PERFORMANCE OF ALPI NEW MEDIUM BETA RESONATORS

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Abstract

All the Nb sputtered medium β cavities installed up to 2011 in ALPI were produced by upgrading of old previously Pb plated substrates. For the first time this year we had the opportunity to test on line four 160 MHz, β=0.11 QWRs which were designed and built in order to be Nb sputtered. These resonators were built in between 2007 and 2008 and they were tested at low fields (up to 3 MV/m) just after their production, when they showed Q_0 values exceeding $1x10^9$. They were then stored for about three years in plastic bags and they were installed in ALPI only this year. The on line tests showed Q_0 values reduced of about a factor five with respect to the ones measured in laboratory. It is the first time we could pick out a Q deterioration caused by storage in air, probably because we previously had the possibility to install the cavities in the on line cryostats within some weeks from the time of cavity production.

So far we have not recognized any Q–degradation, both when the sputtered cavities were maintained in vacuum for many years and also when they were open to air for a few weeks for cryostat maintenance. This time, as it had happened in the maintenance of cryostat CR19 housing high β resonators, we could instead improve the Q-curves by high pressure rinsing the resonators and by making a better rf contact between the cavity and its bottom plate.

INTRODUCTION

A large number of Nb on Cu sputtered cavities are in operation in ALPI since many years [1]. They are Quarter Wave Resonators (QWRs) operating at 160 MHz. Eight high β (β=0.13) and 44 medium β (β=0.11) units are used for beam acceleration. In ALPI there are also further 16, 80 MHz, low β, bulk Nb accelerating QWRs [2]. All these resonators are housed in cryostats containing four cavities each. Further 4Nb/Cu+2Pb/Cu QWRs, two per cryostat, are used for beam bunching.

The four high β cavities presently installed in cryostat CR20 are on line since 1998. Their substrates were designed and built in order to be sputtered and their on line performance exceeds 6 MV/m @ 7 W in average [3]. The remaining four high β resonators, have the same inner shape, but they have a different construction technology [4]. They had been housed in the cryostat CR20 in between 1995 and 1997; in 2001, after being re-sputtered, they were moved into the cryostat CR19. Their maintenance, in 2010, produced a substantial improvement in performance, as described later in this paper. Up to the last year all the installed accelerating medium β resonators were obtained by sputtering old substrates previously lead plated [5]. The cavity renewing process started at the end of 1998 and was completed by 2004 [6]. The cavity upgrading practically doubled their averaged operational accelerating field (4.8 MV/m a @ 7W), but the drawbacks of old substrates did not allow to reach the results obtained in high β resonators [6].

Between 2007 and 2009 we built and tested in laboratory four new medium β cavities properly designed to be sputtered, but only this year we had the possibility to test them on line [7].

THE NEW MEDIUM BETA CAVITY

The new medium β cavity has a shape similar to the ALPI high β resonators: a rounded shorting plate links the inner and the outer conductors. The first, 60 mm in diameter, ends in an hemisphere, the latter, which has an inner radius of 90 mm, extends about 70 mm beyond the inner conductor.

The necessary reduction of optimum β with respect to the high β cavity, is achieved by the plastic deformation of the outer conductor which, around the beam axis, is protruded toward the inner cavity side. The beam ports are external to the cavity body and are screwed to the outer conductor without any gasket. Both the original beam port design and the rounded shorting plate allow smooth connection surfaces where a better sputtered film can be obtained. The cavity shares the cryostat vacuum. Figures 1 and 2 show the new medium β substrate before chemical treatment.

