SUPERCONDUCTING RFQS IN THE PIAVE INJECTOR*

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Abstract

Two superconducting (sc) RFQ's (SRFQ1 and SRFQ2, resonating at 80 MHz, 0.8 m in diameter and 1.34 m and 0.74 m long), were mounted in their common cryostat and connected to the TCF50 refrigerator in the linac building. The SRFQs follow an ECR source on a 350 kV platform and external bunching, and precede 8 sc quarter wave resonators. They are the very low velocity accelerating structures of the new heavy ion injector PIAVE [1], which will soon expand the mass range of accelerated projectiles at INFN-Legnaro up to the heaviest ones. After thorough "off-line" resonator testing was completed and dealt with on previous publications ($E_{sp,n}$> 25.5 MV/m – the design value, Q-values between 5 and 8 x10^8, stability issues in He-to-recovery mode), this paper describes the very first on-line results.

THE BUMBY ROAD TOWARDS BEAM COMMISSIONING

After assemblying both RFQs in their common final cryostat more than a year ago, a number of inconveniences had to be overcome and tests to be made, before the resonators could undergo on-line tests in June this year, prior to their use for beam acceleration.

First of all, their delicate alignment with respect to the beam line (~0.2 mm precision) was complicated by manufacturing errors of the cryostat, which were brought up both at room T and at 77 K (April-September 2003). Then a few months were intensely invested in searching for a cold leak, which was eventually found on one innermost indium sealing (September 2003 – January 2004). At that stage, we had already realized that both mechanical tuners of SRFQ1 were not working at cold temperatures. Aware that an additional disassembly was hence unavoidable later, after fixing the problem, we opted for proceeding anyway with the overall assembly of the cryostat in the linac vault, with a view of addressing then all possibly arising problems in once. Automatic refrigeration with Linde Kr. TCF50 was hence successfully performed on the SRFQ cryostat between February and March 2004. Immediately afterwards, the first on-line testing started, till the beginning of April. Two months were then spent to perfect a significant refurbishing of the slow tuners mechanics (new articulated joints, ball and roller bearings wherever appropriate), to perform their warm and cold off-line tests and to assemble the cryostat once more (see fig.1). June 2004 was then dedicated to prepare the resonators, check the linear response of the slow tuners and eventually investigate the best possible locking conditions, while stepwise approaching with the cryogenic system the conditions of best pressure stability in operation.

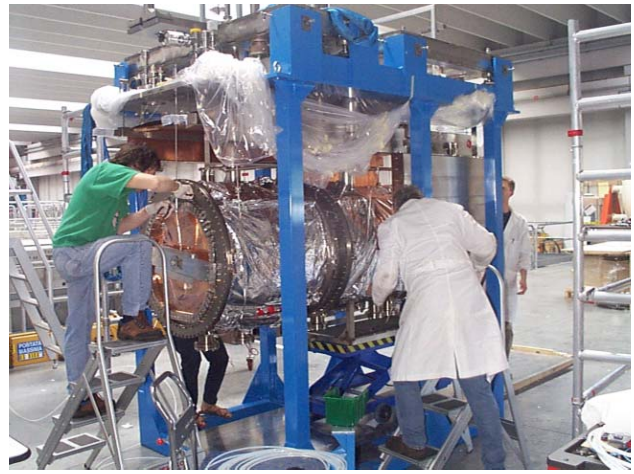

Figure 1: Assembly of SRFQ1 and SRFQ2 on the final cryostat.

PREPARATION FOR THE LOCKING TESTS

Following cryostat evacuation, both SRFQs underwent bakeout at 340÷350 K for about 30 h. With the intermediate shields at 77 K, resonant field emission (RFE) was processed at room temperature. After cool-down to 4 K, residual RFE low level processing (up to peak surface fields $E_{s,p}$ = 3.2 MV/m for SRFQ1 and up to $E_{s,p}$ = 6.2 MV/m for SRFQ2) took 8 h and 2.5 h respectively. Both cavities have always shown a very last RFE level at ~ 9 MV/m: to overcome this and to He-process non resonant field emission (FE) took further 2 h and 9 h respectively.

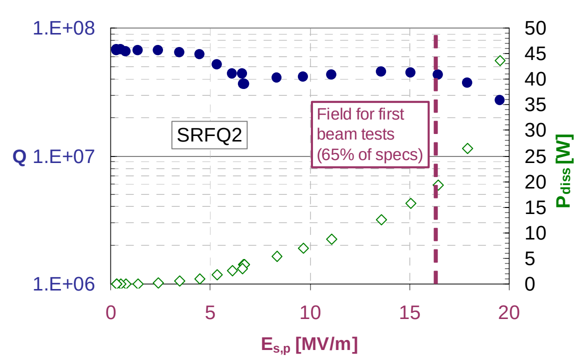

Figure 2: On-line Q-curve of SRFQ2 (Q and P_{diss} are loaded by the VCX, cooled at 77 K)

The on-line Q-curves of the resonators (fig.2 shows the curve of SRFQ2) deserve two comments. First of all, the Q-values are appreciably loaded by the presence of the fast tuner (VCX) loops (refrigerated separately at 77 K). Versus a $Q_L \sim 7x10^7$, we measured from He gas evaporation a critical $Q_0 \sim 5x10^8$, i.e. unaltered with respect to off-line tests. The same holds for SRFQ1. Secondly, since the very first beam test requires only 65% of the design field ($E_{sp,n}$), this was taken in general as a reference value for both FE conditioning and locking tests (this limit was then pushed up to 100% when locking SRFQ1 with the fast tuners, as shown later in this paper).

