# RF aspects in the development of SRFQs at LNL

F. Chiurlotto, L. Bertazzo, G. Bisoffi, A.M. Porcellato

INFN, *Laboratori Nazionali di Legnaro, Via Romea 4, I 35020 Legnaro (PD) Italy*


## Abstract

The development of a low frequency (80 MHz) superconducting RFQ cavity demands adequate performance both from the power coupling line and from the cold fine frequency tuning device.

Besides providing adequate mechanical stiffness through a proper design of the cavity it is necessary to control phase and amplitude of the resonator with respect to a master clock while the resonant frequency changes in a +/- 10 Hz window. The total power required to load the resonator and to control such a frequency jitters amounts to 1 kW (with U=4.2 J), nearly fully reflected. This asks for a special care in the design of the input coupling line with respect to a typical low $\beta$ resonator.

The novel and somewhat complicated design of the superconducting RFQ requires a large fine tuning range at 4 K (- 100/+100 kHz). The design of the tuner is an evolution of the +/- 15 kHz tuner of ALPI Quarter Wave Resonator (QWR).


## Introduction

The superconducting (s.c.) RFQ cavities of the ALPI linac accelerator, made in bulk-niobium, work at 80 MHz frequency.

The quality factor (Q) expected, from experience with other Nb cavities at L.N.L., is supposed to be in the range $5x10^8/5x10^9$ . The stored energy U is 4.2 J at operational $E_a$ (from a simulation with the code M.A.F.I.A.) [1,2].

Two different inductive 50 $\Omega$ RF lines couple power into the cavity; they terminate with copper wire loops of different size.

One of the lines is movable and it is meant both for the Q-value measurement of the s.c. cavity and for the multipactor conditioning when the RFQ is normal conducting (n.c.). This RF line can work up to about 100 W.

The second one is used to overcouple the s.c. cavity with 1 kW forward power c.w. (nearly full reflection)and is hence designed to stand 2kW total power. The overcoupling line is designed to support a considerable c.w. power. Therefore the coaxial line has been provided with precision connectors to avoid overheating and possible consequent short circuit.

All RF lines are in contact with the cavity at 4 K and therefore they must be well insulated from the room temperature region of the cryostat and thermally connected to the 77 K region.

The fine-tuning apparatus is based on pushing or pulling the thin part of the two end plates of the RFQ by means of a rotating camshaft. It is a development of the LNL QWR tuner concept, offering a larger frequency window and being fairly compact in the longitudinal dimension.

**The RF 50Ω lines**

We have two different inductive couplers for the RFQ cavity. (Fig 1a, 1b)

The first one (called "measurement line") is both meant for multipactoring (m.p.) conditioning when the cavity is n.c. and to measure Q versus accelerating field ($E_a$) of the s.c. resonator (fig 1a). The second one (the "power line") (fig 1b) is a RF line used to overcouple and to control in operation the s.c. cavity with respect to a master oscillator. Both are designed to be removable from the cryostat, if necessary, without a disassembly of the liquid helium reservoir.

Two different lines were proposed, in order to avoid possible damage to a line sized for 2kW when moving its precise coaxial connectors.

