SUPERCONDUCTING RADIOFREQUENCY QUADRUPOLES

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Abstract

These superconducting (sc) resonators, originally conceived and prototyped a decade ago, were finally designed, developed and built for the being completed injector at INFN-LNL. The most recent results are discussed together with development highlights, technologies challenges and possible uses.

1 WORTH AND POSSIBLE USES

Radiofrequency quadrupoles (RFQ's) have been largely used since decades for the acceleration of low velocity ions [1]. They combine the strong electric focusing provided by the rf quadrupole with effective acceleration given by the modulation of the vanes, which are machined so as to provide a longitudinal electric field component that is made synchronous with ion bunches. RFQ structures are ideal for ion velocities β=v/c<0.05; they are typically normal conducting (nc), spanning a frequency range 50÷400 MHz, with a 100÷200 kV voltage difference between vanes and a quality factor $Q\sim10^4$. Their power consumption usually limits their duty cycle to values lower than 20%.

The opportunities offered by a sc version are those of a lower power consumption ($Q\sim10^8\div10^9$) and a CW operation duty cycle, whereas a significantly higher vane voltage than in the normal conducting case seems to be beyond present technological developments [2,3].

The possible uses of sc RFQ's are discussed in this chapter, together with the related theoretical and experimental work done worldwide, to the author's knowledge.

1.1 SRFQs for heavy ion acceleration

For the acceleration of slow and relatively low current heavy ion species, the concept of a sequence of independently-phased short sc RFQ structures was developed at Stony Brook in the years 1988–1993 [2,4,5] and was concluded by the design, construction and test of a four-accelerating-cells, 0.42 m long and 50 MHz prototype.

This so called "RFQlet" structure would combine the advantages of rf quadrupole focusing with those typical of sc resonators of many heavy ion boosters: small size, relatively low stored energy, wide transit time factor curve, flexibility of separate resonator approach.

The RFQ-let injector was proposed as a compact alternative to the Positive Ion Injector, which was completed in 1992 at Argonne National Laboratory.

Both the RFQ-let (Stony Brook) and the PII (Argonne) injectors were meant to follow an ECR ion source mounted on a high voltage platform (V = 350÷400 kV). The Argonne PII employed 18 interdigital quarter wave resonators (ID-QWR) of four different classes, with 11 sc solenoids among them for transverse focusing, for a total length of around 10 m [6].

The RFQ-let linac design, which ended up in the construction of a full-scale sc model, foresaw 6 different structures, for a total length of around 4 m [4].

The Stony Brook SRFQ model, designed for a peak surface field $E_{p,s}$ = 15 MV/m, reached about 10 MV/m, limited by a thermal breakdown attributed to a flaw in the bulk Cu material.

At INFN-LNL two 80 MHz sc RFQ's were proposed and are being realized as the very first accelerating structures of a heavy ion injector (named PIAVE) of the sc linac ALPI [7]. Table 1 summarizes their main features.

Table 1: Main features of PIAVE sc RFQ's

Mass to charge ratio	8.5		
Beam current	<5	μA	
RMS Emittance	0.1	mmmrad	norm.
Radio Frequency	80	MHz	
Input Energy	37.1	keV/u	β=.0089
Peak Surface field	25.5	MV/m	
Max. Stored energy	≤4	J/RFQ	
Band width	>20	Hz	
	SRFQ1	**SRFQ2**	
Vanes length	137.8	74.61	cm
Output energy	341.7	586	keV/u
Voltage	148	280	kV
Tank diam. (approx)	65	65	cm
Number of cells	42.6	12.4	
Average aperture R_0	0.8	1.53	cm
Modulation factor m	1.2-3	3	
Synchronous Phase	-40÷-18	-12	deg
Dissipated power	<7	<7	W

The INFN-LNL RFQ's follow an ECR located on a 350 kV voltage platform. Beam bunching is done ahead of the RFQ's (with a consequent 30% current loss) and only the accelerating part of the classical RFQ structures is retained. It was decided to even split the accelerating part between two cavities, doubling the intervane voltage from the first to the second. Consequently the RFQ's are not too long (1.4 and 0.8 m respectively) with tolerable stored energy (within 3.6 J). The voltage ramping in the last structure also allows transverse focusing,

$$B = \frac{eV}{mc^2}\left(\frac{\lambda}{R_0}\right)^2$$

to remain strong enough for good beam transportation.

If one wishes to compare the nc and the sc options, the following should be noted. Beside the mentioned considerations on power consumption and duty cycle, in a normal conducting RFQ of the same frequency an electric peak surface field $E_{s,p}$~ 21 MV/m (twice the Kilpatrick limit) would be at most probably achievable at the low frequency required by strong transverse focusing (80 MHz). Voltage ramping would be difficult because of the V^2-scaling of the dissipated power and the related cooling limitation: this limit does not exist in sc cavities.

