OPERATIONAL EXPERIENCE WITH SUPERCONDUCTING LOW BETA CAVITIES

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1. INTRODUCTION

I intend to discuss in this paper reported experience in the construction and operation of superconducting resonators employed in low β linacs for heavy ions which are presented in table 1. The reader who is interested in the general features of the superconducting machines themselves should refer to the reviews of I. Ben-Zvi [1] and D.W. Storm [2], while specific reviews on the most relevant design issues and the related construction techniques of the various low-β resonators were given by D.W. Storm [3] and K.W. Shepard [4]. At page 129 of Ref. [4] a comparison table shows types and quantities of installed resonators and time of installation, as well as optimum velocity, materials used, acceleration length, average accelerating fields, peak fields and RF energy: it is still an excellent and valid reference and I find it useless to update it for minor changes intervened so far. However a critical comparison of the structure variety and the construction methods adopted is still useful, particularly if related to the extent and the reproducibility of attained performances.

I deliberately leave full and half wave helical structures aside: despite their successful use at Saclay for some years since 1988, I was no longer capable of gathering more information on their operation than those which were published e.g. in references [5][6].

On line operation shows, beside a general decline in performance for the various kinds of cavities with respect to off-line tests – mostly since the overall accelerating field required by the user is often smaller than what is offered by the linac capability itself – a number of general inconveniences (e.g. RF failures, unpredicted shutdowns of the cyogenic plant often imposing reconditioning of the resonators) and some more specific ones, such as the so called Q-disease, frequency drifts and jitters, the experience with which will be discussed.

Finally, some automatic procedures, which assist operators in daily work both in resonant and non resonant conditioning and in setting the resonator phase with respect to the bunch phase, will be reviewed.

INSTITUTION	Date	Cavity type	SC material	Optimum β	f [MHz]
ANL - Argonne	1978	SLR, ID-QWR	Nb	0.008-0.16	48.5-145
SUNY Stony Brook	1983	SLR, QWR	Pb-Sn/Cu	0.068-0.105	150.4
University of Washington	1987	QWR	Pb/Cu	0.1-0.2	150.4
Florida State University	1987	SLR	Nb	0.065-0.105	97
Kansas State University	1990	SLR	Nb	0.065-0.105	97
JAERI	1994	QWR	Nb	0.1	130
INFN-Legnaro	1994	QWR	Pb/Cu, Nb, Nb/Cu	0.05-0.14	80-160
ANU Canberra	1995	SLR,QWR	Pb/Cu, Nb/Cu	0.105	150.4

Tab.1: Brief review of the low β resonators which are herein dealt with.

2. CONSTRUCTION, PREPARATION AND PERFORMANCES

As can be seen in table 1, two kinds of basic geometries are generally adopted for low-β superconducting resonators: split-loop (SLR) and quarter-wave (QWR) resonators (see fig.2.1). The latter were developped both in the traditional coaxial pattern (with two accelerating gaps) and in the so called interdigital (ID) version with four gaps. Whereas SLR's feature a longer acceleration length, QWR's have a broader transit time factor (TTF) and a higher mechanical stiffness, which makes them less sensitive to microphonics. The optimum β of these cavities ranges from the 0.008 of the first ID-QWR on the Argonne linac to the 0.2 of the last QWR's at Seattle. The stored energy spans a rather wide range (17-250 mJ/MV/m) while resonant frequencies are comprised between 50 and 160 [MHz].

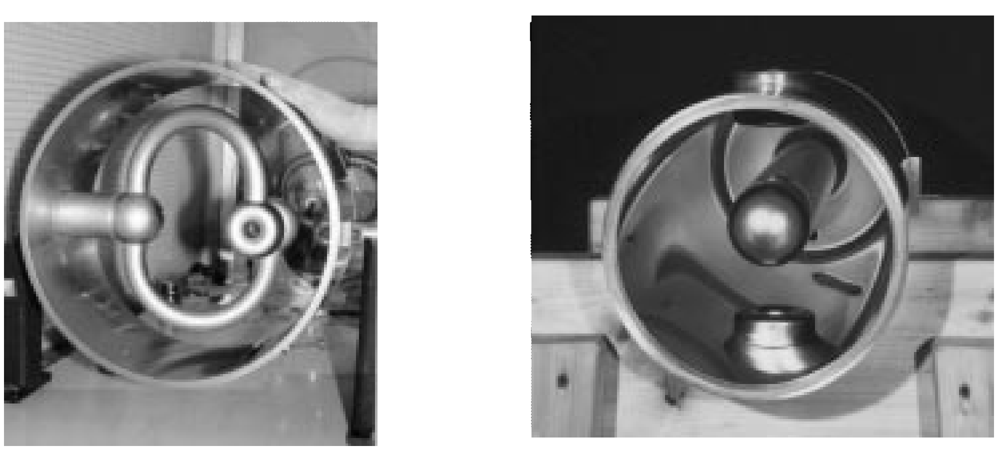

Fig. 2.1 Stony Brook version of the SLR and the Legnaro β = 0.055 QWR.

