Abstract

In the Superconducting linac ALPI, (Acceleratore Lineare Per Ioni) operating at Legnaro, 70 QWRs (Quarter Wave Resonators) are presently installed, 12 of them are full Nb resonators, 58 have been produced by deposition of a superconducting layer on a Cu base. Most of the Cu substrates were initially Pb plated and were later upgraded by the substitution of the Pb layer with a sputtered Nb film. In this way the QWR Nb sputtering technology, developed at Legnaro, allowed a substantial increase in the ALPI performance at a negligible cost.

Accelerating fields exceeding 7 MV/m, at 7 W dissipated power, have been reached in newly designed ALPI QWRs, but lower performance was instead obtained in resonators produced using the old Cu substrates, thus limiting the average accelerating field of sputtered cavities in ALPI to 4.6 MV/m, always at the design dissipated power of 7 W. The Nb sputtered QWRs do not show any deterioration in performance with time; it is still improving due to better conditioning.

The sputtered QWRs are very stiff and are not affected by frequency shifts due to drift in the He bath pressure. This allows their reliable locking up to the accelerating field allowed by the available cryogenic power also in the ALPI vault, where the environmental noise and the field allowed by the available cryogenic power also in the ALPI vault, allowed a substantial increase in the ALPI performance at a negligible cost.

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ALPI SUPERCONDUCTING LINAC

ALPI is a superconducting linac for heavy ions which entered in operation at LNL in 1994 [1]. Initially it was used as a booster of an existing 15 MV XTU Tandem, but since 2005, it has been injected also by PIAVE, a new positive injector based on an ECR ion source followed by two superconducting SRFQs and 8 Nb QWRs [2]. PIAVE extends the range of ALPI accelerated beams both to noble gases and to very heavy ions (up to Pb). In the original design ALPI consisted of 97 Pb on Cu QWRs of three different βs. Only the 44 resonators of the medium β (β=0.11) section, which was completed in 1994, made use of the original resonator design [3]; the low β (β=0.056) section, which was later installed (1998), housed instead the double wall, full Nb, 80 MHz QW Resonators [4]. In the first two cryostats of high β section (β=0.13), we installed 8 QWRs instead, produced using since the beginning the Nb sputtering technology [5]. We did not have the possibility of filling all the originally foreseen cryostat positions up to now, but ALPI beam design energy was anyway reached in 2003, once the whole medium β section had its resonators upgraded by replacing the Pb with Nb [6]. ALPI can now provide beams exceeding 20 MeV/A in case of light ions and up to 6 MeV/A for Pb.

At present only 4 Pb/Cu QWRs, housed in two bunching cryostats, are still installed. The ALPI layout is presented in fig. 1.

QW NB SPUTTERING AT LNL

In 1988, as soon as the construction of ALPI started, a research project devoted to the production of high performance QWRs, realized by Nb sputtering on Cu substrates, was funded.

Since the beginning, we thought about the possibility of combining the better superconducting characteristics of Nb with the mechanical stability of Cu QWRs. As a matter of fact, producing high performance resonators by Nb sputtering would have allowed replacing, at a very low cost, the ALPI Pb/Cu QWRs in the future; moreover we could have had available immediately the less expensive and that time easier to build, Pb on Cu cavities.

We choose to investigate the DC biased sputtering technology, which was expected to reach good thickness uniformity without the complication of developing plasma magnetic confinement structure [7]. If the deposition rate is lower in case of DC biased sputtering with respect to the magnetron sputtering process, the bias presence, which promotes the film impurity release by the bombardment of low energy Ar atoms, allows maintaining the impurities level in the superconducting layer low, enhancing the film superconducting properties.

After setting up the sputtering system, we tried to obtain on the samples good film uniformity and superconducting characteristics. We sputtered a simplified QWR prototype in 1991.

Accelerating fields comparable to the world best operating QWRs were obtained in 1993 in a modified prototype. The chosen rounded shorting plate, joining the inner and outer conductor, resulted very effective in enhancing the film superconducting characteristics.