The Q-curves of sc RFQ's at Legnaro (see chapter 3) have shown that one of the two main demonstrations of feasibility of sc RFQ's, i.e. the possibility to reach a peak electric surface field between 25 and 30 MV/m, could be obtained on repeated occasions.

The remaining crucial issue in sc RFQ's is the control of the cavity eigenfrequency against microphonics: in fact the linac operating frequency must be comprised in the sc RFQ bandwidth at all times, in order to allow phase synchronization.

The natural bandwidth of an 80 MHz cavity at Q = $8x10^8$ is 0.1 Hz. Presumably the smallest mechanical vibrations would cause EM-eigenfrequency jitters significantly larger than 0.1 Hz. A resonator with strong overcoupling would have its bandwidth enlarged (see par. 3.3):

$$\Delta f = \frac{P_{RF}}{2\pi U} = \frac{P_{RF}}{\pi C V^2}$$

(U is the stored EM energy, C the total capacitance and V the inter-electrode voltage).

Most of the power will be reflected backwards and dissipated at room temperature, since the ohmic losses of the resonator are small and beam loading is negligible in a low-current heavy ion structure.

Beside strong overcoupling via a 1 kW amplifier and a dedicated coupling line, other measures were considered at INFN-LNL in order to control the effects of mechanical vibrations: stiffening of the tank by means of a Ti cage [8] and use of fast tuners developed in collaboration with Argonne National Laboratory [9,10].

The latest results obtained at INFN-LNL on sc RFQ's for low intensity heavy ion beams will be discussed in chapter 3. The preliminary success with these structures makes it possible to start conceiving their possible applications to the acceleration of Exotic Ion beams and intermediate intensity proton beams for Positron Emission Tomography [11].

1.2 SRFQ's for acceleration of exotic species

The acceleration of the Nuclear Species produced in an ISOL-type (Isotope Separation On Line) facility typically employs nc CW RFQ's for the low velocity part of both the primary and the secondary accelerators.

In the case of the primary accelerator, concerns in the adoption of a sc RFQ are related to the significantly higher beam intensity (see the nc CW RFQ's considered for high current beam like LEDA [12] -100 mA - and TRASCO [13] -30 mA – for comparison). While the gas load, coming from the space charge neutralization section, can be possibly intercepted so as to avoid cryopumping by the RFQ structure, the beam losses, which for typical transmissions of 95-98% are in the kW range, represent a serious thermal load problem to the resonator and to the entire cryogenic system. And one cannot disregard the activation of the structure either.

R&D activities were started at Argonne and Los Alamos National Laboratories in the early nineties on sc RFQ's for these applications.

A very encouraging result, in terms of peak surface field, was obtained in 1990 at Argonne on a very small sc RFQ device obtained by equipping a Nb split-ring resonator with RFQ unmodulated vanes (65 mm long): CW peak surface fields of 128 MV/m could be achieved [14]. This result will be probably difficult to reproduce on a larger scale. However it encouraged the design and early fabrication of a sc RFQ model at Argonne [15,16] (see fig. 1), meant as a sc model for possible primary acceleration of a 25÷100 mA proton beam and design studies at Los Alamos [34]. The resonant frequency of the ANL model is 200 MHz and the final structure (around 4 m long) would accelerate the protons from 100 keV to 3 MeV. The main design challenge was to provide beam transmission better than 99.5 %, for the considerations on thermal power management mentioned above. The project is temporarily on-hold at Argonne.

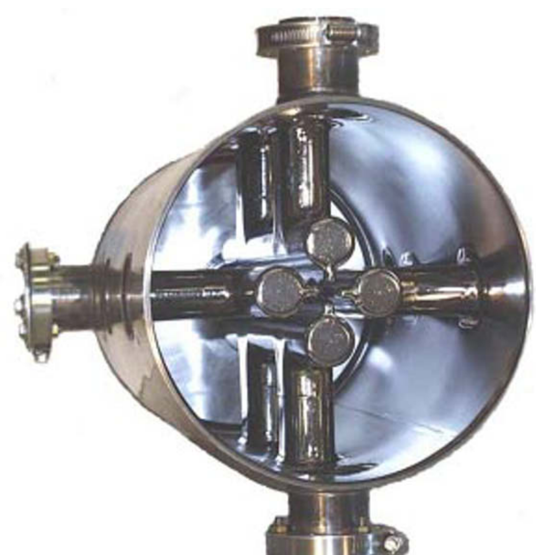

Fig. 1: Photo of the 200 MHz model developed at Argonne for possible high intensity proton accelerators

The application of sc RFQ's for secondary acceleration in exotic beam facilities seems a very sensible solution: it is less demanding because of the much lower beam current and it is very interesting for the intermediate energy Nuclear Physics community. Secondary beams, generated through gas ionization in a hot target, are weak and CW (the memory of the primary accelerator time structure is lost in the gas diffusion process); therefore a sc accelerator, also working in CW mode, seems a good choice.

