

DEVELOPMENTS AND TESTS OF A 700 MHz CRYOMODULE FOR THE SUPERCONDUCTING PROTON LINAC OF MYRRHA*

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Abstract

The MYRRHA projects aims at the construction of an Accelerator Driven System demonstrator. The criticality will be sustained by an external spallation neutron flux; produced thanks to a 600 MeV high intensity proton beam. This beam will be delivered by a superconducting linac which must fulfil very stringent reliability requirements. To carry out “real scale” reliability-oriented experiments a 700 MHz Cryomodule was developed. Several tests were performed to commission the experimental set-up. We review here the obtained results and the lessons learnt by operating this module, as well as the on-going developments.

INTRODUCTION

MYRRHA

Accelerator Driven Systems (ADS) are considered as promising devices to enable the reduction of nuclear waste volume and radio-toxicity; as well as useful schemes for Thorium based energy production [1].

Towards this goal, the MYRRHA (“Multi-purpose Hybrid Research reactor for High-tech Applications”) project aims at the construction of a new flexible fast spectrum research reactor [2]. This reactor will be operated as an ADS demonstrator. The criticality will be sustained by an external spallation neutron flux produced thanks to 2.4 MW proton accelerator (600 MeV, 4 mA maximum), operating in CW mode. [3]

In addition to the high beam power, one has to consider that frequently-repeated beam interruptions can induce high thermal stresses and fatigue on the reactor structures, the target or the fuel elements, with possible significant damages especially on the fuel claddings. Therefore the accelerator will have to be extremely reliable. The present tentative limit for the number of allowable beam trips is: 10 unexpected interruptions longer than 3 seconds per 3-months operation cycle.

In this purpose, the accelerator design is based on a redundant and fault-tolerant scheme to enable the rapid mitigation of RF failures [3]. So, To carry out “real scale” reliability-oriented experiments a prototype of cryomodule was developed by INFN Milano and installed at IPN Orsay (see Figure 1). This module holds a 700 MHz 5-cell elliptical cavity ($\beta_g = 0.47$) equipped with its blade frequency tuner.

The 700 MHz Cryomodule

The Cryomodule design was performed by considering reliable aspects for the assembly, and the cavity handling, derived from the experience accumulated by the TESLA Test Facility (TTF) and the Spallation Neutron Source (SNS). The horizontal cryogenic vessel is a cylinder of 1.5 m long, for a diameter of about 1.4 m. The cryogenic valve box is assembled on top of it. The module was designed to operate the cavity at 1.9 K at a nominal accelerating gradient of 8.5 MV/m with an assumed conservative quality factor value of $Q_0 = 5 \cdot 10^9$. To minimise the losses towards the superfluid helium bath, the thermal radiation - from room temperature surfaces - is intercepted by a thermal shield at intermediate temperature (Nitrogen at 77 K + Mylar[®] blanket). [4]

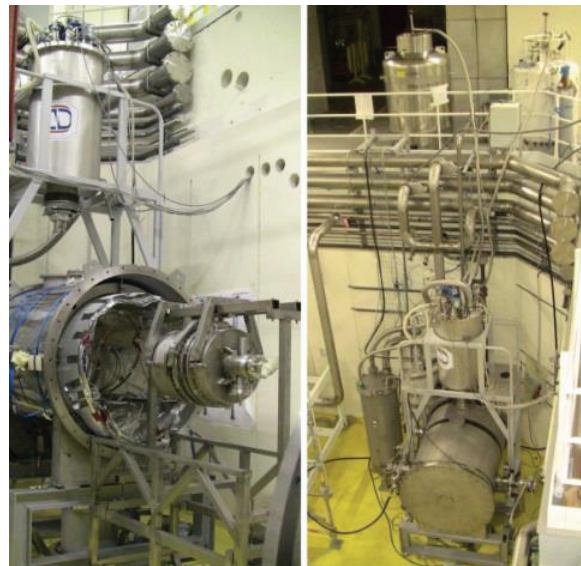


Figure 1: The Cryomodule in the experimental pit.

