CAVITY DEVELOPMENT FOR THE LINEAR IFMIF PROTOTYPE ACCELERATOR

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Abstract

The Linear IFMIF Prototype Accelerator (LIPAc), which is presently under design and realization, aims to accelerate a 125 mA deuteron beam up to 9 MeV. Therefore, a low-beta 175 MHz Half-Wave Resonator (HWR) was initially designed and manufactured with a tuning system based on a capacitive plunger located in the electric field region. Following the results of the vertical tests at 4.2K, this tuning system was abandoned and replaced by a conservative solution based on the HWR wall deformation using an external mechanical tuner. This paper will focus on the manufacturing of the prototype cavity, the studies realized to explain the first test results and the solutions taken to overcome the difficulties, leading to the validation of the prototype. Then, we will present the new cavity design.

INTRODUCTION

In the framework of the International Fusion Materials Irradiation Facility (IFMIF), which consists of two high power accelerator drivers, each delivering a 125 mA deuteron beams at 40 MeV in CW, a Linear IFMIF Prototype Accelerator (LIPAc), is presently under design and realization for the first phase of the project [1,2]. The main purpose of the LIPAc is to validate the technical options for the construction of the accelerator prototype, with a full scale of one of the future IFMIF accelerator, from the injector to the first of the four cryomodules of the SRF Linac.

Due to the short lattice defined by beam dynamics constraints [3], the LIPAc cryomodule is compact. Eight low-beta half-wave resonators with their frequency tuning system, eight RF power couplers and eight solenoid packages are housed in a 6-meter long, 2-meter wide and 3-meter height vacuum can. This one is equipped with cryogenics circuits and a magnetic shield for the good working of the components (the operating temperature for the cavities is 4.4 K). The cryomodule is illustrated in Figure 1 and the latest development can be found in [4].

HWR RF DESIGN AND TESTS OF THE PROTOTYPES

The RF and mechanical design of the low-β HWR has already been presented in [5,6]. The cavity is made of pure niobium, fixed in a titanium vessel, with niobium-titanium flanges. Two tubes with NbTi flanges are welded on each torus to allow a proper cleaning of the HWR inner walls with high pressure rinsing (HPR) (Figure 2).

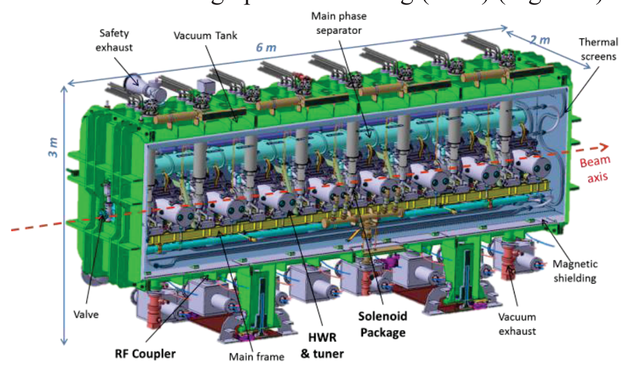

Figure 1: general layout of the LIPAc cryomodule

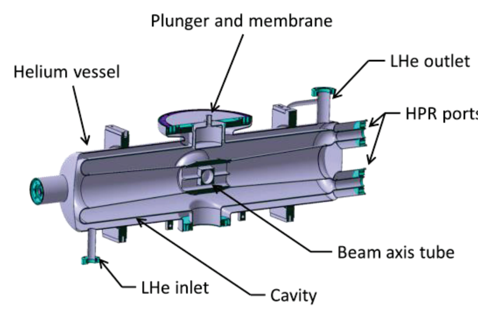

Figure 2: design of the HWR prototype

The main RF parameters are summarized in Table 1. The electric peak surface field E_{peak} is located on the central drift tube area. Its value is 21.6 MV/m at the nominal gradient (4.5 MV/m). The peak magnetic field H_{peak} is located on the junction of the HPR ports to the torus which is smoothed using a fillet. Its value is 49.5 mT at the nominal gradient.

