Superconducting RFQ cavities of the new heavy ion injector at Legnaro.

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Abstract

The new heavy ion injector for the linear superconducting accelerator ALPI [1] is in its prototyping phase at Legnaro. It will consist in two superconducting RFQ's, following the already existing 14.4 GHz ECR source placed on a 350 kV platform, and eight quarter wave resonators (QWR), spanning a total velocity range of $\beta = 0.009$-0.045. While the QWR's will be identical to the ALPI low-β ones, the superconducting RFQ's are of a completely novel design asking for a thorough optimization study, the status of which is reported here.

Introduction

A new injector for the heavy ion superconducting linac ALPI at Legnaro is being designed: it will consist in an ECR source, which has already been commissioned [2] and is being installed on a 350 kV platform, and in low-β accelerating structures which increase the particle velocity to match the linac injection value (β_{opt}=0.055). With respect to the actual injector (a 16 MV XTU tandem), the new injector aims at increasing the beam intensity with higher charge states, since the first stripping at the tandem high voltage terminal is avoided, and at accelerating ions with masses larger than 100 (in fact up to the heaviest ion species).

The accelerating structure adopted for the lower energy part of the injector is a Superconducting RadioFrequency Quadrupole (SRFQ) and it is the first one thought for a real accelerator complex, after a first prototype has been realized and tested in Stony Brook [3]. At the present status of the design two 80 MHz RFQ's cover the velocity range β=0.009-0.035 and eight 80 MHz superconducting QWR's, housed in two separate cryostats following the SRFQs' single cryostat [4], cover the velocity range β = 0.035-0.045. The whole injector has an equivalent voltage of 8.1 MV. While the QWR's are expected to be the same as the linac low-β ones [6], the two SRFQ's (hereafter called SRFQ1 and SRFQ2 respectively) are the real challenging part of the project and deserve a careful design. Their design input parameters, derived from the beam dynamics analysis, are summarized in table 1 [4].

	SRFQ 1		SRFQ 2		
	in	out	in	out	
Energy	37.6	322.5	322.5	571.1	keV/u
β	0.009	0.026	0.026	0.035	
Electrode Voltage	140.0	140.0	280.0	280.0	kV
Length		130.4		75.2	cm
# of cells		41		13	
m	1.3	3.0	3.0	3.0	
a	0.7	0.5	0.8	0.8	cm
R_0	0.8	1.0	1.5	1.6	cm
ϕ_s	-40.0	-18.0	0	0	deg
E_s	24.7	20.1	25.5	24.6	MV/m
Stored Energy		1.5		3.5	J

Table 1 - Input parameters for the SRFQ design obtained from beam dynamics studies.

The superconducting material chosen for the SRFQ's is niobium. Feasibility studies are in progress in the technologies of both bulk niobium (at an italian manufacturer) and sputtered niobium onto a copper substrate (in the sputtering laboratory at LNL) and a final decision between the two will be taken in the next few months. Concerning the bulk niobium resonators, the material thickness will be between 2 and 3 mm (except for the tip of the modulated vanes which will be thicker for the ease of construction) and stems and vanes shall have to be filled with liquid helium. On the other hand, sputtering will be tested on an overall solid substrate, taking advantage of the better thermal conductivity of copper.

Design of the prototype cavity (SRFQ2).

A traditional RFQ design, consisting in a single cavity with a radial matching section, a bunching section, a gentle buncher and an accelerating section, is not suitable to a superconducting resonator since it would lead to a too long structure and thus to a too high stored electromagnetic energy (U). It is in fact sensible to keep U at a reasoably small value (U < 4 [J]) since the amount of power required from the RF power amplifier to keep the resonator locked at the desired frequency is proportional to the stored energy [6]. This is the main reason to have a preacceleration of the beam with a 350 kV platform with a separate bunching system on it, and also to split the SRFQ into two independently fed and phased resonators, characterized by a high parameter of modulation [7] (see table 1).

Beside this basic considerations and the obvious need to conform to the inputs given by the beam dynamics (aperture, modulation factor, frequency, length and voltage difference between couples of electrodes), a proper electromagnetic design of a SRFQ must be a reasonable compromise among all requirements generally imposed on superconducting cavities, i.e. to keep the diamater of the structure small for the chosen frequency, minimize stored electromagnetic energy and maximize the lowest modes of mechanical vibrations to be able to cope with microphonics, assure that the maximum surface magnetic field be far below the critical value for niobium and prepare efficient rough frequency adjustment and fine tuning as well as an overall easy mechanical construction procedure.

