PRELIMINARY RESULTS OF THE IFMIF CAVITY PROTOTYPES TESTS IN VERTICAL CRYOSTAT AND CRYOMODULE DEVELOPMENT

F. Orsini, N. Bazin, P. Bosland, P. Brédy, P. Carbonnier, P. Charon, G. Disset, N. Grouas, P. Hardy, V. Hennion, E. Jacques, H. Jenhani, J. Migne, Y. Penichot, J. Plouin, J. Relland, B. Renard, D. Roudier, CEA, F-91191, Gif-sur-Yvette, France
F. de Aragon, J. Calero, J. de la Gama, J.L. Gutierrez, I. Podadera, S. Sanz, F. Toral, CIEMAT, 28040 Madrid, Spain
E. Zaplatin, FZJ, 52428 Jülich, Germany

Abstract

In the framework of the International Fusion Materials Irradiation Facility (IFMIF), which consists of two high power CW accelerator drivers, each delivering a 125 mA deuteron beam at 40 MeV [1], a Linear IFMIF Prototype Accelerator (LIPAc) is presently under design for the first phase of the project. A superconducting option has been chosen for the 5 MeV RF Linac, based on a cryomodule composed of 8 low-beta Half Wave Resonators, 8 Solenoid Packages and 8 RF couplers. This paper will mainly focus on recent tests in laboratory of the main components of this cryomodule: HWR, RF coupler mock up, and solenoid prototypes. A section is dedicated to the HWR activities: realization and preliminary vertical tests of the two HWR prototypes. One prototype was equipped with the innovating cold tuning system, located in the central region of the cavity. Another section gives results on RF coupler'mock-up and solenoids prototypes. Finally, the LIPAc cryomodule current design is also presented.

INTRODUCTION

The main purpose of the LIPAc project [2] is to validate all the technical options for the construction and commissioning of this accelerator prototype, with a full scale of one of the future IFMIF accelerator, from the injector to the first cryomodule of the SRF Linac. The main requirements for the LIPAc project are as follow:

- Energy of D+ beam on beam dump: 9 MeV
- RF Frequency: 175 MHz
- Beam intensity: 125 mA
- Output rms long. emittance: < 0.55 π.mm.mrad, and < 0.35 π.mm.mrad in transverse.

The general layout of the LIPAc is illustrated in Figure **1**. The LIPAc cryomodule is the most difficult one, essentially due to the short drift lengths between components and small interfaces between sub-systems, in order to design a cryomodule as compact as possible to fulfil the beam dynamics requirements in the case of intense beam [3].

The goals of the cryomodule are to transport and accelerate the deuteron beam of nominal intensity, in continuous wave (CW), with energy from 5 MeV up to 9 MeV at the output of the linac. Good performances in terms of transverse and longitudinal emittances are necessary to fit with the 300 mm diameter aperture at the Beam Dump entrance, and the future footprint for IFMIF: 200 mm × 50 mm, without beam loss (< 1 W/m).

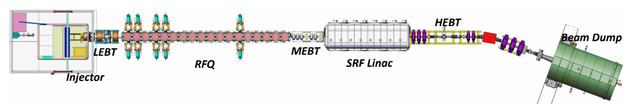


Figure 1: General layout of the accelerator prototype in the vault at the Rokkasho site.

GENERAL DESCRIPTION

The cryomodule is a complex system, due to the huge number of components sharing cryogenics circuits. The cryomodule consists of a horizontal vacuum tank of around 5 m long, ~2.8 m high and ~2.0 m wide, which includes the following elements:

- 8 low-β HWRs with a frequency tuning system,
- 8 RF power couplers,
- 8 Solenoid Packages (including solenoids, H&V steerers and cryo-Beam Position Monitors),
- A cryostat (vacuum tank) with access traps,
- Supports and alignment system,
- Cryogenic, vacuum and electrical systems,
- Magnetic shielding and thermal screen.

The cryomodule under development is illustrated in Figure 2. Main parameters of this cryomodule are summarized in the following Table 1.

Table 1: Summary of cryomodule parameters.