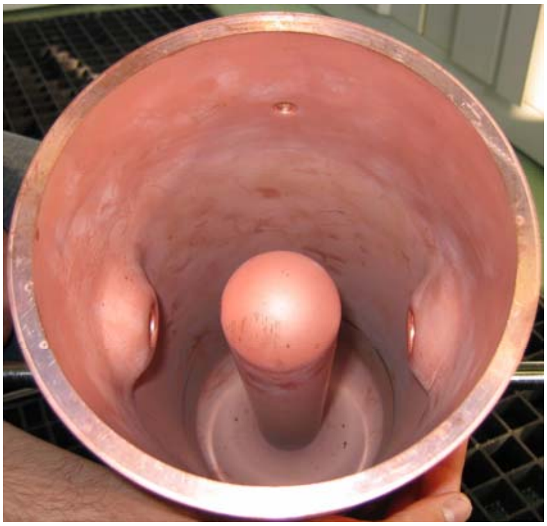

Figure 1: The inside of new medium β substrate before chemica treatment.

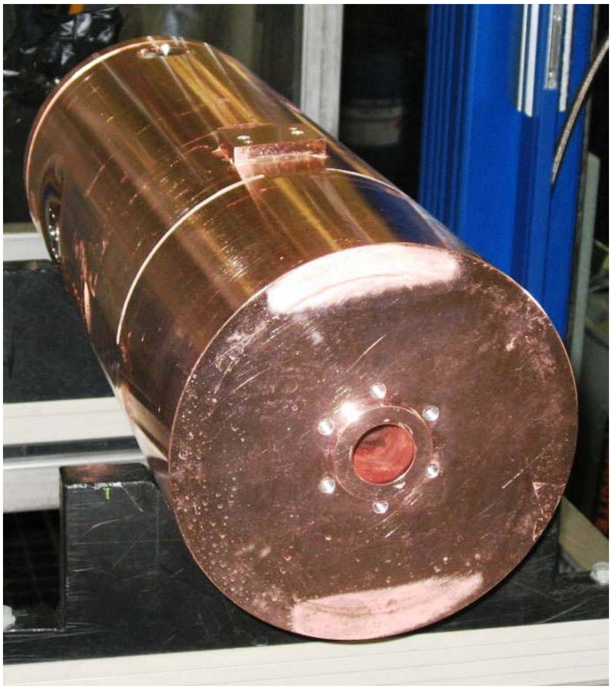

Figure 2: outer part of the new medium β cavity. In the foreground the seating for the cavity collar for connection to the liquid He piping. On top there are the cavity holder and the coupler hole.

It adopts a capacitive coupler, whose antenna penetrates in to the cavity at 90° with respect to the beam axis, shifted of 70 mm towards the cavity bottom. The pick-up antenna is located symmetrically with respect to the coupler. In this way the cavity does not have holes in high current region. The cavity tuning is performed pushing/pulling the bottom plate.

Electromagnetic Parameters

The resonator electromagnetic parameters, computed by HFSS, are listed in Table 1.

Table 1: Electromagnetic parameters of the new medium β cavity.

Frequency	160	MHz
Stored Energy/$(E_a)^2$	65	mJ/(MV/m)^2
β_{opt}	0.11	
Peak magnetic field/E_a	≅ 110	Gauss/(MV/m)
Peak electrical field/E_a	≅ 4.5	
T.T.F.(β_{op})	0.899	
Active length	180	mm
Γ	29	Ω

The cavity, set at 1 MV/m, provides an energy gain of 0.18 MeV/(MVm)/q to the synchronous β_{opt} particle with state of charge q. The wide TTF curve allows efficient acceleration for beams having $0.07<\beta < 0.2$.

Substrate Construction

We produced four cavities starting from OFHC Cu parts left unused since the first ALPI cavity production [5] and named MD1, MBD2, MBD3, MBD4.

Each substrate was obtained from a preformed mushroom shape and a cylinder jointed together by vacuum brazing (fig.3). In order to make the cavities compatible with the standard ALPI cryostat, two cavity supports were connected to the cavity body by a subsequent brazing cycle.

The beam port shaping was developed and performed in house at room temperature and in a single step, after the brazing cycles.