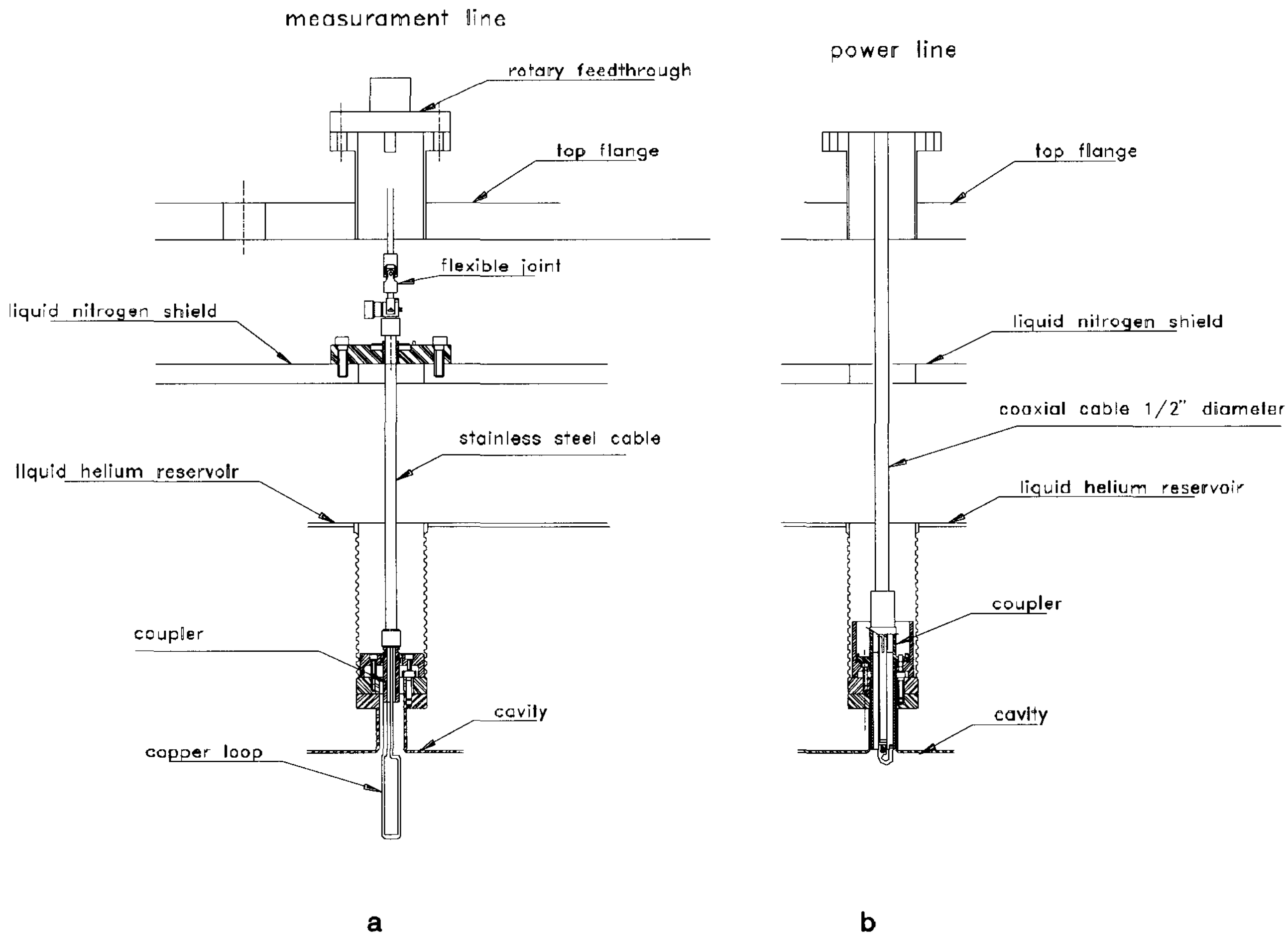


Fig 1: The measurement line (1a) used to multipactoring conditioning when the cavity is n.c. and to measure Q vs. $E_a$ of the s.c. cavity. The power line (1b) used to overcouple and to control in operation the s.c. cavity with respect to a master oscillator.

## The measurement line

The measurement line inside the cryostat consists of a flexible commercial cable connected to the body of the coupler through a coaxial stainless-steel cable.

The line is terminated with an inductive coupler: differently from the inductive coupler used for ALPI QWR's, the critical coupling to the cavity is obtained not with a larger or smaller penetration of the loop into the cavity, but by rotation of the final loop with respect to the magnetic field flux; consequently the mechanical part of the coupler will have a smaller overall dimension than a coupler movable by penetration and it can be adjusted with an equipment similar to that used for the ALPI QWR tuner.