Parameters	Target Value	Units
β value of the HWR	0.094	
Accelerating field E_{acc}	4.5	MV/m
Unloaded Quality factor Q_0 for R_s=20 nΩ	1.4×10^9	
Beam aperture HWR / Solenoid Package	40 / 50	mm
Freq. range of HWR tuning syst	± 50	kHz
Max. transmitted RF power by coupler (CW)	200	kW
External quality factor Q_{ex}	6.3×10^4	
Transmission Lines for HWR	coax 6" 1/8	
Magnetic field B_z on axis max.	6	T
∫ B.dl on axis	≥ 1	T.m
Field at cavity flange	≤ 20	mT
BPM position accuracy	0.25	mm

BPM phase accuracy	2	deg
Total Static/Dynamic Heat losses	25+34/54+10	W+l/h

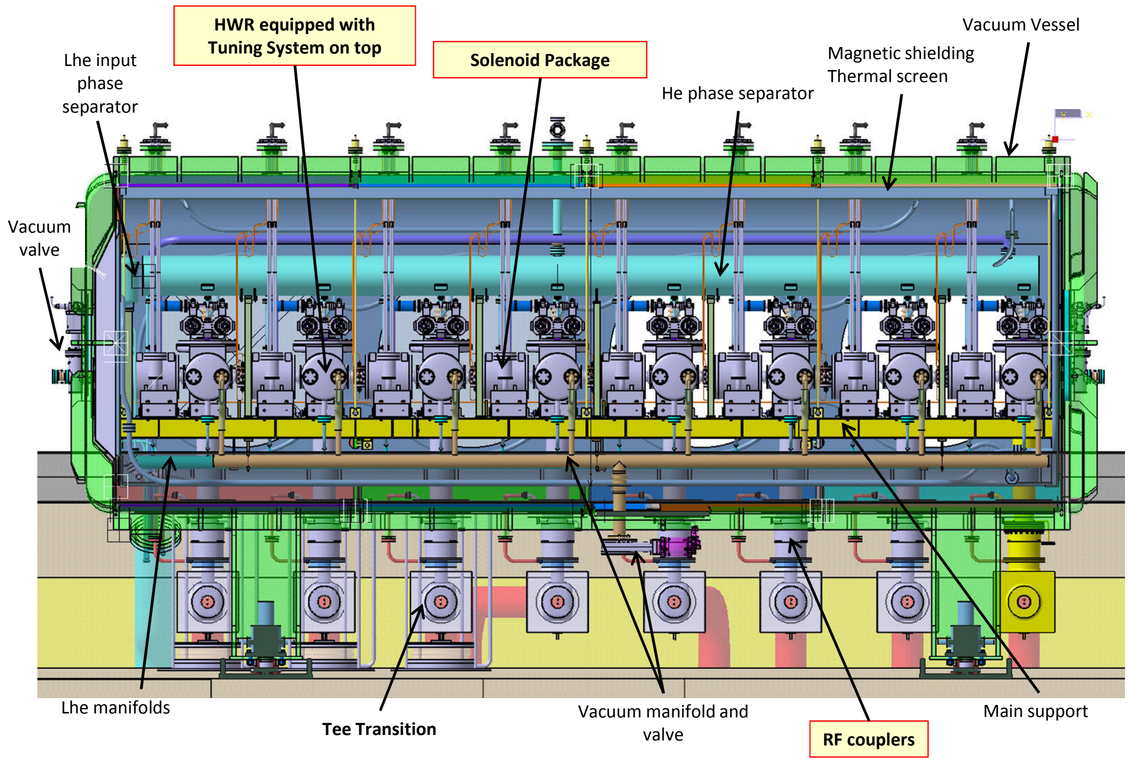


Figure 2: General layout of the LIPAc cryomodule.

PRELIMINARY RESULTS OF VERTICAL TESTS OF LOW-β HWR PROTOTYPES

General Description of Low-β HWR Equipped with Tuning System

The RF and mechanical design of the low-β HWR has already been presented in other papers [4] and [5]. The RF design has been optimized to reduce peak fields on the cavity surface (E_{pk}/E_{acc}=4.42 and B_{pk}/E_{acc}=10.12 mT/MV/m) and to minimize the resonant frequency dependence on the external pressure fluctuations (df/dp=0.04 Hz/mbar). The cavity is made in pure niobium, fixed in a titanium vessel, with NbTi flanges. The cavity is cooled with liquid helium at 4.4 K.

