Applications of Superconducting RFQ linear accelerators

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Abstract

The successful demonstration of PIAVE superconducting RFQ (SRFQ) resonator gives the opportunity of new applications, making possible the construction of compact CW accelerators, driven by small RF systems. In this paper, we outline the basic principles of SRFQ design, and discuss the possible applications to the acceleration of Exotic Ion beams and intermediate intensity proton beams for Positron Emitted tomography.

1 INTRODUCTION

In the last decade different groups have devoted their attention to the large potentialities offered by the Superconducting RFQ's (SRFQ) [1,2,3], which seems to merge perfectly two fundamental ideas of the ion linac development: RFQs, that allow low energy RF acceleration, and superconductivity, i.e. low power consumption and CW operation duty cycle.

At LNL we decided in 1995 to built PIAVE[4], the new injector for ALPI, using two SRFQs. This has implied effort in SRFQ development, and our resonator has now reached the nominal performances [5], and a deep design study, to take the maximum potentiality of this technology [6].

In this paper we analyze the key points that make the design of a SRFQ different from the design of a nc (normal conducting) RFQ, and we outline some possible future use of SRFQs.

2 WHAT MAKES AN SRFQ DIFFERENT

In a superconducting structure RF losses are negligible, so that, Ohm being on our side and Carnot against us, one can generally work CW dissipating few W in the liquid He bath, and paying few kW to the electricity company.

On the other hand, a superconducting structure, with all the associated cryogenic equipment, is rather costly, and having a short structure is very important. In table I the main characteristics of PIAVE SRFQs are listed.

The peak surface field, that is one of the main limitations of any RFQ, is not dramatically different between nc and sc (for a nc version $2E_{KP}$=21 MV/m at 80 MHz); at higher frequency the allowed peak field increases only for the nc case.

Table I main PIAVE SRFQ parameters

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
Max. Surface field	25	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 other key points to achieve a short structure are the modulation factor m, as high as possible, and the intervane voltage V.

It is well known that, for constant V and m, the accelerating field decreases as β^{-1} (being constant the acceleration per cell). Higher acceleration can be achieved increasing V, and consequently the average aperture R_0 (the surface field is proportional to V/R_0), either continuously, like in LEDA [7], or step size, like in PIAVE. This procedure is possible only if the transverse focusing,

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

remains strong enough to transport the beam.

To increase the voltage is not easy in a nc-RFQ, especially CW, since the power dissipation scales like V^2 (in the reasonable approximation that the capacitance C is not function of R_0). In a SRFQ instead the power dissipation is not an issue, even if a (weaker) limitation to the maximum V comes from the RF system.

Indeed, when beam loading is negligible, almost all the RF power P_{RF} is reflected by the over-coupled cavity, so that the available bandwidth is:

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

The bandwidth necessary for the stabilization of the cavity (about 10 Hz) must be paid by P_{RF}. In other words for given RF system and RF transmission lines in the cryostat the bandwidth (and therefore the tolerance to mechanical vibrations) is limited by the stored energy, or by the required intervane voltage.

Therefore, an SRFQ can use high voltages (hundreds kV) and reach accelerating fields of about 2 MV/m. Moreover, in PIAVE we can tolerate losses of 30% of the beam associated with an external bunching, and have an even shorter RFQ.

The construction of SRFQ2 (Fig. 1) have demonstrated many crucial points, like high precision milling of the Nb electrodes, relative position of the electrodes after e-beam welding within 0.1 mm, known after cooling down with the same tolerance, proper cooling with the liquid helium bath up to the nominal power. The use of a similar structure for different applications will take advantage of a large R&D work.

Fig. 1 SRFQ2 of the new LNL injector PIAVE.

3 SRFQ FOR RIBS.

The application of SRFQ most interesting for our users at LNL is the acceleration of the Radioactive Ion Beam (RIB) produced in a ISOL (Isotope Separation On Line) facility. These beams, generated ionizing the gas released by a hot target, are weak, costly and CW (the memory of the primary accelerator time structure is lost in the gas diffusion); therefore a SC accelerator seems a good choice.

In the project study SPES [8] 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, with a mass over charge ratio of 10, accelerated by three superconducting RFQs. The characteristics of the structure are listed in Table II.

Respect to PIAVE we increased the design surface field from 25 to 30 MV/m, that is a value consistent with a second generation RFQ and with the present performances of LNL quarter wave resonators.

The necessity of a third RFQ is due to the choice of a direct injection after 20 kV of ECR extraction voltage, so that is not necessary to mount the RFQ over an HT platform. The RFQ design technique and the algorithms are the same used for our RFQ built for CERN, but with a longer shaper section, so to have higher capture and lower longitudinal emittance [9]. The result is a scenario with three RFQs, a capture above 95% and a final emittance of 1.5 ns keV/u at 672 keV/u.

This 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%.

If one can achieve a breeder efficiency of about 5% this approach equivalent is to the long linac with intermediate strippers of ref. [10].

