The Superconducting Radio Frequency Quadrupole Structures Review

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Abstract

Since 1985 the idea of using the fast developing technology of superconducting cavities for the construction of Superconducting Radio Frequency Quadrupole (SRFQ) has been a challenge proposed by D. Swenson to the accelerator community and the first prototype was proposed by I. Ben-Zvi in 1988. The combination of the effectiveness of the RFQ structures for the focussing and the acceleration of very low ion beams with the possibility of the CW operation of the superconducting accelerators commonly in use in the Nuclear Physics Laboratories around the world was very promising in particular after the development of the high charge state positive ion source capable of high intensity beams, such as the ECR. The paper presents the state of the art of the SRFQ structures starting with the proof of principle, describing the quest for the high surface field, following the evolution of the structures dictated by the beam dynamics and giving an overview of the present projects in the different laboratories. The description of the different technological solutions is also included presenting the mechanical solution to cope with the acoustical noise.

Introduction

The RFQ structure since its first appearance in the accelerator horizons has shown very performing characteristics in focussing and accelerating very low energy particle beams. The first idea of a marriage of the RFQ structure with the superconducting technology, which is very appealing for the CW operation, was proposed by D. A. Swenson [1] for the acceleration of 100 μA of protons up to 100 MeV or low intensity heavy ions beams up to 10 MeV/amu. The most important change in the RFQ design philosophy is the optimisation of the acceleration efficiency using very large values of the modulation factor of the electrodes and avoiding the bunching section inside the structure. Dr. Swenson proposed structures operating at different frequencies and different construction techniques and construction materials from the niobium-on-copper to bulk niobium.

In 1988, I. Ben-Zvi proposed a SRFQ structure as a positive ion injector following an ECR source [2] useful for the heavy ions superconducting booster based on independently phased few gaps resonators. The proposed accelerator was computed as a possible injector for the SUNYLAC operating at the State University of New York at Stony Brook. It consisted in three cavities for a total of 4 meters of accelerating structure with an external bunching. The structure was designed to replace the tandem in order to increase the capability of the machine and to let it accelerate ion species up to uranium. The average accelerating field considered was 1.2 MV/m and the peak surface field was 15 MV/m. The construction technology was based on the SUNY experience in realising superconducting accelerating cavities electroplating lead on copper.

The proposal, under the auspices of the US National Science Foundation, became a project of the construction of a prototype of a SRFQ structure in collaboration with the Laboratori Nazionali di Legnaro of INFN [3].

Independently at Argonne National Laboratory J. R. Delayen and K. W. Shepard tested an RFQ like cavity made welding four fingers on the beam tubes of a split ring resonator (figure 1) and achieved peak electric fields of 128 MV/m at a rf frequency of 64 MHz [4]. In this test the superconducting material used was niobium and that gave a boost to the proposal of the bulk niobium RFQ structures which present quite severe technological problems specially in the eb-welding procedure due to the cavity geometry.

Figure 1. Split ring with four fingers (courtesy of ANL Dr. K. Shepard)

Following this pioneering work some other proposal have been presented for the construction of prototypes of Superconducting RFQ's [5,6].

In 1996 the Laboratori Nazionali di Legnaro presented a proposal of a new positive ion injector for the superconducting booster ALPI operating on its site [7]. The new accelerator is based on two superconducting RFQ structures followed by eight quarter wave resonators and accelerates the ion beams, with a minimum value of the charge over mass ratio of 1/8.5, up to a specific energy of about 1 MeV/u. The RFQ's chain accepts beams coming from an ECR source placed on a 350 kV high voltage platform at an energy of 41.2 keV/u. The project as been funded and is now under construction.

Design criteria.

The RFQ design techniques underwent a revolution to be able to marry the beam dynamics requirements with the superconducting technology.

Concerning the cavity design the first constraint, dictated by the phase lock of the superconducting cavities, is the amount of the energy content of the single resonator. This parameter fixes the power of the rf amplifier to be used and forces to eliminate some functions from the RFQ structure, as it was conceived I. M. Kapchinskij and V. A. Tepljakov in the early 70's in order to reduce the length of the superconducting cavities. Nowadays the superconducting RFQ's proposed need a pre-bunched beam and do not present the radial matching section to adapt the transverse beam motion from axially symmetric beam, coming from the source to a quadrupolar transport channel.

An interesting idea, coming from the experience of the superconducting heavy ion boosters with the independently phased cavities, was to cut the RFQ structure in short sections containing only few accelerating cells (2 to 4) [8]. The main advantages of short RFQ's [RFQlet] are: the large acceptance in velocity of the ions; the low rf energy content; the flexibility in beam handling due to the choice of the rf phase of the single resonator and to the possibility of tapering the RFQ aperture and voltage; the possibility of adjusting the final energy and the soft failure dependence. The disadvantages are: the beam dynamics complexity due to the transitions between the structures specially at low energies and the large number of cavities to be managed.