SLR's were built both in the lead-onto-copper version (at Stony Brook and Canberra) and in the full Nb version, with an explosively bonded Nb-onto-copper tank (at

Argonne). QWR's were developed in all the three known techniques: full niobium, lead-onto-copper, sputtered niobium onto a copper substrate.

2.1 LEAD-ONTO-COPPER.

The use of lead deposited onto a copper substrate gives performances which are only slightly lower than those given by niobium [4], being BCS losses small at low frequencies. Fabrication costs are significantly lower; moreover the solid copper substrate makes the resonators sufficiently stable mechanically, not imposing the use of any fast tuning devices, and avoids the risk of quenches (an overall thermal breakdown is generally the performance limiting phenomenon). The nature of the electrochemical deposition of the lead layer makes it fairly easy to coat a resonator even of a complicated geometry.

A careful copper substrate preparation is widely recognized as one of the most important items in the preparation of the cavity: the size of the grains must be small and the copper surface must be made as smooth as possible by proper tumbling steps, followed by electro-polishing and chemical polishing [7]. Although brazed joints were demonstrated not to diminish the substrate conductivity to a critical extent [8], the Legnaro experience shows that to obtain a full QWR from a single Cu piece (except its beam ports and bottom tuning plate) is not more expensive.

A historic limitation to the successful employment of the lead-onto-copper technique came from the sudden stop, in 1987, of the production of Shinol LF-3, which had always been employed as the best moderator in the lead plating technique which used the traditional fluoborate bath. Whereas Legnaro pursued the line of the production of fresh home made Shinol, with good results only limited by the availability of Ethomeen C25, which is one of its basic ingredients, a completely different alternative was developed at Stony Brook [9], where the refurbishing of two split-loop modules of the booster linac was performed in 1996 successfully, by means of a commercial methane-sulphonate process followed by two de-ionized water rinsing steps and nitrogen drying: the technique proved to be reliable and to give excellent performances (average accelerating field exceeding 3 MV/m in the refurbished modules, with respect to 2-2.5 of the other ones).

At Legnaro recent emphasis was given to the importance of post-plating surface passivation [7], obtained with several rinsing steps with fresh de-ionized (DI) water, interrupted by an intermediate treatment in a light acid solution, so that no sign of oxidation appears for several days after plating. Nevertheless, it continues to be recommendable to store resonators in dry nitrogen before installation.

After installation, a 12 to 24 hours baking at 80 °C is advisable. Resonant field emission (RFE) seems to be treated in the most efficient way by means of freon processing [10] adopted especially at Stony Brook (where one hour treatment is usually sufficient) and Seattle, where the freon treatment was repeated at 300 K, 77 K and 4.2 K. At Legnaro the straight geometry of the inner conductor makes RFE conditioning less problematic and freon processing unnecessary (although it would probably be anyhow useful) and some hours normal processing at 300 K are usually sufficient to overcome all resonant barriers.

Non resonant field emission (NRFE) conditioning requires typically 1 kW pulsed power, followed by hours or sometimes even days long 200 W helium conditioning for QWR's, whereas on SLR's – where magnetic losses on the loop arms rather than E_p are usually the field limiting phenomenon – a few minutes pulsed 200 W power seems sufficient.

Peak fields of lead-plated low-β cavities range from 10 to 20 MV/m, the highest being the recently refurbished SLRs modules at Stony Brook.

2.2 FULL NIOBIUM

Full niobium is adopted for all low-β resonators of the Argonne SC linac, at Florida and Kansas State Universities, at JAERI and on the very low-β section of the Legnaro booster. The resonator tank can be either made out of full niobium or Nb explosively bonded onto Cu.

