EXPERIMENTAL RESULTS ON THE STAINLESS STEEL PROTOTYPE OF A SUPERCONDUCTING RFQ

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Abstract

At INFN-LNL the construction of a new injector for the superconducting booster ALPI was funded in fall 1996. The first accelerating cavities on the beam-line are two superconducting RFQ resonators (SRFQ1 and SRFQ2), which are being built in full niobium. A stainless steel prototype of SRFQ2 was built, with the aim of getting acquainted with all technologies related to the much more expensive superconducting version, particularly with the Electron Beam Welding (EBW) joints of the single components.
Electromagnetic (EM) tests were performed to verify the agreements with M.A.F.I.A. on the distribution of EM fields in the structure and to set up construction tolerances for the subsequent niobium resonator. The range of the slow tuner was also measured and compared with numerical predictions.
Particular emphasis was given in the project to get a high mechanical rigidity of the structure: mechanical eigenmodes spectra were taken and compared with numerical predictions. Preliminary results on the EM frequency sensitivity of SRFQ2 to liquid He pressure variations are reported.

1. THE FULL SCALE MODEL OF SRFQ2

PIAVE [1], the being built low velocity injector for the superconducting linac ALPI, will house two superconducting RFQ's (SRFQ1 and SRFQ2) in a single cryostat. The beam, originating from an ECR source located on a 350 kV platform, is injected through a transport line and the SRFQ's are followed by eight superconducting QWR's matching β_{opt} of the first ALPI resonators.
The RFQ's are of the four-rod type and resonate at 80 MHz (their main parameters are listed in ref.2). They are being built in full Nb (3 mm thick everywhere beside the thicker modulated vanes) and a liquid helium bath will cool all the external surface of the structure, including hollow stems and electrodes, except the end-plates which, realised in Nb-coated Cu, are cooled by thermal conduction. The construction of a full scale stainless steel model of one of the resonators, which is also being built in Nb first (SRFQ2), was motivated by the novelty of the structures, the complicated patterns of the electron beam welding (EBW) joints between their components, the necessity to grant sufficient mechanical stiffness versus both mechanical vibrations and slow pressure changes of the liquid helium bath and the development of novel methods of frequency regulation both in the course of the construction (rough tuning) and around the final resonant frequency at the end of the construction (fine tuning). SRFQ2 was chosen for the model, both because it was shorter and also because its stored energy was nearly twice as high as that of SRFQ1, thus representing a significant test bench for the electromechanical stability of the structure.
The stainless steel model of SRFQ2 (shown in fig.1) was completed in fall 1997 and the construction of the Nb resonator started immediately afterwards. The main construction steps were reviewed in ref.2. Precision of electrodes machining and of their positioning with respect to the SRFQ axis was evaluated by electromagnetic perturbation and the frequency range of the fine tuner was measured and compared with theoretical prediction (par.2). Effectiveness of the stiffening cage in coping with fast and slow causes of resonant frequency changes is described in par.3.

Fig.1: Photo of the complete prototype of SRFQ2

2 ELECTROMAGNETIC MEASUREMENTS

The procedure of adjusting roughly the resonant frequency of SRFQ2 in the course of its construction was described in ref.3, where the method adopted and the experimental results, showing a sensitivity of ~ 0.19 MHz/mm in the stepwise reduction of the stem length, are reported in detail.
At the end of the rough tuning sequence the stems were EB-welded to the tank quarters, the tank quarters joined to one another and eventually the end-flanges, internally machined according to the final perimeter of the structure

resulting from the rough tuning procedure, were welded to the structure.

Fig.2: Result of the bead pull measurements taken along the structure in the four quadrants. Voltage drops are within ± 2% from –367 to + 367 mm, the vane length.

Particular care was taken in positioning the electrodes, each with a precision of ± 0.1 mm with respect to one another and the beam axis and in such a way that the average distance of the electrode from the axis, what affects the EM resonant frequency most, was within ± 0.02 mm. Nevertheless one of the final steps, i.e. the welding of the four quarters of the stiffening cage, produced an unpredicted shrinkage of the structure, resulting in a final average position of the electrodes which was ~ 0.2 mm closer to the axis with respect to the nominal one.

A particularly accurate measurement of electromagnetic perturbation with a Ø=6 mm Plexiglas bead running at 45° between electrodes, at r = 4 mm from the beam axis, allowed to estimate voltage drops and bumps along the structure. These give an overall indication on whether both the positioning procedure was sufficiently accurate and possible mechanical deformations suffered by the electrodes in the final welding stages were sufficiently small for the beam not to be significantly affected by them. Fig. 2 shows the result of the bead-pull measurement: for each longitudinal position along the structure, the difference in the value of $f^{1/2}$ (proportional to the electric field) of each quadrant with respect to the average of the four quadrants is reported: this shows that voltage drops and bumps are within ±2%, a value which is acceptable for beam dynamics.

