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Upgrade of PIAVE superconducting RFQs at INFN-Legnaro

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Abstract. Superconducting RFQs (SRFQs), the first SC RFQs ever made operational for users, have been operated on the PIAVE SC heavy ion linac injector at INFN-Legnaro since 2006. The structure is split into two resonators and is limited to the accelerating RFQ sections. The resonators had never exceeded 80% of the design accelerating fields. In 2015, an upgrade plan started, aimed at increasing the accelerating fields, while improving their slow and fast tuning systems, repairing degraded components, implementing a LASER alignment method. The upgrade plan was successfully concluded in summer 2017. The resonators were kept stably locked for days at a field larger than the nominal one. Eventually, a test beam was accelerated successfully for 72 hours, with negligible locking issues. SRFQs entered once again routine operation in December 2017. The new features will allow to accelerate heavy ions with an A/q value as high as 8.5 (versus a former maximum A/q=7.5), allowing operation of the very first accelerated uranium beams at INFN-LNL, after the related authorizations shall have been issued.

1. Introduction

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The PIAVE injector [1], featuring two superconducting RFQs (SRFQ1 and SRFQ2) and eight quarter wave resonators (QWR) as accelerating structures, has been operational at LNL for ten years. The beam is fed by an ECR ion source on a 400 kV platform and delivered by PIAVE to the SC linac ALPI. With either PIAVE or the 15 MV XTU Tandem as injectors, or the latter in stand-alone mode, around 3600 hours of beam on target have been offered in the last decade annually for Nuclear Physics experiments.

The SRFQs [2] were specified for a maximum surface field $E_{s,m}$=25.5 MV/m, corresponding to an accelerating field E_a suitable for accelerating A/q=8,5 beams from the ECR ($E_{s,m}/E_a$~10 for such structures). This value has been barely reached on SRFQ1, while SRFQ2 has never exceeded 80% of the specified $E_{s,m}$, despite weeks-long conditioning. Within the corresponding operational limit of A/q=7, regular operation for users was possible and eventually quite reliable.

In 2015, it was decided to make an extraordinary maintenance on both SRFQs, with the following goals:

- increase E_a by around 20%, so as to be able to accelerate larger A/q beams
- replace slow and fast frequency tuning systems with more efficient and reliable ones;
- apply LASER tracking alignment of the SRFQs on the beam line, to improve beam transmission;
- increase the He gas draining capability of the resonators, to make RF conditioning more efficient;
- repair heating resistors, T sensors, He and N level meters which got damaged during one decade of operation.

2. Additional surface processing

The Q vs. $E_{m.s}$ curves of SRFQs, on which the first decade of operation was based, are reported in ref.1.

SRFQ2 had been affected, in 2004, by a severe discharge on the input coupler loop, which deposited a thin layer of stainless steel and copper material over a surface of tens of cm^2 of the inner resonator surface, in a high current density region. Buffer Chemical polishing (BCP) would have taken several months on SRFQs due to the complex assembly procedure, so we decided to postpone it and simply polish contaminated surfaces by 3M Scotch Brite lapping, followed by standard HPWR. The cavity had to be kept below 20 MV/m, which had then to be taken as the maximum operational value for both resonators.

After 10 years of operation, however, in the overall maintenance effort described in this paper, further BCP was eventually done. The original BCP, before the accident reported above, had already removed more than 100 μm of Nb thickness on each resonator. We decided, therefore, to apply very limited additional BCP, so as to minimize both the risk of "opening" potential voids in the Electron Beam Welding seals towards the inner cavity surfaces and the change of the resonant frequency (which had been already tuned to 80 MHz) at 4K. Both resonators were delivered to CERN, where standard BCP was applied (fig. 1) for 25 minutes on SRFQ1 and 22 minutes on SRFQ2, with a removal of 13 and 16 um respectively. The frequency increase was 45 kHz for SRFQ1 and 24 kHz for SRFQ2, well within the slow tuning range of both resonators (around 160 kHz for ±3 mm central displacement on both plates).

Figure 1: SRFQs during BCP at CERN.

