

## COMPLETION OF THE LNL BULK NIOBIUM LOW BETA QUARTER WAVE RESONATORS

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### Abstract

The 22 bulk niobium low-beta resonators built for the ALPI and PIAVE linacs at LNL are under installation and commissioning. Most of the cavities have been tested, showing an average gradient of 6.9 MV/m at the nominal power of 7W, with no rejection. Due to specially designed mechanical dampers, the cavities can be operated in the linac without electronic fast tuners, in spite of their large size and low frequency (80 MHz). This paper will report on the latest results on cavities gradients, mechanical dampers and slow tuning systems; effects of high pressure water rinsing in low beta QWRs, helium conditioning and Q degradations following a cavity quench, will be presented. The capability of the present technology to allow for the construction of high gradient, low beta linacs will be also discussed.

### 1 INTRODUCTION

The ALPI and PIAVE heavy ion linacs at Laboratori Nazionali di Legnaro [1] include low beta sections consisting of quarter wave resonators working at 80 MHz, with optimum beta 0.047 for the PIAVE cavities [2] and 0.055 for the ALPI ones [3] (Fig.1). We have built the 21 required resonators plus a spare one. We test and rinse all cavities before mounting them in the linac cryostats and, until now, the performance of 17 cavities has been recorded. Four cavities have been tested on-line and used for beam acceleration.

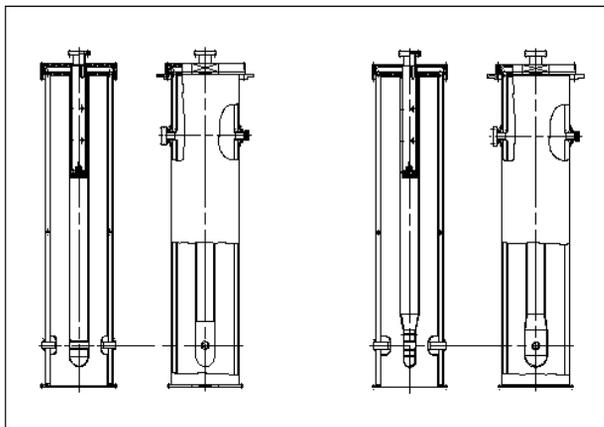


Figure 1. The  $\beta=0.055$  and  $\beta=0.047$  resonators.

The cavities, made of bulk niobium, are equipped with mechanical dampers [4]; this is a unique feature in this kind of low frequency cavities, which usually need powerful electronic fast tuners to counteract mechanical stability problems. The resonators characteristics have been described elsewhere [2,3]; our effort was devoted both to obtaining high performance and to simplifying design and treatment as much as possible, in order to reduce cost and increase reliability. The surface treatment consists of standard chemical polishing 2:1:1 for niobium (CP), performed at CERN, and high-pressure water rinsing (HPR); no high temperature baking is required. The following statistical data include the rf measurement results of all 17 tested cavities, with no selection.

### 2 ON- AND OFF-LINE RESONATORS PERFORMANCE

The statistical data of the rf test results are shown in tab.1: the average accelerating field was 6.9 MV/m at 7 W nominal power, far above the original design requirements of 3 MV/m; after these results, the PIAVE requirements were increased to 5 MV/m. Some cavities, however, could approach or exceed 8 MV/m at 7 W and 10 MV/m (i.e. about 50 MV/m peak) at maximum power (see Fig. 2).