The four refurbished mechanical tuners were cautiously limited in range by a factor 3 (i.e. the end plates were allowed to be pushed/pulled within ±1 mm with respect to their zero): this allowed windows of ± 10 kHz per tuner. At the beginning of operations tuner A (the first on the beam line) was completely pulled out (+10 kHz), while tuner B was completely pushed in (-10 kHz); as described elsewhere [2], the software slow feedback control system makes tuner A to counteract slow frequency drops and tuner B to counteract slow frequency growths. Since all slow frequency changes are linked to the pressure variations of the liquid He bath outside the resonators, the long term net P change is close to zero: as a consequence the two tuners, which have a similar response, tend to reach the opposite extremes of their setup range more or less simultaneously. When the first of the two reaches its end, the motion of both tuners is inverted. Within the conservative ±1 mm range fixed in the June tests, the inversion of motion, which shall also be handled by the control system shortly, occurred every 5÷12 hours, the time varying in relationship to the pressure history of the relevant period.

For this slow tuning feedback to work, it is essential that the mechanical tuner behaviour is monotonic in the whole range of operation, while some variation in the response slope can be tolerated. This was checked quite carefully on all tuners, by sampling portions of the tuning range (separated by 1000 steps) with a 4 step (~ 0.8 Hz) sensitivity.

LOCKING OF SRFQ1 AND SRFQ2 ON THE BEAM LINE

In order to guarantee a stable beam operation, the natural (unlocked) resonant frequency should not differ by more than a few tens of Hz from the master oscillator reference. To achieve this basic condition, both slow liquid He pressure drifts (seconds) and quick mechanical or electro-mechanical vibrations (a few ms or less) have to be controlled.

Off-line tests had shown [2] that the mechanical tuners were capable to control frequency changes up to ~ 2 Hz/s, corresponding to 2.5÷3 mbar/min pressure change speed in the He tank, consistently with the specifications set for the TCF50 refrigerator. The resonators had also been excited through a powerful frequency swept shaker and a heavy hammer and it was preliminarily concluded that they seemed rather stiff with respect the mechanical vibrations. However, the last word on cavity locking could only be said when both resonators would be mounted on their final common cryostat, in the linac hall and connected to the actual refrigeration system, what eventually happened this time.

In June 2004 the 4 refurbished tuners of SRFQ1 and SRFQ2, which would compensate He pressure changes, were all working reliably. Both resonator controllers housed a vector modulator (CPM) [3], capable to control ±10 Hz by strong overcoupling with a 700 W amplifier, and a VCX fast tuner [4]. The window of the VCX was measured to be 80 [Hz] (SRFQ1) and 210 [Hz] (SRFQ2). It was soon noted, however, that the overcoupling of SRFQ1 was insufficient for reliable locking and hence SRFQ1 was then operated with the VCX only.

On the other hand, during preliminary tests a short was induced on a Pin Diode Switch of the SRFQ2 fast tuner. Despite the procedures to solve this inconvenience in real time had been made promptly available by ANL, manufacturer of the VCXs [5] we opted for cautiously postponing this operation and decided to try locking SRFQ2 with the CPM only.

A software tool combining the slow frequency control through the mechanical tuners (two per cavity, as mentioned above) with fast frequency control (either the CPM or the VCX) was implemented with success.

A total period of about 36 h was devoted to check independent or simultaneous locking of SRFQ1 with the VCX and SRFQ2 with the CPM.

The SRFQ2 resonator could be locked reliably (via slow tuner and CPM) up to 50% of $E_{sp,n}$. At 65% of $E_{sp,n}$ (target value in June), the situation was less stable.

Concerning SRFQ1, locking was fairly stable at 65% of $E_{sp,n}$ (12 h long test). Locking tests at 80% and 100% were also made, for a few hours each. Fig. 3 shows a small fraction of the locking test at 80% $E_{sp,n}$. While the picture samples a period of larger instability with respect to average, it was chosen since it represents an interesting collection of the variety of out-of-lock events observed.