The cryogenic module is equipped with one of the two TRASCO cavities fully “dressed” [5]. A magnetic shield made of 1 mm Cryoperm10[®] sheets encloses the cavity. Preliminary Magnetic shield measurements showed that the contribution to the surface resistance by trapped earth magnetic field should remain below 10 nΩ [6]. The cavity and its shield are inside the Titanium “Helium Tank”, which is soldered on the cavity beam pipes by means of two circular flanges. A bellows, in the middle of the tank, enables small longitudinal lengthening of the cavity. These movements are driven by a mechanical “blade tuner” which enables - “fast” and “slow” - frequency tuning of the cavity (see below).

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In its final configuration, the module will be equipped with a coaxial fundamental power coupler (FPC) [7]. Two FPC prototypes were recently conditioned up to 62 kW (see following part).

RF MEASUREMENTS

While the cryomodule was installed at IPNO, the power coupler development was in progress. Consequently, It was chosen to carry out experimental tests of the cavity in “critical coupling”. Since the cavity had already been tested in vertical cryostat [8], a light BCP was processed - to remove a layer of ~ 30 μm - followed by HPR rinsing. Some adaptations were required on the module to enable RF critical coupling: especially for the feed-through of the incident RF signal [9]. The length of the incident antenna was chosen to obtain an incident coupling $Q_i \sim 10^{10}$; for RF measurements at 2 K. The RF characterisation curve is given by Figure 2.

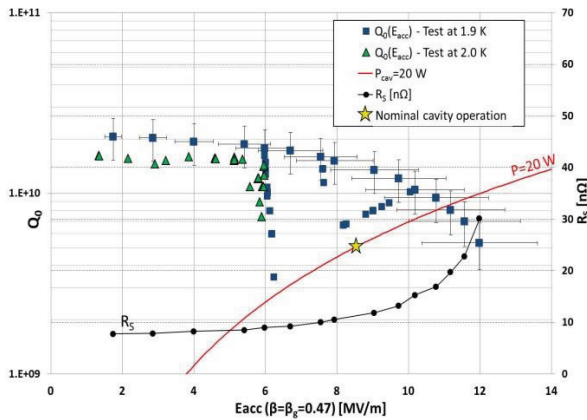


Figure 2: RF characterisation curve of the cavity.

Quench Limit and Field Flatness

During the test two multipacting barriers were identified but easily processed: around $E_{acc} \sim 6$ MV/m and 7.5 MV/m. At low field the Q_0 value ($\sim 2 \cdot 10^{10}$ at 1.9 K - squares on Figure 2) is also in accordance with the previous vertical test [8]. However the measured quench value ($E_{acc} \sim 12$ MV/m) is below the measured limit obtained during the vertical tests (~ 14 MV/m). One explanation could be the “field flatness” degradation: from ~ 94 % to ~ 45 %. The cause of this degradation is not identified yet, but an analysis (“bead-pull” measurements + cavity matrix reconstruction) enabled to identify that only one cell of the cavity was plastically deformed [10]. Since the cavity is enclosed inside its helium tank and the performances remained acceptable for our prototyping studies, it was chosen to keep the cavity flatness as it was. A preliminary RF model of the “no-flat” cavity showed that the Geometrical Factor (G) and the Shunt Impedance (r/Q) do not vary by more than 5 % from the nominal “flat Design”: where $G = 160 \Omega$ and $(r/Q)^{\#} = 90 \Omega$ (for $\beta = \beta_g = 0.47$).

[#] (r/Q) is defined as $P_{cav} = (E_{acc} L_{acc})^2 / (2(r/Q)Q_0)$

Surface Resistance and Magnetic Shielding

The black dots curve in Figure 2 gives an estimation, at 1.9 K, of the cavity surface resistance: $R_s = G/Q_0$. The total surface resistance is also given by:

$$R_s = R_{BCS} + R_{mag} + R_{res} \quad (1)$$

Where for niobium at $T < T_c/2$

$$R_{BCS} \approx 9 \cdot 10^{-5} \frac{(f[GHz])^2}{T} \exp\left(-1.83 \frac{T_c}{T}\right), \quad (2)$$

and

$$R_{mag} = 3[n\Omega] \langle B_{ext} [\mu T] \rangle \sqrt{f[GHz]}. \quad (3)$$

R_{BCS} is a temperature and frequency dependent term; where T_c is the critical temperature of Niobium. R_{mag} is a term which characterise the pinning and trapping of DC magnetic flux (typically the earth magnetic field); where $\langle B_{ext} \rangle$ is the average magnetic field seen by the cavity during the cool down. Finally R_0 is due to the quality preparation of the cavity surface and the material properties.