Advantages of this solution are basically very good performances and a consolidated technique, and its adaptability to cavities of various and complicated geometry (being only limited by possible complicated patterns of the Electron Beam Welding seams (EBW)). A drawback is the high cost of the bulk high RRR material; then one usually opts for small thickness because of the limited thermal conductivity ($\rho_{th} \approx$ RRR/4 W/m K at 4 K) [11]: small thicknesses usually make the structure less rigid mechanically and hence more susceptible to mechanical vibrations and to changes in the pressure of the liquid helium bath (as more deeply discussed in chapter 3).

Whereas EBW is the typical technique of joining previously machined niobium pieces, the RRR of which ranges usually between 80 and 250, electro-polishing in a mixture of sulphuric and hydrofluoric acid was favoured at Argonne and JAERI as a surface treatment (plus heat treatment, when possible, of full niobium parts), while Legnaro adopts chemical polishing in nitric, ortophosphoric and fluoridric acid. Both treatments are followed by rinsing steps in DI and pressurized water and drying and storage in nitrogen gas.

RFE is conditioned in 15-60 min at room temperature, while it can take 2 – 10 hours at 4.2 K and with fixed coupler. NRFE is conditioned in 15 to 30 min with a pulsed 1 – 1.5 kW power; in some cases, where the surface has been properly cleaned, design values of accelerating field can be achieved without any signs of field emission. JAERI's experience represents a valid example of how typical off-line values (averaging at about 6.5 MV/m) are about 15% higher than those which can be actually reached on the beam line, whereas daily operation is normally done at a field that can be only 60 % of what can be achieved off-line, the reason being only the lower average performance required by the physics experiments. Fig. 2.2 shows, as an example, the latest bunch of tests performed at Legnaro on full niobium QWR's.

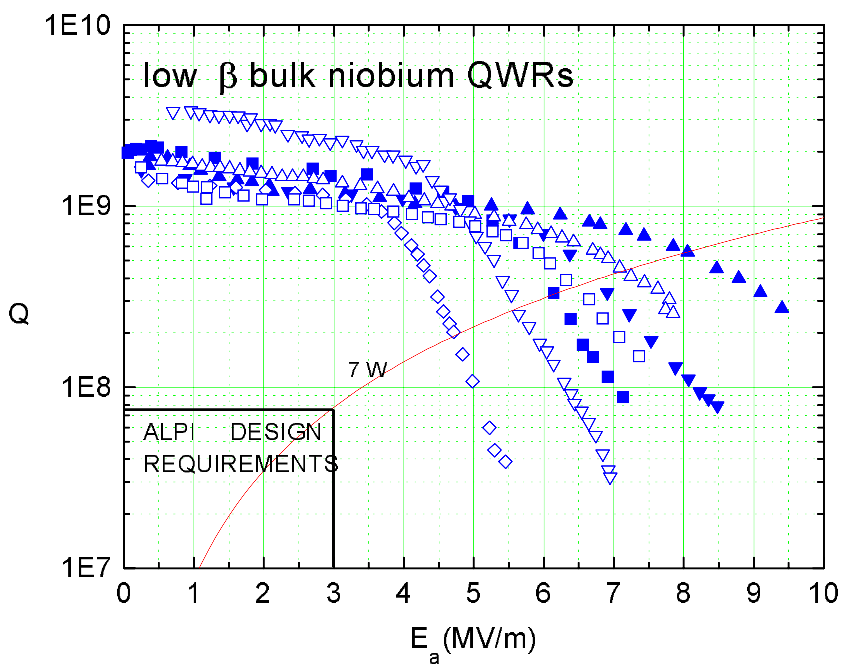

Fig. 2.2 Q_0 vs. E_a fields of LNL full Nb QWR's. It can be noted that the cavity reaching the higher Q_0 drops at lower fields, while the resonator reaching 8 MV/m at 7 W was high pressure rinsed, a phenomenon which is known to slightly reduce Q_0 at low fields but to push the FE limitation to higher fields

A notable still unsurpassed advantage of full niobium structures is that they are capable of the highest performances in resonators of complicated geometry, where the deposition of a layer of SC material onto a copper substrate would be not straightforward. Fig. 2.3 shows two remarkable examples: the recently built New Delhi/ Argonne 97 MHz modified QWR, where the capacitive load on the thicker central stem enables to reduce the stem length (and hence fabrication costs) and to increase lower order mechanical vibrations resonant frequencies (preliminary tests show that the cavity can hold E_a = 4 MV/m for a long time), and the Legnaro superconducting RFQ, so far just prototyped in stainless steel, which is designed to reach a peak field E_p = 25 MV/m.

