenging characteristics of the IFMIF accelerator – 125 mA CW D+ beam up to 40 MeV – is has been decided to have a staged approach, with a first step called Engineering Validation and Engineering Design Activities for the International Fusion Materials Irradiation Facility (IFMIF/EVEDA). This project is one of the three projects of the Broader Approach (BA) agreement between the Japanese government and EURATOM. The goal is to provide the detailed engineering design of the IFMIF and to validate the technological challenges on the major components with the construction of the Linear IFMIF Prototype Accelerator (LIPAc) at Rokkasho, in Japan. The LIPAc shall validate the low energy section of the IFMIF accelerator, including the first cryomodule housing accelerating superconducting cavities, by accelerating the 125 mA CW D+ beam up to 9 MeV.

The need of a neutron source for the qualification of materials to be used in future fusion power reactors have been recognized in the European (EU) fusion programme for many years. The construction and exploitation of this facility is presently considered to be in the critical path of DEMO. This issue prompted the EU to launch activities for the design and engineering of the IFMIF-DONES (International Fusion Materials Irradiation Facility-DEMO Oriented Neutron Source) facility in parallel with the construction and operation of LIPAc.

IFMIF/LIPAC AND IFMIF-DONES SUPERCONDUCTING LINACS

In LIPAc [1], the deuteron beam delivered by the high-intensity injector is accelerated by the Radio Frequency Quadrupole (RFQ) and the superconducting linac (SRF Linac) to respectively 5 and 9 MeV. Beam lines inserted along the accelerator allow to transport, shape and match the beam to maximize the transmission through the successive components, with the ultimate goal to damp the 1.125 MW beam into the dedicated Beam Dump. The SRF Linac mostly consists of one cryomodule that houses eight superconducting cavities (β=0.091, called "low-beta cavities" hereafter) to accelerate the beam and eight superconducting solenoids to focus it.

The IFMIF-DONES accelerator consists of a section similar to LIPAc with the addition of four cryomodules in order to increase the energy from 9 to 40 MeV. To optimize the efficiency of the SRF Linac, two first cryomodules are equipped with low-beta cavities and the three others with high-beta cavities (β=0.18) [2]. A High Energy Beam Transport (HEBT) line transports and shapes the beam from the SRF linac towards a lithium target to produce the neutron beam. A second line to a beam dump is used during the commissioning phase of the accelerator (Figure 1). Details on each sub-system of the IFMIF-DONES accelerator could be found in [3].

THE IFMIF/EVEDA CRYOMODULE

The IFMIF/EVEDA cryomodule is designed to be as short as possible to meet the beam dynamics requirements. As shown in Figure 2, it is made of a rectangular section vacuum vessel, a warm magnetic shield, a thermal shield and a cold mass. The temperature of this one is 4.45 K (temperature of liquid helium at the pressure of 1.25 bar), while the thermal shield is cooled using cold helium gas from the phase separator (estimated shield temperature around 50 K).

The cold mass is made of the cavity string supported by a titanium frame and a cryogenic circuit to cool down the superconducting components to liquid helium temperature. There are two independent supply lines, one for the cavities and one for the solenoids. The gas boil-off is recovered inside a common upper main phase separator vessel collecting both the cavity and solenoid helium. The main part of the cold gas is then returned towards the cold box, and a small fraction is used to cool down the thermal shield.

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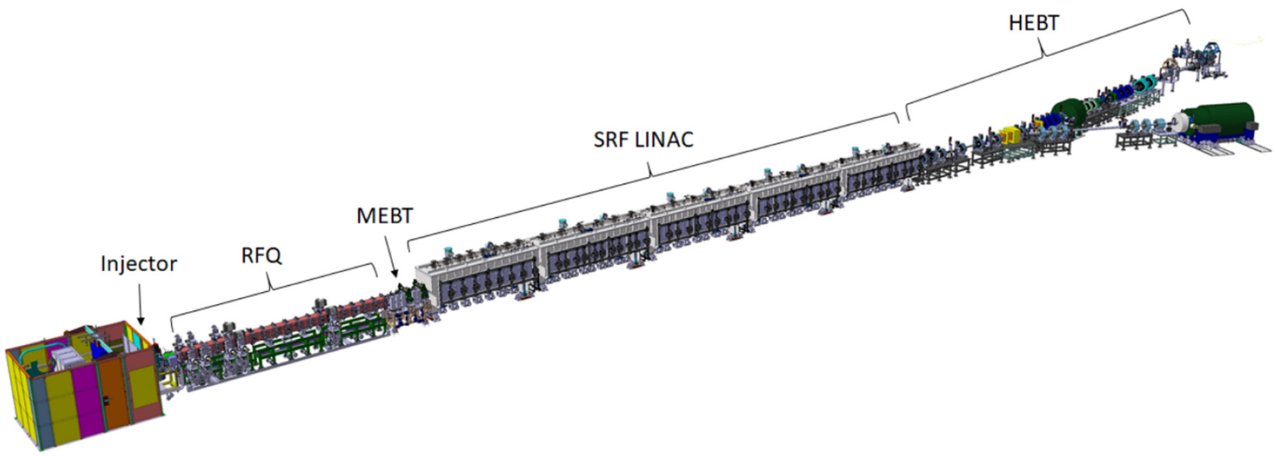