Starting from the Faraday's law we can calculated the loop surface S, intercepting the magnetic flux in the critical coupling condition ($Z_o$= 50Ω ).

$$S = (\sqrt{2PZ_o}) / (\omega \mu_o H)$$

We assume to know, by the MAFIA computation code, the magnetic field near the loop and the power dissipated by the cavity when the stored energy is U=4.2 J. With a $Q_O$-value of $5\times10^8$ the surface value for the critical coupling is $S_{n.c.}=1.1\times10^{-3}$ $m^2$ in n.c. regime and $S_{s.c.}$= 4mm$^2$ in s.c. regime ; the angle θ between direction of the magnetic field and the normal to the loop surface is calculated by: $S_{s.c.}=S_{n.c.}\sin\theta$, so we find $\theta=0.2^o$. If the maximum $Q_O$-value for the RFQ were $5\times10^9$, we would have $S_{n.c.}=1.2\times10^{-3}$ $m^2$ and a $S_{s.c.}$= 1.8 mm$^2$ with $\theta=0.056^o$

Critical coupling is obtained by rotation steps of 0.007$^o$ of amplitude from 0$^o$ to 180$^o$ of the loop with respect to the flux lines . In this way we attain the minimum angle required by both $Q_O$-values, with a small percentage of $S_{s.c.}$ indetermination (4% & 12% respectively).

The rotation is obtained by a rotating vacuum feedthrough with a stepping motor and a 1:120 reducer.

The power dissipation on the coupler, due to its attenuation [5], when it is in operation with 100 W power, is: $P_{1diss}$=4 mW; in fact the thermal insulation of the RF 50Ω line, which works at 4 K, from the part of the cryostat which works at 77 K is obtained by a stainless steel, 50 Ω,copper plated cable, similar to that of the coupler of the QWR for ALPI. It is supposed that the attenuation of the entire RF line will be better then 0.1dB at 160 MHz from the high similarity of the RFQ measurement line to the RF line of the QWR.

The thermal gradient in the cryostat between the 77 K shield and the 4 K cavity leaves a gradient of ΔT= 55 K on the final part of the RF line and the coupler, with a consequent heat leakage dQ/dT= 0.14 W.

When this line is not used the loop will be parallel to the flux's magnetic field H; therefore an amount of power will be dissipated along the loop because of the skin-depth effect. The mean power dissipated $<P_{diss}>$ is a function of the parallel component of the magnetic field H// and of the copper loop's surface resistivity $R_S$ [3,4]; assuming that the $\underline{B}$ value is the average value in the region calculated with M.A.F.I.A. the dissipated power at a stored energy of 4J is:

$$<P_{diss}> = R_s \int\int |H_{//}|^2 ds/2 = 0.4\ W$$

The dissipation is sufficiently small for not compromising the s.c. condition of the cavity and is tolerable in terms of the He dissipation, but it is necessary to take it into account to determine the resonator quality factor.

## The power line

An adequate mechanical stiffness and a proper design of the cavity limit the resonant frequency foreseen jitters to +/- 10 Hz. These frequency fluctuation have to be included in the resonator bandwith in order

In order to phase & amplitude lock the RFQ to the linac ALPI master oscillator frequency [6]. It is necessary to increase the bandwidth by the means of overcoupling (coupling coefficient $\beta$=50)

If the stored energy of the s.c. cavity is: U = 4.2 J and if we need a frequency window $\Delta F$=20Hz the required Q loaded is $Q_l = f/df = 4 x 10^6$; but $Q_l = 2\pi fU/P_{tot}$, and then $P_{tot}$=500W. This $P_{tot}$ should be $P_{max}/2$, where $P_{max}$ is the maximum power from the amplifier, for optimum control [7]. The rest is reactive power. The total power $P_{tot}$, required from the amplifier, is thus 1kW.

Hence the final power for the RF lines is 2kW c.w. because of the nearly full reflection condition.

It is possible to withdraw this line from the RFQ when the other coupler works removing the loop by 40 mm into a $\Phi$=20 mm. collar, so as to avoid any possible interference with the $Q_o$-measurement; in this way even the most penetrating mode in a circular waveguide of 20 mm diameter, is attenuated by 16 dB/cm. [3] . A RF 50 $\Omega$ feedthrough, calibrated for 2 kW power, connects the internal coupler line to the external measurement device. The entire line can be pulled out of the cavity by a bellow on the top flange of the cryostat. All connectors are of type EIA 7/8"; these are precision connectors linked by a flange to minimise insertion loss. The final coupler parts were made in stainless steel in the LNL workshop and will be gold plated; the cable is a commercial 50$\Omega$ one, with a attenuation of 2.7 dB/100m and a maximum average power of 5.7 kW in air at 80 MHz, 1/2" outer diameter, with the outer conductor of solid corrugated copper. We plan to test its performance in vacuum soon.