Later on, we drilled the holes for the beam line, coupler and pick up. We had then to mill the cavity for preparing the seats both for coupler and external beam ports. The latter are screwed to the cavity body before the sputtering process in order to be covered with the Nb film together with the cavity inner surface (figure 4). The final substrate machining includes turning of the groove for fixing the tuning system, preparation, always by lathe machining, of the surface where the stainless steel cavity collar is fixed and, at the end, drilling and threading of the holes used for joining the ancillary equipment to the cavity.

A detailed description of the substrate construction technology is reported in reference 8.

The inner cavity surfaces needed to be grinded both to eliminate the signs left by the dies used during the plastic deformation and to smooth the surface interested by the mechanical deformation.

The cavity target frequency was reached by decreasing the inner conductor length, purposely left slightly longer than necessary.

Figure 3: OFHC Cu cavity parts before vacuum brazing.

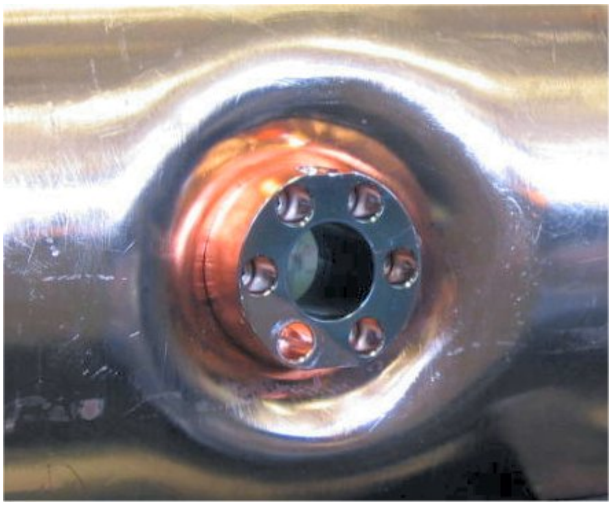

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Figure 4: Particular of the external beam port. It is screwed to the cavity body before the cavity sputtering process.

This process was performed by removing material from the inner conductor tip by electro-polishing. If the electro-polishing solution was suitably mixed during the process, a few hundred microns were easily subtracted leading to a smooth surface.

In these cavities we eliminated the indium wire traditionally used to ensure rf contact between the cavity and its bottom plate to have the possibility to rinse the resonator by high pressure water just before its assembling into the line cryostat. This asked for minor changes both in the standard cavity bottom plate and in its fixing ring in order both to increase the tightening torque and to shift the contact line between the plate and the cavity border towards the inner cavity side, where the sputtered film has still a sufficiently good quality. Small adjustments on the standard tuning system allowed maintaining a smooth tuning movement in all its range.

Surface Preparation

The inner cavity surface treatment included a few days of tumbling followed by the electro-polishing and chemical polishing cycles and by a final high water pressure rinsing according to a well established procedure [8].

The chemical solution is renewed only after treating two/three cavities, one after the other in following days. Usually the first polished cavity was immediately put in vacuum in the sputtering chamber, the others were instead stored in plastic bags in air and rinsed again just before their assembling in the sputtering chamber.

Fresh chemical solution was used for all the new medium β cavities, but MBD2, which then had its sputtering postponed of about one month with respect to the chemical treatment. As usual, few days of resonator baking in the sputtering chamber, up to 700° C, preceded the superconducting layer deposition.

By the D.C. biased Nb sputtering technology developed at LNL [3], we deposited a Nb layer, about 2 microns thick, in 14 sputtering steps of about 15 minutes each with three hours of pause in between to maintain the cavity below the baking temperature. Figure 5 shows the first sputtered new medium β cavity.

Regarding to the sputtering process, we used the standard sputtering parameters which were adopted for the production of ALPI cavities and initially we tried the cathodes which were already available.

For MBD3, the first cavity produced, we adopted the cathode used for the old medium β cavities and we obtained an inner resonator surface having some shadows in the beam port area; in spite of that the cavity presented quite good performances, though lower than those obtained in high β cavities.

The use of the cathode for high β substrates in the sputtering of the cavity MBD2 led instead to bad results ($Q_0= 2x10^8$) so the cavity had to be stripped.

