COMPLETION OF THE FIRST SUPERCONDUCTING RFQ AT INFN-LNL

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Abstract

The construction of SRFQ2, the first built superconducting RFQ for the low velocity accelerator PIAVE (injector of the SC linac ALPI at INFN-Legnaro) was completed.

It resonates at 80 MHz, it is made of full niobium and it is mechanically stiffened by a titanium jacket which is welded by electron beam welding on the tank. The cavity is about 0.8 m both in length and in diameter.

After completion of the mechanical construction, the structure went under a number of experimental tests, which are reported in the paper, in order to check: voltage unbalance among the four quadrants through bead-pulling; vacuum tightness; frequency change under vacuum and additional external pressurization; frequency change between 300 and 77 K; frequency change given by stepwise chemical etching of the internal surface.

The paper reports as well the most recent achievements obtained when the resonator was mounted into the cryostat, purpose-built to test it in the superconducting regime, and cooled down to the working temperature.

1 THE SUPERCONDUCTING RFQS OF THE NEW ALPI LINAC INJECTOR

The realisation of the first bulk niobium superconducting (SC) RFQ (SRFQ2) was completed in May 1999. It is the second RFQ on the beam line of PIAVE [1], the being built injector of the SC booster ALPI at INFN-LNL. The whole layout comprises two SRFQs in a single cryostat, followed by eight Quarter Wave Resonators (QWRs, β_{opt}=0.047). The 80 MHz resonant frequency, plus the typical issues related to the construction of a superconducting resonator [2] imposed the design of a four-rod structure, with 90°-apart stems [3]. These, together with the stiffening structure of the outer tank, were carefully optimised in shape so that the large size resonator (~0.8 m in length and in diameter) was made rigid towards mechanical vibrations. A full scale stainless steel model was built and tested [4]: the technological achievements made with the steel model allowed us to optimise the construction procedure of its SC version, which is now completed and under cryogeni[1]c tests.

Figure 1 shows a picture of SRFQ2, taken after chemical polishing and before high pressure rinsing.

Figure1 : Photo of SRFQ2, prior to final rinsing and assembly into the test cryostat

2 TESTS WITH THE COMPLETED RESONATOR

After completion, SRFQ2 went under several tests, which were meant to assess its quality, with respect both to the behavior to be expected at 4 K and to beam transport.

2.1 Bead pull tests

Two sets of bead-pull tests were done on SRFQ2 after the construction was completed.

The first set of tests aimed at determining how good the final alignment of the structure was, looking at voltage drops and relative voltage unbalances among the four quadrants. For this measurement a table tennis ball run along the structure in the four quadrants, touching the side planes of the modulated vanes (the position of the ball is far enough from the modulation that the latter can be barely seen in the experiment). $\Delta\phi$ is monitored on a network analyzer.
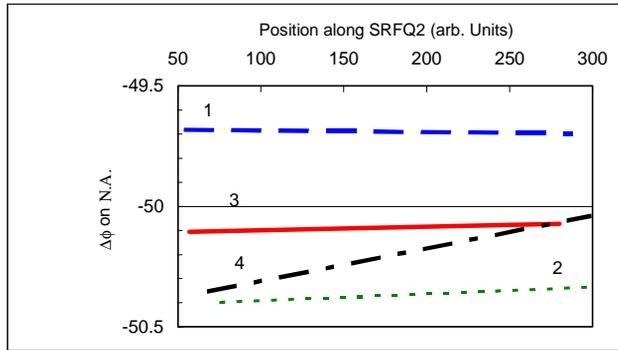
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Figure2: Proper alignment of the four electrodes was checked by pulling a bead along the four quadrants of SRFQ2 and looking at the phase on a network analyzer.

Figure 2 shows the interpolation of measured data in the four quadrants along the entire length of the resonator. In terms of the related transverse electric field, the unbalance of the four quadrants from their averaged value $(E_{t,i} - E_{av})/E_{av}$ is shown in table 1.

Table 1: Transverse field unbalance among the four quadrants (measured by bead-pulling method)

Quadrant	$(E_{t,i} - E_{av})/E_{av}$
i=1	+0.393 %
i=2	- 0.278 %
i=3	+ 0.007 %
i=4	- 0.107 %

The second bead-pull test aimed at a measurement of the capacitance of the structure. A 4.3 mm diameter metallic bead run on the axis of SRFQ2, giving relative frequency changes proportional to E_0^2; E_0 is just an accelerating field, being the transverse field contribution negligible around the axis, as shown in the bead pull plot in figure 3.