The tuning system is based on a capacitive plunger installed in the electric field region, perpendicular to the beam axis. To avoid an enhancement of E_{pk}/E_{acc}, the capacitive gap is kept low (4 mm plunger penetration in the cavity volume). To achieve the required tuning sensitivity (>50 kHz/mm), the plunger diameter is 100 mm.

The plunger is connected to a flexible membrane (1.5 mm thick) via a 5 mm stem. The whole tuner structure is dismountable from the cavity body (see drawing of cavity Figure 2). The tuning force is applied to the tuner stem. The membrane will be deformed in the range of ±1 mm. For mechanical reason, the membrane is made in NbTi alloy, whereas the plunger and stem are made in Nb. Indeed, during leak tests of HWR, the thin membrane has to support external atmospheric pressure strength, whereas the cavity is under vacuum.

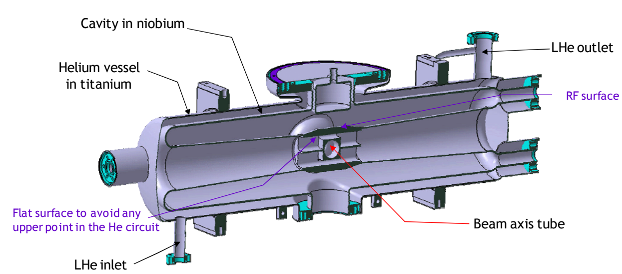


Figure 3: Final drawing of the HWR prototype.

Preliminary Vertical Test Results

Two prototypes have been realized with success in 2010 by 2 different manufacturers. For the vertical tests, the 2 prototypes have been prepared identically: BCP treatment to remove ~ 130 µm of Nb, HPR procedure with 100 bars multi-jets and assembly of coupling antenna and valve in clean room (ISO 4).

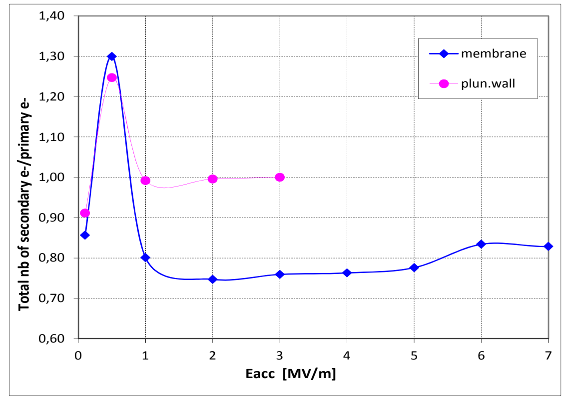
Figure 4: HWR prototype preparation for tests in vertical cryostat.

Vertical test of cavity, without helium vessel, and without tuning system:

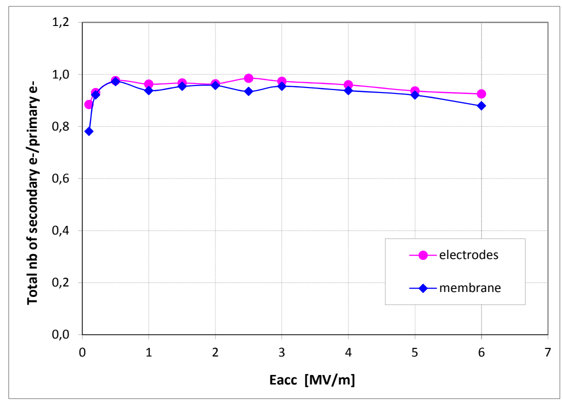
Due to the long delay of raw material provisioning for the membrane of the tuner, first tests were performed with a temporary Nb membrane (and temporary gasket), instead of the real NbTi membrane welded to the Nb plunger. This temporary solution caused problems of vacuum leakages at cold temperature, when cavity was in the helium bath of the cryostat at 4.2 K.

During tests performed on both prototypes, several multipactor (MP) barriers were observed starting at very low accelerating field (1^{rst} barrier at ~12 kV/m). This 1^{rst} barrier could not be passed easily, and because the coupling of antenna was fixed and not optimized, the validation test has failed after few days of attempts. According to 3D simulations, these MP barriers were predicted in the area of E_{acc}: 0→1 MV/m (see Figure 5(a) where the ratio secondary e- over primary e- is above 1). Indeed, with the cavity configuration without plunger and coupler, large apertures, remaining empty, offer volumes where resonance conditions for MP are favourable (lots of space available for a certain length of particle trajectories at low field level able to gain the required energy for secondary electron's ejection).