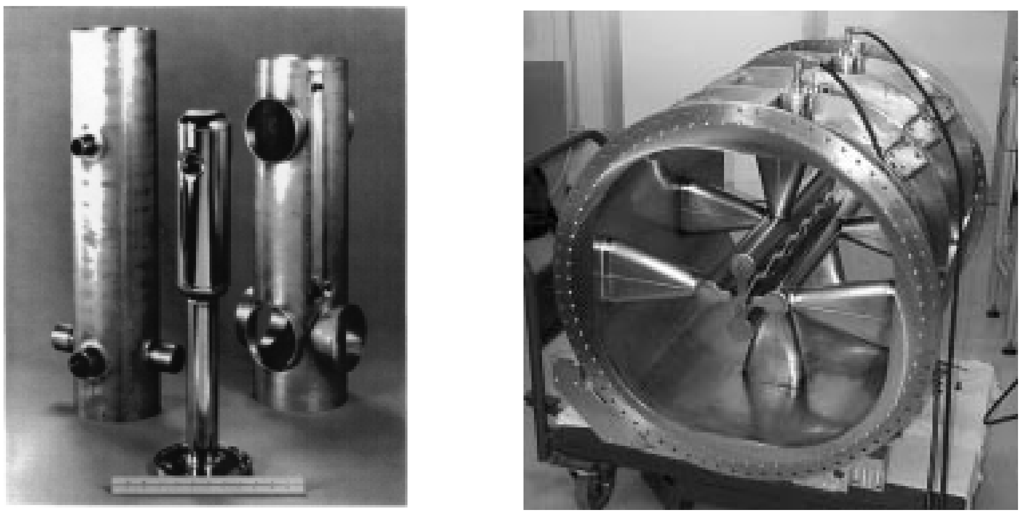

Fig. 2.3 Full Nb low-β cavities are favoured in case of complicated geometry. The New Delhi/ Argonne modified QWR and the being built LNL superconducting RFQ are shown as examples.

2.3 NIOBIUM-ONTO-COPPER.

Born as a spin-off of a similar technique adopted for high β resonators [12], the technique of sputtering a few μm of niobium onto a copper substrate was developed and adopted at Legnaro (DC-biased sputtering) [13] and Canberra (magnetron sputtering) [14] on quarter wave resonators. Once the technology is mature, niobium sputtering largely reduces the cost of resonators, offers performances which are as high as those of full niobium cavities and is possibly suitable to push the maximum reachable accelerating fields even further, since the higher thermal conductivity of the bulk material tends to push quenches to higher fields (at least as long as RRR values significantly lower than 1000 are adopted for niobium). Moreover, because of the thick copper substrate, these resonators are less sensitive to mechanical vibrations and to pressure fluctuations in the helium refrigeration bath. On the other hand, it is not easy – and requires an important research effort – to coat with a sufficiently uniform niobium layer a

complicated geometry: a maximum ratio of 5 is approximately allowed between maximum and minimum thickness on the resonator surface, so as to have a sufficiently large thickness everywhere, meanwhile avoiding peeling of the thicker regions.
Fig. 2.4 shows the Q vs. E_a curves of some sputtered Nb QWR's at Legnaro [15].