The design of the RF coupling line should be such that its cryogenic load to the cryostat is minimum.

The power dissipation on the coupler when the system is in full reflection mode (1kW+1kW) is $P_{1diss}$=340mW; the power dissipation on the coaxial cable because of its attenuation (only along the internal conductor), is $P_{2diss}$=2.7 W.

The thermal gradient in the cryostat between the 77 K shield and the 4 K cavity, leaves a gradient of $\Delta T$=26 K on the coupler with a consequent heat dissipation dQ/dt=728mW. Finally, even if we assume that 100% of these dissipation (3.7 W in total) is a thermal load to the liquid helium, this is still only a 40% with respect to the power consumed by the cavity in operation (10 W are available for the RFQ from the cryogenic system).

## The RFQ's fine tuning system

The RFQ cavity has a fine-tuning system based on pushing or pulling the thin part of two bottom plates. The frequency window (±100kHz) [9] is conservatively large, but believed to be appropriate for a cavity of a completely novel geometry. In order to achieve it, each end plate can be deformed by as much as +/-1.5 mm.

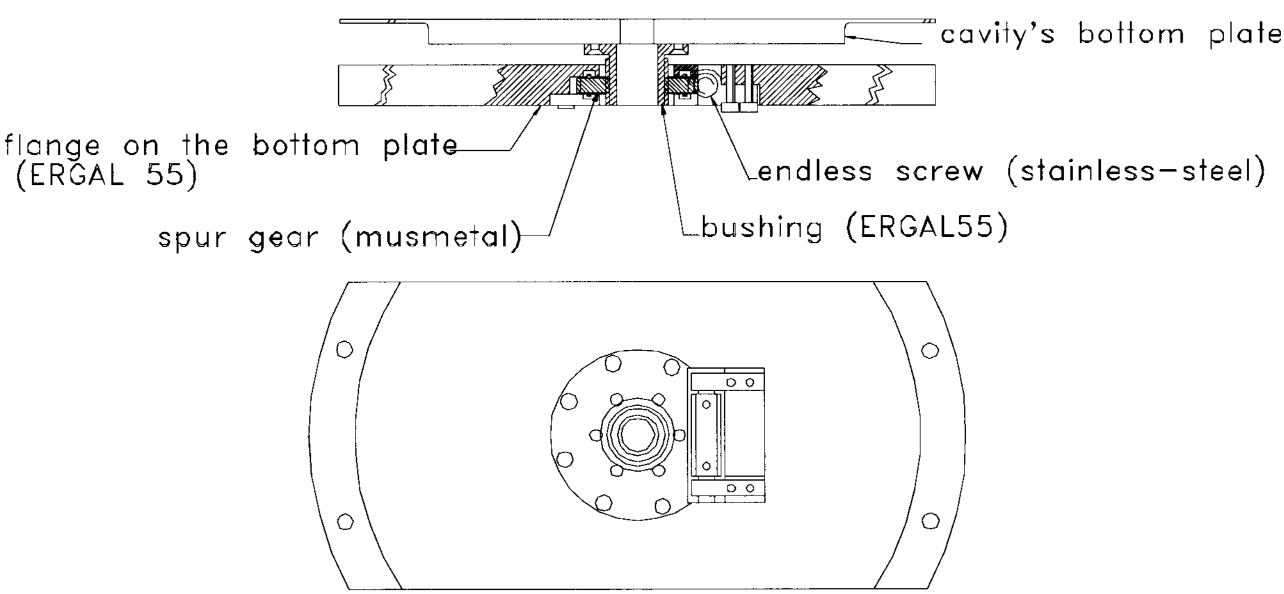


Fig 2: The fine tuning of the RFQ cavity is based on a bushing coupled through a spur gear to an endless screw which in turn is rotated by a stepping motor.