Nevertheless, Q_0 of cavity was measured at 1.4×10^9, with E_{acc} positioned just before the 1^{rst} MP barrier, and this value is in agreement with the theoretical one.



(a)



(b)

Figure 5: Multipactor simulations for a cavity without plunger (a) and with plunger (b).

Vertical test of cavity equipped with helium vessel, and tuning system (plunger + membrane):

During this second campaign of test, the tuning system was delivered and one cavity was also equipped with the helium vessel. The coupling of antennas has been improved. The leak test was successful and the cavity vacuum during the test was very good.

Still several MP barriers were observed starting at very low accelerating field (1^{rst} barrier still at ~12 kV/m) and up to ~ 300-500 kV/m. According to 3D simulations, these MP barriers are essentially due to the coupler port which still offers large aperture (this port remained empty). On the opposite side of the cavity, the presence of the tuning system allowed reducing the gaps between plunger and membrane and its housing (see Figure 5 (b)). In this case, small gaps do not allow electrons to gain enough energy to hit out secondary electrons from the walls.

During the test, 1^{rst} barrier was passed easily by increasing the input power of incident antenna, but when $E_{acc} \geq 1$ MV/m, the temperature of membrane increased instantaneously from 4.2 K up to 9-10 K, transit to normal state implying systematic cavity thermal quenches. The source of these thermal quenches can be explained by the NbTi material of membrane. With this material, surface resistance R_s increases rapidly with small value of magnetic field [6]. In simulations, magnetic field distribution over membrane shows a maximum value of ~20% of peak field located on the center of the membrane, which represents ~ 2.5 mT at 1 MV/m or probably more with simulation approximations. This value seems to be sufficient to make NbTi material transit to normal state.

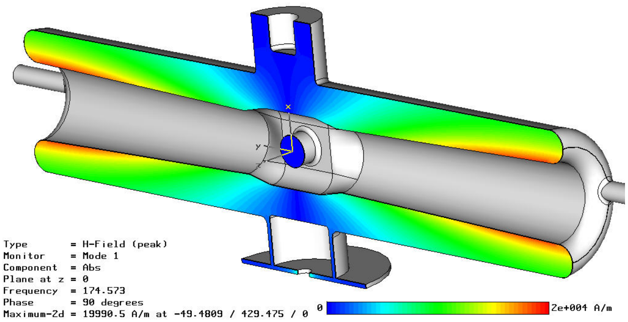


Figure 6: Integral of magnetic field inside the cavity.

In addition, Q_0 of cavity was degraded by a factor ~8 and measured at 1.8×10^8. This degradation can be also explained by the R_s of NbTi material which is ~1100 nΩ at 175 MHz. In a next vertical test, a cavity mounted with a simple Nb membrane could be tested to confirm these explanations. A technical solution has to be implemented in the near future to replace the NbTi membrane.

LLRF RESULTS ON THE RF COUPLER' MOCK-UP WITH TEE-TRANSITION

General Description

The IFMIF coupler is designed to operate at 200 kW CW RF power at 175 MHz TW, but should also be tested in full reflection mode. This coupler has a 50 Ω coaxial geometry and consists of three main parts [7]:

- The RF window and the antenna part (including the coaxial disk ceramic),
- The cooled external conductor part, which is a cylindrical double-wall tube cooled with gas helium,
- The Tee-transition part, which is an interface between the RF window and the input power coaxial line.

For the RF window, the ceramic thickness is optimized according to the relative dielectric constant ε_r of ~9.4 for the chosen ceramic (AL 995). In addition, to prevent multipacting problems on the ceramic, a 10 nm TiN coating layer is deposed on its vacuum side. Associated diagnostics are located around the RF window (e- pick up, sapphire window equipped with a photomultiplier and a vacuum gauge).

Validation Tests of the Mock-up

In order to validate the design of the coupler before launching production, it was decided to realize a mock-up (identical to final coupler window with truncated antenna) and a Tee-transition (see picture of the mock-up on Figure 7).

Leak tests have been performed on the mock-up with success (brazing procedure is validated). Copper coating adhesion has been tested before and after thermal shocks on a representative sample (copper coating is found on antenna and on the outer conductor). Thickness and uniformity of the copper coating fulfil our requirements (~ 46±4 μm). In addition, the thickness of the TiN coating on ceramic has been also measured and is found within 5 nm to 11 nm.