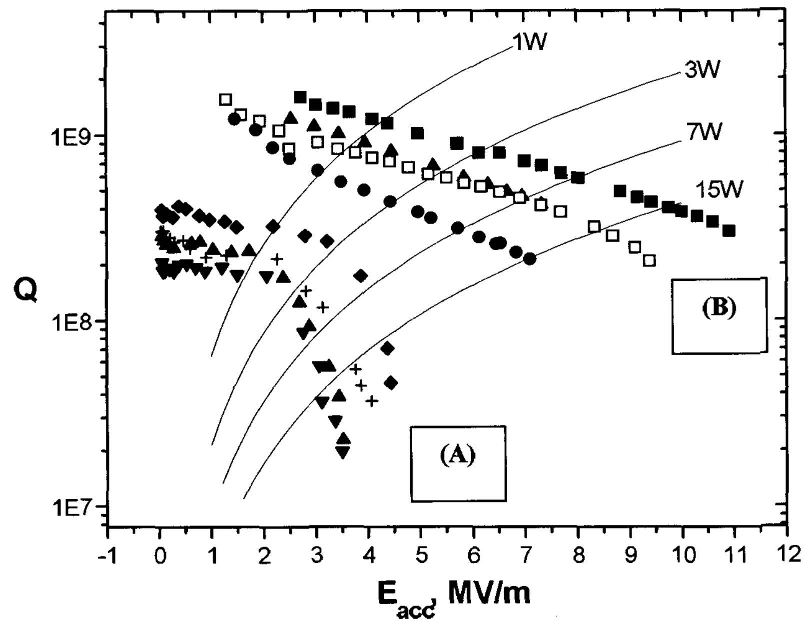

Fig. 2.4 Group (A) represents those cavities which are currently installed in ALPI and operating since 1995: these Q_0 values were as low also in off-line tests, the reason being an inconvenience which occurred during sputtering. Group (B) shows the present off-line state-of-the-art: accelerating fields ranging between 5.8 and 8 MV/m can be achieved without field emission drop and with the same reliable sputtering recipe (the field limiting phenomenon is a general warm-up of the resonators).

3. INCONVENIENCES.

Low-β resonators are affected by typical problems such as failures of the coupler moving parts or the RF feedthroughs, which are normally repaired every 2 to 4 years on the occasion of programmed maintenance periods. In case a vacuum accident occurs or if a cryostat needs to be opened, the whole baking and the conditioning procedure has to be restarted. Resonators are very marginally affected by problems of the cryogenic plant, provided that it is possible to keep them safely at liquid nitrogen temperature during a shutdown: a compressor motor problem caused a 5 months stoppage at Stony Brook in 1995, while various problems at compressors at Legnaro allowed operation from October to December in 1996 and in 1997 since July.

The so called Q disease is reported in some cases as a possible inconvenience of full niobium cavities. Baking them at ~ 800 °C is known to remove the content of hydrogen from the bulk material, which would otherwise move to the surface in the 130 to 90 K region during cool-down. Unfortunately most niobium low β resonators are equipped with indium gaskets, which do not allow such a heavy baking on line. JAERI QWR's are reported to have been strongly affected by the Q disease, which was attributed to strong hydrogen pollution during electro-polishing of the resonators. The problem was solved by both bubbling nitrogen gas during electro-polishing and by a faster cool-down in the critical region between 130 and 90 K [16]. In fact no Q-disease is reported on full Nb QWR's at Legnaro, where chemical etching is adopted and despite the typical cooling down in the "forbidden" region takes some hours. The problem was observed at Argonne only once, when the interdigital resonators had been left in the forbidden temperature range for about three or four weeks (electro-polishing was the surface treatment method): warming up to 300 K and cooling down again in the normal cooling down cycle was sufficient to let the Q recover. Q-disease was never observed in Argonne split ring resonators.

It is common to speak of electromechanical instabilities in all cases in which mechanical vibrations induce a change in the electromagnetic resonant frequency of the cavity. Phenomena such as radiation pressure and vibrations introduced by beam bunches are not a problem in low β resonators, where the operation mode is CW (thus introducing a know but static change in the resonant frequency $\Delta f = -kE_a^2$, where k depends on the resonator, being e.g. k = 0.6 on the JAERI QWR's) and where the amount of charge in a single bunch is negligible in this respect. Much more relevant can be the effects of mechanical vibrations generally caused by the environmental mechanical noise surrounding the cavity (called microphonics) or the effects of pressure changes of the helium bath in the cryostat dewar, causing sometimes significant, though often slow, changes of the EM resonant frequency.
At low values of β, the need of useful accelerating lengths ($\beta\lambda$) implies that the wavelength λ has to be large and therefore that the resonant frequency has to be small. Low β resonators tend hence to be large in size. The content of stored energy is also consequently large and the amount of reactive power needed to phase and amplitude lock the resonator in case of microphonics may be too large for the jitters in capacitance (and consequently in the resonant frequency) caused by mechanical vibrations.

In the design phase of the resonator it is surely beneficial to foresee a stiffening structure [17][18] capable of moving the lower frequency mechanical eigenmodes to sufficiently high values so as to avoid the most noisy environmental region. This effort should be at best accompanied by an accurate investigation on the sources of mechanical vibrations in the area [19].

Once a resonator is built, if one of its eigenmodes happens to sit on top of the frequency of an environmental mechanical vibration, it is sometimes possible to stiffen the structure "a posteriori". Fig. 3.1 shows the stiffening of the shorting plate on a full niobium QWR at JAERI [20]; a similar stiffening was applied to full Nb QWR's at Legnaro. More often, however, the source of noise is searched and, when possible, eliminated.