The Q- curves measured after the maintenance are shown on fig. 2. In both cavities, the curves are loaded by the VCX fast tuners which, albeit dissipating their power in a liquid N bath and hence not contributing to liquid He consumption, lower the Q values with respect to unloaded ones, which start at a low field Q_0 of ~$1x10^9$ [3]. The curves look smoother than those measured before the last BCP (no signs of residual multipacting), although no substantial increase of the field emission (FE) knee (still at ~ 20 MV/m) is observed.

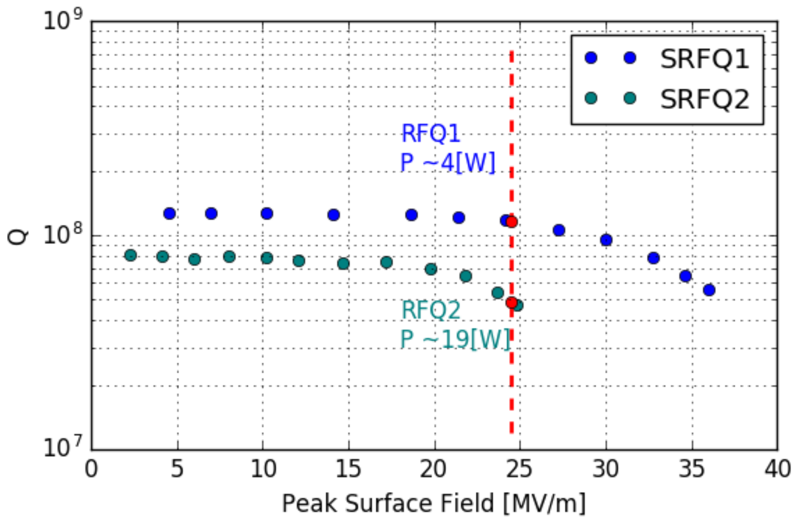

Figure 2: Q vs $E_{m,s}$ curves of SRFQ1 and SRFQ2 after the herein described special maintenance.

3. The new slow and fast tuners

Besides providing clean and smooth inner surfaces, reliable operation of the SRFQs depends, on one hand, on a slow tuning system characterized by good linearity and limited backlash and, on the other, on a fast tuning system, which must be efficient in coping with mechanical resonances which tend to change the resonator RF frequency. On the LNL SRFQs, we triggered the design of a

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combined slow+fast tuning system, which was mounted during the special maintenance described in this paper.

The original fast tuning system is based on VCX devices [4]: a reactive load is switched, through RF PIN diodes, with 25 kHz frequency and a variable duty-cycle: thanks to the high Q value typical of SC resonators, the average cavity frequency can be tuned by simply changing the duty-cycle of the diode on-off state within a given window. VCX fast tuners have some assets (no moving mechanical parts and good linearity) and several drawbacks:

- being normal conducting, they represent an additional RF load to the cavity;
- PIN diodes, connected in parallel, are subject to thermal runaway and breakage, which would call for periodic complex maintenance on SRFQs;
- design is based on parts which are out of production;
- design of the switching driver is custom-made and also based on parts which are out of production.

For these reasons we opted for a fast piezoelectric tuning system (PT), properly combined with a renovated slow tuning lever (ST). The assembly is shown in fig. 3.

The four-arm linkage (parallelogram) forming the slow tuner has a long bar bound to the main cavity frame, while the other one is connected to the tuning plate beam port. One of the two short arms hosts a PT actuator, which can vary its length depending on the RF frequency of the resonator. The opposite short arm is moved by an endless screw, actuated by a stepper motor. Hence the tuning plate can be deformed by two different mechanical actuators: the stepper motor for coarse slow movements and the piezo-actuator for fine and fast ones.

Figure 3: Photo of the combined slow+fast tuner, assembled onto one SRFQ end-plate

The useful and linear range around the central point of the ST is about ±2 mm, while the PT can move the tuning plate by ~ ±15μm at 4 K. The time scales of the two devices are appropriate to counteract SRFQs spontaneous frequency variations: the ST has to cope with variations of the liquid He bath pressure as large as 2 mbar/min, corresponding to an RF frequency variation $\Delta f/\Delta t \leq 2$ Hz/s; the PT has to counteract mechanical resonances up to 500 Hz.