Table 1: RF Parameters of the IFMIF HWR

Parameter	Value	Unit
Frequency	175.366	MHz
Maximum r/Q	150	Ohm
Optimum beta	0.11	
Design beta	0.094	
r/Q @ design beta	140	Ohm
Epk/Eacc	4.8	
Bpk/Eacc	11	mT/(MV/m)

The tuning system is based on a capacitive plunger located in the electric field region of the HWR, perpendicular to the beam axis. This plunger, filled with liquid helium, is connected to a thin membrane – 1.7 mm thick – via a 5 mm stem where the tuning force is applied. In order to clean the cavity, the whole tuning system is

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dismountable from the cavity body and a Garlock Helicoflex joint is used for the vacuum tightness.

For mechanical reasons, the membrane was made of niobium-titanium alloy, whereas the stem and the plunger are made of pure niobium. The membrane can be deformed in the range of ±1 mm which allows a tuning range of ±50 kHz.

Two prototypes were manufactured with success by two different companies. For the tuning system, several problems occurred: during the metallurgical process, the thin sheet of niobium-titanium broke when being rolled. During the manufacturing, the weld between the plunger and the membrane was leaky and had to be repaired. By consequence the thin membrane was slightly deformed and no more flat. Nevertheless, when the tuner was installed on the cavity and clamped with a counter flange, the membrane retrieved its flatness. A visual inspection of the plunger performed through a beam tube revealed that it perfectly fits inside the cavity.

Vertical Test with the Plunger

After a proper preparation at IPN Orsay (BCP treatment, high pressure rinsing and assembly in an ISO 4 clean room), the prototype 1 equipped with the niobium-titanium plunger was tested in a vertical cryostat at 4K. Quench events at E_{acc} = 1 MV/m were observed on the NbTi membrane and $Q_0 = 1.7x10^8$ at low field [7].

RF simulations were performed and individual contributions to RF losses of the surfaces of the cavity were calculated. The observed low Q_0 could not be explained by any high surface resistance for the superconducting materials. Only losses on the normal conducting plunger gasket (1W) could explain the Q_0 value. In theory, the gasket placed in a groove on the niobium-titanium flange of the cavity does not produce RF dissipation. But simulations show that whatever the size of the gap, 90% of the field on the rim penetrates on the gasket. The value of the losses is extremely difficult to predict as they depend on the seal surface seen by the RF. In the worst case (i.e. half of the surface of the seal affected by the field) up to 25 W are dissipated at the nominal accelerating field.

A thermal model has been developed taking into account all the non-linear properties of the materials and the effect of the RF field [8]. For E_{acc} = 1 MV/m, the critical temperature of the niobium-titanium (9.2 K) is reached on the membrane when 1 W is dissipated in the seal. This result is consistent with the test results.

The RF and thermal simulations show that the test results are well understood: the combination of the dissipated power in the seal and the poor thermal conductivity of the niobium-titanium lead to a thermal quench of the membrane.

Proof-of-Principle Niobium Plunger

To validate the concept of the frequency tuning and the RF design of the cavity, a simple fixed position plunger was manufactured. Its design was modified compared to the original one to take into account the defaults revealed by the previous test: the stem was removed to simplify the manufacturing process. This modification doesn't change the field value on the rim due to the coaxial shape still existing between the plunger and the tuning port of the cavity (Figure 3). To minimize the RF dissipation in the gasket, an indium seal was used instead of the Helicoflex seal. After the vertical test, the thickness of the indium seal has been measured at 0.5 mm. Therefore the RF losses of the sealed are divided by a factor of 11. Finally the plunger was made of high RRR niobium only.

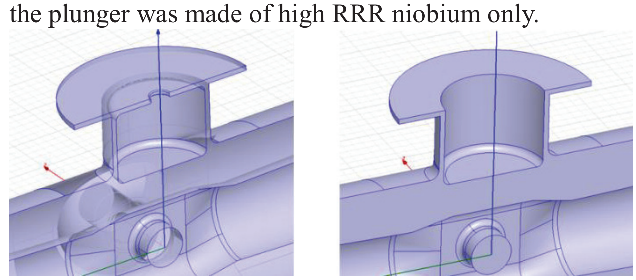

Figure 3: geometry of the proof-of-principle niobium plunger (right) compared to the original geometry (left).

The two prototypes were tested with the niobium plunger in a vertical cryostat. Multipactor barriers were observed at very low field from ~10 kV/m up to 200 kV/m, but were easily overpassed, like a barrier around 1.5 MV/m for the prototype 1. The results at 4 K were the followings:

- Prototype 1 quenched for E_{acc} = 2.6 MV/m. The Q_0 was measured at $2.5x10^8$ at Eacc = 1 MV/m.
- Prototype 2 quenched for E_{acc} = 1.23 MV/m. The Q0 was measured around $4x10^8$ at low field.