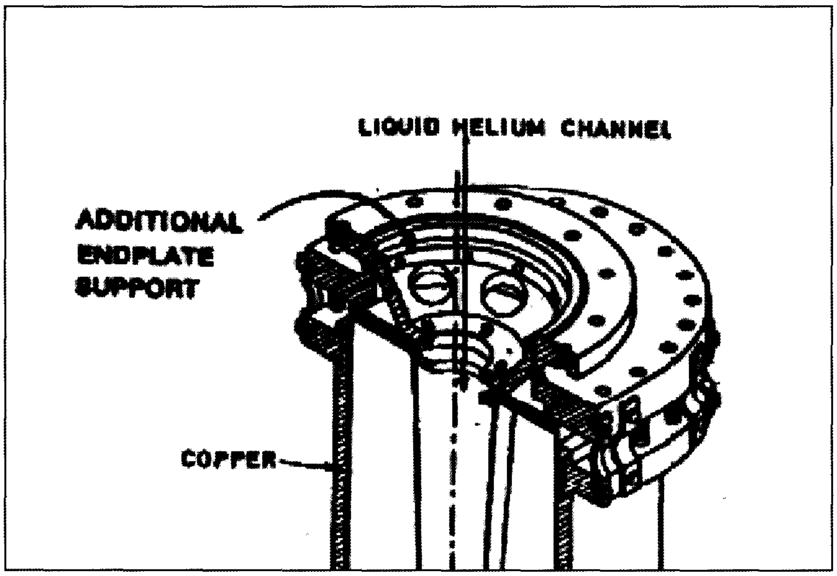

Fig. 3.1 The shorting plate of a full Nb QWR at JAERI is represented, showing the stiffening support which improved the mechanical rigidity of the structure.

The care in the resonator design and the measures taken a posteriori can reduce the resonator frequency jitter but not eliminate it completely. To keep these resonators frequency locked, one is eventually obliged to resort to both broaden the natural bandwidth of the cavity by overcoupling it (i.e. by sufficiently lowering the loaded Q) and lock phase and amplitude of the resonator through a proper feedback system [21][22]: a frequency jitter $\Delta f = \pm 5 \div \pm 15$ Hz around the resonant frequency can be in general controlled in this way, depending both on the stored energy content of the resonator and the amount of power available from the RF power supply.

Particularly critical environmental conditions motivated the engineering of a VCX (Voltage Controlled Reactance) device at Argonne [23]: it is a fast tuner, inductively coupled to the resonator, in which a set of Pin Diode Switches is switched in response

to a phase error signal. The device is capable of controlling a frequency jitter of ± 200 Hz on line with a reactive power of 30 kVA; the whole electronics is cooled in a liquid nitrogen bath, where the power consumption is about 100 W. Only these extremely powerful devices seem capable of allowing operation of resonators where the liquid helium coolant needs to be fluxed through the structure, what happens e.g. in SLR's at Argonne. VCX's are employed on both SLR's and ID-QWR's there.
In the geometrically simple case of a QWR an extremely efficient damper of mechanical vibrations was designed at Legnaro: the mechanical Q value is reduced by means of friction, artificially introduced in the motion of the central stem of the QWR when it is subject to mechanical vibrations [24].
It must be pointed out that all copper based resonators can be efficiently controlled with the simpler phase/amplitude feedback devices such as those described in ref. [21] and even some full Nb QWR's [20] adopt them, experiencing rather infrequent unlocks.

Much slower is usually the time scale of changes in the resonator frequency due to pressure changes, occurring when the cryostat dewar is refilled with liquid helium, or more generally to a correlation between the pressure in the cryostat dewar and any pressure changes in the cold helium gas sent back to the refrigerator.
While on copper based QWR's one seems to barely notice the phenomenon (at Legnaro and Seattle the change in frequency does not exceed a few Hz for a pressure variation of up to 250-300 Hz), Pb/Cu SLR's seem more sensitive. Both at Stony Brook and Canberra slow frequency tracking devices are available, but they are seldom used since they tend to introduce undesired mechanical vibrations: on these machines a stronger overcoupling is sufficient to keep resonators locked in the usual way. The sensitivity was measured to be 1600 Hz/bar on Canberra SLR's, and the resonator remained locked during the test up to an accelerating field of E_a = 2.4 MV/m.
Full Nb cavities are certainly more sensitive to slow pressure changes, also because of their normally higher stored energy demanding more power form the amplifier in the phase/amplitude feedback control system. At JAERI the reported sensitivity of 270 Hz/bar began to be a serious locking problem for the resonator above E_a = 4 MV/m. The two actions which were taken there, namely a mechanical stiffening of the QWR shorting plate and an increase from 80 to 135 W of the RF amplifier power, which gave sufficient overcoupling, allowed them to operate their QWR's reliably. On Legnaro full Nb QWR's, where the sensitivity to pressure fluctuations is 1000 Hz/bar, the shorting plate was also stiffened and a frequency tracking procedure was recently implemented.