It was decided to start with a prototype of SRFQ2, since its stored energy is more than twice the stored energy of SRFQ1 and the stems are unavoidably longer, hence the mechanical stability more critical, because the frequency is the same (80 MHz) but the length of the vanes about half with respect to SRFQ1 (table 1). The drawing of SRFQ2 is given in fig.1.

The length of the vanes impose a number of stems equal to two because a single stem would make the structure too unstable mechanically, while three stems would make the diameter too large. The stems have a trapezoidal cross section, necessary to increase the lowest modes of mecahnical vibration with respect to simple straight cylinders (the angle of the trapezoid is 15°), ending with a straight 25 mm long section, useful for both electron beam welding (in the case of full niobium) and for a warm temperature rough frequency adjustment by changing the length of the supports themselves.

The electromagnetic characteristics of SRFQ2, calculated with the finite integration algorithm analysis performed by the code M.A.F.I.A. [8], are summarized in table 2. One can note that the diameter ($\varnothing_{in}$ = 624. mm), and the stored energy (U = 3.65 [J]) are not excessive, and that the magnetic field, which reaches its maximum at the insertion of the stem into the hollow cylinder on the back of the vane, is far below the niobium critical field. The E-field bump (0.5 %), which measures the relative variation of$E_{x/y}$ at half the aperture (x/y = a/2) along the beam direction and is due to the voltage drop in each RF cell, is also acceptable.