During the tests, several thermal sensors were placed on the plunger close to the indium seal. For prototype 1, the increasing of the temperature was around 40 mK when increasing the acceleration field to 2.6 MV/m. These values are consistent with the ones obtained with the previously mentioned thermal model, excluding the plunger as the origin of the quench.

Based on the previously described RF model, the contributions to breakdown were calculated: the Q_0 is around $8x10^8$ for E_{acc} = 2.58 MV/m, the total power dissipated in the cavity being 1.5 W (0.6 W dissipated by the indium seal). These values are not coherent with the ones measured for the prototype 1: 4.5 W were dissipated for E_{acc} = 2.58 MV/m. 3 W are dissipating somewhere in the cavity and could not be explained by the analysis. For prototype 2, the difference between the calculated watts dissipated in the cavity system and the measured watts is 560 mW.

Changing the plunger membrane material from NbTi to Nb prevents heat built-up or low field quench on this one. But it does not improve the Q_0. Changing the seal material lowers the dissipated power in the gasket area. But the origin of the new quench is unknown.

Prototype 1: Inverted Plunger Test

To determine if the cavity limitation comes from the main cavity body or from the tuner flange a test without the plunger in the electric field area was performed. Instead of using a niobium sheet to close the plunger tuner port, the proof-of-principle niobium tuner used in the previous tests was mounted upside down on the flange (Figure 4). For this setup, the H-field is reduced by a factor of 25 on the NbTi tuner flange with respect to the previous setup.

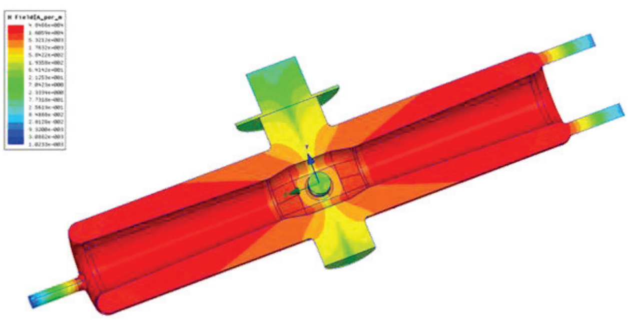

Figure 4: the inverted plunger setup: H-field is reduced by a factor of 25 on the NbTi tuner flange with respect to the original setup with the plunger.

The helium tank was removed to give access to the cavity body. Thereby temperature sensors were fixed on critical areas of the cavity external envelope: tuner and coupler ports next to NbTi flange connection, welds of the inner conductor, bases of the HPR ports and torus. Even if the cavity is bathed in liquid helium, the high sensitivity of the Cernox sensors at 4 K should detect an eventual heating.

The results of the vertical test are presented on Figure 5. The Q_0 is now satisfactory, 1.6×10^9 for $E_{acc} = 1$ MV/m. But the cavity quenches at 4 MV/m whereas the acceptance criteria is 4.5 MV/m. Thanks to the temperature sensors placed on several critical areas, the origin of the quench was localized at the base on one HPR port where the magnetic field is maximum.

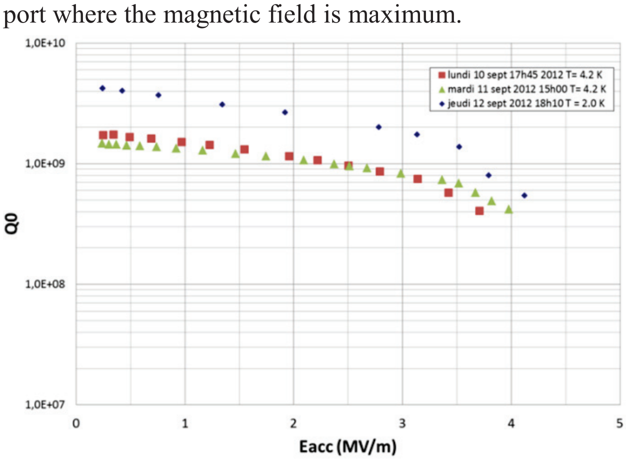

Figure 5: prototype 1 with inverted plunger: Q_0 Vs E_{acc}.