4. ON LINE AUTOMATIC PROCEDURES

Some tools assisting the operator in both conditioning and setup of resonators were recently implemented at Legnaro [25] [26] (some of these features are also available on those controllers developped by Applied Supperconductivity Inc. which are adopted in many low β linacs).
A push-button menu is available to prepare the resonator for phase and amplitude locking and to perform the following actions: to let the cavity freely oscillate, to get the correct loop phase shift, to move the coupler in a predefined way and accordingly adjust the power in order to obtain the correct field and eventually to move the slow tuner so as to get the right frequency (within ± 2 Hz on lead-onto-copper QWR's).
Two semi-automatic procedures, at the choice of the operator, were developped to condition multipacting levels in an comfortable way. They are normally used after proper baking and both are allowed to be operated only after checking vacuum conditions as well as the temperatures of cavities and cryostat shield; they are switched on after adjusting the controller parameters for free self excited oscillation. Procedure 1 raises the power in steps, which can be customized in range (1 to 20%) and time (1 to 40 min) up to a maximum, after which the system is ready for a manual restart: it is particularly valuable for the beginning of the multipacting conditioning process, when outgassing can be particularly severe and the increase in power has to be necessarily slow. Procedure 2 ramps the power periodically from 0 to 100% without any time limits, where just the increase rate can be adjusted: after procedure 1 has done the rough work, procedure 2 proved excellent in removing all multipacting levels at room temperature. All resonators can be operated contemporarily.
Combined actions on the Vacuum Control System (VCS) and the RF control system constitute an efficient procedure for automatic helium conditioning at Legnaro. On the VCS a procedure was implemented to allow an inlet of He gas at $P = 4x10^{-5}$ Torr in any of the cryostats; on the RF controller, in turn, another procedure allows to modulate in pulse mode the direct power feeding the self oscillating resonators (500 ms long pulses every 2 s). Thus each resonator can be fed, at a 25% duty cycle, with a peak power which is four times larger than the average CW power: this does not cause any overloading of the cryogenic system even on those circumstances when automatic helium conditioning is performed on all resonators at a time.

5. RESONATOR PHASE SETTING

During a beam time the resonator phase is set at usually -10°÷-20° with respect to the master oscillator phase. This is done by searching first of all the -90° phase of the switched-on cavity, in one of the following ways: looking at zero beam deflection by a downstream dipole in a beam profile minitor (BPM) or in a Farady Cup (FC) with a collimator in front (at Legnaro, Stony Brook, Seattle and Canberra) or looking for zero energy gain (interpolating some points in this region) on a solid state detector at Argonne. Then the desired phase is set.

At JAERI three normal conducting QWR's are used along the linac as phase detectors and the energy is measured on a solid state detector whenever needed.

It was not easy to obtain a common quotation of the precision of this operation from the various laboratories: Argonne quotes a ± 1°, JAERI states that the two detected zeroes are usually 180±3° apart, while at Legnaro it was noticed how operations with the same beam and resonators performed with either the manual or the automated system differ by ±2° at most.

At Legnaro an automated procedure is in fact available, which makes use of a communication between the RF control system and the diagnostics system: the BPM is read and interpreted, the beam-bunch phase difference is read and the two zeroes can be found. A similar ROBOT software is available at Stony Brook, where a code scales the quadrupoles downstream the cavity as well, although these are eventually adjusted for best transmission. At Seattle an automated procedure exists as well, but it is seldom used since the manual setting is reported to be as fast and to give a better understanding of what is going on.

As far as phase setting is concerned, some useful experimental evidence deserves being reported.

Recalling dipoles and quadrupoles fields, if the ion species and charge state as well as the incident energy remained the same, or scaling them for different q/m ratios is reported to work well both at Stony Brook and Argonne, but only if the single accelerating fields of the resonators have remained approximately the same and anyway if the field recalling/scaling operation is done weeks or months after the one they refer to, but not years later.

Both Legnaro and Stony Brook report the advantage of changing sometimes the phase difference which is typically set between the single resonator and the master, and in some cases of switching even to positive values if distortion of the phase space is an issue.