Figure 1: Layout of the IFMIF-DONES accelerator.

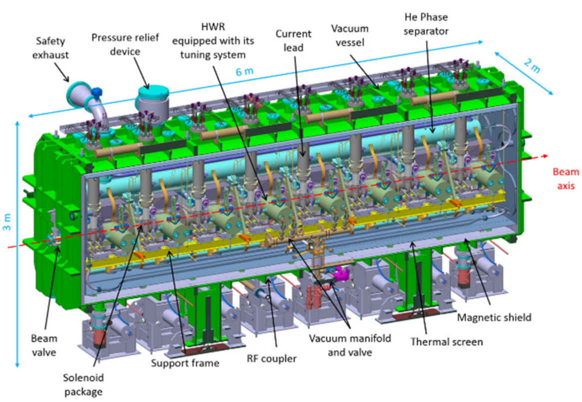

Figure 2: Overview of the IFMIF/EVEDA cryomodule.

The cold mass is hang to the top of the vacuum vessel thanks to ten vertical tie rods made of titanium alloy TA6V (titanium grade 5). It is possible to adjust the vertical position of the cold mass in the vessel by tuning the force on each rod. Four horizontal tie rods allow setting the position of the cold mass in horizontal plane of the vacuum vessel (Figure 3).

The cavity string is made of eight 176 MHz low-beta half-wave resonators with their power couplers [4], eight focusing solenoids - each equipped with beam position monitors (BPMs) [5]. All the elements are placed on a frame made of titanium grade 2. Because of the thermal shrinking of the 5.5 meter long frame during the cool down of the cryomodule - about 8.4 mm – it is not possible to directly attach the cavities and the solenoids on this one in order to be compatible with the couplers which are in interface not only with cold cavities but also the room temperature vacuum vessel.

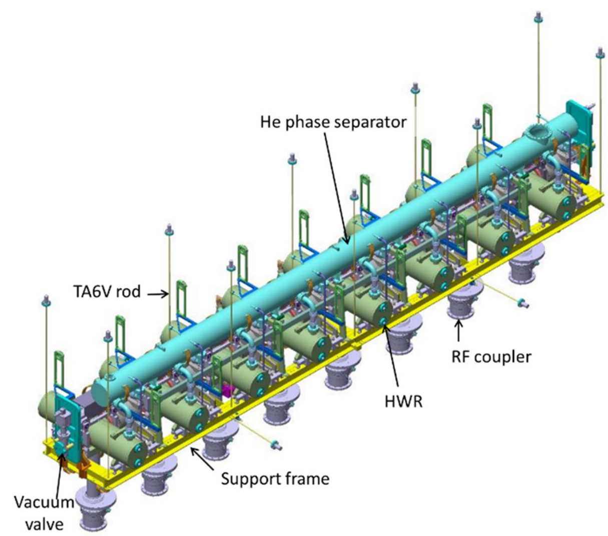

Figure 3: Cold mass of the IFMIF/EVEDA cryomodule.