The NbTi – Nb Weld Connection as a Possible Source of Extra Heat Dissipation

The RF calculations performed to explain the test results pointed out that some watts are dissipating in an unknown area. The test of the prototype 1 with the inverted plunger indicates that the main body of the niobium cavity is not the cause of the early quench but the niobium-titanium tuner port. As explained earlier, this flange is exposed to the RF field, especially the weld between the NbTi flange and the Nb cavity body.

The thermal model was used to perform some simulations with the missing watts dissipated in the NbTi / Nb weld (Figure 6).

- Prototype 1: 3 W are dissipated in the weld. The critical temperature of NbTi is overpassed in a 2.5 mm wide strip.
- Prototype 2: 560 mW are dissipated in the weld. This weld is heating up to 6 K.

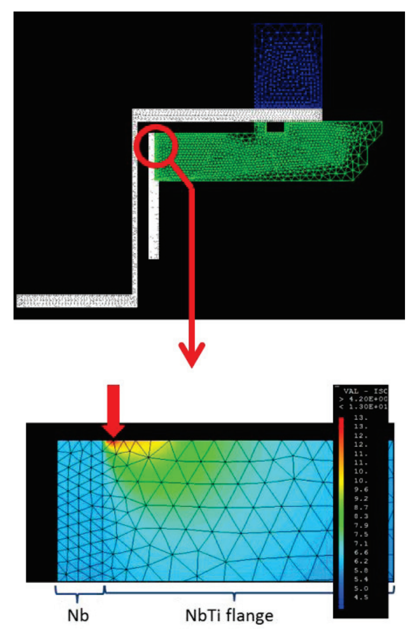

Figure 6: simulation on the NbTi flange with RF dissipation in the NbTi / Nb weld. Bottom: results for prototype 1. Top: the simulated geometry (white: the niobium plunger and part of the cavity body – green: the NbTi tuner flange).

For the prototype 1, a dissipation of 3 watts in the weld can explain the quench of the cavity. For the prototype 2, the heating of the weld is below the critical temperature of the used niobium-titanium. Unless the weld is not homogeneous: during the welding process there might be some migrations of niobium atoms and titanium atoms and some areas of the weld could possess less niobium than expected. The critical temperature of a niobium titanium alloy depends on the concentration of each element: the more titanium the alloy has, the lower the critical temperature is [9]. The critical temperature for the Nb53Ti47 alloy used for the tuner flange of prototype 1 is 9.2 K. For 30 % niobium the critical temperature is around 8.7 K. This one falls to 7.2 K for 20% niobium and 0.4 K for titanium alone. Therefore 560 mW could be sufficient to heat a surface with a low concentration of niobium above the critical temperature.

The NbTi / Nb weld could be the guilty part of the early quench when the plunger is mounted on the cavity. This theory is under investigation, preliminary material analysis results are presented in [10].

Prototype 2: Qualification Test

The original plunger tuner port of the prototype 2 was cut as flush as possible and closed with a 5 mm thick high purity niobium disk as shown on Figure 7. The helium vessel had previously been removed in order to enable this modification.

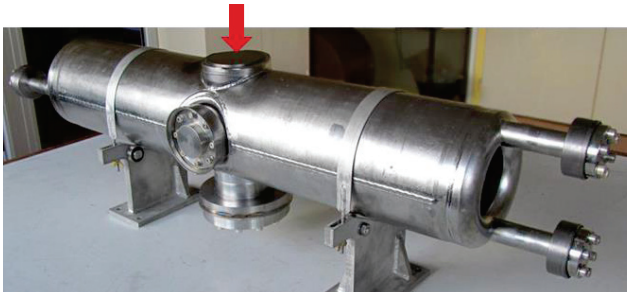

Figure 7: prototype 2 after the plunger port removal. The red arrow points on the welded niobium closing disc.

The results of the vertical test are presented on Figure 8. Like for the cavity setup with the plunger, multipactor barriers around 10 kV/m and 1.2 MV/m were observed. Therefore these barriers are due to the RF design of the HWR main body and not to the plunger tuner. Nevertheless, these barriers were easily overpassed. Q_0 at 4 K was above specifications and measured at $2x10^9$ at the accelerating field of 1 MV/m. Quench appeared at 8 MV/m, well above the nominal accelerating field of 4.5 MV/m. The dissipated RF power in the cavity is 4 W at 4.5 MV/m. Field emission appeared at 5.4 MV/m during this test.