We applied the sputtering technology to the production of cavities of the ALPI high β section.

The high β cavity design was optimized for its production by sputtering: we adopted the rounded shorting plate and also a capacitive coupler to avoid holes in high current region and external beam ports. These, jointed to the resonator body by indium gaskets, allowed avoiding shadow areas where the sputtered film used to be of bad quality.
Figure 1: ALPI layout scheme. The low $\beta$ cryostats are represented by green circles and house 80 MHz full Nb QWRs. The medium $\beta$ and the high $\beta$ cryostats are represented by red and by magenta circles respectively. All of them house 160 MHz, Nb on Cu sputtered QWRs. B2, B3 and B4 are bunching cryostats. All of them house medium $\beta$ cavities; B2 house Nb on Cu QWR; B3 and B4 still have installed Pb on Cu resonators. A few positions are still available to host other cryostats in future.

We installed the first high $\beta$ cryostat in 1996, but some troubles in the cryostat assembling limited the cavity performance to an average value of 4 MV/m at 7 W of dissipated power [8].

In 1998 we had the opportunity to replace the resonators with completely new units, which, since then, operate in ALPI at an average accelerating field of 6 MV/m, always at 7 W dissipated power.

A second high $\beta$ cryostat, housing the first produced high $\beta$ cavities, was installed in 2001. In the cavities of the latter cryostat we could not obtain the same performance, mainly because we did not used good quality substrates.

Later, being other high $\beta$ cryostats not available, we investigated the possibility to enhance the performance of the installed medium $\beta$ cavities. A systematic cavity upgrading programme could start only in 1999, when we had to repair or prevent cryogenic leaks, which began to appear in some cryostats.

The upgrading program was completed in 2003 increasing the average accelerating field of medium $\beta$ resonators from 2.2 MV/m (average field of Pb resonators before removal) to more than 4.5 MV/m.

Recently we obtained funds for the production of 4 new, medium $\beta$ QWR substrates and we are going to have them available for the sputtering process soon. We expect the same performance reached in high $\beta$ resonators.

**ALPI SPUTTERED QWRS**

*High $\beta$ QWRs*

One of the ALPI high $\beta$ cavities is presented in fig. 2. Such resonators are housed in two different cryostats, CR20 and CR19. All of them have the same inner geometrical shape, a capacitive coupler and external beam ports.

Figure 2 ALPI high $\beta$ QWR.
The substrates of the cavities included in the two cryostats make use of both different Cu quality and construction technology.

The CR20 cavities are drilled out of OFHC 99.95%, certificated graded Cu billets and do not have any brazing joint, being the collar screwed to the cavity body after the sputtering process. Also the system used to hang the cavities to the cryostat does not foresee any brazed connection, as it is instead the case of medium β installed resonators.

The CR19 cavities are made instead of Se Cu and have a circumferential joint in the outer conductor, about 14 cm apart from the shorting plate. Moreover they have both the cavity collar (in stainless steel) and the cavity supports both brazed to the cavity body. All these brazed joints showed to be very risky. In many cases, when the cavity temperature was rising during the sputtering process, they released impurities, which deteriorated the film quality, lowering the cavity performance.

The Q-curves of operational high β resonators are summed up in fig. 3 (CR19-1 is not working because of a damaged rf input line).

We reached very good performance for three of the CR20 resonators as it is possible to notice in fig. 3. All the resonators, but one, have \( Q_0 \) exceeding \( 1 \times 10^9 \). The average \( E_a \) at the design cryogenic power of 7 W is near to 6 MV/m. The cavity, CR20-3 in particular, during laboratory test, could sustain \( E_a \) up to 11 MV/m, which corresponds to a surface maximum field exceeding 50 MV/m.

The cavities are operational since 1998 and still do not show any reduction in performance when properly conditioned.