We were consequently forced to build a new cathode more appropriate for the new resonator shape. It was adopted for the production of MBD1, MBD4 and also for the new sputtering of the cavity MBD2. Being the obtained cavities performance better than the old medium β resonators, we did not look for further improvements of the sputtering process, but we installed the cavities in ALPI as soon as possible in order to take advantage of their performance.

We, as usual, prepared the cavity bottom plates in a different sputtering chamber where it is possible to produce up to 9 units in the same time by D.C biased sputtering.

Figure 5: New medium β cavity after being sputtered and before being closed by its bottom plate.

PERFORMANCE OF THE NEW MEDIUM BETA RESONATORS

Laboratory Tests

As soon as dismounted from the sputtering chamber, we tested the cavities one by one up to an accelerating field of 3MV/m (maximum allowed field by radioprotection rules in the test laboratory). As usual, we rinsed the cavities by high pressure water before closing them by their bottom plate without any gasket.

We mounted the cavities in the test cryostat equipped with their coupler, pick-up, tuner, resistors and temperature sensors. We pumped down the cryostat very slowly (a few hours before opening the turbo pump gate) in order to reduce cavity contaminations, that are possible because we did not have the possibility to assemble cryostat and cavities in clean room. We baked the cavities in vacuum for about 24 hours at 350 K. We started to perform multipactoring conditioning at room temperature and we completed it in few hours during the cooling of the cryostat thermal shield. As usual, we cooled the resonators at 77 K by liquid nitrogen and then to 4.2 K by liquid He. The cooling time is not critical for these resonators because they are not affected by Q-disease.

At liquid He temperature we performed only low power conditioning to get rid both of the multipactoring level which usually appears at about 1.2 MV/m and of any other residual low field multipactoring.

Fig. 6 presents the Q-curves obtained after 1-2 hours of conditioning. As it is possible to notice, MBD4 presented a Q_0 value of $2x10^9$ and its Q-curve at low field was comparable to the best ones obtained in high β resonators [3]. The Q- curve slope above 2 MV/m was due to the short conditioning. As we mentioned before, MBD3 was sputtered using the old, not optimized, medium β cathode. The resulting cavity inner surface presented shadows in the beam ports area and this is a possible reason of the lower Q curve.

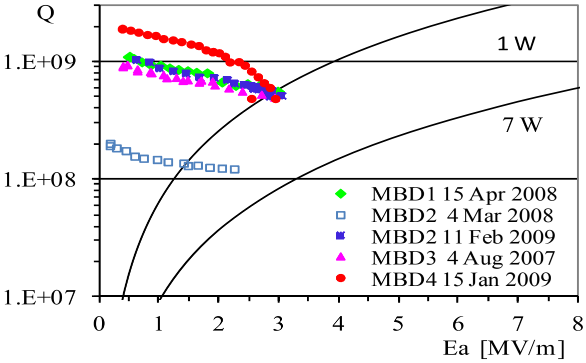

Figure 6: Q-Curves of the new medium β resonators as measured in laboratory after low power conditioning. Radioprotection rules do not allow to exceed 3 MV/m. After the first sputtering cycle the Cavity MBD2 was stripped and sputtered again.

A further contribution to the lower performance could be due to the cryostat venting we had to perform before the cavity test to adjust the coupling range of the cavity.

The replacement of the sputtering cathode in the second sputtering cycle significantly increased the performance of the cavity MBD2, which remains however lower than MBD4 cavity. MBD2 was chemically treated using the same solutions previously used for cavity MBD4 and it was sputtered a few weeks after the chemical process. Both these conditions may be a possible reason for the reduction in performance.

The first circumferential brazing of the MBD1 substrate was not performed correctly and had to be repeated without having the possibility to follow the standard assembling procedure [5]. As a consequence, some unusual shadows of brazing material appeared around the brazed joint. We tried to scratch out all the visible material, but it is probable that some contamination remained still included in the copper surface thus affecting the surface quality and consequently the cavity performance.