As shown in figure 4 (taken at room temperature), the tuning curves of the two SRFQs feature a very good linearity and repeatability, with acceptable backlash. Frequency offset (+120kHz for SRFQ1 and +20kHz for SRFQ2) for the middle point of the tuning range (0 Hz corresponds to 80 MHz) were chosen, so as to compensate for the expected frequency shifts during cavity cool down.

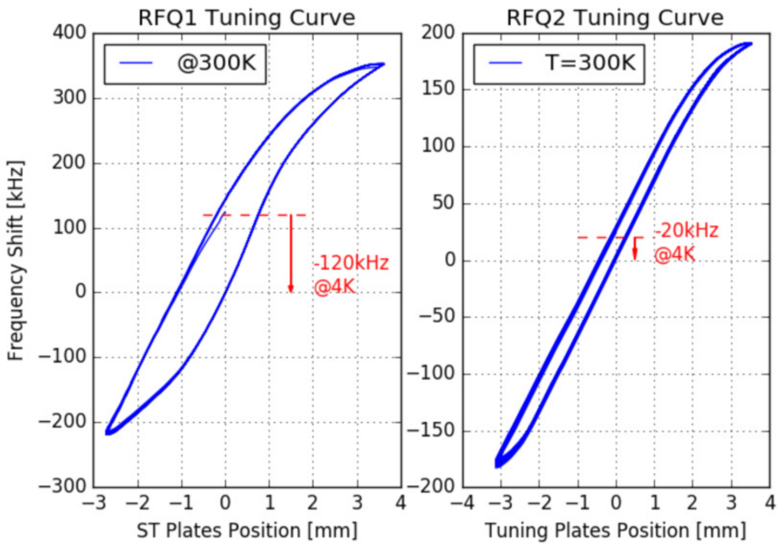

Figure 4: Tuning curves of two SRFQs using both tuning plates.

At the end of the herein described special maintenance the piezo-tuning system was assembled, but is not yet available. Static charaterization tests at 4K have been performed and presented hereafter, but a complete static and dynamic charaterization of the system will require further tests: a full description of the dynanic response of the system (cavity frequency vs piezo-acutator voltage) is necessary, to properly design the control loop of the new piezo tuning system. For this reason the old VCX (Voltage Controlled Reactance) system was kept operational.

Before being mounted back on the resonators, VCX fast tuners were in their turn maintained, in collaboration with ANL (USA): all electronic components were taken apart and measured, all capacitors, diodes, fuses, joining cables were replaced, and a few loose bolts were identified. Diodes behaviour was properly checked. Since frequency measures with Hz sensitivity are not easy at 300°K, they were performed using a VNA, tracking the phase value close to the maximum of the resonance curve, where the phase curve slope is high and the frequency measurement is less affected by the noise.

After the maintenance, the frequency change between the on and off statuses complies with specifications: ~ 60 Hz for SRFQ1 and ~ 200 Hz for SRFQ2 (fig.5).

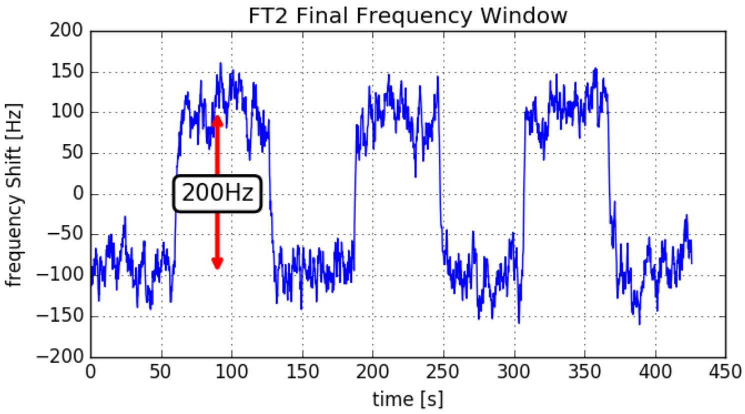

Figure 5: Tuning window of the Fast Tuners of SRFQ2

As anticipated above, the PT system is mounted, but it is not yet characterized and hence not yet available. Preliminary static characterizations were performed: cavity frequency vs. piezo voltage is shown in figure 6 in static conditions. Through an automated measurement set up, cavity frequencies were measured at 300°K with the same technique used for the Soft Tuner measurement.