From Slater's theorem [5] for our spherical metallic bead one obtains $|E_0(z)| \sim 1620 \sqrt{(\Delta f(z))}$, while from the RFQ theory [6]

$$|E_0|^2 = \left(\frac{\pi}{L_C}\right)^2 \frac{A^2 V^2}{4}$$

where E_0 is the accelerating field of a cell of length L_C and acceleration parameter A, V being the voltage between electrode couples.

For any of the RFQ cells E_0 and L_C can be determined by the bead pull measurement shown in figure 3, while A is tabulated, as derived from the theoretical design of the RFQ itself [7]. Thus an inter-electrode voltage (V_{el}) can be derived from each cell and, through their averaged
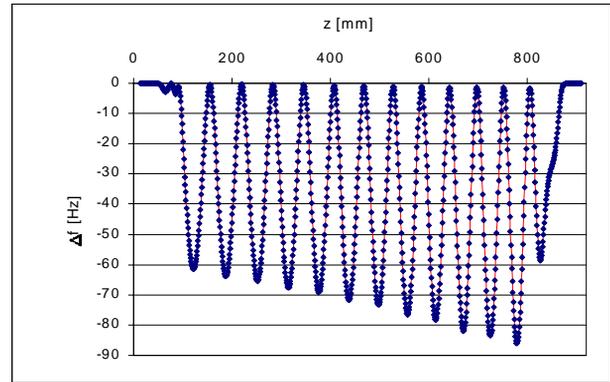

Figure3: Bead pulling of a spherical bead along the SRFQ2 axis allows to give an experimental evaluation of the structure capacitance (126.9 pF/m)

value and a measurement of the stored energy U, an experimental value of the total SRFQ2 capacitance can be evaluated. The result is a capacitance per unit length C/l_C ~ 127 pF/m, versus 135 pF/m given by M.A.F.I.A. simulations [4].

Then, once the measurement of the stored energy is correlated with the pick-up antenna signal, V_{el}, the peak surface field E_p and the total accelerating field of the structure E_a can be deduced.

2.2 Frequency response of the resonator to vacuum and to extra pressure from outside

Once mechanically completed, the resonator was tested for vacuum tightness and for its frequency change under vacuum, closing it at the extremities with two 20 mm thick aluminum flanges with a viton o-ring. The leak rate was observed to be below 3×10^{-9} mbar l/s (corresponding to the maximum sensitivity of the helium leak detector) at a base pressure below 1.3×10^{-3} mbar.

Repeated cycles, from atmospheric pressure in dry nitrogen to vacuum and back, gave the resonant frequency response shown in figure 4. Of the Δf = -62 kHz given by the test, a $\Delta f \sim$ -15 kHz was attributed to the deformation of the end-flanges [4], while the residual Δf ~ -47 kHz is expected to be the actual net effect of the deformation of the outer tank, causing each modulated vane to get closer to the cavity axis by ~ 50 µm.

Had one taken into account the frequency drop measured with the stainless steel model of the same resonator [4] by simply scaling the Young modulus of the stiffening jacket from steel to titanium, the expected result would have been $\Delta f \sim$ -30 kHz: apparently then the deformation of the niobium tank and electrodes accounts for another ~ 50% of frequency change.
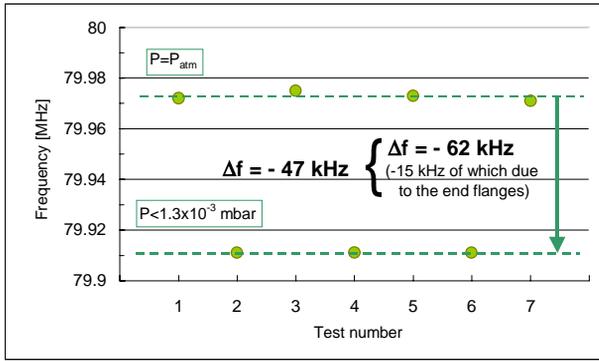
Figure 4: Frequency drops in repeated evacuation cycles of SRFQ2

SRFQ2 went then under tests of extra-pressure from the outside, in order to check the tightness of the electron-beam welding joints, to check the sensitivity of the resonant frequency change to future pressure changes in the liquid helium bath and to confirm that – within a significant extra-pressure range – all deformations are well within the elastic regime.