In the project study SPES [17] we considered the acceleration of RIBs in ALPI, fed by a new injector similar to a replica of PIAVE. More in detail, we considered the beam after the 20 kV extractions from a charge breeder (efficiency ~ 5%), with a mass over charge ratio of 10, accelerated by three sc RFQs. The full results of these studies are reported in ref. [11]. The scenario is a sequence of three RFQ's, capture efficiency above 95% and a final emittance of 1.5 ns keV/u at 672 keV/u.

The design of the resonators is essentially the same as that of PIAVE structures, thus taking the largest possible advantage obtained in their development. The resonant frequency is still 80 MHz. With respect to PIAVE we increased the design surface field from 25 to 30 MV/m, consistently with a second generation RFQ and with the present performances of LNL quarter wave resonators in Nb.

With three RFQ's we can have direct injection after the 20 kV ECR extractor, thus avoiding the PIAVE 350 kV high voltage platform. The output emittance is perfectly suited for the injection into ALPI. Two additional cryostats of Quarter Wave Resonators complete the injector (like in PIAVE). It is possible to accelerate the ^{132}Sn reference beam without intermediate stripping up to ALPI end (5.3 MeV/u) with a transmission of 75-85%.

1.3 SRFQ's for Positron Emission Tomography

We finally considered the use of a sc RFQ for the production of the short-lived isotope markers needed for Positron Emission Tomography (PET) [11]. In this case a proton beam of few hundreds microamperes, 10 MeV, has to be produced in a hospital environment: the half-life of radioisotopes used to synthesize the radio pharmaceuticals is 2÷110 min and it is essential that the PET and the accelerators are only a few minutes away from each other.

It would be a single 160 MHz sc RFQ (5.6 m long, 0.35 m diameter), along which the vane voltage would vary between 170 and 400 kV, for a maximum surface field of 33.6 MV/m. The 0.5 mA beam current with a 10 MeV final energy would exit with 98.7 % transmission, losing 12 W on the surface walls, on which the rf power consumption would be around 70 W. The beam loading adsorbs the main part of the power, and the bandwidth is naturally enlarged.

The use of a sc structure implies some costs (e.g. purchase a small liquid helium liquefier) and some additional R&D. On the other side: the structure is rather short; it is by far less heavy than typical cyclotrons used for the same purpose; the RF system is small (5.5 kW solid state amplifier); mains power and overall cost could be competitive with cyclotrons (i.e. 18 MeV and 70 μA) widely adopted for the same purpose.

T. Wangler did in 1993 a similar exercise at Los Alamos [18]. Beam energy and current are comparable to our case. He assumed a more optimistic 44 MV/m for the peak surface field and ended up with a smaller structure (3 m long and 0.2 m diameter for a resonant frequency of 425 MHz). It would produce a 2.5 MeV proton beam with an intensity of 50 mA.

2 TECHNOLOGICAL CHALLENGES

In this chapter I review the design criteria, the main technological issues and the choices related to the construction of the resonators SRFQ1 and SRFQ2 for the INFN-LNL CW injector of heavy ions PIAVE (see table 1). Most of the treated arguments would roughly maintain their validity also for sc RFQ's designed for the other above-mentioned possible purposes.

2.1 The geometry

The design criteria of a sc RFQ combine the requirements of typical normal conducting RFQ's with the requirements of sc resonators. SRFQ2 was prototyped in stainless steel [8] and built in full Nb before starting the construction of SRFQ1, since it was both shorter and more critical for its mechanical stability (U is larger). A photo of SRFQ2 is shown in fig. 2.

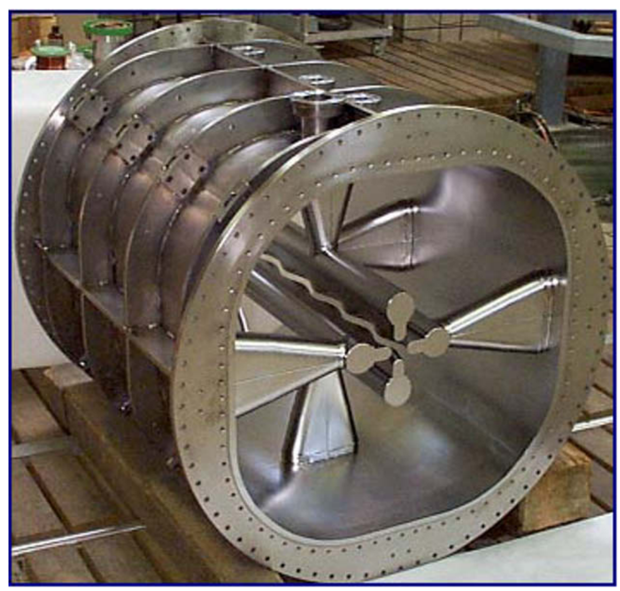

Fig. 2: Photo of SRFQ2 for the heavy ion injector PIAVE.