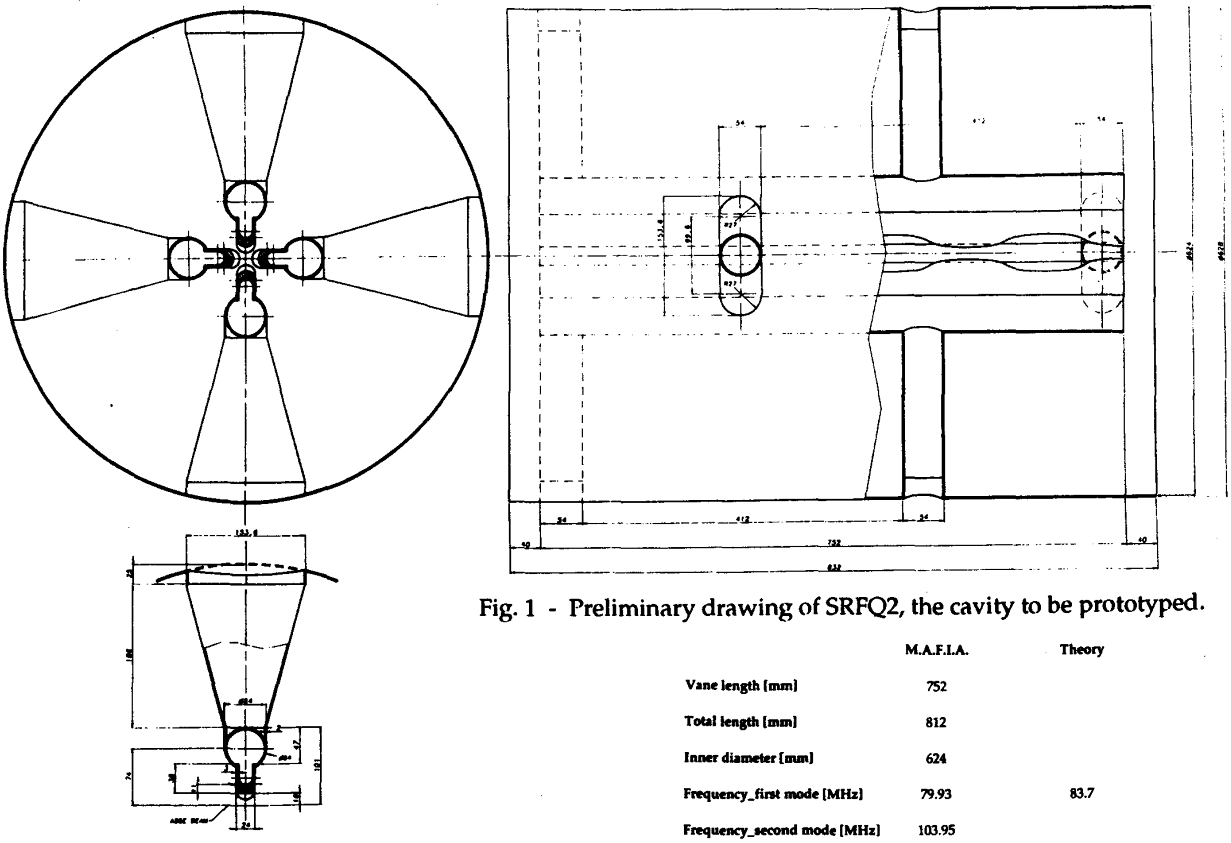

Fig. 1 - Preliminary drawing of SRFQ2, the cavity to be prototyped.

	M.A.F.I.A.	Theory
Vane length [mm]	752	
Total length [mm]	812	
Inner diameter [mm]	624	
Frequency_first mode [MHz]	79.93	83.7
Frequency_second mode [MHz]	103.95	
Vane voltage difference [kV]	280	Input value
Max. surface electric field [MV/m]	25.5	25.4
Stored energy [J]	3.65	2.89
Capacitance /length [pF/m]	135	107
Max. surf. magnetic field [Gauss]	241	286
Q value (Nb)	5.00E+08	4.00E+08
Shunt impedance [ohm*m] (Nb)	1.48E+10	1.42E+10
Dissipated power [W] (Nb)	3.68	4.14
E-field bump [%]	0.5	
Lowest mechanical resonance [Hz]	230	

Table 2 - Electromagnetic parameters of SRFQ2 (M.A.F.I.A. values and corresponding theoretical estimation).

The Q value is obtained scaling the value given by M.A.F.I.A., assuming that the resistivity of niobium at the operational accelerating field (where E_{sup} = 25.5 MV/m) is 20 times the BCS value, which is a reasonably safe assumption. The shunt impedance and the dissipated power are scaled accordingly.

Frequency adjustment and fine tuning.

Since M.A.F.I.A. is affected by an error of the order of 1% in the determination of the resonator frequency, a rough frequency adjustment has to be foreseen with a wide enough operational range in the assembly stage (Δf = 2 MHz). The rough tuning system chosen for the SRFQ's is to vary the diameter of the external tank: the efficiency of this system, computed using M.A.F.I.A. and a theoretical estimation, is shown in fig.2. Modification of the capacitance between the electrodes and the end plates, though easier to realize, is not as efficient, since the inductance has a comparable variation, but of opposite sign. In the full niobium prototype, which will be the first one to be ready, we therefore foresee the construction of the outer tank in four quadrants, with holes in them of the same size as the cross section of the final straight part of the stems and we intend to adjust the welding point of the stems, according to the warm temperature frequency measurement, as the second last assembly step, the last one being the EBW of the four quadrants together. The most promising system for the fine tuning of the cold cavity is a push/pull of both end plates of the resonator, a concept which is very similar to the one already adopted for the linac QWR's. It seems resonable to cover a frequency range of +/- 100 kHz for the fine tuning and this is accomplished with +/- 2.5 mm displacement of the end plates, as can be seen in fig.3, which is still an acceptable stretching on the material (about 1 mm thick), given the considerable diameter of the plate. We prefer this method to a change of the inductance in a region of high magnetic field done with a cold movable cylinder, because it would be less efficient (+/- 100 kHz require a displacement of about 60 mm in the highest magnetic field region of a cold finger of 54 mm diameter), about 0.5 W would be additionally dissipated on the tuner and the mechanics would be cumbersome.