For the Legnaro project has been taken the choice of cutting the RFQ structure in two [9] having a more conventional beam dynamics with a careful analysis of the gap between the two resonators. Independently the Los Alamos and the Argonne groups did the same choice for their prototype designing a single 'long', in terms of number of accelerating cells, cavity [6,7].

All the presented structure operates at a temperature of 4.2 K and the most interesting design parameters are summarised in table 1.

	Stony Brook	**Argonne**	**Los Alamos**	**Legnaro (PIAVE)**
Structure	4 rods	4 rods	4 rods	4 rods
Superconducting material	lead-on copper	EB welded niobium	EB welded niobium	EB welded niobium
Number of cavities	6	1	1	2
Rf frequency [MHz]	50	194	350	80
RFQ length [m]	2.77	.46	1.10	2.11
Ion species	Heavy ions a/q= 5.9	Heavy ions a/q= 10	protons	Heavy ions a/q= 8.5
β_{in}	0.01	0.02	0.01	0.009
β_{out}	0.051	0.035	0.07	0.035
Peak surface electric field [MV/m]	16.	120	80	25
Average accelerating field [MV/m]	2.4	8.64	2.27	2.16
Intervane Voltage [kV]	135 ÷ 607	465	210	150 ÷ 280
Peak magnetic field [G]	≈ 150	680	11	≤ 300

Table 1.

Construction technologies.

The SRFQ resonator geometry is very complicated to realise specially concerning the mechanical tolerances and the sensitivity to the vibrations. Different solutions have been proposed as far as the material and the construction technique are concerned.