Table II main parameters of SPES reaccelerator SRFQ

Mass to charge ratio	10			
Beam current	<5	μA		
Transmission	>95	%		
RMS Emittance	0.1	mmmrad norm.		
Radio Frequency	80	MHz		
Input Energy	2.35	keV/u (β=.0022)		
Max. Surface field	30	MV/m		
Max. stored energy	≤6	J/RFQ		
Band width (1 kW)	>20	Hz		
SRFQ	**#1**	**#2**	**#3**	
Vanes length	148	128	83	cm
Output energy	169	423	672	keV/u
Voltage	109	235	341	kV
Tank diam. (approx)	65	65	65	cm
Number of cells	167	29	13	
Average aperture R_0	0.5	1	1.6	cm
Modulation factor m	1-2.6	1.2-3	3	
Synchronous Phase	-90÷ -25	-40÷ -18	-8	deg
Dissipated power	<7	<7	<7	W

4 SRFQ FOR PET.

As a third example we considered an RFQ for the production of the short-lived isotope markers needed for the positron-emitted tomography (PET). In this case a proton beam of few hundreds microamperes, 10 MeV, has to be produced in an hospital environment. In table III we show a possible list of accelerator parameters.

Table III Parameters for a PET SRFQ.

Energy range	0.040 ÷ 10	MeV
Radio frequency	160	MHz
p current	0.5	mA
RMS norm. Emittance	0.2	mmmrad
Transmission (up to 1 mA)	>98.7	%
Length	561.	cm
Approx. tank diameter	35	cm
vane voltage	170 ÷ 400	kV
Average aperture R_0	0.93-1.76	cm
Final modulation factor	-2.84	
Final synchronous phase	-12	deg
Maximum surface field	33.6	MV/m
RF power dissipation	73	W
Beam power	5	kW
Lost beam power	12	W
Band width	22	Hz
Stored energy	36	J

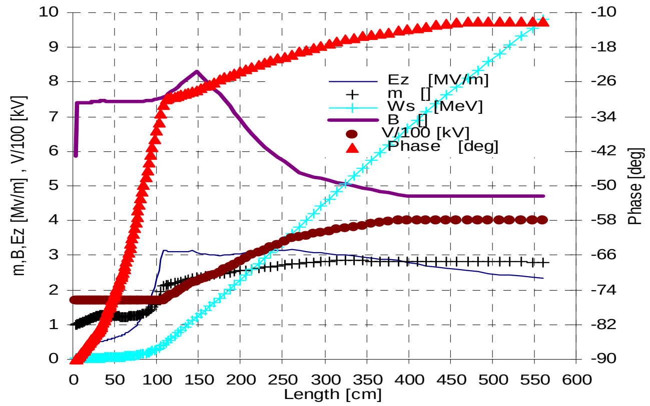

Fig 2: Main SRFQ parameters for PET application.

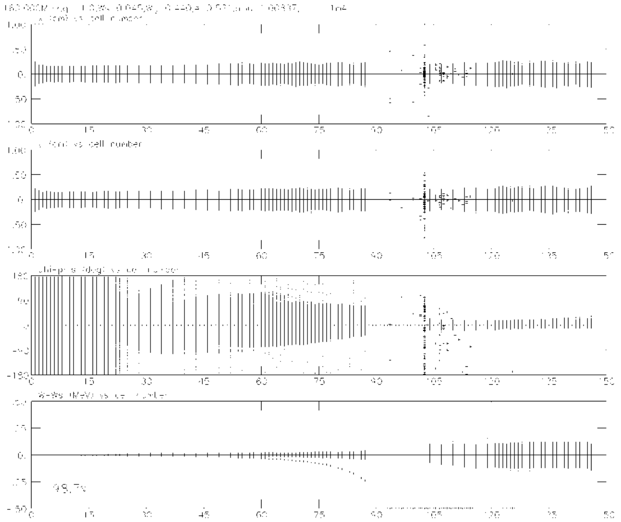

Fig. 3: PARMTEQM simulation of PET SRFQ.

The use of a superconducting structure implies some costs and complication, like the use of a small He liquefier, but on the other side, the structure is rather short and the RF system is small (5.5 kW solid state amplifier). The beam loading adsorbs the main part of the power, and the bandwidth is naturally enlarged.

The resonator can be again of PIAVE kind, with tank transverse dimensions half-scaled and similar modulation ($\beta\lambda$ and R_0 are similar). The first aspect makes easier the construction, the second implies similar the mechanical tolerances. The beam dynamics design is classical, with radial matcher, shaper, gentle buncher, and an accelerating section where V is increased together with R_0 (Fig. 2). The high transmission (Fig. 3) allows, together with low levels of radioactivity during operation, a reasonable deposited power in the cavity and a low thermal load.

Other possible CW applications are for high intensity RFQ like LEDA (100 mA) and TRASCO (30 mA) [11]. Concerns are implied by this passage from intermediate to high intensity. In primis the gas load from the LEBT, where the space charge is neutralized with residual gas that can interfere with superconducting operation. Moreover, the beam losses, which for typical transmissions of 95-98% are in the kW range, represent a thermal load problem even before than an activation problem.

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