TESTS OF THE LOW BETA CAVITIES AND CRYOMODULES FOR THE SPIRAL 2 LINAC

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Abstract

The IRFU institute of CEA Saclay is in charge of the 12 low beta cryomodules that will be installed on the first section of the SPIRAL 2 superconducting LINAC. Each cryomodule houses a single QWR cavity at 88MHz and β=0.07 cooled with liquid helium at 4.4 K. All components of the cryomodules are manufactured by the industry. The power coupler is provided by LPSC Grenoble. The assembling and tests are performed by the CEA.

The RF power tests (P_{max} = 10 kW) were performed on the qualifying cryomodule at the end of 2008 before launching the order of the 11 serial cryomodules. The two first cavities of the series were tested in vertical cryostat before the summer 2009. A summary of these tests and the present status of this project are reported.

INTRODUCTION

The GANIL's SPIRAL 2 Project [1] aims at delivering high intensities of rare isotope beams by adopting the best production method for each respective radioactive beam.

The unstable beams will be produced by the ISOL, "Isotope Separation On-Line", method via a converter, or by direct irradiation of fissile material. On the basis of referee reports of international experts and committees, the positive evaluations by IN2P3/CNRS and DSM/CEA, GANIL, and the support of the region of Basse-Normandie, the French Minister of Research took the decision on the construction of SPIRAL 2 in May 2005.

The SC linac is composed of cryomodules A developed by CEA Saclay, and cryomodules B developed by IPN Orsay. Both types of cavities are equipped with the same power coupler specified for a maximum power of 40 kW CW (in travelling wave), developed in a third laboratory, LPSC Grenoble [2].

General development programs are quite similar for both types of cryomodule: a first qualification cryomodule has been tested before launching the series. All the components (cavities and cryomodules) are manufactured by industry. Cavities chemical treatments, HPR rinsing in clean room, assembly, and RF tests of the cavities in vertical cryostat and RF power tests of the cryomodules are performed in the labs.

This paper presents the results of the RF tests performed in vertical cryostat on the qualification cavity as well as on the first 2 cavities of the series. RF power tests were performed on the complete qualification cryomodule up to the maximum power of 10 kW. A summary of all measurements and results obtained during these tests are presented.

SUMMARY OF THE CRYOMODULE DESIGN

Details of the cavity and cryomodule design were described in [3, 4]. Each of the 12 cryomodule A contains only one cavity β = 0.07. Due to beam dynamic considerations, the length along the beam axis of the vacuum tank (Figure 1) was minimized (610 mm). We could shorten this length by developing the cavity tuner that deforms the cavity perpendicularly to the beam axis. The cavity mechanical design was optimized in order to reach a full tuning range of 25 kHz at 4 K without plastic deformation of the niobium cavity.

Figure 1: Cryomodule inside the test stand, connected to the valves box. RF coupler is below, hidden by the support frame.

The first cavities of the accelerator low beta section will work at low accelerating field ($E_{acc} \approx 0.5$ MV/m) while the last cavities of the section will work at about $E_{acc} = 5$ MV/m.

TESTS IN VERTICAL CRYOSTAT

Q Curves

Results obtained during the first tests in vertical cryostat of the qualification cavity showed a very low Q_0 value of 2.10^8 whereas the prototype cavity was working correctly with $Q_0 = 2\ 10^9$ (Figure 2). However the cavity reached very high accelerating fields close to 11 MV/m.

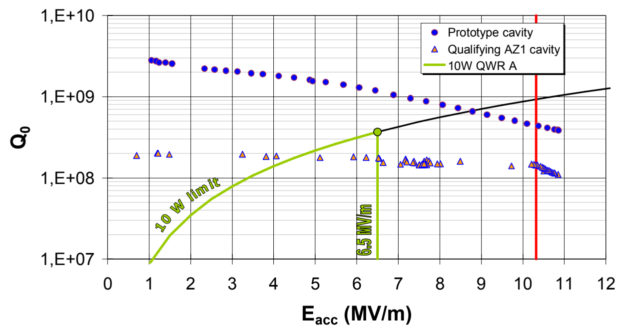

Figure 2: Q_0 vs. E_{acc} curve for the AZ1 (pink triangles) and prototype (blue squares) cavities. The red line showed the maximum field reach in the qualifying cryomodule.

Several tests and analyses were conducted in order to understand the origin of the degraded Q_0. These tests allowed locating the dissipation zone around the bottom of the cavity, but not on the removable bottom plate itself. The high magnetic field region, located on the torus and at the top of the stem, was not the location of the additional RF losses.