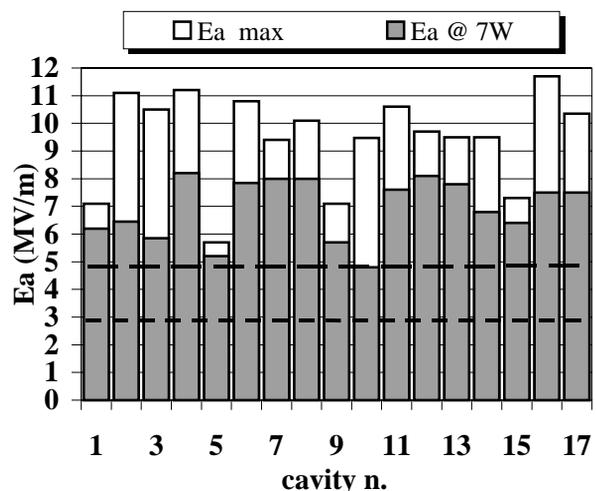


Figure 2. Accelerating field measured at 7W and at maximum power. The dashed lines represent the ALPI and PIAVE design requirements.

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The average value of the maximum surface electric field was 46 MV/m, limited mainly by the conditioning time (15' in the test cryostat) and the available power (<200 W pulsed). The average low power quality factor was  $1.5 \times 10^9$ , resulting in an average residual resistance of about 8 nΩ. The highest recorded Q was  $3.3 \times 10^9$ , i.e.  $R_{res} \approx 3 \text{ n}\Omega$ . The on- and off-line resonators average results were comparable; the on-line cavities reached very high maximum fields because of the longer conditioning time (2 hours). We did not reject any cavity until now; the least performing one, affected by a welding defect and kept as spare cavity, was repaired, underwent a second CP and could finally exceed 5 MV/m at 7W.

| Average values   | $\langle E_a \rangle$<br>@7W<br>MV/m | $\langle E_p \rangle$<br>MV/m | $\langle H_p \rangle$<br>G | $\langle Q_0 \rangle$<br>$\times 10^9$ | $\langle R_{RES} \rangle$<br>nohm |
|------------------|--------------------------------------|-------------------------------|----------------------------|--|-----------------------------------|
| All cavities     | 6.9                                  | 47                            | 950                        | 1.5                                    | 8                                 |
| On-line cryostat | 7.1                                  | 54                            | 1090                       | 1.3                                    | 9                                 |
| Best cryostat    | 7.9                                  | 50                            | 1000                       | 1.7                                    | 7                                 |
| Best results     | 8.3                                  | 58                            | 1170                       | 3.3                                    | 3                                 |

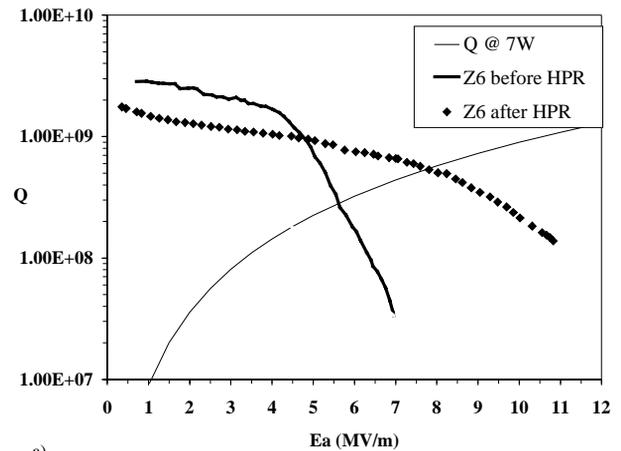
Tab. 1 Statistical representation of the rf measurement results.

### 2.1. Effects of HPR

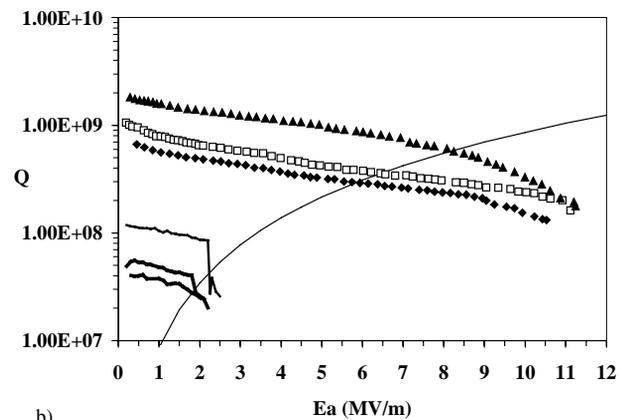
Even if some cavities could reach excellent performance after CP, we decided to do HPR in all cavities, to eliminate the risk of dust particle contamination following the long storage time (years for some cavities) in plastic bags before installation in the linac. The quality factor, after HPR, tended to decrease at low gradient while increasing at high gradient (fig.3a). By means of HPR we could fully recover cavities n. 2,3,4 that, during their first permanence in the linac, had been heavily contaminated by dust, with intolerable degradation of their performance (fig.3b). All these cavities could later exceed 10 MV/m on line and their final quality factor after HPR was roughly proportional to the value before HPR.