The frequency range of the fine tuning system, consisting in mechanically deforming the end-plates of the resonator by ± 4 mm with respect to a rigid ERGAL bar on the outside, was experimentally evaluated at room temperature (fig.3). The full frequency range attainable by deforming both end-plates is +100 ÷ -200 kHz, consistently with M.A.F.I.A. [4] prediction.

Fig.3: measurement of the frequency range of one of the two fine tuners. The full fine tuning range is hence +100÷-200 kHz

3 MECHANICAL MEASUREMENTS

Full Nb SC resonators, particularly if f_{res} <100 MHz, are affected by problems of electromechanical instabilities: tending to be large in size, the frequency of their mechanical vibration eigenmodes is low (typically 60 Hz or less [5]): the content of stored energy is also consequently large and the amount of reactive power needed to phase and amplitude lock the resonator in case of microphonics may be too large for the jitters in capacitance (and consequently in the resonant frequency) caused by mechanical vibrations. In our case, where the stored energy per unit peak field U/E_p is large (~ 0.14 J/MV/m), the frequency bandwidth Δf that can be controlled by typical electronic feedback systems [6,7] is Δf = 20 Hz with P_a= 1 kW, where P_a is the power of the RF amplifier feeding the resonator.

If the environmental mechanical energy exciting the resonator is not known "a priori", as it is usually the case, and assumed to be a constant over the frequency range, it is easy to show that, for the same vibration mode, the higher its eigenfrequency, the smaller its amplitude and hence the change in the electromagnetic resonant frequency of the structure.

A big effort was hence put, in the design phase of our superconducting RFQ's, in conceiving a simple-to-build but rigid external stiffening cage (visible in fig.1), which aimed at exceeding f_1 = 100 Hz for the lower eigenmode of mechanical vibration.

The mechanical design was elaborated by means of the code I-DEAS [8] and the vibration resonant frequency were measured by means of a direction sensitive accelerometer tightly attached in various points of the resonator, connected to a spectrum analyser through low noise coaxial cable and a power-supply/preamplification unit. Table 1 compares computation and measurements for the three lowest vibration modes of the resonator.

MODE	EXP	F.E.M. code	Δf/f [%]
First	130	151.2	-14.0
Second	149	167.1	-10.8
Third	174	190.7	-8.8

Table 1: Experimental evaluation of the three lowest modes of mechanical vibration is compared with computational results. The welded end-flanges increased these values even further.

Translating the Young modulus and the density of AISI304L stainless steel into those of Nb (RRR=250) for tank, stems and electrodes and into those of Ti for the stiffening cage, the lowest vibration eigenmodes for the superconducting version of SRFQ2 is ~ 120 Hz, which well exceeds the target value of 100 Hz. Moreover it should be noted that the data shown in table 1 were taken when the end-flanges – constituting a further mechanical stiffening - were not yet attached to the cavity: more recent preliminary results show that, with EB-welded end-flanges, the experimental values of the first and second modes are 150 Hz and 186 Hz respectively.

A preliminary evaluation of the sensitivity in the change of EM f_{res} versus changes of the liquid helium pressure could be inferred from some tests on the model. Once we shall be able to also determine the velocity of the slow tuner in following pressure variations (to be done with the Nb cavity in the test cryostat), the maximum allowable pressure variation rate will be clear.

In its final configuration, the outer shell of the Nb SRFQ will be the inner wall of the liquid helium reservoir: the pressure outside the resonator will be hence subject to variations around the atmospheric pressure, the SRFQ being in high vacuum. Experimentally, we could evacuate the cavity (varying the value of its residual pressure) and were able to measure both the global frequency change from P=1 bar (dry nitrogen) down to 10^{-1} mbar and, with the resolution of 1 μm, the mechanical deformation of the stiffening ribs and the average change of the distance between opposite electrodes in the same frequency range.

The global frequency change from 1000 to 0.1 mbar was -8 kHz. Since a Δf = +23 kHz is to be expected from the change of the dielectric constant, the overall frequency change attributed to mechanical deformations is –31 kHz. Subtracting the effect of the deformation of the thick temporary end plates which had to be used to be able to evacuate the resonator, a total -15.7 kHz frequency change has to be expected from the mechanical deformation of those parts of the SRFQ (ribs, tank, stems) which would be subject to a pressure difference also in the cryostat. From 1000 to 0.1 mbar the average distance of the electrode from the resonator axis decreases, quite linearly, down to 18 μm, and the phenomenon is basically fully explained by a deformation of the four long bar (12 mm thick and 60 mm high) of the stiffening cage, the maximum deformation of which averages to 21 μm. We can conclude that, provided that the overall pressure difference seen by the outer wall of the resonator is 1 ±10% bar, the frequency sensitivity in that range is not larger than 10 Hz/mbar.

4 CONCLUSION

Room temperature experiments the prototype of SRFQ2 have been completed. When the test cryostat for both SRFQ1 and SRFQ2 will be available (presumably fall 1998), f_{res} change and behaviour of the fine tuning system, as well as electrode alignment, possible deformations and mechanical eigenmodes will be measured.

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