The resonator was placed in the external vacuum chamber of the test cryostat and was evacuated through an independent line; then the tank was pressurized up to +0.5 atm with gaseous helium ($\Delta P = 1.5$ atm on the resonator).   The leak rate from the whole resonator increased from $2x10^{-9}$ to $1.7x10^{-7}$ mbar l/s during the test: proper insulation of the closing flanges during the tests showed that a leak on their viton o-ring was responsible for the leak increase and the rest of the resonator was He-tight.

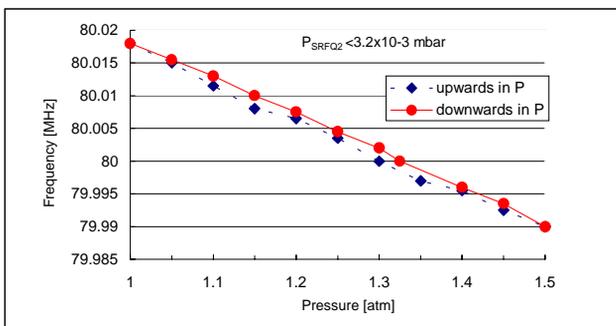Figure 5 shows the resonant frequency response to the extra-pressure tests.

Figure 5:   Resonant frequency change due to extra-pressure from outside the resonator.   There is no hysteresis up to the final value of $\Delta P = +1.5$ atm: the cavity can hence suffer such extra-pressure without any plastic deformations.

2.3 Frequency response of the resonator to cooling at liquid nitrogen temperature

The resonant frequency of the steel SRFQ2 model changed by $\Delta f \sim +220$ kHz, following extremely well the theoretical prediction given by the homogeneous contraction of stainless steel ($\Delta f/f = \alpha_{300-77K,SS}$).

The SC version of SRFQ2, however, is composed of two materials (niobium and titanium for the stiffening cage) which, though similar, are not identical in the value of the thermal contraction factor between 300 and 77 K. The thermal contraction factor of both niobium and titanium is anyway much smaller than that of stainless steel: hence the frequency change was expected anyhow to be significantly smaller than that measured with the model ($\alpha_{300-77K,SS} = 2.9x10^{-3}$, versus $\alpha_{300-77K,Nb} = 1.43x10^{-3}$ and $\alpha_{300-77K,Ti} = 1.51x10^{-3}$).   A frequency increase of about $\Delta f \sim +50\div100$ kHz was foreseen.

The experimental result, shown in figure 6, differed from the expected value and the frequency changed rather in the opposite direction.   This phenomenon was attributed to the significant shrinkage of the Al closing plates ($\alpha_{300-77K,Al} = 4.15x10^{-3}$, much higher than that of both Nb and Ti) which might have exerted some extra-shrinkage of the Ti end-flanges and hence some capacitance increase (the electrodes would get closer to the center).
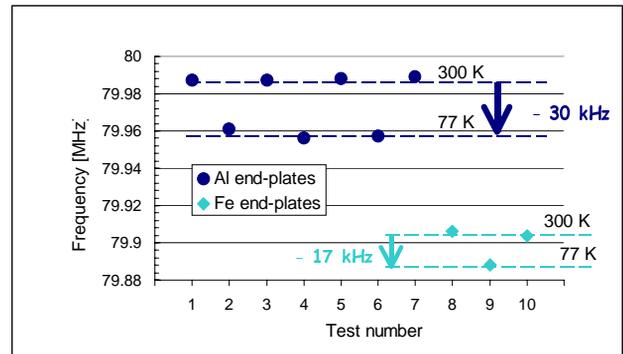

Figure 6: Frequency change of SRFQ2 from 300 to 77 K. The two graphs refer to Al and Fe closing plates respectively.

In order to investigate the situation better, the Al closing plates were replaced by iron ones ($\alpha_{300-77K,Fe} = 1.98x10^{-3}$ being much closer to the thermal contraction factor of Ti and Nb): in fact the frequency drop was half (from $\Delta f = -30$ kHz to $\Delta f = -17$ kHz), but the frequency did not increase, as it should have been expected without the influence of the closing plates.