### 2.2. Q degradation

We have never observed Q degradation that could be attributed to hydride contamination, even after long permanence at a temperature around 150 K. In two cases, while driving cavities in CW mode at high gradient (above 50 MV/m peak electric field) we observed Q degradation after a quench caused by field emission. In one case the degradation was rather strong, moving the 7W gradient from above 8 MV/m to less than 5.



a)



b)

Figure 3. Effects of HPR: a) in the clean cavity n. 6; b) in cavities n.2, 3 and 4 contaminated by dust. The data obtained before HPR are represented by lines.

A less harming degradation, affecting the quality factor only above 7 MV/m, appeared in similar conditions in a PIAVE type cavity tested after CP with no HPR. We interpreted these degradation events as caused by surface modification following a field emitter explosion. A short rf conditioning at 150W could not restore the original performance; we could not verify yet whether a high pulsed power rf processing, HPR or a second CP would be required.

### 2.3. Mechanical dampers performance

Mechanical damping in low frequency superconducting quarter wave resonators was developed at LNL to prevent the setting up of mechanical resonant modes, which are the main cause of phase unlocking in large size, low-beta

resonators. This technique is used at LNL instead of electronic fast tuning; when applicable, as in our case, mechanical damping gives significant advantages in terms of simplicity, low cost and high accelerating gradient. Specially designed mechanical dampers are being mounted in all our low beta cavities. We have tested on-line the dampers effect by measuring the frequency fluctuations induced by a mechanical oscillator coupled to the linac low beta cryostats [5]. We compared the response of 4 damped accelerating cavities to that of the buncher cavity without damper. While the background noise of the latter was lower, the damped cavities could resist to a much stronger excitation without unlocking (Fig. 4).

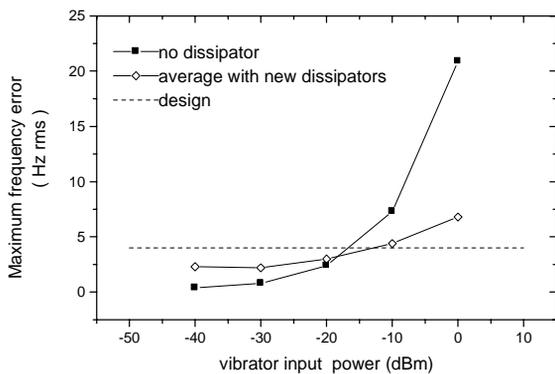


Figure 4. Frequency error, in cavities with and without dampers, at different levels of mechanical vibrations induced in the cryostats artificially.

#### 2.4. Frequency tracking system performance

The sensitivity of the resonators to helium pressure fluctuations, which can reach, in our cryogenic system, 200 mbar at a speed above 1 mbar/sec, has been counteracted by means of a software control of the mechanical tuning system. The low frequency component of the residual phase error of the resonator, locked to the reference frequency, is used as the control signal. This system, during normal operation of the linac, keeps the cavity resonant frequency within 2 Hz from the reference one. Delays are introduced in the control system by the poor reproducibility and by the backlash of the mechanical tuner, originally built for quasi-static operation.