The advantages of four-rod and four-vane models are combined [19,20,21], like in the Argonne structure of fig. 1. The vane-shaped rods reduce the influence of modes higher than the quadrupole one on the charge particle motion, whereas the quite low resonant frequency (80 MHz) implies the use of supporting stems, instead of vanes, thus resorting to a lumped parameter resonator of the four-rod type [22]. The resonator diameter (< 0.8 m) can be kept within a value compatible with a reasonable size of the cryostat and around 50% smaller than the corresponding four-vane type.

It was chosen to place the stems of one couple of electrodes in an intermediate position between those of the other couple (the so called “90°-apart-stem RFQ”). The small decrease in the degree of geometric symmetry is compensated by a halved surface magnetic field in the region of the electrodes (as has been clarified in the lumped element analysis in [23]), which is the only part of the resonator machined in a computer controlled milling machine from a thick niobium bar and therefore more critical from the point of view of surface current density. Moreover it is thus possible, as described in Ref. [24], to exploit the entrance and exit gaps of the resonators as accelerating gaps, their length turning up to be of the same order of magnitude of βλ.

The distribution of electromagnetic (EM) fields in the resonator were simulated by means of M.A.F.I.A. code [25], and the resulting fundamental eigenfrequency could be compared with the theoretical estimate one with the lumped element circuit.

The code gave f_0 = 76.6 MHz, i.e. –6% with respect to the theoretical estimate. The corresponding tank inner size was 0.62 m. At the design peak electric surface field of 25.5 MV/m (needed for the 280 kV vane voltage difference), the peak magnetic field was smaller than 0.025 T and the ratio of the stored EM energy to the square of the peak electric surface field U/ $E_{s,p}^2$ = 0.0048 J/(MV/m)^2. Fig. 3 shows one graphic output of the EM code.

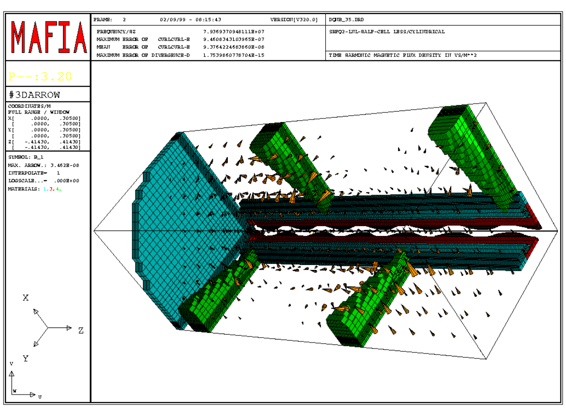

Fig. 3: Distribution of the magnetic field in a quarter of SRFQ2, as calculated by M.A.F.I.A.

2.2 The superconducting material

The high value of $E_{p,s}$ required by both resonators (25.5 MV/m, see table 1) forced us to use niobium as a superconductor. Full Nb was preferred to niobium sputtered onto copper, which would have required a substantial R&D effort.

The technique of electron-beam-welding (EBW) properly shaped portions of high quality (RRR ~ 250) niobium sheet is well established, but the somewhat limited thermal conductivity of niobium (ρ_{th} ~ 75 W/mK) imposes to fill with liquid helium all the parts where the surface is subject to a high current density. The whole structure shown in fig.2 is immersed in a liquid helium bath where the resonator cylindrical wall represents the inner wall of the helium dewar in the cryostat; helium penetrates into the stems and fills also the cylinders ($Ø_{in}$=48. mm) located on the back of the modulated vanes. The latter, made from 24. mm thick niobium bars for the ease of modulation, are also carved inside to allow efficient cooling of the vanes themselves. The cylinders on the back of the electrode serve also as the natural geometric connection between the vane-shaped rods and the stems: by extrusion from these cylinders proper matching with the stems is found. The various steps in the mechanical construction are extensively discussed in ref. [8].

Removal of gaseous He from the hollow lower electrode is accomplished by natural siphoning through dedicated tubes, under the natural though small pressure of the liquid helium stored in the dewar [26].

2.3 Electro-mechanical stability

Superconducting cavities are characterized by high intrinsic Q and by a consequently narrow bandwidth around the resonant frequency. They are therefore sensitive to frequency variations caused by the liquid helium pressure changes and by environmental mechanical noise and microphonics. The solution of the problem is usually a combination of electronic control and development of stable mechanical design.