This process, which cannot be performed in clean room, very often leads to heavy field emission, which asks for long time to be conditioned. Anyway, looking to the CR19 Q-curve behavior, we do not expect to obtain an accelerating average values exceeding 5.5 MV/m even after conditioning.

**Medium β QWRs**

We have 44 medium β accelerating cavities in ALPI. A picture of their inner shape is presented in fig 4. Further 6 similar resonators are housed in the bunching cryostats B2, B3 and B4.

Only four cavities, two in the cryostat B3 and two in the cryostat B4, maintain their original Pb superconducting layer [9], while all the remaining 46 were upgraded substituting the Pb with Nb in between 1999 and 2003 [10].

The particular features of the medium β resonators made difficult to obtain good performance on them. The low (10 mm) curvature radius, which joints the flat shorting plate to the inner and outer conductors, cannot be easily covered with a film of sufficient quality, because the bias in that region is not much effective in removing impurities.

It is moreover difficult to have a good Nb film both on the surface around the beam ports and in the hole, drilled in the shorting plate, which were adopted to make the Pb plating process easier. The aperture for the inductive coupler, located in high current area, also increases the rf losses. Moreover the sharp edge of both the above mentioned holes cannot easily be sputtered.

The brazed joints in the cavity body are a further handicap. During the sputtering process, the delivery of junk, due to the opening of enclaves trapped into the joints, contaminates the growing film decreasing the cavity performance.
The detailed production procedure of the sputtering cavity is described in reference 11. It was maintained for all the production period, not having time for testing new working conditions.

We could anyway accumulate experience with time, thus counteracting the above mentioned drawbacks and decreasing their negative effects:

- We increased the Ar pressure to increase the film quality in the critical area
- We fixed an extension to the cavity coupler hole which was sputtered together with the cavity. It allows the rf field to decay before meeting normal conducting surfaces
- We rounded the edges of all the holes facing the cavity inner surface
- We opened all the possible volumes trapped between brazed surfaces on the outer cavity body before cavity processing.

As a result, the performance of the cavities has been improving with time up to reach, in the last sputtered units, $Q_0$-value of $7 \times 10^9$ and $E_a$ of 6 MV/m at 7 W approaching the performance obtained in high $\beta$ resonators. The average $E_a$ of ALPI medium $\beta$ QWRs has been anyway affected by the performance of cavities produced in between 2001 and 2002, when only bad substrates were available and when the production schedule was very tight. Also substrates having further inconveniences, as for example, an exceeding coupler hole (drilled by mistake) or defects in the inner cavity surface, contributed to decrease the average performance. In fig. 5 the operational accelerating field at 7 W sustained by Nb sputtered resonators housed in medium $\beta$ cryostats is presented in comparison with the performance reached by the same resonator when they were Pb plated. As it is possible to notice, the resulting average $E_a$ of 4.5 MV/m is about a factor two higher than the ones previously obtained. In spite of operating at about twice higher accelerating fields than before, the cavities maintain the same cryostat, the same control system, the same rf hardware and software.

PRODUCTION EXPERIENCE

In 1998-1999, after a few years of operation, four leaks opened in ALPI cryostats. Consequently the cryostats had had to be removed from the beam line, thus significantly decreasing the available energy of ALPI beams. In most of the cases the problem was caused by the leakage of a cryogenic valve, controlled by a 16 bar He circuit, installed inside the cryostat. A sudden deterioration of the cryostat vacuum could result in a fast and potentially very dangerous, evaporation of the liquid He stored in the cryostat, so we decided to replace the valve in all the installed cryostats as soon as possible. The cryostat maintenance gave a chance to upgrade the resonators installed in them substituting their superconductor. Nb/Cu resonators not only were expected to offer better performance, but would have simplified the maintenance process because they did not need to remain in N atmosphere for avoiding oxidation as it would have been instead necessary in case of Pb/Cu resonators. The choice forced us to upgrade and install in a short time as many resonators as possible in order to restore the original ALPI Voltage. As a consequence, most of the resonators were upgraded in between 1999 and 2003 as it is possible to notice in Fig. 5, where the $E_a$ reached on line by the resonators at 7 W, is presented.