The bad RF contact of the copper seal located between the cavity and the bottom flange was shown to be the cause of the additional RF losses. A new gasket was designed to improve the quality of the RF contact, and the expected Q_0 curve could be obtained. Figure 3 represents the curves of the qualification cavity (AZ1) and of the 2 first cavities of the series (AZ2 and AS3). These 2 serial cavities were manufactured by 2 different companies. All 3 cavities have performances above the required specifications.

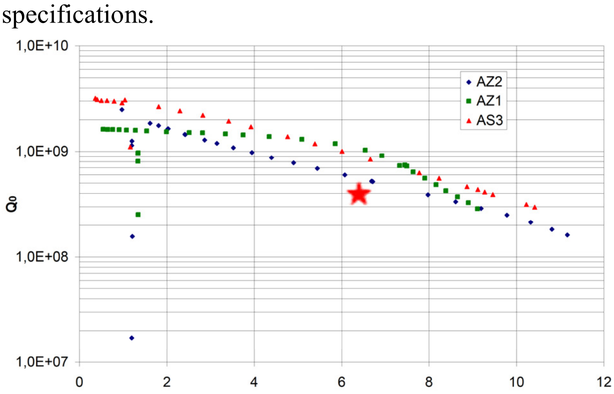

Figure 3: Q curves of the 3 first cavities manufactured. The red star is the specification point.

Multipacting

Strong multipactor (MP) barriers at very low field, E_{acc}=17 and 53 kV/m caused difficulties to measure the Q_o curve of the cavities. By chance they could be always passed after hours of attempts. This phenomenon may cause the qualification of the cavities to last several days more than foreseen. Once the barriers are passed, they do not show any processing effect at all even after days of RF. Other MP barriers at higher fields (1.2 and 2.3 MV/m) can be processed.

During one of the tests we could locate by chance one of the multipactor barriers at very low field: a thermal sensor that was placed on the bottom dismountable flange of the cavity showed an increase of temperature during the time the MP barrier at E_{acc}=53 kV/m was activated. This observation confirms the estimation of the multipacting that we performed on a 2D model of the cavity close to the non symmetric real cavity (Figure 4).

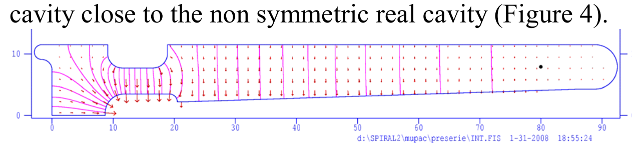

Figure 4 : 2D Superfish model of the cavity.

This 2D model is such that the cavity diameter, top torus region, stem and cavity bottom flange are identical to the real cavity. The beam region is tuned in order to obtain a resonant frequency of 88 MHz, therefore it differs from the real cavity, and is also axisymmetric. The field normalisation between this 2D and the 3D design model was done on the magnetic field, because this region is identical in both models.

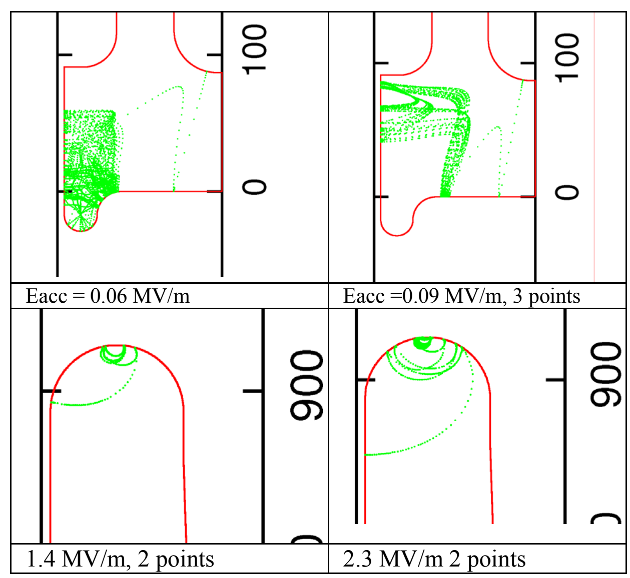

Figure 5: multipacting simulation on a simpler 2D model of the SPIRAL 2 cavity β=0.07.