Certainly it would have been interesting to repeat the sputtering process in the less performing cavities, but we preferred to take advantage immediately of the new cavities better performance.

On-line Performance

Once dismounted from the test cryostat, the cavities were stored in plastic (PE-LD) bags waiting to be installed in ALPI. We had all the cavities ready by the beginning of 2009, but, unfortunately, the cryostat installation was postponed up to end of 2011, when we had the possibility to open the cryostat CR15, the first medium β cryostat uninstalled.

The absence of the indium gasket gave the possibility to open the cavity bottom plate and to rinse each cavity by high pressure water before installation into the line cryostat. This does not prevent possible contamination during cryostat assembling and alignment procedures, the latter performed with cavities opened to the unclean laboratory air, but it can remove dust entering into the cavity during the test cryostat venting.

After the assembling procedure, we slowly pumped the cryostat down to $1x10^{-6}$ mbar and we installed it on line without breaking the vacuum.

The cavities were again baked on line in vacuum at 350 K for 24 hours and then conditioned before being cooled to 4 K. As expected by the not clean assembling, the cavities were heavily affected by field emission. They were conditioned for a few hours using the line amplifiers and then in pulsed mode (1 kW peak; about 20 W average power) by an auxiliary amplifier for about 3 hours each. Later the cavity were warmed up to 20 K before being cooled down again at 4 K for the final Q measurements.

Figure 7 presents laboratory and on line Q-curves of the four new medium β resonators while table 2 shows Q_0 and Q-curve slope values obtained fitting the $\log_{10}$ Q data of the new medium β resonators (fig.7).