On the production stage, every cavity reaching 4 MV/m was installed, and sometimes, because of lack of time, we had to install also resonators which had encountered troubles during the chemical or sputtering process and resulted in lower performance. By December 2003, the ALPI upgrading programme was completed.

From 2004, when we had a less tight schedule and a few cavities still available, we could further optimize the production process by:

- The systematic high pressure resonator rinsing before its mounting in the line cryostat
- The use of a new, thicker, Nb cathode
- The elimination of the In wire in the end plate-cavity joint. This was made possible by a stronger end plate contact both by increasing the strength doubling the number of tightening screws and by adjusting the end plate shape.

We have not installed on line all the cavities produced since the beginning of 2004 yet, but we expect their $E_a$ will overcome on line 5-5.5 MV/m, even though we can not be completely sure of the results, because both the resonator alignment procedure (with their beam port open to air) and the closing of the cryogenic circuits after the resonator assembling, may contaminate the cavities.

We have no possibility to assemble cryostats in a clean room, so the following operations would surely help in future to avoid the resonator performance degradation:

- A systematic high pressure resonator rinsing before mounting the cavity into the line cryostat
- Perform high pressure rinsing after resonator alignment (made possible in absence of the In joint)
- Assembling the cryostat in a cleaner environment
- Rinsing the resonator after every cryostat venting.

![Figure 5: Operational Ea of medium $\beta$ ALPI resonators when they were still Pb plated and in 2006 after their upgrading by Nb sputtering.](image-url)
• Longer rf and He conditioning to overcome the field emission process
  A further increase in performance, which should reach that of high $\beta$ resonator, is expected in the new medium $\beta$ prototypes, which are now under construction (fig.6).
  The rounded shorting plate, the absence of both holes in high current area and of brazed joints in the outer resonator body, make the construction technology of these resonators very similar to the high $\beta$ cavities. We had however to maintain the circumferential brazing in the outer conductor as in the old medium $\beta$, because we used recovered Cu parts for their construction.
  The actual new feature of these resonators is the beam port shape. It is obtained by plastic deformation of the outer conductor in order to increase the curvature radii of the surfaces around the beam port, favoring the Nb deposition process during sputtering.

![Figure 6: New ALPI medium $\beta$ QWR prototype. Notice the new beam port shape](image)

**OPERATIONAL EXPERIENCE**

In ALPI we have had the unique possibility to evaluate the performance of different types of cavities in the same environment [12].

The number and type of cavities operating in ALPI in the previous years is presented in fig. 7. The equivalent voltage provided by them in the years between 1994 and 2006 is instead presented in the fig. 8 where it is possible to notice that since 2002 most of the ALPI equivalent voltage is provided by Nb sputtered cavities.

At present, one Nb/Cu resonator is not working because of the rupture of an rf input line inside the cryostat which happened during the first high power conditioning. Other two resonators operate at lower field than the one reachable a 7 W, the first one because of a reduced power management capability of an rf line, a second one because the reachable $E_a$ depends on frequency (bad end plate contact).

All the remaining resonators can be set and locked to the $E_a$ sustained at the design 7 W cryogenic power, when this is available.

Nb/Cu cavities do not need continuous frequency compensation; once set to the linac operational frequency, they maintain the resonant frequency value for weeks. Due to their frequency stability, the cavities can operate at $E_{as}$ sustained at 7 W dissipated power (up to 7.3 MV/m in one case) only slightly over-coupled; the forward power is usually set at about twice the cavity dissipated power.

![Figure 7: number and type of cavities operating in ALPI between 1995 and 2006](image)

![Figure 8: Contribution to the accelerating gradient of ALPI by the different types of QWRs](image)
inner conductor), had a completely new tuner mechanism, a new stepping motor controller. Also the rf controller had to be modified by increasing the gain of the feedback circuits.