When RF losses are small (below $E_{acc} \sim 10$ MV/m), $R_s \sim 10$ nΩ and one can estimate that $R_{mag} + R_0 \sim 5$ nΩ. This shows that the external magnetic field is properly attenuated.

Such a result was not a straight forward issue. Indeed, there is a residual magnetic field (up to 3 Gauss, randomly distributed), inside the experimental pit at Orsay. This is because the module is installed in the former experimental pit of the AGOR cyclotron [11], which magnetised the floor and the walls. To attenuate this parasitic field, a magnetic shield was directly “strapped” around the cryomodule (1.5 mm thickness of mu-metal). The DC magnetic field which then remained inside the module was measured with intensities from 20 μT to 50 μT. This remaining parasitic random field is finally attenuated thanks to the Cryoperm10[®] shield. This result is in good agreement with the expectations from the shielding design [6].

CRYOGENIC ASPECTS

The cryogenic performances of the module and its cold-box were also evaluated. In this purpose, heaters were placed on the cavity helium tank to simulate dynamic heat loads (equivalent to RF losses). In a first time, the cavity was cooled down with liquid helium at 4.2 K, and then cooled with superfluid helium at 1.9 K. The helium bath temperature was monitored with both thermal sensors and a pressure measurement thanks to a pick-up on the helium tank. The Figure 3 shows the flow rate evolution of the “hot” helium gas, flowing out of the module, as function of the heat loads on the cavity.

Considering that 1 m³/h of helium gas, escaping the module, is equivalent to 1.03 W heat loads, we measured a total static heat load of ~ 9 W (i.e. heaters off) on the cryomodule and its components. The static heat load of the valve box alone was also measured at ~ 2.5 W. The Table 1 summarise the measured and foreseen heat loads

budget [4] for each component of the cryomodule. It shows that measured performances are in agreement with expectations: at 1.9 K one can operate the module up to ~ 35 W dynamic heat loads on the cavity.

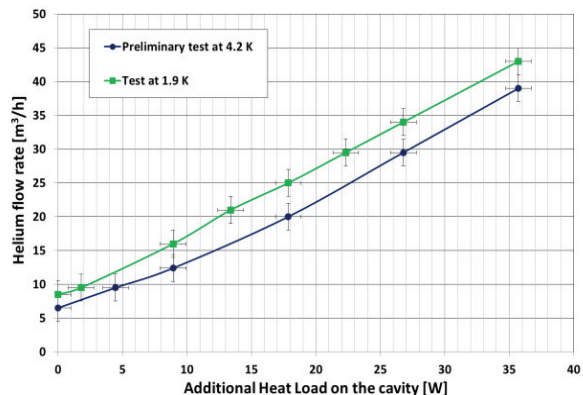


Figure 3: Helium consumption measurements at 4.2 K and 1.9 K.

This limitation seems to be due to the diameter size of the valves inside the cold box. In addition, “warm points”, at the interconnection between the valves box and the cryostat, were also detected. So, even if the losses were quite low, there are still some margins for further improvements in view of the module test in its final configuration.

Table 1: Heat Loads Budget and Experimental Results

Components	Design	Measured
Valve Box (4.2 K)	2.0 W	~ 2.5 W
Power Coupler	1.2 W	-
Module + Transfert lines (Static at 1.9 K)	6.0 W	~ 6.5 W
Cryomodule (Dynamic at 1.9 K)	25 W	~ 36 W max.

COLD TUNING SYSTEM

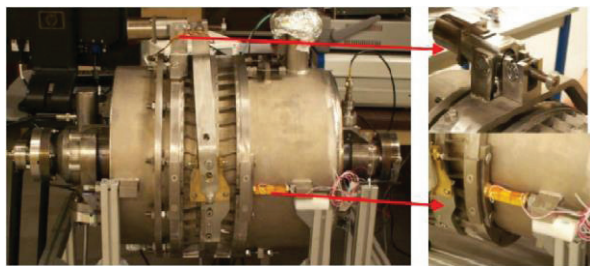


Figure 4: The TRASCO cavity at IPN Orsay, fully dressed with stepper motor and piezoelectric actuators.