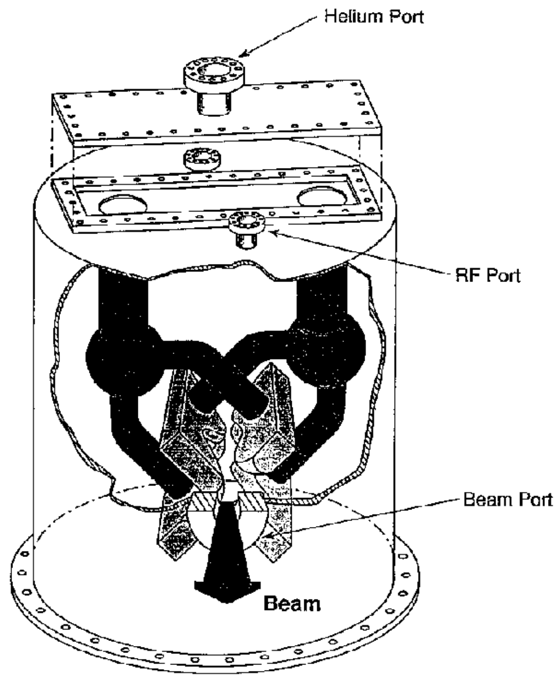

Figure 2. Schematic of SUNY prototype

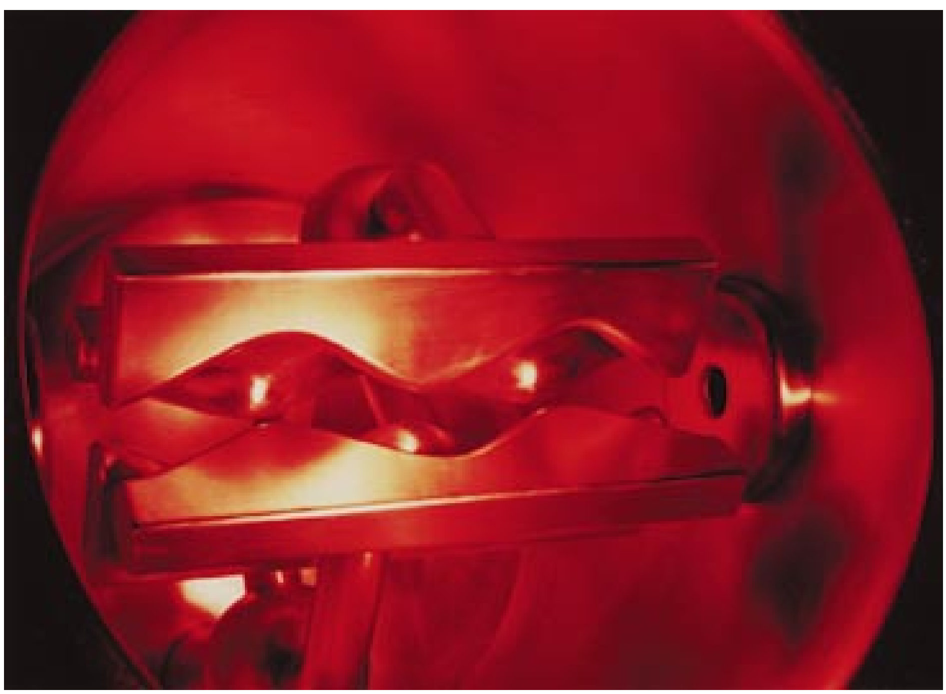

Figure 3. Bottom view of the SUNY SRFQ resonator

The Stony Brook Prototype was realised in copper and then electroplated with lead following the same construction procedure as the Quarter Wave Resonators. The cavity geometry is similar to the QWR's one. Each pair of electrodes is suspended using a split stem connected with the upper plate (see figures 2,3). The electrode, made out of bulk copper, were hollowed and connected with copper tubing in order to fill all the resonator part of liquid helium. The whole copper structure was brazed and lead plated. The structure, recalling a pair of tuning forks, is very sensitive to the mechanical noise as described later [10,11].

Figure 4. View of the Niobium RFQ electrodes of the Los Alamos four vanes model before the welding.(Courtesy of Dr. James Stovall)

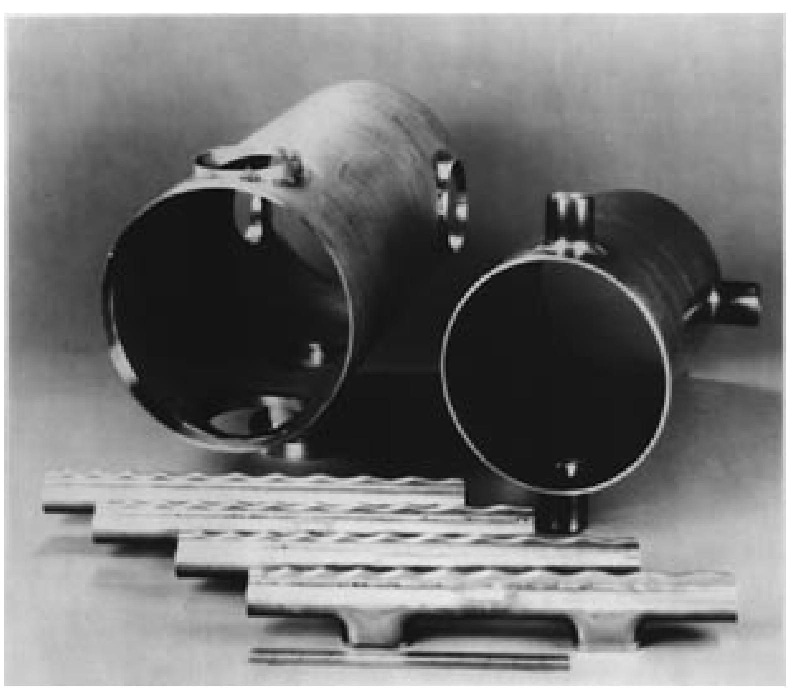

Figure 5. View of the electrodes and the external jackets before the final welding. (Courtesy of Dr. Kennet Shepard)

All the other three SRFQ's proposed, namely the Los Alamos prototype (figure 4), the Argonne prototype (figure 5) and the Legnaro project (figure 6), are made out of bulk niobium parts formed, machined and electron beam welded.

The choice of the material is suggested by the higher values of surface electric and magnetic fields achievable with niobium respect to the copper ones. The niobium cavities have to be fully immersed in liquid helium bath to cope with the poor thermal conductivity of the metal. The mechanical stiffness is related to the size of the structure and appears to be more severe in the PIAVE structure than in the Argonne and Los Alamos ones. For this reason the Legnaro structure has been designed with titanium stiffeners [12].

Prototypes results.

At present the experimental results on superconducting RFQ resonators are related to the Argonne first four fingers niobium structure [4] and the Stony Brook SRFQ [10, 11].

The main results of the Argonne Split Ring resonator with four fingers are the surface electric field level achieved, 115 MV/m with an input rf power of 0.9 W, and the maximum surface magnetic field of 740 G. It also demonstrated that the conditioning of the resonator was no more complicated or troublesome of the Split Ring installed in ATLAS. The problem in overcoming 128 MV/m was the cooling efficiency of the electrodes. In pulsed mode, using a 2.5 kW rf amplifier and a pulse of 1 ms, the structure sustained 210 MV/m of surface electric field.