In the full Nb cavities the frequency is 100 times more sensitive to He bath pressure drifts than the one of Nb/Cu QWRs. In the ALPI environment this leads to frequency excursions wider than the resonator loaded bandwidth. For this reason the standard rf control software had to be upgraded in order to include the continuous tuner movement, driven by the cavity phase error signal, so that the resonant frequency could be continuously adjusted.

In the low β resonators it was necessary the continuous monitoring of the forward power, in order to allow its large excursion to overcome occasional and short unlocking conditions; the resonator power amplifiers are instead switched off, avoiding overloading the rf lines, in case the unlocking condition was not promptly recovered.

Even if now, after the upgrading of the mechanical tuners, the frequency changes of low β cavities can usually be compensated, in case of cryogenic system instability, they can sometimes still lead to resonator unlocking. Moreover the continuous moving of the cold tuner mechanism can lead to ruptures that can affect the reliability of cavity operation.

Due to locking difficulties and in spite of all these improvements, the operational accelerating field in bulk Nb resonator is still limited by the power necessary to maintain the resonator locked in phase. As a consequence, the excellent fields reached at 7 W in laboratory can not be sustained on line and the low β resonators, which can reach average field of 6 MV/m at 7 W, have to be presently locked at an average field not higher than 3 MV/m in the ALPI environment. A plan is now funded to raise the accelerating field by increasing the rf driving power. That will ask for new rf cryostat lines and a cooled coupler.

The Nb/Cu cavities do not show any degradation with time after installation. We had a reduction in the operational field after a cryostat venting only in two cavities.

Generally the resonator Q remains constant and, in many cases, the accelerating field at 7 W is still improving due to longer conditioning time.

The Nb/Cu resonators are not affected by Q-disease as some of the bulk Nb QWR. For this reason they do not need fast cooling and can be maintained at the critical temperature (70-150 K) for weeks without any problem thus making the cryogenic system operation easier.

**ADVANTAGYES OF NB SPUTTERED QWRS**

Summing up, the main advantages we found in the Nb sputtered QWRs are:

- Mechanical stability, which make them insensitive to mechanical vibrations
- Frequency not affected by changes in He bath Δp (<0.01Hz/mbar), which makes both the cryogenic system operations less critical and does not ask for continuous cavity tuning
- The frequency stability allows setting the cavity at reduced over-coupling which means a smaller power driving amplifier, simpler, not cooled, coupler design and a reduced power dissipation in feeding cryostat rf lines
- High thermal stability which makes the cavity less prone to hot spots and help in the conditioning process
- Cavity stiffness, which makes less critical a possible leak in the isolation vacuum
- Absence of Q-disease leads to fewer demands on cryogenic system cooling velocity and reliability
- Insensitivity to small magnetic fields, which avoids the necessity of magnetic shielding
- High Quality factor of the normal conducting cavity, which makes possible the multipactoring conditioning also at room temperature
- Absence of In vacuum joints which makes vacuum leaks less probable
- Reduced cavity price both for material and construction

The lower performance of Nb/Cu cavities at high fields, due to the more pronounced Q-slope of Nb/Cu resonators, is not an issue in QWRs as it is in β>0.5 cavities, because beam dynamic constraints require anyway to limit the accelerating gradient in the low β section of linacs to values well reachable by Nb sputtered resonator.

**CONCLUSIONS**

The Nb sputtering technology shows to be very effective in producing reliable resonators, which have high performance, are very steadily phase locked and are easy to put into operation.

Better results are foreseen by the use of suitable substrates.

The high number of produced and operational resonators and the reliability of the sputtering process (rejection rate less than 10%) demonstrate that the technology is mature and very competitive and could be industrially applied.

**REFERENCES**


[12] A.M. Porcellato et al., ‘Operation Experience with ALPI Nb/Cu Resonators’ Proceedings of 9th European Particle Accelerator Conference, Lucerne (Switzerland), July 5-9, 2004