In this context the EXCEL electronic sheet running on a PC, which was prepared at Legnaro to calculate the beam parameters (energy, transit time factor, magnetic rigidity) cavity by cavity as a function of the accelerating field and phase on single resonators, can be an excellent tool to help understanding what is happening in the phase space during the beam time, since the on-line multiparticle simulation that it offers can be promptly compared with the linac diagnostics. The code is being presently tested.

6. CONCLUDING REMARKS.

While there does not seem to be a real proliferation of new projects for the near future, very interesting and successful R&D is being carried out at New Delhi and Bombay in India, at Sao Paulo in Brazil and in China. Beside that, the two most recently built linacs are working on funded upgrading of their operational facilities: at Legnaro the installation of more $\beta=0.05$ full Nb resonators is foreseen in 1998 and PIAVE - a positive ion injector with superconducting RFQ's and QWR's - is expected to be operational by the beginning of year 2000; at Canberra a time-energy lens consisting in a niobium sputtered QWR will be installed by the end of 1997, four lead-onto-copper SLR's will be refurbished in 1998, and 20 more Nb/Cu QWR's will be installed in 1999.

Large part of the information contained in this review paper cannot be found in the literature and were given to the author by A. Facco, N. Lobanov, E.G. Myers, V. Needham, J.W. Noè, V. Palmieri, A.M. Porcellato, S. Stark, A. Roy, D. Storm, S. Takeuchi, G.P. Zinkann. The author acknowledges their essential help.

REFERENCES

[1] I. Ben-Zvi, Nuclear Instruments and Methods A287 (1990) 216-223

[2] D.W. Storm, Nuclear Instruments and Methods A328 (1993) 213-220

[3] D.W. Storm, Proc. of the 6th Workshop on RF Superconductivity, Newport News, October 1993, 216 – 235]

[4] K.W. Shepard, Nuclear Instruments and Methods A382 (1996) 125-131

[5] B. Cauvin et al., Nuclear Instruments and Methods A287 (1990) 263-267

[6] B. Cauvin et al., Proc. of the 6th Workshop on RF Superconductivity, Newport News – USA, Sept. 1993, 1020-1027

[7] V. Palmieri, "New developments in low beta superconducting structures", Proc. of the 7th Workshop on RF Superconductivity, Gif-sur-Yvette, October 1995, 237- 258

[8] R. Pengo and P. Favaron, Cryogenics 30 (1990) 74

[9] A. Lipski, J.W. Noé and C. Realmuto, "An environmentally friendly method for resonator surface fabrication", Proc. of the SNEAP-30, Woods Hole, October 1996, to be published

[10] J.W. Noé, Nuclear Instruments and Methods A328 (1993) 291-292

[11] H. Padamsee et al., Proc. of the "1991 Electron Beam Melting and Refining Conference", November 1991

[12] C. Benvenuti, N. Circelli, M. Hauer, Appl. Phys.Lett. 45,583 (1984)
[13] V. Palmieri et al., Nuclear Instruments and Methods A382 (1996) 112-117
[14] N. Lobanov and D. Weisser, "Nb sputter coating on QWR in ANU", this conference
[15] S. Stark, "Niobium biased diode sputtering for QWRs", this conference
[16] S. Takeuchi and M. Matsuda, "First three years operational experience with the JAERI tandem-booster", this conference
[17] G. Bisoffi et al., "Status of the 80 MHz superconducting RFQ development at LNL", this conference
[18] D.L. Schrage, E. Swensen, B. Rusnak. Proc. of the 7th Workshop on RF Superconductivity, 629-633
[19] N. Lobanov et al., "Vibration studies of the Superconducting Split Loop Resonator", to be published.
[20] S. Takeuchi, T. Ishii, M. Matsuda, Y. Zhang, T. Yoshida, , Nuclear Instruments and Methods A382 (1996) 153-160
[21] I. Ben-Zvi et al., Nuclear Instruments and Methods A245 (1986) 1-12
[22] G. Bassato et al., Nuclear Instruments and Methods A328 (1993) 195-198
[23] J. M. Bogaty, B.E. Clifft, K.W. Shepard and G.P. Zinkann, Proc. of the 1989 IEEE Particle Accelerator Conference,
[24] A. Facco, "Mechanical mode damping in superconducting low beta resonators", this conference.
[25] G. Bassato, A. Battistella, M. Bellato, S. Canella, Nuclear Instruments and Methods A328 (1993) 195-198
[26] S. Canella et al., Proc. of the 5th European Particle Accelerator Conference, Barcelona, June 1996