In the final configuration the two SRFQ's will be hosted in the same cryostat. In order to minimise the drift space between the two; the overall longitudinal dimension of each tuner was kept within 50 mm. The mechanics of each tuner (fig.2) is based on a bushing coupled through a spur gear to an endless screw which in turn is rotated by a stepping motor through a 1:10 reducer, a rotating vacuum feedthrough and an adjustable length of the stainless steel tubing with flexible joints; the tuner system is coupled to the bottom plate of the cavity with a flange made of ERGAL55 that ensures a good thermal conduction between the cavity and the tuner system while providing very good resistance to mechanical stress (ERGAL55's thermal conductivity at 20°C $C_T$=130W/m K; minimum breaking load of extruded ERGAL $B_l$=540 N/mm$^2$[8])

The choice of the materials, for the parts of the tuner, has also taken into account the different mean linear expansion of the various materials, to avoid any friction at 4 K.

The thermal dissipation of the entire tuner system due to the irradiation from the shield of the cryostat (at 77 K) produce a thermal gradient, calculated by Stephan-Boltzmann formula, $\Delta T_1$=0.03 K.

The walls of the cavity are at 4 K, but the tuner system and the bottom plate are coupled to the cavity by a flange located outside of the helium bath, and then the RF dissipation on the bottom plate, estimated 0.2 W [1], leaves a thermal gradient between the centre of the flange and its connection to the liquid He dewar. The gradient is $\Delta T_2$=0.15 K if the bottom plate is made of bulk Cu with a layer of s.c. material (either Nb or Pb) and $\Delta T_3$=1.5K if the bottom plate is made of bulk Nb. This is the reason why the bottom plates will be made with a s.c. layer deposited on to a copper substrate. We can overcome this gradient by a thermal short circuit from the middle of the bottom plate to the helium bath.

## Conclusion and future developments

We think that the choice of two separated RF lines is a reliable and flexible solution that allows multipacting conditioning even at room temperature, provides accurate Q vs. $E_a$ curves and maintains the cavity locked by means of overcoupling. The thermal dissipation of the lines is tolerable in terms of cryogenic load. The measurement line is very similar to the coupler line of the QWR for ALPI that showed to be reliable and than no problem is expected. We will soon test the behaviour in vacuum of the power line in the previously mentioned power reflected condition.

Before mounting the fine tuner on the bulk Nb cavity, we will test the performances of the mechanical components in liquid nitrogen and the tuning range on the RFQ prototype, made in stainless-steel, which is close to completion [10].

## References

[1] G. Bisoffi et al. "Prototype of a superconducting RFQ for heavy ions injector LINAC."Proc.. 1997 Particle Acc. Conf., Vancouver, Canada, May 1997

[2] R. Klatt et al. "MAFIA - A three dimensional Electromagnetic CAD system for magnets,RF structures and transients Wake-field calculation", Proc. 1986 linear Acc. Conf., Standford, California, June 1986

[3] Ramo, Whinnery, Van Duzier "Field and waves in communication electronics" New York, John Weley & Sons 2nd Ed, 1965 pages. 152-153, 425.

[4] M. Conte "Physics of Particle Accelerator" W W Mc. Kay Word Scientific, 1991 pages. 154-155

[5] P.A. Rizzi "Microwave engineering" New Jersey, Prentice- Hall, 1988 pages. 185-186

[6] G. Bassato et al. "The control system of the L.N.L. Linac", Proc. of the Third European Particle Accelerator Conference, Berlin, Germany, 1992

[7] I. Ben-Zvi et al. "The control and electronics of a superconducting booster module",NIM A 245 (1986)

[8] Metals Handbook Ninth Ed. vol. 2 page 117

[9] G. Bisoffi et al. “Superconducting RFQ cavities of the new heavy ion injector at Legnaro”", Proc. of the Seventh Workshop on RF Superconductivity , Gif sur Yvette, France, October 1995.

[10] G. Bisoffi et al "Status of the 80 MHz superconducting RFQ development at LNL" presented at this Workshop