PROTOYPE OF A SUPERCONDUCTING RFQ FOR A HEAVY ION INJECTOR LINAC

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Abstract

Two superconducting radiofrequency quadrupoles, SRFQ1 and SRFQ2, resonating at 80 MHz, will provide acceleration from β=v/c=0.009 to 0.035 in PIAVE, the new injector for the superconducting linac ALPI at INFN – Laboratori Nazionali di Legnaro [1]. The construction of the full niobium structures was preceded by the development of a full size stainless steel prototype of SRFQ2 (fig.1), through which most of the construction techniques also applying to the niobium cavities, electromagnetic characterization of the resonator and its mechanical vibration spectrum can be investigated. This paper presents the most relevant design issues of the superconducting RFQ resonators and the construction techniques adopted.

1 INTRODUCTION

Preliminary analysis of a heavy ion accelerator for very low energies consisting of six short superconducting RFQs was proposed in 1988 [2] and in 1991 [3]. To study the feasibility of a superconducting RFQ the third of these six resonators was prototyped at Stony Brook using the technology of electroplating lead onto a copper base [4]. The construction of a full niobium prototype of a high current superconducting RFQ is being carried out at Argonne [5], where a proof of principle of a small unmododulated RFQ, obtained on a modified split ring resonator, yielded a CW peak electric field of 128 MV/m [6]. At INFN-LNL the following scheme is proposed [7]: two SRFQs accelerate a highly charged heavy ion beam from an ECR ion source, located on a 350 kV platform, and prebunched through a three harmonic buncher [1]. Eight quarter wave resonators (QWRs) follow, to match the optimum velocity (β=0.055) at the beginning of ALPI. Table 1 summarizes the characteristics of SRFQ1 and SRFQ2, whereas the geometry of SRFQ2, which was prototyped in a full scale stainless steel model, is shown in fig.1.

When designing a superconducting RFQ, besides obeying the constraints dictated by the beam dynamics for the vanes [7], other specifications typical of superconducting resonators must be considered. First of all the SRFQ diameter is limited to 800 mm to keep the size of the cryostat reasonable: a four-rod-RFQ is chosen, since the four-vane-RFQ would be 50% larger in size. The choice of the superconductor was essentially between lead and niobium. Lead, electrochemically plated onto copper, gives peak surface fields which are not larger than ≈ 16 MV/m, too low for our application.

	SRFQ1		SRFQ2	
	in	out	in	out
Length (mm)		1304.		752.
m	1.2	3.0	3.0	3.0
a (mm)	7.	5.	8.	8.
E_p (MV/m)		25.5		25.5
U (J)		1.5		4
$\varnothing_{tank}$ (mm)		460.		620.
H_p (Gauss)		280.		295.
Q - expected		$7\text{x}10^8$		$9\text{x}10^8$
$P_{diss,\,4K}$ (W)		7		7
f (MHz)		80.		80.

Table 1: SRFQs parameters

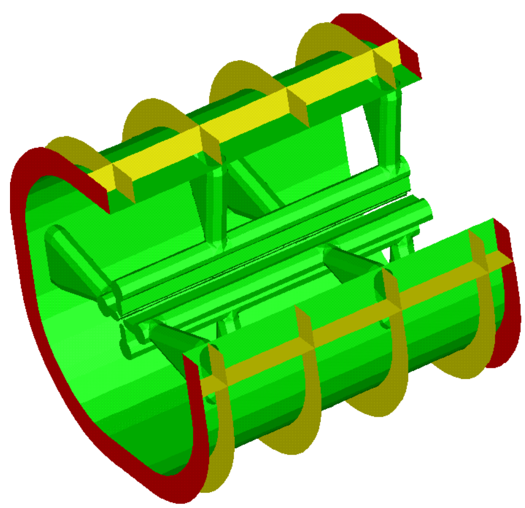

Fig.1 Geometry of SRFQ2

R&D of niobium sputtering onto copper would have taken too long for the short-term scale of an approved project. We opted for full 3 mm thick niobium (RRR ≈300) for the whole resonator except the thicker vanes. Though quite expensive and not trivial to assemble by electron beam welding (EBW), it yields high fields with a fairly established technology. The quite low thermal conductivity forces to bring the liquid helium bath close to the whole surface exposed to the fields: stems are then hollow, vanes are carved and equipped with a hollow cylinder on the back, filled with liquid helium so as to bring the cooling liquid close to the dissipating surfaces. The peak surface electric field E_p = 26 MV/m is quite conservative e.g. with respect to the values reached at INFN-LNL for full niobium QWRs [8]. The peak magnetic field, H_p < 300 Gauss, is well below the critical field of Nb at 4 K.