LLRF tests have been performed on the mock-up equipped with Tee-transition. Good transmission of signal has been found at 175 MHz. S_{11} parameter, measured on each part and then on the full assembly, was found better than -29 dB in the range 174-176 MHz.

Figure 7: Picture of the coupler'mock-up.

PRELIMINATY RESULTS OF COLD TESTS OF SOLENOID PROTOTYPES

General Description

Each Solenoid Package includes a cryo- Beam Position Monitor (CBPM), a focusing element and a pair of steerers (horizontal and vertical). For the magnetic lens, the configuration with one solenoid has been chosen [8]. It has the advantage to take little room for a high integrated field ≥ 1 T.m, which is convenient for the compact design of the cryomodule, but the fringe field value of this type of magnet is high. In order to reduce the fringe field at the cavity entrance down to ~ 20 mT, the chosen solution consists to add an active shielding using an anti-solenoid. This external solenoid, properly aligned,

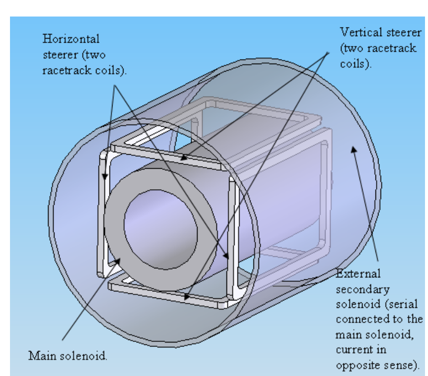


Figure 8: Coils configuration layout.

is connected in series with the inner one, but the current is established in opposite sense.

Concerning the steerers design, the configuration selected is a pair of racetrack coils connected in series. Field quality is modest but acceptable for a corrector. Figure 8 illustrates the coils configuration.

Concerning the current leads of magnets, as they are critical elements, two configurations will be tested at cold temperature in the coming months: the first one, based in commercial Vapour Cooled Current Leads with Nb3Sn or Cu extension; the second one, a self-made configuration with brass wires of diameter 1 mm in a glass fiber tube.

Preliminary Cold Tests Results with Prototypes

One inner and one outer solenoid prototype have been wound with NbTi superconducting wire (with theoretical filling factor of 90.7%). In the cold test campaign, the magnets are tested at 4.2 K in vertical position instead of horizontal position (see picture on Figure 9). The objective of these tests is to check the critical current of the solenoids and to perform the training of the coils after thermal cycling. The setup was prepared to test separately the inner coil, the outer coil and both coils together.

Figure 9: Solenoid prototypes preparation for tests in vertical cryostat.

The outer coil reached without any quench up to 220 A (nominal current being 210 A). The inner coil achieved without any quench a current of 177.4 A, which is equivalent to 210 A in operation together with the outer coil. The outer coil reduces the peak field in the inner coil, which affects the critical current.

The first quench of inner and outer coil together was at 240.8 A. They were successive quenches at higher values. From these test results, the main objectives are fulfilled, without any damages of the coils. In addition, measurements of propagation of quenches have shown that magnets do not need a fast quench protection system.

Nevertheless, it was not possible to measure the field in the axis of the solenoid, due to a damage of the magnetic probe during the test. Another test is planned in the near future to check that there is no degradation of the critical current after a thermal cycle and additionally to check the steerers at cold conditions. In this future test, the missing measurements of the magnetic field in the solenoid axis will be performed.

CRYOMODULE MECHANICAL DESIGN

The cryomodule is around 5 m long, 2 m wide and 2.8 m high with a mass around 15 tons. The component positions are defined according to beam dynamics requirements and the beam axis position is fixed for the whole accelerator at 1.5 m above the ground. Inside the cryomodule, the coupler is positioned vertically to limit the mechanical stresses on its ceramic window and the cavity is therefore fixed horizontally. Interfaces between HWRs and Solenoid Packages are shortened as much as possible, in order to design a cryomodule very compact [9] to fulfil the beam dynamics requirements in the case of intense beam.

Vacuum Tank, Magnetic Shielding and Thermal Screen

The vacuum tank of the cryomodule has been designed to maintain an insulating vacuum but also to support the cold mass keeping a correct alignment of the components. The vacuum tank is a reinforced structure in stainless steel able to support vacuum strength and external pressure. The feet should include actuators to align the cryomodule in the Rokkasho vault.