The Stony Brook SRFQ is the pioneer resonator which was tested both as a superconducting cavity and as an accelerator. The cavity chosen for the prototype work was the third one of the chain of six resonator already mentioned in order to use the SUNY tandem beam for the acceleration test. The resonator achieved, after the helium processing and high power processing, an accelerating gradient E_a of 1.2 MV/m with $Q \approx 10^8$ on the test bench which is half of the design value. The resonator was put on the beam line and tested with a chlorine beam with a charge state +6 and an input energy of 28. MeV and achieved an accelerating field of ~ 0.5 MV/m [13]. The resonant frequency at helium temperature was 57.6 MHz, instead of the designed 50 MHz, but no effort was made to have a precise value of the resonant frequency. The main problems related to the superconducting resonator were:

- Frequency stability. The measured stability was ±150 Hz free running due to mechanical noise with a frequency of 60 Hz generated by a vacuum pump, reduced to 20 Hz disconnecting the pump. This was the evidence that a serious effort has to be put in the mechanical analysis of the SRFQ structure operating at relatively low frequency to avoid vibrations.

- The accelerating gradient. The resonator reached only 1/2 of the designed value of E_a=2.4 MV/m in the test laboratory and less than 1/5 on the beam line. The reason for that was the poor thermal dissipation of the bottom flange of the resonator and was expected but not in such a severe evidence.

A new challenge: PIAVE.

The combined results of the two structure described before led to the Legnaro PIAVE project which is a positive ion injector for the ALPI booster operating at LNL based on two SRFQ's made of niobium eb-welded operating at 80 MHz followed by eight QWR's. The beam will be delivered by an ECR source placed on a high voltage platform capable of 350 kV (figure 6).

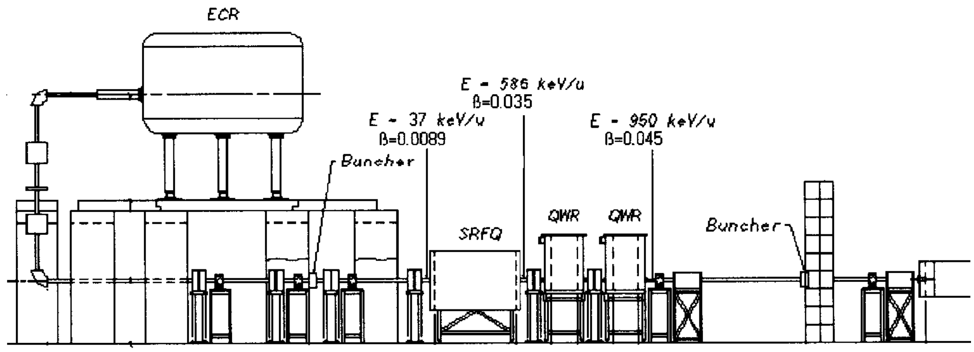

Figure 6 The schematic layout of PIAVE.

The SRFQ structures are four-rod-like and the main parameters are summarised in table 1. The cavity is realised in 3 mm thick niobium sheets formed and eb-welded. The electrodes and the relative supports are hollow and permit the helium bath to reach as close as possible the dissipating surface and to keep all the structure at 4.5 K. The tip of the electrodes are made out of niobium bars machined after being welded on a niobium tube.

A very extensive study of the mechanical properties of the structure was made and the result was to foresee titanium stiffeners welded on the tank of the cavity to force the fundamental vibration mode to have a frequency of the order of 150 Hz (figure 7).

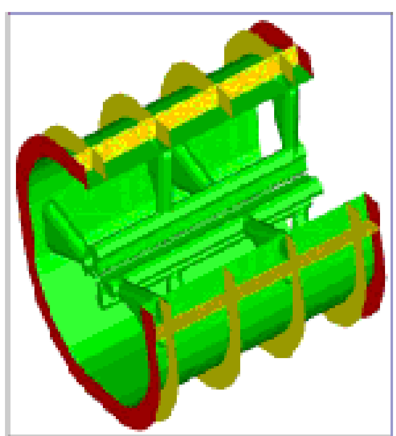

Figure 7. IDEAS SRFQ2 model.

In order to define the construction procedures and process a stainless steel model of the second resonator was constructed (figure 8) [12] and it will be tested as soon as possible concerning the mechanical characteristics and the electromagnetic behaviour.

Figure 8. View of the stainless steel model of the Legnaro SRFQ resonator number 2

Conclusions.

The Superconducting RFQ field is very promising for the CW machine specially dealing with very heavy ion with a reasonable charge state. The work done up to the present show a growing interest in this kind of structures and we all hope to have nice results by all the prototypes and projects around the world. Nevertheless a lot has to be done to say that the SRFQ is a reality working routinely on the beam lines.

Concerning the construction technique the RFQ's need very high mechanical tolerances in the beam region. The stainless steel model made at Legnaro, and the niobium prototype made at Argonne, seems to give a yes answer to the eb-welding of pre-formed niobium sheets but for a definite answer we have to wait for the beam test.

Some studies are in progress to check the possibility of sputtering niobium on a copper substrate for a RFQ (dr. V. Palmieri and co-workers) to have more stiff resonators less sensitive to the mechanical noise and to the pressure fluctuations of the liquid helium bath.

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