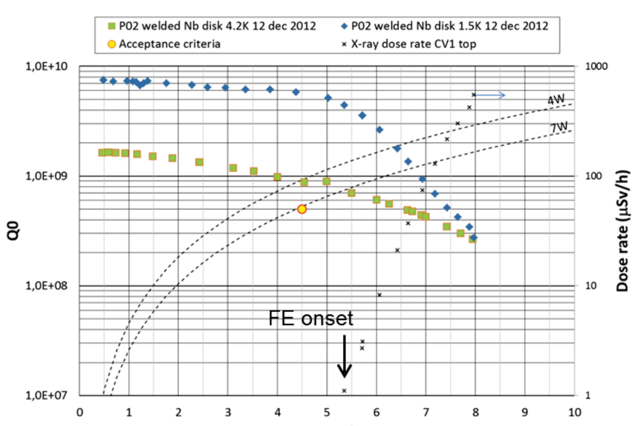

Figure 8:qualification test of the prototype 2: Q_0 Vs E_{acc}.

Q_0 Vs E_{acc} measurements were also realised at 1.5 K by pumping on the helium bath. The multipactor barrier at 1.2 MV/m is still observed, as the Q_0 decreasing from 5.4 MV/m due to field emission and the cavity quench at 8 MV/m. The non-optimal replacement of a feedthrough during the HWR preparation in clean room could explain the field emission. From these measurements at 1.5 K, the estimated residual resistance of niobium is 3.6 nΩ.

NEW CAVITY DESIGN

Following the cold test results on the prototype equipped with the original design of the capacitive plunger and due to the tight time schedule of the LIPAc, the project decided to change the tuning system by a more conservative solution based on the wall deformation of the half-wave resonator.

The tuning of the cavity is done by applying a force on its beam flanges (Figure 9). To respect the frequency tuning requirement of 60 kHz, a displacement of 0.3 mm of each beam port is needed, corresponding of a force of 8000N on each beam flange for a 3 mm thick cavity.

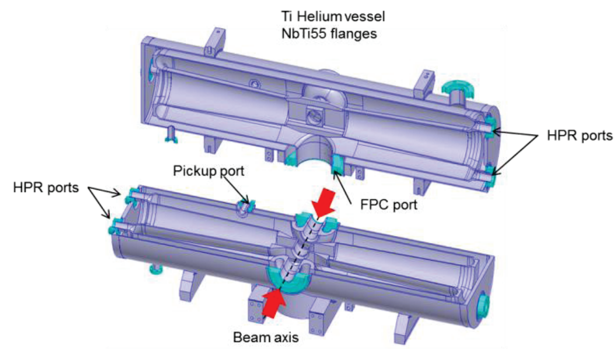

Figure 9: the new cavity design. The red arrow represents the force applied by the tuning system on the beam ports.

Mechanical Design

As the cavities will finally be installed in Japan, they are submitted to the Japanese High Pressure Gas Safety Regulation (HPGSR) for pressurized vessels containing cryogenics fluids. A complete analysis has therefore been performed. Two calculations cases have to be considered:

- 'Standard' case: the cavity is submitted to a pressure of 0.15 MPa at room temperature. This pressure is the absolute maximum one in case of a problem in the cryogenic circuits (pressure in normal operation is 0.12 MPa and is controlled by rupture disks).
- 'Operation' case: the cavity is submitted to a pressure of 0.15 MPa and an 8000N tuning force is applied on each beam flange only at cold temperature.

The allowable stress has been calculated using the following formula:

$$Min\left(\frac{S_y}{1.5};\frac{S_u}{4}\right)$$

where S_y is the material yield strength and S_u the material ultimate strength. For niobium, the allowable stress is 23.75 MPa at room temperature and 150 MPa at liquid helium temperature.

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The stress distribution resulting from a finite element analysis for the two cases is given on Figure 10 for a 3 mm thick cavity. The Von Mises stresses are well below the allowable stresses: below 23 MPa for the 'standard' case, below 132 MPa for the 'operation' case, the most critical areas concerning the beam opening and the coupler port.