Although the phenomenon was not completely understood, the frequency changes were observed to be anyhow about one order of magnitude smaller than the frequency tuning window of the resonator: the

discrepancy was hence not critical for the resonator operation.

2.4 Frequency response of the resonator to chemical polishing

Following ref. [8], we thought it was proper to remove eventually a total of about 100 µm of niobium from the internal surface of SRFQ2 by chemical polishing (CP). CP was done at CERN, following the very successful collaboration on this topic done with the LNL full Nb Quarter Wave Resonators. A 1:1:2 bath (of H_3PO_4, HF and HNO_3 respectively) was used first to polish the modulated vanes and welded stems, prior to completion of the cavity mechanical construction: i.e. 60 µm were removed at this stage on the region were the magnetic field inside the resonator is expected to be highest (top and bottom parts of the stems). The first CP stage preceded the rough frequency tuning of the resonator [4] and had hence no direct influence on the final value of the resonant frequency. The second CP stage followed the completion of the resonator, thus changing its resonant frequency. A rough estimation of the frequency change was done ($\Delta f \sim +15$ kHz/mm) calculating the change in capacitance of SRFQ2 by the removal of material from the electrodes. The experimental results are shown in figure 7: CP was performed in three steps and the frequency change rate was slightly higher than expected ($\Delta f \sim +18$ kHz/mm): the linearity of the curve demonstrates the excellent uniformity of the CP treatment. At the end a total of 120 µm was hence removed from electrodes and stems and 60 µm from the tank.
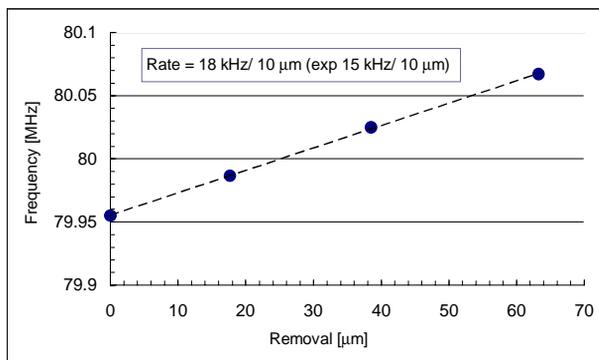

Figure 7: Frequency change of SRFQ2 during the final 64 µm chemical polishing.

2.5 Response of the end-plate tuning at room and liquid nitrogen temperatures

In its present final version, SRFQ2 comprises two closing plates in Cu, sputtered with some µm Nb on the cavity side. These two closing plates can be pushed and pulled by ± 4 mm each, to obtain fine frequency tuning. The frequency range spanned by this tuning method had been previously observed elsewhere [4]. Now we could thoroughly check it also at 77 K, mainly for the sake of the proper transmission of the mechanical motion at such temperature. The mechanical movement was quite good: some excessive friction showed up at 77 K, possibly due to imperfect cleaning of some joints.

Figure 8 compares the frequency range of the tuning of each closing-plate at 300 and 77 K. The frequency response is nearly identical at the two temperatures for tuner B, while tuner A shows a somewhat lower range at 77 K. The overall 280 kHz frequency window remains anyhow more than safely large.
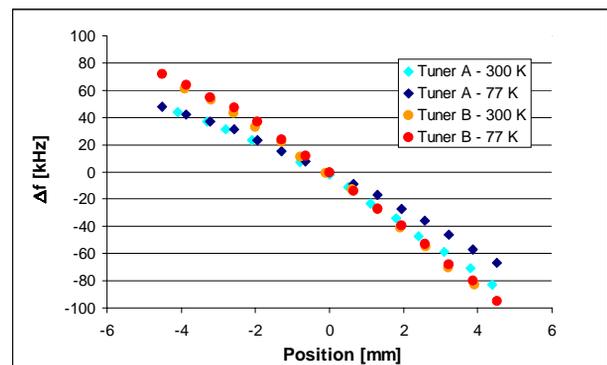

Figure 8: Measurement of the frequency range of the two tuners (pushing/pulling each closing plate) at 300 K and at 77 K.

3 BEGINNING OF TESTS AT 4 K

After the completion of the SRFQ2 construction in May 1999 and the execution of the above described experimental measurements, a significant effort has been spent by the whole PIAVE group in preparing the test cryostat to house the SRFQ2 resonator and eventually cool it to liquid helium temperature.