The MUPAC [5] code was used to compute the MP barriers. The simulation (Figure 5) identified 2 barriers on the bottom flange of the cavity at the following gradients: E_{acc}=60 and 90 kV/m. The energy gaps of these 2 barriers are in the same range than the measured ones on the real cavity. 3D simulation of the cavity should be performed to identify more precisely the barriers. However this first 2D simulation allows to determine important points:

1. several MP barriers at very low gradients (<200 keV) are at the bottom part of the cavity,

2. the energy of the electrons is too low to perform the processing of the surface
3. Two higher field 2 points MP barriers are located in the top torus, computed at 1.4 and 2.3 MV/m

The resonant trajectories are shown on figure 4

The AZ1 cavity (red curve on Figure 3) was tested with a bottom cap made out of copper, and multipacting at very low field was not observed. This could be due to the fact that the coefficient of secondary electron emission of copper oxide is lower (1.8 maximum) than that of niobium oxides (2.8 maximum). Next measurements of the future serial cavities will also be performed with a copper bottom and will perhaps confirm this hypothesis.

Copper Bottom Cap of the Cavities

The value of the coefficient $1/2\int H^2 dS$ on the bottom flange (1.6 10^2 W/Ω) represents 3.6 10^{-3} % of the whole cavity one (4.33 10^6 W/Ω). Taking into account the surface resistance of copper and niobium, the calculated power dissipated on the different bottom caps at the nominal accelerating field 6.5 MV/m are the following:

* 0.6 W for copper RRR = 200
* 6.6 10^{-5} W for superconducting niobium
* 1.6 W for normal conducting niobium RRR = 200

The disadvantage of the niobium is that this bottom flange could not be cooldown below 14 K inside the cryomodule, keeping the niobium in the normal conducting state (see following section). That is the reason why using copper is interesting. The power dissipated by the copper flange is about 15% of the total cavity dissipation (~4 W at 6.5 MV/m with a copper flange) keeping the overall dissipation of the cavity below the requirements of the cryogenic system of the LINAC (7 W per cavity). Therefore all cavities in the low beta cryomodules will be equipped with copper bottom flanges.

TESTS OF THE QUALIFICATION CRYOMODULE

A specific test stand (Figure 1) has been installed at Saclay in order to qualify all cryomodules A. A 10 kW amplifier, identical to the Linac ones, provides the RF power. The cryogenic valves box is also of the same type as used in the Linac.

RF power tests were performed from the end of December 2008 to April 2009. The qualification cryomodule was tested with the AZ1 cavity before we found the causes of the abnormal RF dissipations. In this configuration the cavity dissipated 100 W at the maximum accelerating field (11 MV/m). Therefore the initial test stand cryogenic system that was designed to accept a total of 40 W had to be modified in order to allow the surplus of helium consumption.

The assembling of the cryomodule has been previously performed in the SupraTech clean room of IPN Orsay. This operation was made by CEA Saclay's team with the help of the people from IPN Orsay.

Cryogenic Measurements

The cooling down is performed by cooling at first the copper thermal shield down to about 100K. Before the temperature of the cavity reaches 150 K, the liquid helium valve is opened and about 1 hour latter the cavity is at 4 K. The tuner, installed on the cavity in the insulating vacuum, could only be thermalized after 4 days.

Static consumption of the cryomodule itself has been measured by isolating it from the valve box and connecting the helium return gas to a pressure stabilized helium pipe. The measure of the return gas flow and of the helium level decrease gave the same result: static losses are comprised between 6.5 and 7.0 W. These values are a little higher than the first estimations (4 W) but they remain within the limit fixed by the cryogenic system of the SPIRAL2 LINAC (8.5 W).

The dismountable bottom flange of the cavity is cooled down by several copper breads connected to the liquid helium bath. The RF power coupler that is connected to this bottom flange carries about 1 W to 1.5 W to the flange. As described above, we did not succeed to cool the bottom flange down to temperatures lower than 14 K to 17 K (depending on the thermalization scheme). Further thermal simulations showed that, unlike the first estimations we made, the copper breads cannot evacuate the power coming through the coupler. The main reason is that the efficiency of this cooling system is limited by the thermal resistance of the contacts between the breads and the copper blocks. It is the main reason of the high temperature of the bottom.

The dynamic cryogenic losses include the losses of the cryogenic line (with one cold valve), the losses of the valves box, and the losses of the cryomodule. These losses are measured by the return helium gas flow meter. Measured values are much higher (around 35 W) than expected (about 15 W). The helium gas return gas pipe is undersized, and causes pressure increase when additional load (cavity RF power) is added to the static loads. As a consequence the helium level was difficult to stabilize in the first step of the tests. Modifications of the return gas pipe allowed helium level stabilisation in a second step.