A scheme of alternate stems for oppositely charged electrode couples has the merit of halving the magnetic field on the surface of the modulated vanes and it allows to exploit the end-gaps of the SRFQ as accelerating gaps [7].

2. ELECTROMECHANICAL STABILITY

Superconducting cavities are characterized by an intrinsicly high Q and by a consequently narrow bandwidth around the resonant frequency. The necessary phase locking of an on-line superconducting cavity to a master clock is therefore extremely sensitive to resonant frequency variations caused both by the liquid helium pressure changes and by environmetal mechanical noise and microphonics. The solution is usually a combination of electronic control and development of a stable mechanical design. A comprehensive description of phase and amplitude control of a superconducting resonator is given in ref. 10. It is shown [11] that the ideal amount of resonator overcoupling that minimizes the total RF-amplifier power is found when $\Delta f_L = \delta f_{max}$, Δf_L being the loaded bandwidth and δf_{max} the maximum frequency deviation to be controlled, provided that $\delta f_0 << \delta f_{max}$, where δf_0 is the intrinsic bandwidth. The RF power amplifier must be capable of a maximum output power P_{max} = 1 kW to reach $\Delta f_L = \pm$ 10 Hz. Resonant frequency variations due to pressure fluctuation on the liquid helium are usually slow enough to be controlled inserting the mechanical fine tuner into a separate phase feedback circuit. Resonant frequency jitters due to environmental noise and microphonics can be counteracted, in a design phase, through a robust mechanical design of the resonator. The mechanical design of SRFQ2 [12] aimed at pushing the lowest mechanical vibration mode of the resonator up to the highest possible frequency. By developping particularly rigid stems and with the fundamental support of a stiffening jacket welded outside the resonator tank (fig. 1), this frequency was pushed to 143±15 Hz. Fig. 2 shows the vibration pattern of the lowest frequency mode, as evaluated with the 3D-FEM code I-DEAS [13]. In our case the stored energy is far higher in SRFQ2 (4 J) than in SRFQ1 (1.5 J) and this was the main reason to choose the former for a full size stainless steel prototype. The prototype is being assembled at present: beside enabling to test EBW and assembly techniques, it will allow to experimentally evaluate the vibration spectrum of the resonator, both on the shelf and inside the warm and cooled cryostat.

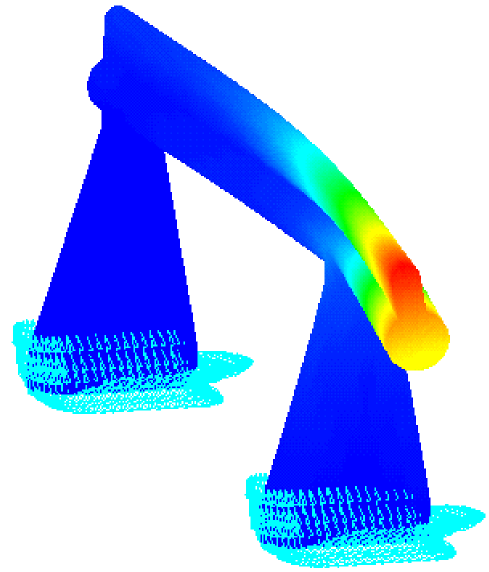

Fig. 2 Pattern of the lowest mechanical vibration mode of a single SRFQ2 electrode.