To leave the cavities and solenoids longitudinal position independent from the titanium frame, C-shaped elements with needle rollers and spring washers are used. Each cavity and each solenoid is fixed on an invar rod which is attached to the frame in its centre. Because of the low thermal expansion coefficient of invar (0.4 mm/m between ambient temperature and liquid helium temperature to compare to 1.5 mm/m for titanium), this invar rod fixture determines the longitudinal positions of the couplers. The C-shaped elements also assure a fine alignment of the cavities and solenoids around the beam axis with accuracy of ±1 mm and ±10 mrad for the solenoids and of ±2 mm and ±20 mrad for the cavities. The cavity alignment is particularly critical for the power couplers which are rather long (70 cm). The coupler is connected to the vacuum tank through a flexible bellows and to a RF line. A deformation of the bellows or a small force in the RF line connection could drive to a turning moment, which could affect the cavity alignment. The force of the spring washer has been calculated to balance this resulting moment and to keep the cavity alignment.

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The support frame enables to hold together all the cold mass components from the first assembly steps in clean room to the final assembly inside the vacuum tank. It aims to minimize the handling of a heavy cold mass (around 2.5 tons) and to avoid as much as possible to damage the components. It also allows assembling the cold mass and adjusting the component alignment outside the vacuum tank. The cryomodule is for that reason designed in two main sub-assemblies as illustrated in Figure 4: the cold mass and the vacuum vessel fitted with the magnetic shield and the thermal shield. The cold mass is inserted inside the vacuum vessel from the side and then attached to the vessel with the tie rods.

Note that the vacuum vessel is outfitted with large lateral trapdoors that allow the access to the cold mass to carry out various controls during its installation. These trapdoors also allow the maintainability of the cold mass after the installation of the cryomodule in the accelerator vault in Rokkasho.

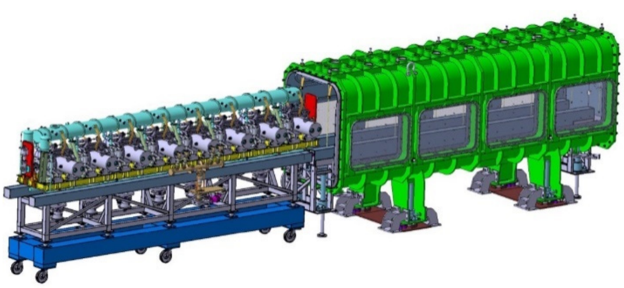

Figure 4: The two main sub-assemblies before the insertion of the cold mass inside the vacuum vessel.

THE IFMIF-DONES CRYOMODULES

The IFMIF-DONES superconducting linac is made of five cryomodules. The first one is identical to the IFMIF/EVEDA cryomodule and houses the low-beta cavities. The second also houses low-beta cavities but the number is different, as for the solenoids. The three other cryomodules are identical and houses high-beta cavities. Note that the solenoids are identical whatever the type of cryomodule. The number of cavities and solenoids for each cryomodule is presented in Table 1.

Table 1: Parameters of the cryomodules of the IFMIF-DONES superconducting linac.

Cryo-module	Output energy	Solenoids	Cavities	Type of cavities
CM1	8.3 MeV	8	8	Low-β
CM2	13.9 MeV	6	11	Low-β
CM3	21.3 MeV	5	9	High-β
CM4	30.3 MeV	5	9	High-β
CM5	40 MeV	5	9	High-β

Thanks to the developments already performed in the IFMIF/EVEDA project, as-built dimensions of the SRF Linac components (low beta cavities, solenoids, RF power couplers, cold-warm transitions, etc.) are available. Consequently, dimensions of the second cryomodule (equipped with low-beta cavities too) can be precisely defined.

For the other cryomodules, as the development and qualification of high beta cavities is in work [6], only the RF design is available. However, thanks to our experience on frequency tuners, space has been reserved allowing to extrapolate the length of the high beta cryomodules, considering that the other beam line components are identical for all the cryomodules. Because the high-beta is cavity is bigger than the low-beta one, the power coupler for the high beta cryomodules needs to be shortened by 70 mm to keep enough space below the vacuum vessel to install the RF transition between this one and the coaxial line coming from the RF power source.

From previous experiences in design and/or fabrication of QWR and HWR cryomodules (SPIRAL2, IFMIF/EVEDA, SARAF-Phase II) [7], it is concluded that the insertion of the cold load into the vacuum vessel following a “top loading” approach has several advantages with respect to the “side loading” one used for the IFMIF/EVEDA cryomodule.