A comprehensive description of phase and amplitude control of a sc resonator is given in Ref. [27]. It is also shown [28] that the ideal amount of overcoupling of the resonator which minimizes the total power of the rf amplifier P_{max} is found when $\Delta f_L = \delta f_{max}$, Δf_L being the loaded bandwidth and δf_{max} the maximum angular frequency deviation to be controlled, provided that the intrinsic bandwidth $\delta f_0 << \delta f_{max}$. In our case we can assume to be able to reach an unloaded Q_0= 10^9, yielding at f=80 MHz an intrinsic bandwidth δf_0=0.08 Hz. The loaded Q_L value needed to reach Δf_L=20 Hz is hence 4x10^6. The “in phase” power needed to obtain Q_L = 2x10^6 with a stored energy content U = 4 J is then

$$P_{oc} = \frac{2\pi f U}{Q_L} = 0.5 \text{ kW}$$

The rf amplifier unit for the resonator must be capable of an output power which be P_{max} = 2 P_{oc}. Most of P_{oc} is reflected back by the cavity and absorbed by a load through a circulator. Resonant frequency changes cause phase errors between the cavity and an RF clock when the cavity is in operation: under phase error conditions, the controller circuit will add reactive power to keep the loop locked, bringing the amplifier power up to P_{max} at the maximum phase excursion, i.e. at the maximum frequency change which can be sustained.

It is reasonable to assume that the phase and amplitude feedback control system works reliably up to a P_{max} ~ 1 kW [29]. Once this limitation is given, clearly the lower the stored energy U the larger the frequency variation range that can be controlled electronically: hence, since the voltage is fixed by beam dynamics requirements, this poses a design limitation on the resonator length, being the capacitance per unit length also quite constant in RFQ's.

As far as possible sources of mechanical noise are concerned, resonant frequency variations due to liquid helium pressure changes were estimated to amount to about 3 Hz/mbar in the Stony Brook SRFQ prototype and to 1 Hz/mbar in LNL full niobium QWR's [30]: anyway they are usually slow enough to be controlled connecting the mechanical slow tuner to a separate phase feedback circuit. The amount of resonant frequency variations due to environmental noise and microphonics is even more difficult to predict than that due to changes in the liquid helium pressure. It depends on several factors, such as frequency spectrum and amplitude of mechanical noise in the accelerator vault, efficiency of the cryostat in damping external noise, possible white noise due to the feeding of liquid helium in the cryostat or to helium gas removal or bubbling, more or less robust mechanical design of the resonator.

The mechanical design of the cavity, more extensively treated by G.Algise and referred to in Ref. [31], aimed at pushing to the higher possible frequency the lowest mechanical vibration mode of the resonator, far above 0÷60 Hz (the known noisy region in the ALPI vault at INFN-LNL). By developing particularly rigid stems and with the fundamental support of a titanium stiffening jacket (visible in fig.2) welded outside the resonator tank, this frequency was pushed as high as 120±15 Hz, as predicted by the simulation code I-DEAS [32] (see fig. 4).

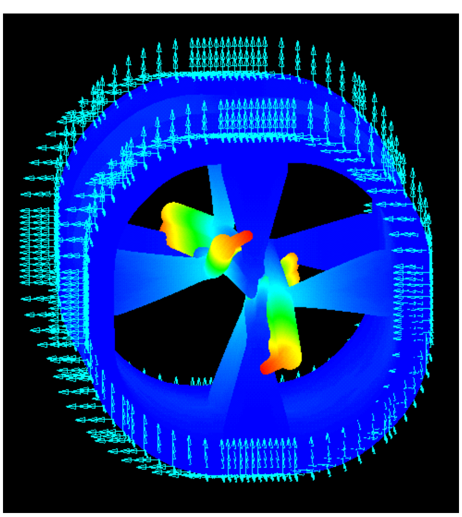

Fig. 4: Pattern of the lowest mode of mechanical vibration of SRFQ2, as shown by the I-DEAS code. Amplitudes are deliberately exaggerated.

Ti was chosen as the appropriate material of the stiffening jacket for various reasons: it can be nicely joined to Nb by electron beam welding (EBW); the relative contraction factor between 300 K and 4 K of Nb and Ti is very similar; it is cheap and readily available. Moreover it should be noted that mechanical eigenfrequencies scale like $(E/\rho)^{1/2}$, where E is the Young modulus (similar between the two materials) and ρ is the density (very low for Ti): this favours Ti too.

2.4 Mechanical adjustment of the electromagnetic frequency

The precision in determining the resonator frequency by the electromagnetic simulation code M.A.F.I.A. proved to be better than 0.5%; however experience in the construction of various types of resonators suggests considering a possible discrepancy up to ±1% between the prediction of the code and the real resonator.

The target frequency at room temperature had clearly to take into account all frequency changes to which the cavity is subject before being operational in a cryostat, i.e. those given to evacuation, chemical etching and cool-down. They were partly predicted through the stainless steel model and were described in detail in refs. [8,33].

In the assembly phase of the resonator a procedure must hence be foreseen to change the resonant frequency by ±800 kHz around the value estimated by the code at 300 K ("rough tuning") and to eventually be well within the resonator fine tuner range at 4 K. Rough frequency tuning has been described in ref. [8] for SRFQ2 and was obtained by a stepwise reduction of the stem length (and of the tank perimeter consequently) before the final EB welds.