RF Power Tests

Before mounted on the cavity, the power coupler had been previously conditioned on a specific stand in LPSC Grenoble [2]. Once mounted on the cryomodule, the power coupler was conditioned up to the full power of 10 kW two times: at room temperature before cooling down the cryomodule, and when the cavity was cooled at 4 K. Conditioning was performed at 89 MHz, 90 MHz and 87.69 MHz (cavity frequency at 300K), with a 50 Hz repetition rate and impulsion width ranging from 20 μs to CW. Multipactor barriers appeared during conditioning at 300 K, the main ones at 4, 26, 131 and 220 W. They proved impossible to fully process, as they systematically reappeared after conditioning of the next level.

External Q factor has been measured by two means (cavity at 4 K): transmission method (using the 10 kW amplifier and a network analyser), and using the decay time factor (at low field, 5 Hz, 5% duty cycle). Measured values are 5.2 10^5 and 5.4 10^5 respectively, for 10 mm of penetration of the coupler's antenna inside the cavity.

The RF operation was hampered by the low Q factor of the AZ1 cavity before improvement. The RF losses of the cavity are about 10 times higher than the expected value, thus the power dissipated by the cavity was about 35 W at 6.5 MV/m accelerating field (design accelerating gradient).

The maximum accelerating field reached was 10.3 MV/m, higher than the design value required by the SPIRAL 2 project (6.5 MV/m). However duty cycle was reduced down to 5% (5 Hz) in order limit the thermal load that could destabilize the cryogenic system.

Continuous mode could be maintained at a gradient of 6.5 MV/m for about 40 minutes.

Tests of the Tuning System

As described in previous papers, the tuning system works by deforming the cavity in the region of the accelerating gaps [3, 4]. The tuning system is screwed on the cavity on one side, and a sliding system was put on the other side. Therefore, it can be used to squeeze the cavity but not to pull it. The cavity has to be tuned in such a way that at the working frequency (88.052 MHz) the tuner is working around the middle of its whole tuning range (25 kHz).

For the first test, the tuning system was initially put just in contact with the cavity (at the extremity of its range), and not bolted to it. After a single thermal cycle of cooling down and warming up, the resonance frequency of the cavity was permanently lowered by 5 kHz. This can be explained by the differential shrinkage between niobium (of the cavity) and stainless steel (of the tuning system) (see figure 6).

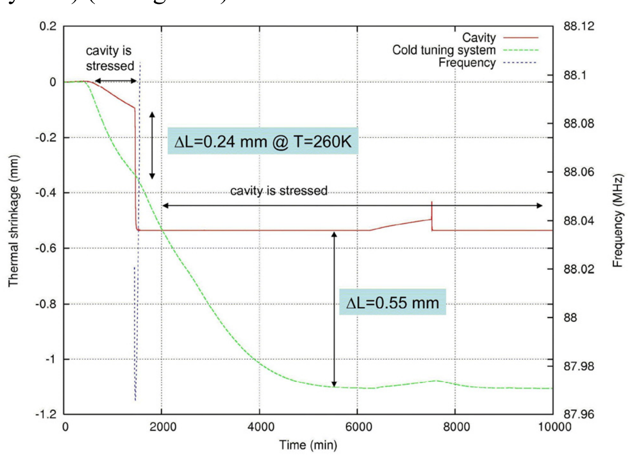

Figure 6: Differential shrinkage of the cavity and tuning system during cooldown.

During the nitrogen cooldown of the copper thermal shield (0 to 1500 min on fig. 3), the cavity and the tuning system are slowly cooling down. During this period the stainless steel tuning system shrinks three times more than the niobium cavity. Therefore the cavity is squeezed by the tuning system. During the helium cooldown phase (about 1500 min on figure 6) shrinkage of the cavity is higher than the one of the tuning system: thus the cavity is free. Then while the tuning system temperature cools down slowly its shrinkage becomes once more higher than the one of the cavity, now stabilized at 4 K (between 2000 and 6000 min on figure 6): once more the cavity is constrained It shall be remembered that the niobium elastic limit is 40 MPa at room temperature and around 400 MPa at 4 K. Therefore, while the deformations caused by the differential shrinkage at 4 K remain purely in the elastic domain, the cavity is plastically deformed during the nitrogen cooldown phase.