The “side loading” requires rails for the insertion of the cold mass inside the vacuum vessel. For the IFMIF/EVEDA cryomodule, which is around 6-meter long, it has been difficult to leave room for them at the bottom of the frame. Indeed, because the bending of the rails shall be minimized in order to avoid stressing too much the bellows of the cavity string and tilting too much the couplers, the rails are big, heavy and difficult to handle. As the IFMIF-DONES high beta cryomodules are a bit longer than the IFMIF/EVEDA cryomodule and with less space for the insertion rails due to shorter power couplers, it becomes inappropriate to use the same assembly process.

With the “side loading” configuration, many operations shall be performed to complete the assembly after the insertion of the cold mass inside the vacuum vessel: installation of the current leads, connection of the remaining elements of the helium circuitry, connection of the instrumentation and the beam diagnostics, completion of the multilayer insulation of the cold mass, closing the doors of the thermal screen, the magnetic shield and the vacuum vessel doors. Some operations have to be done through the lateral trapdoors of the vacuum vessel with small access room for the operators. With a “top loading” configuration, all these operations are performed before the insertion of the cold mass inside the vacuum vessel are all the interfaces but the power couplers and the beam valves are only with the top plate of the vacuum vessel and not the main body.

The design principle of the IFMIF-DONES is presented in Figure 5 and Figure 6. Except the vacuum vessel, most of the other components are similar to the IFMIF-EVEDA cryomodule. The cavity string is supported by a titanium frame. The cold mass is attached to the top plate thanks to titanium alloy tie rods and horizontal tie rods fix the horizontal position in the vessel. To avoid difficulties faced during the manufacturing of the IFMIF/EVEDA with the magnetic shielding and its interfaces with the vacuum ves-

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sel, it has been decided not to fix every panels of the magnetic shield on the vessel inner surface, but to have a "floating" shield between the vacuum vessel and the thermal shield [8].

Another major difference between the cryomodules of the two projects is the cryogenic distribution system. For IFMIF/EVEDA, the cryogenic system provides saturated liquid helium at the nominal temperature of 4.45 K. However, evaporation of liquid occurs in the transfer line, between the cold box and the valve box equipped with the cryogenic valves needed for the operation of the cryomodule that is installed close to it. This may lead to two-phase flow instability. To avoid this harmful situation, a small phase separator is also installed in the valve box.

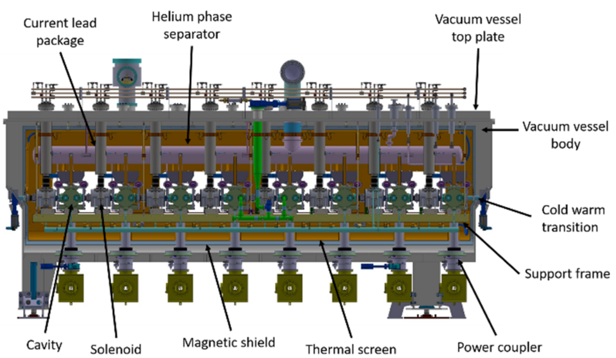

Figure 5: Overview of the IFMIF-DONES cryomodules (example of the first low-beta cryomodule CM1, the design principle is similar for the others).

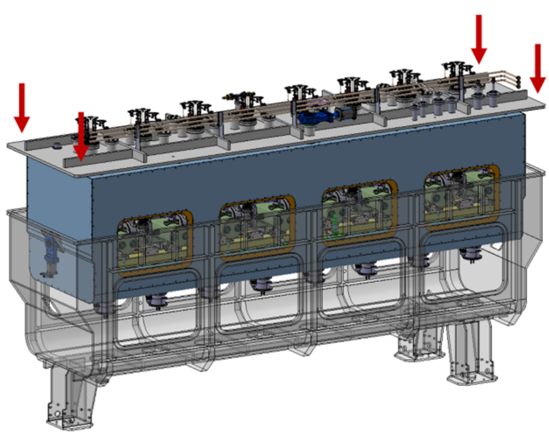

Figure 6: Insertion of the cold mass inside the vacuum vessel for the IFMIF-DONES cryomodules.

For the IFMIF/DONES superconducting linac, the cold box will produce supercritical helium (6 K / 5 bars) in order to prevent the emergence of two-phase flow inside the transfer line. The production of saturated liquid helium at 4.45 K (1.25 bar) for the superconducting cavities and solenoids is performed inside the valve box installed close to each cryomodule thanks to the expansion of supercritical helium through a Joule-Thomson (JT) valve (Figure 7). Last, the thermal shield will be cooled down to a temperature between 60 K and 70 K using pressurized cold helium gas delivered by the cold box.