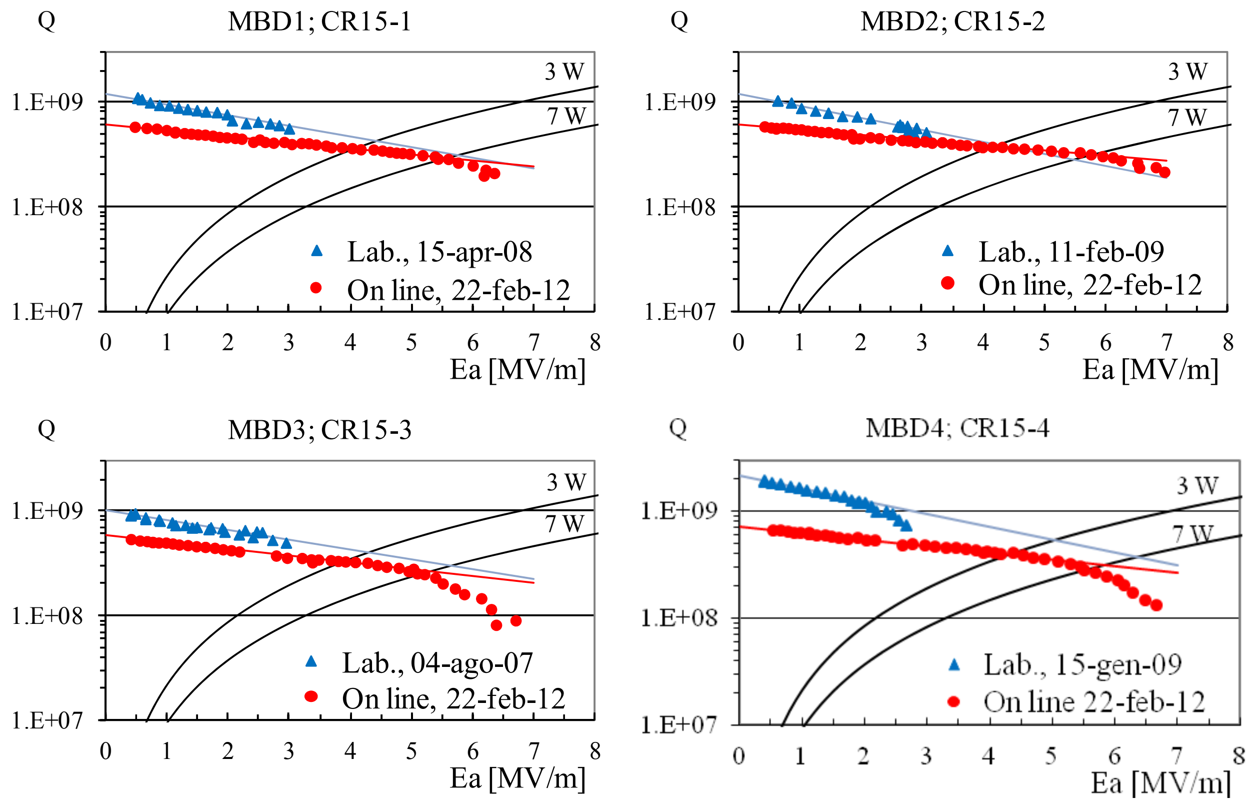

Figure 7: Laboratory (blue) and on line (red) measurements of the four new medium β resonators installed in cryostat CR15 after they had been stored in air for at least 3 years. The straight lines represents the liner best fit of the $\log_{10}$ of the Q-data as a function of the accelerating field in the linear range of the Q-curve. The fit parameters are summed up in Table 3. The Q_0 values are lower in the on line measurements for all resonators, but the reduced slope in the on line measurement mitigates the accelerating field losses at 7W.

As it is possible to notice in fig. 7, the Q_0 values measured on line are all lower by at least a factor 5 with respect to those measured in laboratory. The on line Q-curves are straight up to an accelerating field exceeding 5 MV/m; their slope is lower than the one obtained in laboratory for all the cavities. This is compatible with an increase in the surface resistance which depends on the accelerating field. It can be due to surface degradation during the long storage in air. It is the first time we put in evidence such effects, probably, not only because it is the first time we store high Q cavities in air for such a long time, but also because, the more reliable cavity closing method and the rinsing procedure we adopted, made the cavity performance less depending from events difficult to control.

The resonator Q measured on line in these cavities can be obtained by the parallel contribution of the Q measured in laboratory and of a constant Q value ($Q_{//}$). That means that the Q decrease of resonators can be thought as to the contribution of a surface resistance, depending quadratically by the accelerating field, in series to the cavity initial surface resistances.

Table 1 sums up both the values of Q// we found for the four new medium β resonators and their accelerating fields at 7W, as deduced by the Q-curve fitting. In spite of the losses of performance with respect to the laboratory tests, the new cavities can operate at accelerating fields exceeding 5.6 MV/m at 7W in average, after a full conditioning process.

A reduced storage time and the use of the optimized cathode for all the resonators would have certainly increased the average accelerating field value of 6 MV/m.

If properly built substrates were available it would be then possible increase substantially the ALPI accelerating voltage

Table 2: Values of Q_0 and Q-curve slope obtained fitting the $\log_{10}$ Q data of the new medium β resonators (fig.7).

	Laboratory		On line test	
Cavity	**Qo**	**Slope [MV/m]$^{-1}$**	**Qo**	**Slope [MV/m]$^{-1}$**
MBD1	1.19E+09	-0.100	6.02E+08	-0.056
MBD2	1.17E+09	-0.112	6.00E+08	-0.049
MBD3	9.93E+08	-0.093	5.71E+08	-0.065
MBD4	2.14E+09	-0.120	7.20E+08	-0.061

Table 3: $Q_{//}$: constant Q-value that, added in parallel to the laboratory measured Q-curve data, reproduces the on line Q curve; E_a is the accelerating field at 7W as it results by the fitting process.

Cavity	$Q_{//}$ due to storage	E_a at 7W
MBD1	1.22E+09	5.64
MBD2	1.24E+09	5.81
MBD3	1.34E+09	5.31
MBD4	1.08E+09	5.86

IMPROVEMENT IN HIGH BETA RESONATOR PERFORMANCE

The benefit of the better cavity closing system that we systematically stated to adopt in 2007 for the new medium β resonators, appears evident also in the increment of performance we obtained in CR19 cavities after the cryostat maintenance we performed in 2010. This cryostat houses the high β resonators hb1, hb2, hb3, hb4. They were sputtered a first time in 1995 and they were installed in ALPI in the cryostat CR20 up to 1998, when they were substituted by new more performing cavities that are still in operation at an average accelerating field approaching 6 MV/m @ 7 W cryogenic dissipated power.