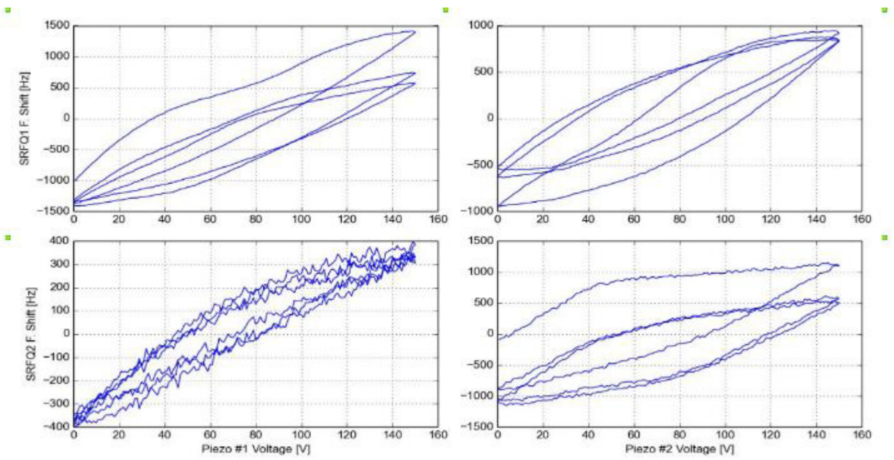

Fig. 6 – Tuning window of the Fast Tuners of SRFQ2 after the maintenance.

Frequency drifts in the curves are likely due to the overall long measurement time: NA IF bandwidth was 30 Hz; the cavity was probably drifting in frequency due to room temperature change. The tuning ranges are good (~1.5÷2 kHz) and consistent with the expected performance at 4K. Non linearities are due to some elastic range of the mechanical system. A full dynamical characterization of the PT system will be done soon, so as to properly design the control loop.

4. Maintenance on the SRFQs cryomodule

The special maintenance was complemented by repairs and upgrades on the cryogenics components and instrumentation (both to increase reliability and to improve SRFQ diagnostics) and by a LASER tracking (LT) alignment setup of the SRFQs with respect to the cryostat structure and the beam line.

Temperature sensors, applied on the rear of the SRFQs surface, were replaced by new ones with better surface contact, their number was increased and

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implemented on a renovated supervision SRFQ panel for better overview during RF operation: they were connected to the control system by screened data-transmission twisted-pair cables, which are less sensitive to electrical noise.

The syphon pipes, conveying the vapour generated in the bottom electrode of the SRFQs [5], were found to be almost totally obstructed by the indium sealing and were the cause of the well-known severe limitation to the RF power which could be fed to the SRFQs during FE conditioning. Indium sealing was replaced by Cu gaskets and this limitation was removed.

The SRFQs alignment to the beam line, previously relying on optical methods, was replaced with LT one. The cavities were measured in order to correctly identify their beam axis and the information were reported to reference points, external to the cryostat. They can thus be regularly checked with respect to the accelerator hall LT network.

5. Beam commissioning

After maintenance, the SRFQ module was transported into the PIAVE tunnel, assembled, aligned and cooled down in Spring 2017. RF conditioning took ~ 40 hours in total (vs. several weeks previously), both SRFQs were kept stably locked in July beyond the nominal field ($E_{s,m}$~25.5 MV/m). A test beam shift with $^{16}O^{2+}$ beam (A/q=8, $E_{s,m}$~24 MV/m) was then carried out for 72 hours with unprecedented stability. Regular operation of PIAVE-ALPI for users' experiments restared in November 2017. Operation of PIAVE-ALPI with A/q values as large as 8,5 (the value needed for a ^{238}U beam) has become possible.

6. References

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