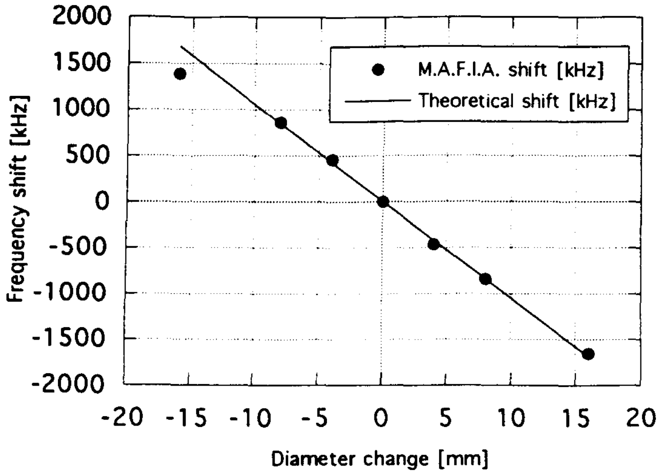

Fig. 2 - Sensitivity of the rough tuning adjustment by changing the RFQ cavity diameter.

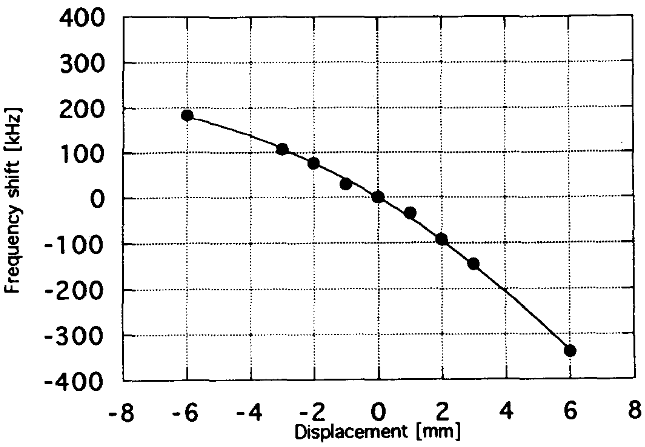

Fig. 3 - Capacitive tuning by pushing/pulling both end plates.

Sensitivity to mechanical vibrations.

The lower modes of mechanical resonance of both SRFQ2 and SRFQ1 have been evaluated with IDEA-S [9], a computer code for mechanical design. The optimization of the stem geometry has been done assuming absolute stiffness of the wall the supports are attached to, which is of course an unphysical condition, but useful for this specific purpose. The frequency of the lowest vibrational mode is 194 or 230 Hz for the 2 or 3 mm niobium thickness respectively; next higher modes resonate at 227/277 Hz and 274/311 Hz.

The next step in the optimization of the mechanical design will be to simulate the whole SRFQ2 as a single resonant body, and study the most efficient array of structure stiffening, putting properly placed bars and rings in niobium or titanium welded ouside the resonator tank.

SRFQ1.

For the first RFQ, which is nearly twice as long as SRFQ2, one is in principle allowed to choose among two, three or four stems per vane, still keeping the resonator diameter within the size of the shorter resonator. The results of this preliminary investigation, with a design similar to that for SRFQ2 though adapted to the beam dynamics input given in table 1, is summarized in table 3. The two-stem structure is mainly ruled out by the big electric field bump, due to the voltage drop in the too long RF cell and by the poor mechanical performance. The low value (187 Hz) of the firstresonant mode is related to the long distance between the stems as well. The three-stem and the four-stem options deserve a deeper investigationbefore choosing between them. In fact at this stage the former is characterized by better mechanical performances and a smaller diameter, whereas the voltage drop in the RF cell (called E-field bump in the table) would make the latter preferable.

Number of supports	2	3	4
Vane length [mm]	1304	1304	1304
Total length [mm]	1384	1384	1384
Inner diameter [mm]	*180*	*400*	*603*
Frequency [MHz]	81.8	81.7	80.3
Vane voltage difference [kV]	140	140	140
Max. surface electric field [MV/m]	24.7	24.7	24.7
Stored energy [J]	*1.53*	*1.51*	*1.55*
Capacitance /length [pF/m]	120	115	117
Max. surface magnetic field [Gauss]	*388*	*191*	*126*
Q value (Nb)	2.26E+08	4.60E+08	5.40E+08
Shunt impedance [ohm*m] (Nb)	7.50E+09	1.58E+10	1.83E+10
Dissipated power [W] (Nb)	3.4	1.65	1.44
E-field bump [%]	*5.5*	*1.32*	*0.5*
Lowest mechanical resonance [Hz]	*187*	*434*	*288*

Table 3 - Electromagnetic parameters and vibrational frequency of SRFQ1 versus the number of supports.

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