It must be emphasized that a mechanical positioning precision better than ± 100 μm has to be achieved for each quadrant in the three Cartesian axes for reasons of good beam dynamics. The fulfilment of this task, by both optical tools and bead pulling measurements (at 300 K) and evaluation of the splitting of the dipole modes (at 300 K and 4 K) was reported in ref. [3] for SRFQ2. We eventually estimated that the obtained precision was around ± 50 μm, hence better than specified.

The fine-tuning method needs a tuning range of tens of kHz and a sensitivity of 1 Hz at most. Fine tuning is achieved by pushing/pulling the 1 mm thick end-plates, made of OFHC Cu, sputtered with a Nb layer by S. Stark and V. Palmieri at INFN-LNL. The tuning range was first estimated by M.A.F.I.A.; then tested at 300 K and 77 K [33]. The present working range, on SRFQ2 mounted in its test cryostat, is shown in paragraph 3.2.

3 LATEST RESULTS OF SRFQ1 AND SRFQ2

In the previous chapter, design, technological challenges, choices and tests in the development of sc RFQ's have been described, with specific reference to the particular application of those sc RFQ's for heavy ions developed for the ALPI injector at INFN-LNL.

In the present chapter only the most recent and yet unpublished results obtained in the development of these resonators will be reported.

After performing the first sc test on SRFQ2 in May 2000 [3] the experimental activity was interrupted until February 2001 because of a cold vacuum leak in the test cryostat. After solving this problem, the following tests aimed at: reproducing or possibly improving the Q vs. $E_{s,p}$ performance curve; improving the mechanics and testing the frequency range of the fine tuning system; checking the electro-mechanical stability of the resonator in the environment of the test cryostat. Meanwhile the construction of the twice-longer SRFQ1 resonator was nearly completed.

3.1 Q curves of SRFQ2 in 2001 tests

The graph of fig 5 compares the three Q curves obtained this year with the very first one obtained in May 2000. The purpose of the repeated tests was to show reproducibility of the result, to optimize design and performances of rf ancillary equipment (antennas and fine tuner), to start checking the frequency stability of the structure, both in free oscillation and with respect to a master oscillator, to test the reproducibility in the behavior of the tight gasket-free rf joint of the Nb-sputtered end flanges to the target body.

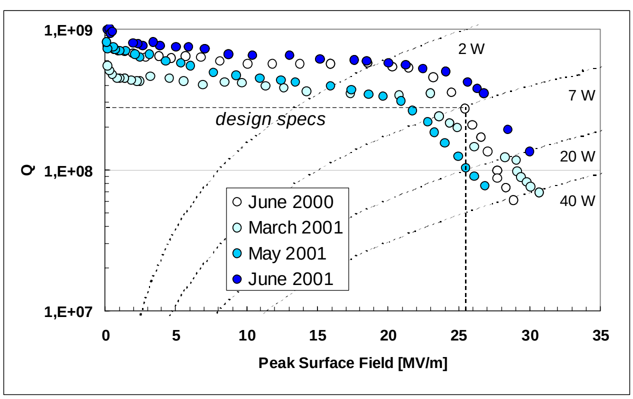

Fig.5: The performance tests of SRFQ2 obtained in 2001 are compared in the graph with the very first obtained in June 2000.

The lower Q in the March 2001 curve with respect to June 2000 is due to the repeated openings of the cryostat while looking for the cold leak: the cavity was handled quite carefully, but no High Pressure Rinsing (HPR) was done in between. Fresh HPR was done before the May 2001 curve and the Q improved, while between May and June 2001 the cavity was kept under vacuum at room temperature, waiting for the next supply of liquid helium, and it took only around two hours to be conditioned by resonant and non-resonant field emission (RFE and FE), as compared to typical 15÷20 hours for the other cases.

In general the resonator almost reached the design specifications or even exceeded them. It can be however concluded that, to reduce FE significantly (what seems to be highly relevant for frequency locking purposes), much longer conditioning sessions must be programmed, with the appropriate quantity of refrigerant available. Fig. 6 shows the dose rate (in µSv/hour) due to FE in the June 2001 measurements: beyond 15 MV/m the first signs of FE can be already appreciated.

On the other hand, as pointed out above, the results of the effort can be readily recovered, as long as the resonator is kept in good vacuum.

RFE is typically processed in a few hours at room temperature and in a few hours at 4 K.

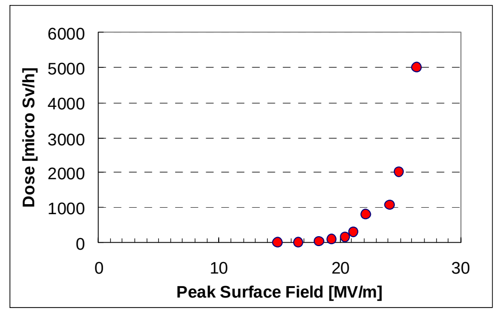

Fig.6: The dose rate detected as a function of the peak surface field shows that FE conditioning needs further processing beyond 15 MV/m.