The goal of the magnetic shielding of the cryomodule is to protect HWRs from the earth magnetic field (~500 mG), which can be trapped during the cool down. The objective is to decrease magnetic field down to 20 mG. According to 2D FEM calculations, it is necessary and sufficient to add a sheet of 1 mm mu-metal as close as possible to the vacuum tank. The many apertures of the cryomodule are critical for the shielding, and overlap of mu-metal sheets are mandatory.

The thermal screen is designed to maintain the cryostat shielding at 60 K all the time. It is composed of large Al sheets of 4 mm thick, where 2 long parallel cooling circuits are welded to the tank. These circuits under vacuum and pressurized at 9.5 bars, are made of several parts, connected to each other by Al flanges. Due to the difficulty of implementation, no cooling circuit on access traps is foreseen.

Cryogenic Distribution

The superconducting HWRs and Solenoid Packages (SP) are operating at 4.4 K and each of these elements has its own saturated liquid helium bath (thus a total of 16 vessels). A double liquid helium cryogenic distribution system has been designed as it is necessary to control the HWRs cooling independently from the SPs one [10]. Two helium inlets manifolds have therefore been connected to the cavity vessels or to the solenoid vessels but there is only one phase separator collecting the output helium gas at the top of the cryomodule. Some specific circuits have been added to cool down the cavity tuning systems, the current leads and the RF power couplers.

The nominal pressure of the liquid helium circuit has been fixed at 0.12 MPa and its maximum pressure will be controlled at 0.15 MPa by safety valves on the external cryogenic system.

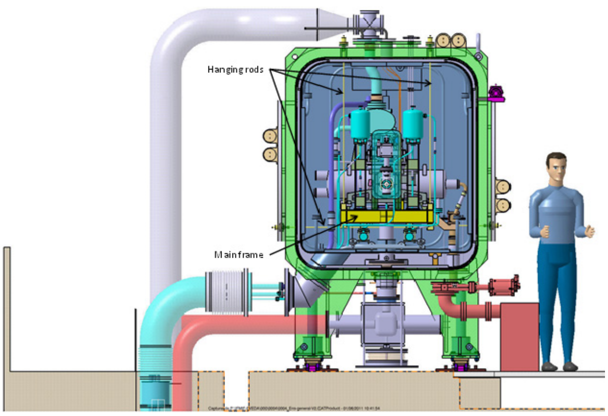


Figure 10: front view of the SRF Linac with its support, hanging rods and internal piping for cooling.

To decrease the heat losses between the vacuum tank and the cold mass, the cryomodule includes a thermal screen cooled down at 60 K by gas helium (HP GHe 50 K/9.5 bars abs circuit). This low temperature reduces the heat load falling on the cold mass, hence improves cryogenic stability and reduces temperature gradients on the cold mass. Moreover, GHe is a gas that will circulate efficiently in all lines and cryostat shielding circuits regardless of gravity and will present any risk of activation under operation at Rokkasho's site.

Internal Support Concept

Due to the cryomodule length, the thermal shrinking between 300 K and 4.4 K is not negligible and has to be taken into account for the mechanical design.

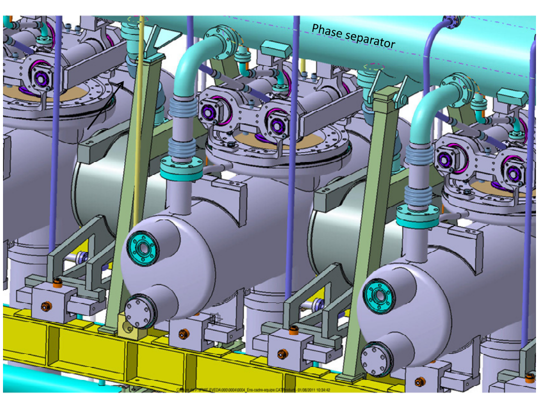


Figure 11: Attachment concept of components.

The HWRs and Solenoid Packages are supported on a common specific mechanical frame (in yellow on drawings). It has been defined from "a double support" concept, composed of a stainless steel frame to support all the cold mass. HWRs and SPs are fixed on their center on an invar reference rod, in order to control the alignment along the beam axis. To allow the shrinking of the main frame, HWRs and SPs slide at their extremities on the frame to manage the differential thermal deformation between the steel frame and the invar rod.