A coaxial Blade Tuner derived from the one successfully tested at DESY was developed and fabricated (see Figure 4) within the EU FP6 CARE-HIPPI program [12]. This device, mounted on the tank and across the bellows, allows for cavity frequency setup and both slow and fast detuning compensation. The rotation

torque provided by a stepper motor is transformed into a longitudinal displacement along the cavity axis by means of bending blades and enables the control of the resonance frequency within a range up to 350 kHz and the static compensation of Lorentz’s force detuning (LFD). This coaxial device is assisted by a pair of piezoelectric actuators symmetrically installed on both sides of the tank along the tuner force line. The two piezo unit installed, 70 mm long multi-layer ceramic stack with 100 μm nominal stroke at 200 V driving voltage, provide capability to dynamically adjust the cavity frequency within 10 kHz range with nanometric resolution.

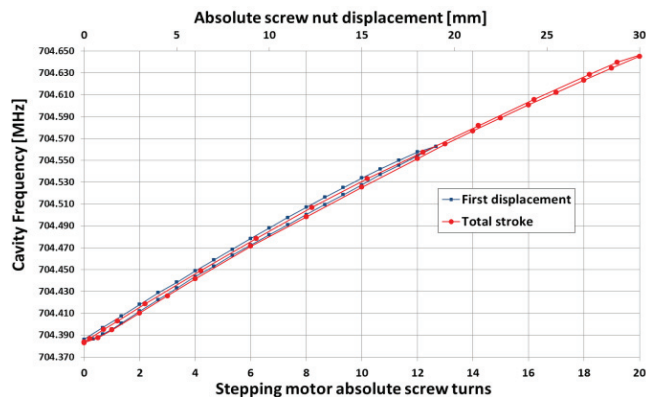


Figure 5: First cold run of the static tuner at IPN Orsay.

After a thorough characterization at room temperature [13], expected tuner performances have been partially met during the first cold run of the tuner in October 2011 test: about 260 kHz range with about 1 Hz/step resolution was measured (see Figure 5). Additionally, further affirmative results came from the cold test of the twin TRASCO cavity at CEA Saclay where, among other results, 310 kHz static range and 6.8 kHz dynamic range (with piezo voltage limited to 150 V) were measured.

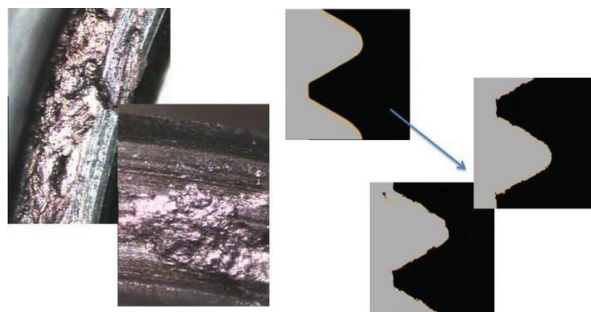


Figure 6: Close-view of the largest copper deposition on steel thread (left) and profile-view of the CuBe screw (right, used vs. unused sections).

Unluckily, after several tuning cycles at cold, the stepper motor drive unit failed. Although the motor coils were properly energized no tuning action could be detected, proving that a seizing in the transmission line has to be addressed.

During the following months the whole motor unit, a prototype model manufactured and coated by INFN according to TTF/FLASH specifications, was transferred at INFN for investigation and it clearly exhibited seizing of the stainless steel nut on the copper-beryllium screw.

After exposing the thread interiors by cutting apart the nut, clear evidences of critical friction appeared: copper depositions on steel were diffuse and, in few spots, a considerable quantity of material seemed to be stripped away (see Figure 6).

This failing prototype unit has been replaced for the incoming cold tests with a special commercial unit, a replica of the motor system chosen for the European-XFEL linac, whose severe specifications for reliability at cold are shared with the ongoing MYRRHA demonstrator cryomodule project.