3. ASSEMBLY, ELECTRON BEAM WELDING AND FREQUENCY TUNING

As mentioned above the resonator parts are made of 3 mm thick niobium sheet. The assembly procedure is not trivial and a large effort has been put on its optimization. For the Nb SRFQ2 it is foreseen to follow the same assembly and welding steps which are being adopted for the stainless steel model. SRFQ2 is built up in quarters: for the sequence of assembly, EBW and rough frequency tuning

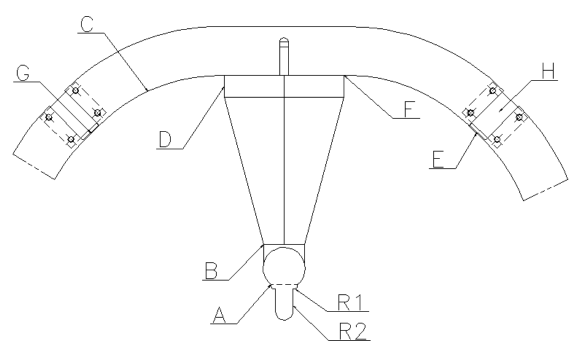

Fig. 3 Procedure of SRFQ2 assembly and EBW

we refer to fig.3.

After the stems are assembled, the still unmodulated vanes are welded to the rear cylinders ((A) in fig.3): these are extruded at the longitudinal position of the stems with extrusions which are only ≈ 2% smaller in diameter than the cylinder themselves: the joints are properly machined and EBW between extruded parts and stems is done (B). At this stage both transverse reference planes (R1 and R2 in fig.3) and modulation are obtained by means of a computer controlled milling machine. The 10 mm wide 60 mm high stiffening ribs are, in parallel, EB-welded outside the resonator tank (C). It should be noted that, in the full niobium SRFQ2, the stiffening ribs will be mostly made out of Ti instead of Nb, so as to increase the rigidity of the stiffening structure. However, in order to avoid the risk of titanium diffusion into the 3 mm thick niobium wall during the high temperature electron beam welding of the ribs to the tank, a 6 mm high standard quality niobium insertion is foreseen between the two: the welding time should be short enough to avoid this phenomenon [13] but no experimental tests were performed yet.

The length of the lower straight part of the stems (D), and consistently the length of the straight edges of the quarters of the resonator tank (E), are kept conservatively large and are then stepwise reduced (rough frequency tuning) so as to bring the resonator frequency to the desired value (estimated to be around 79.9 MHz, thus taking thermal shrinking of niobium between 300 and 4 K into account): the frequency range of such a procedure is $\Delta f \approx 1.6$ MHz and the sensitivity $\Delta f/l_s \approx 100$ KHz/mm, l_s being the stem length [12]. After rough tuning the stems are welded to the resonator tank (F). This is done from the inside of the RFQ, so as to keep the highest weld quality possible, and in two passes for the sake of symmetry of the deformation introduced by EBW. Finally the four SRFQ quarters are EB-welded together from the outside (G). The latter two welding steps follow the last rough frequency estimation and require particular care since the SRFQ frequency must fall within the range of the fine tuning, which is $\Delta f = \pm 100$ kHz [10]. Fine tuning is obtained by pushing and pulling both end plates of the resonator by ± 2.5 mm with respect to 20-mm-thick 750-mm-long ERGAL bars, bolted to the end flanges of the resonator.

The continuity of the stiffening ribs on the resonator tank is eventually obtained by filling in the gaps with properly shaped insertions (H).

The stainless steel model is being rough tuned at present and fig.4 shows a photo of it during the first assembly [15].

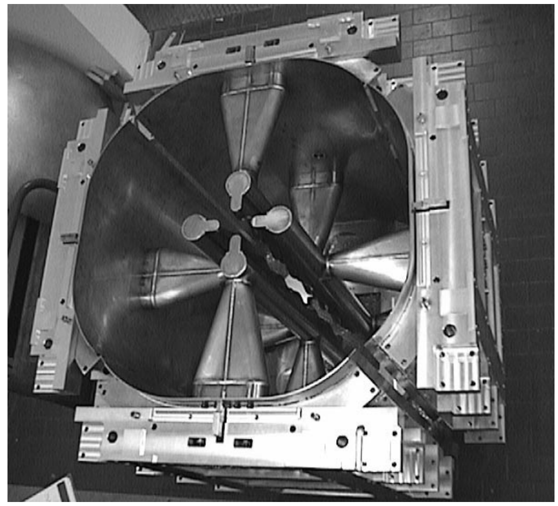

Fig. 4 Photo of the stainless steel model of SRFQ2 during the procedure of assembly and rough tuning in an external jig.

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