3.2 Frequency tuning range in operation

As described in chapter 2, frequency tuning is obtained by pushing/pulling any of the two Nb/Cu sputtered end plates with respect to a stiff Ergal bar. Not negligible mechanical upgrade was necessary during year 2001 to obtain the more than acceptable tuning range shown in fig. 7. The main challenge was related to finding the appropriate tolerance in the mechanical joints of the pushing/pulling system and in the correct choice of the materials for the various components (steel, brass and Teflon) so as to allow smooth movement while keeping backlash within acceptable values.

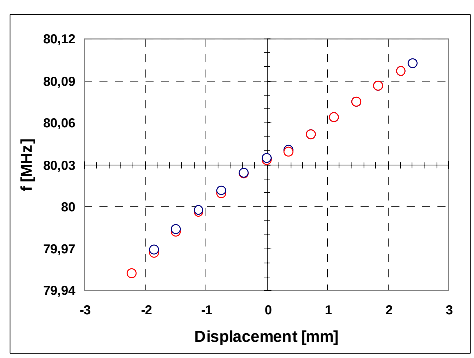

Fig.7: Present tuning range of SRFQ2, starting from the rest frequency of 80.033 MHz. The contribution of the two end plates is summed up. Red dots indicate outwards movement; blue dots indicate inwards movement.

3.3 Tests of electro-mechanical stability

It is very difficult to keep the resonator locked under FE conditions since eigenfrequency instabilities caused by the extracted electrons superimpose onto that related to the high stored energy (see par. 2.3 above). Thorough FE conditioning at least up to the specified field is hence necessary for the frequency locking in the overcoupling mode to be effective. The tests done in the first half of year 2001 were severely limited by an irregular supply of liquid He, which never allowed us to reach the appropriate conditions of operation. The situation is expected to improve in fall this year.

We decided anyway to perform some preliminary investigations at a somewhat lower field.

For instance we registered (see fig. 8) the natural change of the SRFQ2 frequency at 18.6 MV/m, where the curve was still reasonably flat and the emitted dose (~5÷10 μSv/hour) showed that FE was still rather marginal.

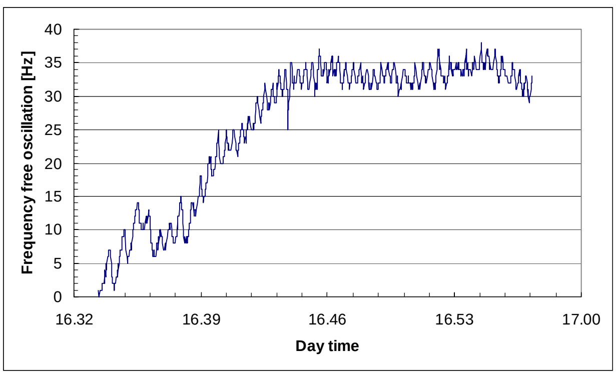

Fig. 8: SRFQ2, not locked to the master oscillator, shows the free oscillations of its resonant frequency for a registration time of about half an hour at a 18.6 MV/m peak surface field.

The picture shows a quite regular rather fast variation (a few Hz on a 20÷30 s period) superimposed onto a much slower change. A feedback-controlled fine tuner can control the latter: the procedure has been already implemented on the SRFQs' controller and full characterization of the mechanical backlash is being done. The former should be easily controlled by the phase and amplitude feedback control system which, with an rf power amplifier of 1 kW in strong overcoupling mode, is expected to control a frequency window Δf = 20 Hz.

The stored energy at this field is however only slightly more than half of that of the specified field. Hence to prepare the cavity for thorough locking tests at that field is the present priority in SRFQ2 development.

To be on the safe side, we started to implement both sc RFQ's with fast tuners [9], which are being developed in collaboration with Argonne National Laboratory. They should be capable of controlling a frequency window Δf~100 Hz.

3.4 Construction of the SRFQ1 resonator

Well aware of the technological challenges to be unfolded by the developments of sc RFQ's, we decided to minimize investment risk by starting the construction of SRFQ1 only after the performances of SRFQ2 had reached the specifications in terms of Q and $E_{s,p}$.

SRFQ1, except for being nearly twice longer, retains the basic rf cell geometry of SRFQ2, thus keeping the advantages of most R&D done on that resonator.

Due to the lack of space in the EB welding machine of Zanon SpA (Schio, Italy), which is responsible for all welds on the sc RFQ's, each quadrant of SRFQ1 had to be built in two parts, then joined longitudinally before machining the vane modulation. This suggested reconsidering the rough tuning approach, since the stems were already welded to the tank quarter when rough tuning had to start.