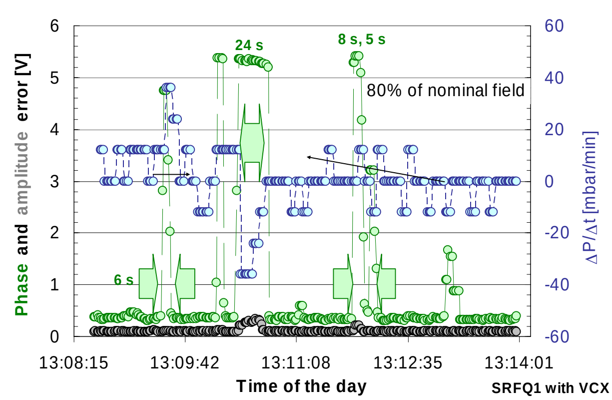

Figure 3: Samples of locking and out-of-lock periods of SRFQ1, with the VCX fast tuner and 80% of the nominal field. Every second, the maximum of |Δϕ| and |ΔA| detected in the last 400 ms is shown on the graph.

As can be seen in fig.3, most out-of-lock events are clearly related to changes of the liquid He bath pressure which are larger than specified, while few are not. Moreover, the 24 s long out-of-lock event in the middle of the graph corresponds to the on/off switching of the TCF50 internal purifier: this is by far the largest kind of pressure change observed during the tests and shall be eliminated in the near future by the cryogenics experts. In all cases, locking can get lost for periods of 5÷10 s at most, every one or more minutes. It remains to be assessed whether this can be an acceptable operating condition for initial beam tests.

As far as slow He pressure variations in general are concerned, the following comments can be made. After good systematic work of the cryogenics engineers, conditions were found where the pressure change could be kept within ±5 mbar/min for periods of hours. The threshold on the rate of pressure fluctuations that can be safely compensated by the mechanical tuner seems to be ~ 5 mbar/min. The large frequency window given to SRFQ1 by the VCX offers an additional margin (the threshold moves from ~5 to ~10 mbar/min) for those cases in which a slow variation of such rate does not last longer than a few seconds. This is another reason, why we find it compulsory to use the VCX fast tuner with SRFQ2 too, in the near future.

Additional systematic work is required on the cryogenic system to further improve conditions, which are already reasonably satisfactory.

ELECTRO-MECHANICAL VIBRATIONS

Noting that some out-of-lock events were “not” related to sharp He pressure fluctuations, preliminary mechanical spectra were taken. Accelerometers were placed outside the cryostat on the bars which directly hold the SRFQs through their liquid He tanks. They were hence rather sensitive to cavity vibrations, despite being rather far and at room T. Accelerometers placed on the pumping system of the cryostat excluded, incidentally, any influence of the latter on the cavity vibration spectrum.

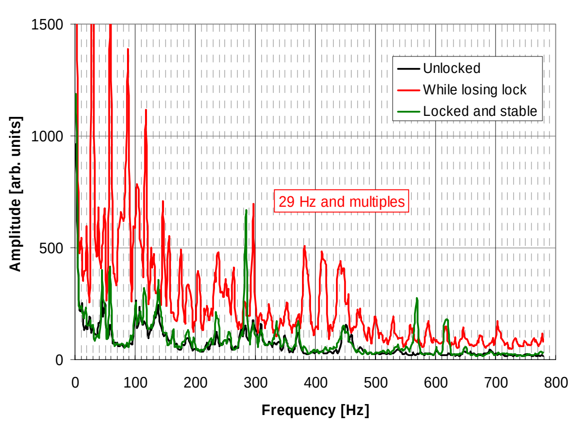

Figure 4: Spectra were taken on the suspension bar of SRFQ2 in three conditions: out-of-lock cavity (black line); stable locked cavity (green line); transition period during which the cavity is losing lock (red line).

Fig. 4 compares the spectra of unlocked and locked resonators with the spectrum measured in the time span while the cavity is losing lock and the feedback control system is trying to compensate for the significant phase and amplitude errors which are increasingly high. The out-of-lock resonator is the most stable. On the contrary, the transition from the lock to out-of-lock conditions triggers a well reproducible spectrum of a 29 [Hz] fundamental frequency and all its multiples, which tends to hinder the previous spectrum. The green curve (fairly stably locked resonator) is an interesting combination of the modes of the other two graphs, particularly below 250 Hz where the vibration energy is higher.

A possible explanation of fig.4 is that the action of locking (or losing lock) triggers an electro-mechanical vibration of the resonator itself, which is strong enough to be clearly detected outside the cryostat.

This might also explain why, on a relevant fraction of cases during the June tests (around 30%), the action of locking SRFQ2 drove the previously VCX-locked SRFQ1 out of lock (mechanical shaking transmitted through the cryostat).

These experimental investigations deserve to be conducted more systematically in the near future.

CONCLUSION

The experience of the latest tests (VCX working only on SRFQ1), described in this paper, has shown that the SRFQs are already in the condition to accelerate beam at more than 50% of the nominal peak surface field $E_{sp,n}$ (which is 25.5 MV/m).

Operation of the VCX on SRFQ2 and possible broadening of the SRFQ1 VCX window (from 80 to the design 200 [Hz]) should soon make it possible to work reliably at 65% $E_{sp,n}$, reducing number and length of out-of-lock events.

Further work on the TCF50 refrigerator parameters is expected to reduce to a minimum those out-of-lock events which are related to fluctuations of the liquid He pressure. We shall continue to work, so as to reach reliable locking at 100% $E_{sp,n}$.

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