#### 2.5. Phase stability

The phase locking of the low beta cavities has been thoroughly tested in the linac. In normal operation, phase lock up to 6 MV/m could be maintained with the mechanically damped cavities, provided that the resonators rf bandwidth was at least 3 Hz FWHM (obtained by overcoupling of the power feeder: most of

the rf power, in this case, is reflected and dissipated at room temperature). The average phase noise recorded in the 4 on-line resonators, when locked, was below 1 degree; peak values of several degrees have been recorded during spurious fast changes of the helium gas pressure. Fast pressure fluctuations lead to cavity unlocking above 6 MV/m, which is probably the highest value compatible with the beam dynamics design of our linac in the low beta section.

Operation above 6 MV/m, however, would be possible with most of the resonators; this would require the replacement of components originally dimensioned to operate at 3 MV/m, i.e., the maximum power of our rf amplifier (about 150 W), the relatively slow response of our mechanical tuner and power losses along rf cables inside cryostats.

### 3 PERSPECTIVES IN LOW BETA LINACS

The present technology allows producing superconducting low beta cavities capable of very high gradients.

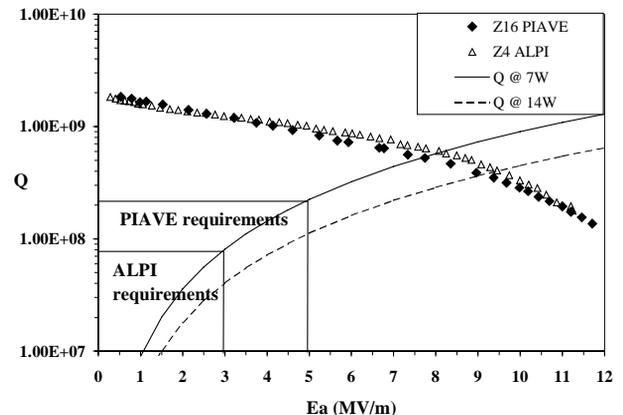


Figure 5. Best ALPI and PIAVE low beta cavities results.

Most of the final product can be purchased from industry and can be handled even in a normal laboratory environment. Cavities contaminated by dust can be fully recovered in-house by means of relatively inexpensive HPR. High vacuum furnace baking of resonators is not needed. As a result, a superconducting low beta linac could be built and maintained even without large in-house structures for cavity construction and treatment. The good reproducibility of the performance allows setting low beta linac design requirements at least at 6 MV/m (about 30 MV/m peak surface electric field), even for low beta resonators working at low frequency. With some selection of the cavities, or with some supplementary treatment of the least performing ones, this limit could be already set around 8 MV/m (see Fig. 5). The number of cavities required for a typical low beta heavy ion linac could be

much lower than it was only a few years ago; since most of the linac cost is concentrated in cavity equipment, cryogenics, rf system, buildings, control systems etc., the resonator cost become a secondary parameter compared with performance and reliability. The overall cost of a future heavy ion linac could be nearly halved in comparison with the amount required only a decade ago.

#### 4 SUMMARY AND CONCLUSIONS

The construction of the 80 MHz, low beta bulk niobium cavities developed for the LNL linacs, was completed. Most of the cavities have been tested showing an average gradient of 6.9 MV/m at 7 W; no cavity was rejected. On- and off-line testing gave similar results. Mechanical dampers, inserted in the cavities to attenuate mechanical vibrations, allow locking the cavities at high gradient without electronic fast tuners. No Q degradation to be attributed to hydrides has been observed, while in two cases degradation could be attributed to surface modification following the explosion of field emitters. The present technology is mature for producing reliably high gradient, low-beta cavities in an industrial environment. Nowadays, the accelerating gradient of a future low beta heavy ion linac could be realistically set at 6-8 MV/m with significant reduction in size and cost.

#### 5 ACKNOWLEDGEMENTS

We thank F. Stivanello and S. Stark for the Pb plating and the Nb sputtering of the tuning disks. We are grateful to A. Porcellato, L. Bertazzo and all the people involved in the cryostat assembling.

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