It was hence decided to leave some extra Nb material aside the vanes, and to remove it stepwise while checking the changes in the EM eigenfrequency of the quadrupole mode. The method has been checked by several simulation codes (Superfish, M.A.F.I.A. static and eigenmode solvers) and via a half scale room temperature model [34]. Rough tuning was completed a few weeks before the present workshop. Fig. 9 shows a photo of SRFQ1 during the assembly and fig. 10 compares the measured frequency plot with Superfish and M.A.F.I.A. simulations.

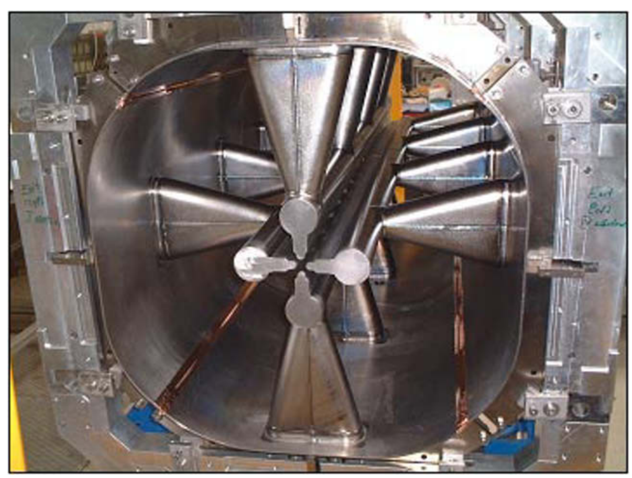

Fig. 9: The 1.4 m long SRFQ1 resonator assembled for one phase of the capacitive rough tuning.

The target frequency of 79.65 MHz at room temperature has been achieved in only two vane cutting steps (see fig. 11), thanks to the accuracy of the simulation codes and to the experience acquired in the development of the half scale Al model.

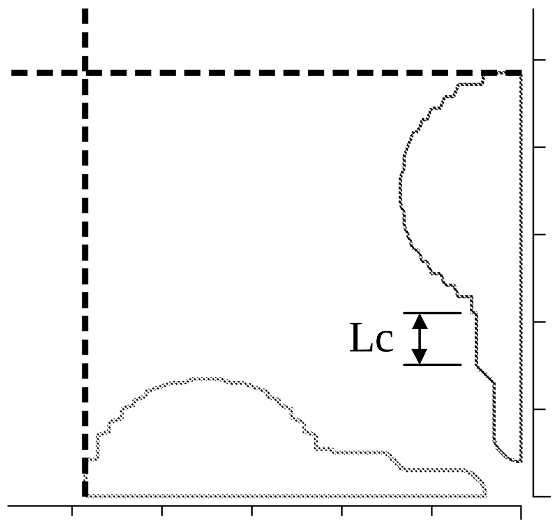

Fig.10: The rough frequency tuning of SRFQ1 differs from that of SRFQ2: instead of stepwise reducing the stem length and the tank perimeter (inductive rough tuning), the length L_C of additional Nb aside the vanes is stepwise reduced (capacitive rough tuning).

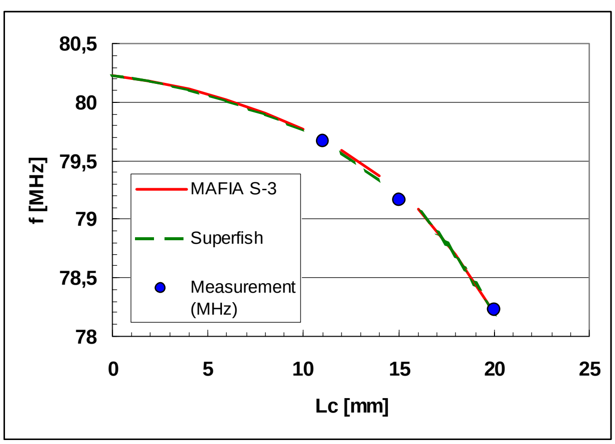

Fig.11: Experimental results of SRFQ1 capacitive tuning are compared to the numerical prediction of two simulation codes.

4 CONCLUSIONS

Further FE conditioning and completion of the tests on electro-mechanical stability will conclude the preparatory work on the superconducting radiofrequency quadrupole SRFQ2 at INFN-LNL in fall this year. Meanwhile the construction of SRFQ1 will be completed and in February 2002 we foresee to start sc tests of this resonator in the test cryostat. Soon afterwards both resonators will be mounted in the injector cryostat, which is being built by the Budker Institute (Novosibirsk, Russia), following joint engineering. The rest of the injector has been basically completed, hence its commissioning is expected to be completed by the year 2002.

If the development of these two sc RFQ's for our heavy ion injector continues to be successful, it seems sensible to consider developing similar structures for other heavy ion injectors, for re-acceleration of exotic species or for the production of radioisotopes for Positron Emission Tomography in a hospital environment.

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