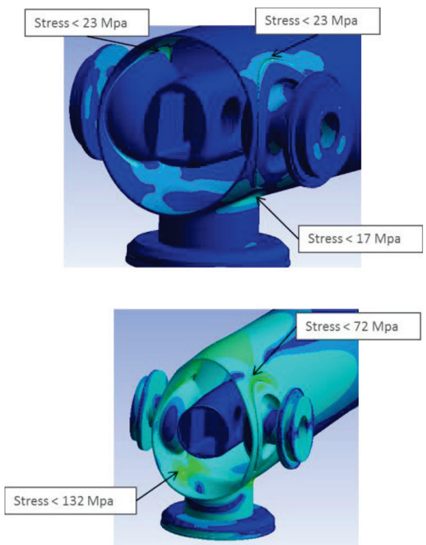

Figure 10: Von Mises stresses given by the finite element analysis. Top: 'standart' case – room temperature. Bottom: 'operation' case – liquid helium temperature.

Frequency Tuning System

To have the minimum impact on the length of the beam lattice of the cryomodule, the cavity interface with the tuning system has been optimized to be as small as possible. The full range of tuning can only be obtained by compressing the cavity.

The tuning system – presented on Figure 11- is based on the ones already developed at Saclay with lever arms and eccentric rotating shaft [11-13]. As the motor is activating the screw, it shifts the arm extremities, which make the eccentric shafts rotating and apply a force at the lever tops. This force deforms elastically the lever flexible area and makes the lever pressing on the cavity beam flanges.

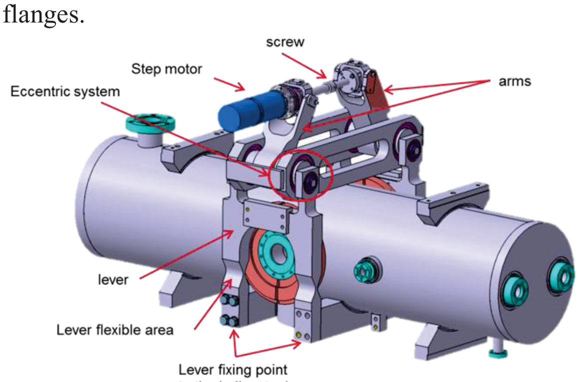

Figure 11:tuning system design.

Due to the high level of stress in the flexible area, the lever arms are made of titanium alloy. The calculated maximum Von Mises stress is about 240 MPa, well below the allowable stress (445 MPa) for the chosen alloy.

The tuning system has been designed to be disengaged during the cryomodule cooling down and warming up. As niobium has very low yield stress at room temperature, any applied load could damage the cavity when this one is not completely cold. The release system is based on a simple concept with an axis in a racetrack hole (Figure 12). The first steps of the motor are used to put in contact the axis with the tuning arm before transmitting the force on the system.

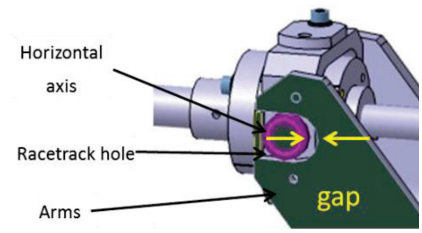

Figure 12: principle of the disengagement system.

SUMMARY AND FUTURE PLANS

The original tuner design, a niobium plunger welded on a thin niobium-titanium membrane, coupled to a niobium-titanium flange on the cavity, caused early quenches. RF and thermal models were developed to understand the phenomena happening in the tuner area of the cavity. Nevertheless complementary material analysis should be performed to confirm the theory of the dissipation of the weld between the niobium-titanium flange and the niobium cavity body. Taking into account the problem of niobium-titanium exposed to RF field, a conceptual design was realised with a niobium plunger and a bi-material flange on the cavity: the part of the flange exposed to the RF field is made of niobium. The part with threated holes needed to connect the tuner to the cavity is made of niobium-titanium for mechanical reasons. The weld between the two parts is also not exposed to the RF field.

Due to the tight time schedule of the LIPAc, the project decided to change the tuning system by a more conservative solution based on the wall deformation of the half-wave resonator. To validate the RF design of the main cavity body, the prototype 2 was modified and successfully tested.

A new cavity compliant to the Japanese High Pressure Gas Safety Regulation has been design with a Saclay-type tuner. Due to the constraints imposed by the beam dynamics group, the tuner will be used only in compression mode to have the minimum impact on the beam lattice. A disengagement system was design in order to avoid damage on the cavity during the cooling down and warming up of the cryomodule. The production of these components for the series should be launched in the next few weeks.

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