Thus, before any cooldown, the tuning system shall be placed some 1.3 mm away from the cavity. This was performed during the next cooldowns and no more permanent frequency shifts were observed.

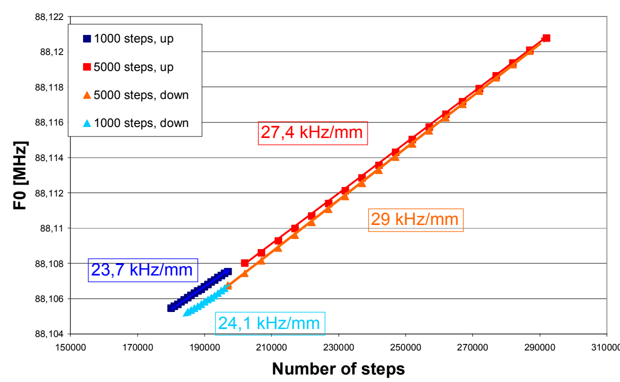

Figure 7: cavity frequency versus the motor steps. The slight hysteresis of 1 kHz disappeared after 2 cycles.

The measured sensitivity of the tuning system is about 27 kHz/mm (25 kHz/mm expected). Full excursion of the tuning system and way back show a slight hysteresis of about 1 kHz (figure 7). This hysteresis disappeared after 2 cycles. Frequency linearity downward is slightly better than upward. One can explain it by the fact that the tuner contact on the cavity is better when the force applied is stronger.

Cavity Alignment

Alignment tolerances of the cavities beam axis in the SPIRAL 2 superconducting LINAC are +/-1 mm.

Displacements of the cavity inside the cryomodule during pumping, cooldown and warming up operations have been measured by two means. First, the beam port flanges of the cavity were equipped with special copper vacuum seals. These seals were machined with lug-shaped sights (three per seal), which allowed to check the cavity movements by optical means in all directions. Second, a displacement sensor (Swema) qualified for cryogenic temperatures operation was mounted on the bottom flange of the cavity. The moveable part of the captor was tied on the cryostat top and bottom walls with an Invar wire in order to check vertical displacement of the cavity.

Pumping shows a vertical displacement of the beam axis lower than 0.1 mm.

Cooldown show a vertical displacement of 1.13 mm by optical method, and of 1.07 mm by the displacement captor. No horizontal displacement is measured. These measurements are similar to the estimated value of 1.11 mm upward during cooldown.

Therefore the cavities will be shifted downward of 1.1 mm during the cryomodules assembly to compensate for the beam axis displacement during cooldown.

FUTURE ACTIVITIES

As the first two cavities (AZ2 and AS3) reached the required performances, the following cavities fabrication was shared between the two manufacturers (5 cavities each). Next cavities will be delivered between May and July 2010. They will be tested in vertical cryostat at Saclay after their delivery and before assembly inside the cryomodules.

The planning of the cryomodules delivery is in phase with that of the cavity delivery. The cryomodules components were ordered. The first of the series will be delivered at the beginning of 2010, and the 10 following ones will be delivered between July and December 2010.

The clean assembling of the cryomodules will be performed in the future large clean room at Saclay that was designed for the assembly of the X-FEL cryomodule (Figure 5).

The qualification cryomodule will be assembled and tested by the end of 2009 and the beginning of 2010. The main upgrade is the new magnetic shield. It consists now in a 1-mm thick foil of Mumetall® placed on the inner face of the cryostat (at room temperature).

Figure 5: the new large ISO 4 clean room being built at CEA Saclay.

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REFERENCES

[1] T. Junquera, P. Bertrand, R. Ferdinand, M. Jacquemet, "The high intensity superconducting Linac for the SPIRAL 2 project at GANIL", proc LINAC 2006, Knoxville, USA, p 142-144.

[2] Y. Gomez Martinez et al." Last SPIRAL 2 10kW CW RF Coupleur design", LINAC 8.Victoria Bristish Columbia. CANADA.

[3] P-E. Bernaudin et al., "Design of the Low-Beta, Quarter-Wave Resonator and its Cryomodule for the SPIRAL2 Project", EPAC 2004, Lucerne, Switzerland, July 2004,

[4] G. Devanz, "SPIRAL2 Resonators", 12th SRF Workshop 2005, Cornell University, July 2005, MoPO2.

[5] Multipactor simulations in superconducting cavities and power couplers, G. Devanz, Phys. Rev. ST Accel. Beams 4, 012001 (2001)