So as to check the proper behavior of the test cryostat, the stainless steel model of the SRFQ2 resonator served as a dummy cavity first: this resonator was properly mounted into the liquid helium reservoir, the liquid nitrogen shield was closed on it and the whole assembly was introduced into the room temperature outer tank. During the tests with the steel model, the mounting procedure, the vacuum tightness tests and the refrigeration of both the thermal shield and the helium reservoir with liquid nitrogen were tested with success.

Subsequently the superconducting version of SRFQ2 was equipped with Nb-sputtered Cu closing plates and mounted into the cryostat. A 1.2 mm thick magnetic shielding provided a reduction of earth magnetic field by more than a factor 10, which is believed to be adequate for the SC tests.

After filling the liquid nitrogen reservoir, conditioning of resonant field emission started: two bands of resonant field emission were found ($V_{el,1}$ = 340 ÷ 1050 V, $V_{el,2}$ = 2000 ÷ 6600 V), which could be easily overcome since the very beginning and which took less than 24 hours to be fully conditioned.

The resonant frequency was 80.000 MHz at room temperature and in atmospheric pressure of dry nitrogen, dropped by 30 kHz due to evacuation and increased by 14 kHz due to cooling to liquid helium temperature. The final frequency was then 79.984 MHz, 10 times closer to the working frequency than half the fine tuner range.
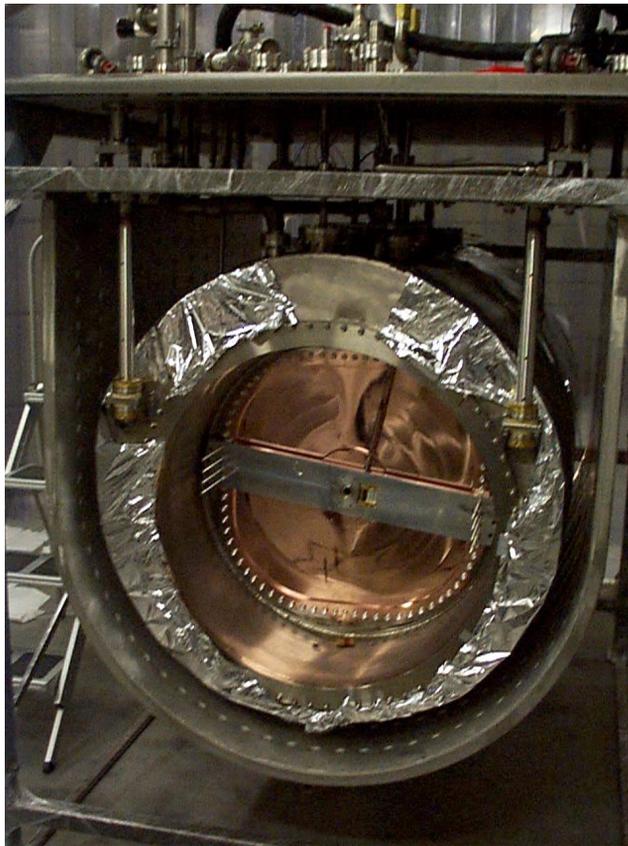

Figure 9: SRFQ2 mounted inside the liquid helium reservoir of the test cryostat.

Unfortunately mechanical problems with the coupler – impossible to solve without warming up and opening the cryostat - impeded an analysis of the superconducting performances of the resonator in this very first test.
The static consumption of the test cryostat was shown to be around 5 l/h, as measured from the gaseous He flux.

4 OUTLOOK

Further tests at 4 K of SRFQ2 are foreseen in the next few months, hoping to obtain a significant Q vs E_a curve soon. The construction of the other SRFQ for PIAVE (SRFQ1, which was designed to be quite similar in cross section, though nearly twice as long [9]) just started: it seems sensible to postpone the first welding stages of that resonator until SRFQ2 has proven to meet its design specifications in SC regime.

Collaboration with the Argonne National Laboratory has started, on the adaptation to each SRFQs of one or two fast tuners, very similar to those, which were successfully implemented on Argonne SC resonators. Due to the high stored energy of both resonators (SRFQ2 in particular) it seemed mandatory to develop a reliable system, capable of keeping the cavity locked when it will be in operation in the accelerator.

5 ACKNOWLEDGEMENT

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