POWER COUPLER

In view of the high power (CW) test of the 700 MHz module, a power coupler was designed at Orsay [7]. Based on this design (see Figure 7), two FPC were then manufactured by SCT Company and conditioned by IPNO.

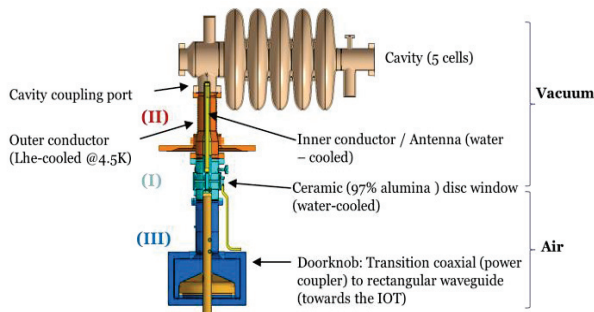


Figure 7: sectional view of the power coupler.

Conditioning Bench

The FPC conditioning had been performed in the 700 MHz experimental area of IPNO. The experimental bench was designed to condition a pair of power couplers in travelling wave mode at room temperature. The RF power was transferred from the RF source (IOT THALES 793-1) towards the water cooled load, through the two FPC prototypes (see Figure 8). The couplers were assembled, in vertical position, on a 704.4 MHz resonant cavity which was specially designed for the FPCs conditioning.

The RF power, travelling through the couplers, can induce physical phenomenon (breakdown voltage, multipactor effect ...) which can damage the ceramic window and thus induce the loss of the vacuum tightness. To prevent from coupler damages, hardware security systems, interlocks and diagnostics were implemented to the conditioning bench. The diagnostics parameters monitored during the conditioning are: the vacuum level, and the electron multipacting current close to the ceramic

window. This electronic activity was measured with a pickup antenna kept at an electrical potential of 45 V. The threshold for the multipacting current was set to 25 $\mu\text{A/V}$. The vacuum threshold for the couplers was set to $5 \cdot 10^{-8}$ mbar. Thus, the hardware security system turned off the RF power when one of these parameters exceeded the maximum threshold. In addition, thermal sensors were installed on each coupler to measure the temperature increase of the water cooling circuit.

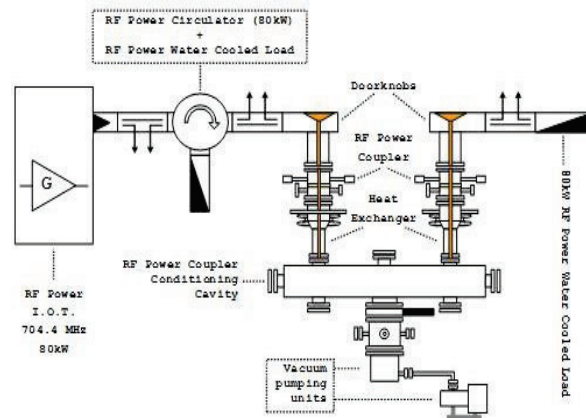


Figure 8: Schematic view of the conditioning bench.

During the first RF conditioning campaign (November 2012), the ceramic window of one of the FPCs failed. Among the hypothesis that had been proposed, the most probable reason for this window breakage is a too fast increase of the CW RF power. It might have induced high thermal stresses that weakened the ceramic. To resume the conditioning procedures it was then chosen to use a spare RF window - initially manufactured by TOSHIBA Company. The construction and adaptation of the antenna for this spare window was achieved at IPN Orsay.

A coupler electro-polishing was performed in LPSC Grenoble. Then, the experimental bench was assembled in an ISO5 class clean room, and all the components were high pressure rinsed. To prevent from breakdown voltage, the pressure inside the conditioning cavity had to be kept below $2.5 \cdot 10^{-7}$ mbar. To reach this vacuum level, a baking procedure was performed. After baking, the measured pressure close to ceramic window was $5.8 \cdot 10^{-9}$ mbar.

Results

The couplers conditioning was carried out in pulsed mode. The conditioning method consisted in gradually increasing the power level from a few kW up to a maximum power, by starting from a pulse time-width of 100 μs up to 495 ms with a repetition rate of 2 Hz. The RF power ramp-up was performed according to the vacuum pressure. Once, the maximum power was reached, the power was kept at the same level in order to test the ability of the module to withstand such power. If no interlock trigger were observed, the power ramp-up operation was resumed again, but with a larger pulse width.