In 2001 the uninstalled hb cavity substrates were stripped and Nb sputtered again. All the resonators reached in laboratory Q_0 values in between 5 and $7x10^8$. We have to mention that the cavity hb2 obtained such result only after a third sputtering process, once that a small pit, located on the cavity shorting plate, was detected and smoothed. At the end of 2001 we installed the renewed cavities in the cryostat CR19 where they reached on line accelerating field in between 4 and 5 MV/m, limited by field emission. However the hb1 resonator became unusable just after the first high power conditioning (1kW, pulsed); due to a short in the rf input line. Moreover, a couple of years ago, the use of the second cavity, hb2, became impossible because its tuner stuck.

When we uninstalled the cryostat CR19 in 2009 for maintenance, we decided to re-sputter only hb2, which was both the worst performing resonator and the only one which needed frequency readjustment. Before to re-sputter the resonator, we took the opportunity to open and rub up a new pit which showed up in the cavity shorting plate during the stripping of the old Nb film. We also smoothed more deeply the pit we had already discovered before the previous sputtering. The cavity was then chemically treated and sputtered again in the standard way before being tested in laboratory. The only difference of this resonator with respect to the cavities produced in 2001 was the higher number of sputtering cycles, which results in a film thickness about 50% higher.

All the other cavities maintained their previous sputtered film, but had their bottom plate changed. We removed accurately the indium gasket that was previously used to join the old plate to the cavity body. All the cavities were then High-Pressure Water Rinsed and closed by bottom plates, which were previously modified on the lathe to improve their rf contact with the cavity body. We also modified the connection flanges in order to increase further the strength on the junction.

Once the cryostat CR19 was again on line, we tested again the cavities. Figures 8 shows their Q- curve, after a few hours of He conditioning using the 100 W installed amplifiers.

As it is possible to notice in the picture, all the cavities raised their Q_0 values to about $1x10^9$. This is a clear evidence of the benefit of the newly adopted plate assembling procedure, which allows avoiding the indium gasket.

The Q-curve slopes of the cavities, that were only rinsed and closed by the new plate closure system, remained practically unchanged, only the curves were shifted towards higher Q-values. This suggested that, by the new assembling system, we could eliminate a power dissipation process depending quadratically by the accelerating field or, in other words, that we eliminate the contribution of a constant resistance to the cavity power losses.

The cavity hb2 was tested, just after its new sputtering, without indium gasket also in laboratory and, consequently, there was no reason to have better performance. It presents instead an increased Q slope, however lower than the ones of CR15 cavities.

Table 4 sums up the fitting parameters of Q-curves both for laboratory and on line measurements.

Table 4: Values of Q_0 and Q-curve slope obtained fitting the $\log_{10}$ Q data (fig. 8) of the high β resonators installed in cryostat CR19. Only hb2 had its superconducting layer renewed before being tested in laboratory, all the others, produced in 2001, were only rinsed

	Laboratory test		On line test	
Cavity	**Qo**	**Slope $[MV/m]^{-1}$**	**Qo**	**Slope $[MV/m]^{-1}$**
hb1	1.19E+09	-0.100	9.28E+08	-0.061
hb2	1.17E+09	-0.112	1.14E+09	-0.064
hb3	9.93E+08	-0.093	1.16E+09	-0.070
hb4	2.14E+09	-0.120	1.16E+09	-0.070