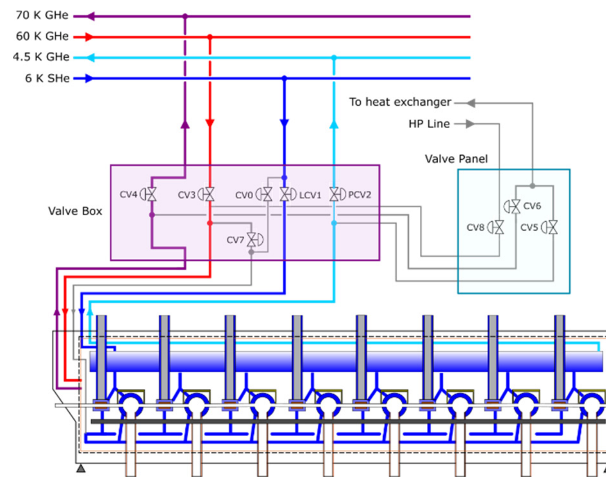

Figure 7: Principe of the cryogenic circuits of the IFMIF-DONES cryomodules with the flow of fluids in nominal operation. Note that LCV1 is the Joule-Thomson valve and that the valves needed for the cool-down process are also represented.

MAGNETIC HYGIENE: LESSONS LEARNT FROM IFMIF/EVEDA

The main feedback from the manufacturing of the IFMIF/EVEDA cryomodule components is on the magnetic hygiene. The residual magnetic field around the superconducting cavities is a crucial factor for their performances. Indeed, a superconducting cavity can trap magnetic flux while cooling down through transition, increasing the residual surface resistance of the niobium.

Moreover some components inside the cryomodule could be magnetized by the fringe field of the solenoids. As long as the cavity stays in the superconducting state, the performances are not affected. But in case of a cavity quench, flux may be trapped, reducing the performances. Therefore all the parts which could be magnetized near the cavity areas where the magnetic field is the highest shall be in non-magnetic material as far as possible.

Several mitigation actions taken on the IFMIF/EVEDA cryomodule [9] will be applied on the IFMIF-DONES ones: the support frame will be made of titanium welded beams instead of stainless steel beams as experience showed that the permeability of the weld rim may be higher than expected even for 316L stainless steel. Homemade needle bearings will be used instead of off-the-shelf ones as measurements performed on samples showed that these ones are magnetized [10]. When magnetic materials must be used, like invar which is ferromagnetic and can be magnetized [11], mitigations using magnetic foils could be investigated in order to limit the magnetic pollution.

For the parts of the IFMIF/EVEDA cryomodule made of 316L stainless steel a magnetic hygiene plan was set:

- Identification of the parts close to the cavities which could cause magnetic pollution.
- Material specification and certifications.
- Incoming material inspection.
- Inspection after manufacturing.

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Nevertheless, it was not sufficient as several problems occurred during the manufacturing:

- Procurement of the raw material for the thick plates needed for the cold-warm transitions was tedious, because required magnetic permeability below 1.02 was difficult to reach without annealing which often induced deformations of the plates during the process.
- Rods meeting the requirements on the magnetic permeability were used for the flanges of the cryogenic pipes. But after machining, some were non-compliant and required annealing before being welded on tubes. However, the annealing process was not completely successful for all the parts.
- Even if fully austenitic filler metal have been used during the welding process to avoid magnetic phases in the weld rims, the magnetic permeability was over the required value of 1.02 on some rims.
- For some parts of the C-shaped elements, despite all the corrective actions, the magnetic permeability value was too high on most of the final parts. New procurements of parts made of titanium had to be launched.

Based on these experiences, it is planned to make the parts close to the cavities and solenoids (piping, C-shaped elements, tuning system) out of 316LN stainless steel or titanium.

CONCLUSION

Taking into account the feedback on manufacture of the components of the LIPAc SRF Linac as well as the development of specific pieces of cryomodules for other projects of accelerators, we are implementing improvements into the design of the 5-cryomodules of the IFMIF-DONES SRF linac in several aspect (mechanical, thermal, cryogenic, integration, quality assurance and quality control …). It is anticipated that other changes will be desirable or even necessary in the future, once the assembly at Rokkasho of LIPAc cryomodule is complete, and more likely after the commissioning with CW high intensity beam.

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