A first power ramping up to 54 kW was achieved with 100 μ s pulses, which corresponds to a duty cycle of 0.009 %. Afterwards, the duty cycle had been gradually increased. In this way, the induced degassing effect (from the walls of the cavity and the couplers) was monitored and controlled to ensure an efficient conditioning. This procedure enabled to reach high power for different pulse width. Finally, in June 2013, the FPCs were successfully conditioned up to 62 kW in CW mode (see Figure 9). And recently, the FPC, with the TOSHIBA window, had been assembled to the 5-cell elliptical cavity ($\beta_g = 0.47$) in view of the first test of the cryomodule in “machine configuration”.

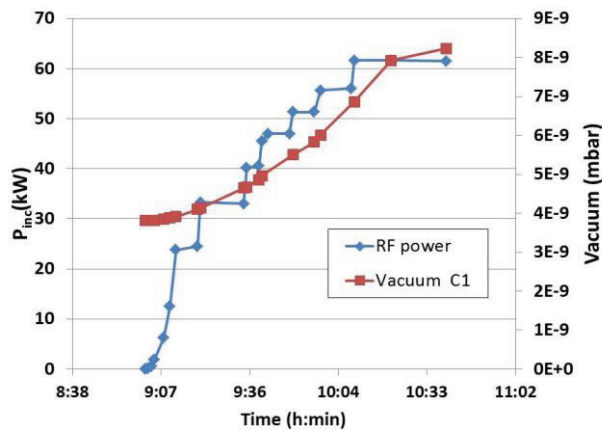


Figure 9: First FPC conditioning results at IPN Orsay.

CONCLUSION

Together INFN/LASA and IPNO teams have made great efforts worked to develop, to build and to commission the cryomodule as well as its entire experimental area at Orsay. Several tests were necessary to improve the module and to condition the power couplers. The installation of the cryomodule in its final configuration is now in progress. The final objective is to dispose of a test bench to perform reliability-oriented experiments and to study “fast fault-recovery” procedures for the MYRRHA superconducting linac.

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REFERENCES

- [1] D. Vandeplassche et al., “Accelerator Driven Systems”, Proc. IPAC2012, New Orleans, Louisiana, USA, 2012, MOYAP01.
- [2] See e.g. <http://myrrha.sckcen.be/>

- [3] J-L. Biarrotte, “Design of the MYRRHA 17-600 MeV superconducting linac”, These Proceedings, MOP018.
- [4] S. Barbanotti et al, “Design of the prototypical cryomodule for the EUROTRANS superconducting linac for nuclear waste transmutation”, Proc. EPAC’08, Genoa, Italy, MOP114.
- [5] P. Pierini et al., “Low beta elliptical cavities for pulsed and CW operation”, Proc. PAC09, Vancouver, BC, Canada, WE5FPF034.
- [6] P. Pierini et al., “Design of the magnetic shield for TRASCO low beta elliptical cavities”, Proc. SRF 2007, Beijing, China, WEP61.
- [7] F. Bouly et al., Proc. SRF2009, Berlin, Germany, TUPPO008.
- [8] A. Bosotti et al., “RF Tests of the Beta=0.5 Five Cell TRASCO Cavities”, Proc. of EPAC’04, Lucerne, Switzerland, TUPKF026.
- [9] A. Bosotti et al., “A reliable coaxial feedthrough to avoid breakdown in vertical test facilities for SC cavity measurements”, 2001, INFN/TC-01/05.
- [10] F. Bouly, PhD Thesis, <http://tel.archives-ouvertes.fr/tel-00660392>, 2011.
- [11] S. Brandenburg, “The superconducting cyclotron AGOR: accelerator for light and heavy ions.”, Proc. PAC 1987, Washington, USA.
- [12] P. Pierini et al., “Report on tuner design”, CARE Note-2006-003-HIPPI.
- [13] F. Bouly et al., “Developments and tests of a 700 MHz prototypical cryomodule for the MYRRHA ADS proton linear accelerator”, Proc. LINAC10, Tsukuba, Japan, THP023.