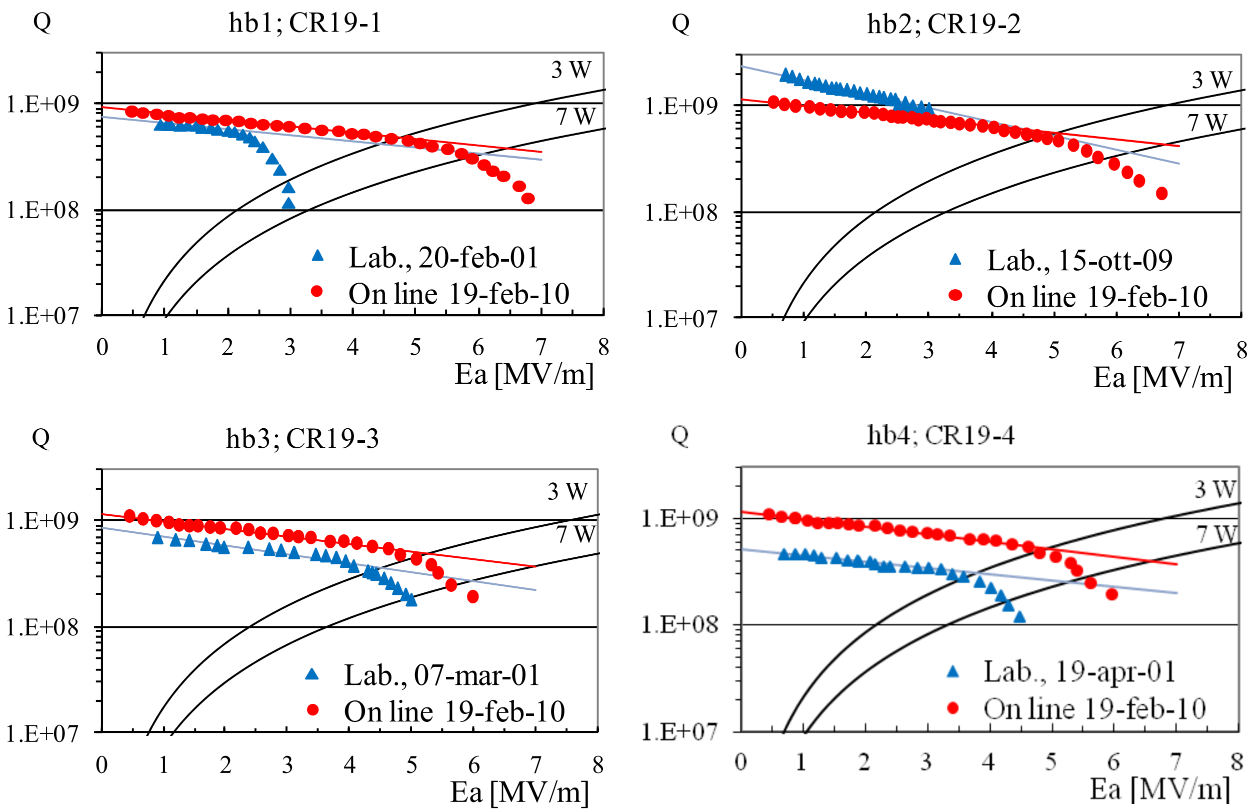

Figure 8: Laboratory (blue) and on line (red) Q curves of the high β resonators installed in ALPI cryostat CR19. Only hb2 had its superconducting layer renewed before being tested in laboratory, all the others were only rinsed. The straight lines represents the liner best fit of the $\log_{10}$ of the Q-data as a function of the accelerating field.

CONCLUSIONS

Four new Nb sputtered medium β cavities have been developed and built at Legnaro. The performance obtained in these cavities demonstrate that it would be possible to obtain accelerating fields exceeding 6 MV/m at 7W also in medium β cavities if properly built substrates were available, thus increasing substantially ALPI accelerating voltage. We obtained an increase of performance also in three high β Nb/Cu cavities, which were produced more than nine years ago, by changing the closure system of their bottom plate and performing high pressure water rinsing on them. We also were able to re-sputter a cavity and maintain the same level of performance we used to have in the production stage of the high β section.

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