The large phase separator, located above the HWRs and SPs and which contains a mixture of two phases helium, is supported on several points by the main frame. This phase separator is fixed at its center in a rigid way on 1 attachment point (center of the cryomodule). Because the cool down of the phase separator will be faster than the main frame, this phase separator can slide on the other attachment points (see Figure 11).

All the cold mass, with a total weight estimated about 2.8 T, is attached to the vacuum tank with 10 vertical and 4 horizontal rods (see Figure 10).

FUTURE PLANS

The 2 HWRs prototypes did not reached the required performances yet, but several details have been understood and are useful for the validation of our design. Solutions will be realized and tested in the coming months. As soon as a HWR prototype will be qualified, the contract for the series will be launched. Nevertheless, the planning of HWRs activities will be impacted by these first unsuccessful tests, and by the time which will be necessary to bring new solutions.

The detailed design of RF coupler is now completed. Manufacturing files are already produced. The realization of the coupler'mock-up and Tee-transition have allowed validating many steps of the design. Two complete couplers prototypes will be realized soon, and a RF conditioning test bench is in preparation in CIEMAT for the future qualification of couplers prototypes.

The solenoids prototypes got promising results after the first campaign of cold tests. Additional tests are needed on these prototypes to complete their qualification. Steerers will be tested soon at cold temperature, and a complete Solenoid Package prototype (including the CBPM and vessel) is in preparation for future tests in laboratory.

The thermo mechanical design of the cryomodule is going to end soon. Some details need to be defined in order to complete the integration: the current leads of the Solenoid Package, the instrumentation and cables, and the alignment system based on small sensors. The realization of the cryomodule will start as soon as all components will be defined and integrated, and also when Japanese authorities will give an approval on the cryomodule design (the cryomodule being submitted to the Japanese High Pressure Gas Safety Regulations).

ACKNOWLEDGMENT

The authors wish to thank the IPN Orsay team: S. Bousson, F. Chatelet, C. Joly, G. Morel, R. Martret, G. Olry, P. Szott, for their precious and essential contribution for providing the LLRF system, the preparation of the HWRs prototypes and vertical tests in their infrastructure and their fruitful advices for vertical tests analysis.

In addition, authors wish also to thank S. Einarson and T. Treado from CPI for the efficient work done on the RF coupler design, and the nice realization of the coupler'mock-up and Tee-transition.

REFERENCES

[1] "IFMIF Comprehensive Design Report", an Activity of the International Energy Agency (2004).

[2] A. Mosnier et al., "Development of the IFMIF-EVEDA Accelerator", PAC09, Vancouver, Canada, TU2RAI01, p.663 (2009).

[3] N. Chauvin et al, "Alternative Designs and Beam Dynamics Simulations of the SC HWR of the IFMIF Linac", PAC09, Vancouver, Canada, TH5PFP005, p.3193 (2009).

[4] E. Zaplatin et al., "IFMIF-EVEDA SC β=0.094 Half Wave Resonator Study", SRF09, Berlin, Germany, THPPO015, p.569 (2009).

[5] F. Orsini et al., "Study and realization of the first superconducting Half Wave Resonator for the SRF Linac of the IFMIF project", IPAC 2010, Kyoto, Japan, MOPEC054, p.591 (2010).

[6] M. Juillard et al., "Superconducting surface resistance measurements with a TE011 cavity", EPAC 1990, Nice, France, p.1106 (1990).

[7] A. Jenhani et al., "Status of the CW RF Power Couplers for the SRF Linac of the IFMIF Project", IPAC 2010, Kyoto, Japan. MOPEC055, p.585 (2010).

[8] S. Sanz et al., "Calculation and design of the magnet package in the superconducting SRF Linac of IFMIF", IPAC 2010, Kyoto, Japan. MOPEB041, p.364 (2010).

[9] N. Grouas et al., "Mechanical and Cryogenic System design of the 1rst Cryomodule for the IFMIF project", IPAC 2010, Kyoto, Japan, MOPEC054, p.582 (2010).

[10] B. Renard and P. Bredy, "Pressure drop in the IFMIF-EVEDA cryomodule cavities and solenoids helium circuits", CEA internal technical note, ref. IFMIF – EVEDA – ASG –DL10-N028-A (2011).