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Production, installation and test of Nb-sputtered QWRs for ALPI

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Abstract. Eight cryostats, each housing 4 sputtered Nb/Cu, 160 MHz, quarter wave resonators (QWR), are now in operation in ALPI [1]. Two of them house high β cavities; the others are equipped with medium β resonators. Another medium β cryostat is ready and will be installed in the early 2002. Pb/Cu medium β accelerating cavities are now present only in four cryostats and they will have their Pb superconducting (SC) layer replaced by sputtered Nb soon.

The substitution of the Pb SC layer in ALPI medium β resonators did not interfere with ALPI operation; the upgrading of resonators went on parallel to the cryostat maintenance programme. The average accelerating field of these resonators, at the design power of 7 W, overcomes 4 MV/m, whereas, when Pb electroplated, their average value was 2.7 MV/m. The sputtered resonator combines the good SC characteristics of Nb with the higher thermal conductivity and better stability to change of He bath pressure, which is typical of copper resonators. This leads to a very high reliability, as routinely experienced during beam acceleration.

Keywords. Niobium superconducting cavities; heavy ion LINAC; Nb sputtering.

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1. Introduction

The medium β section of ALPI [2], the SC booster for heavy ions of LNL, includes 44 QWRs. They were built using Pb as superconductor because, when, in 1988, the LINAC was designed, the Pb electroplating on Cu appeared a cheaper and more affordable process than the production of Nb resonators for our laboratory that had no experience in rf superconductivity.

The installation of Pb/Cu resonators was completed in 1993 and since May 1994 these resonators have been used to provide ions species, ranging from ^{28}Si to ^{90}Zr, for nuclear physics experiments.

Since 1988 however, motivated by the better SC characteristics of Nb with respect to Pb, a research project aimed at investigating the possibility to realize QWR's by Nb sputtering on Cu was carried out at LNL in parallel with the Pb/Cu resonator production.

The technology was first applied for the production of the resonators of the high β section, also operating at 160 MHz, whose copper base was designed and built keeping into account the peculiarity of the sputtering process. In this way resonators operating at accelerating fields higher than 6 MV/m, at 7 W dissipated power, could be produced. When we had to uninstall, at the end of 1998, a couple of medium β cryostats for maintenance, we decided to apply the sputtering technology for the upgrading of their resonators, even though their shape and the way of production of the copper bases made it difficult to take advantage of the full potential of this technology.

The refurbishing of resonators went on parallel to a maintenance program necessary to restore the cryostat reliability, which was compromised by the development of leaks in cryogenic valves located inside the cryostat [3]. Two thirds of the medium β resonators have, by now, their Pb SC layer replaced by Nb and we plan to replace the Pb layer by sputtered Nb in all of them in the near future.

This paper describes the production process of these renewed resonators and summarizes the obtained performances.

Three other cryostats, housing low β, 80 MHz, full Nb resonators, are installed in ALPI. Their average accelerating field, at 7 W dissipated power, surpasses 6 MV/m. Their equipment with mechanical dampers and software tuners made it possible to lock them in frequency even at such high fields [4].

2. ALPI medium β resonators

In figure 1 a medium β Pb/Cu QWR resonator is shown. The shape is very simple: it is a shorted coaxial line having a 60 mm diameter inner conductor and a 180 mm diameter coaxial outer conductor. The first ends in a hemisphere, the latter extends by about 7 cm beyond the inner conductor. A 20 mm beam bore is drilled in the inner conductor, 65 mm from the tip. The flat shorting plate links inner and outer conductor edges by 10 mm curvature radius.

Out of the 57 resonators produced, most have the body built in two parts: a mushroom shaped one and a cylinder, which are connected together by a vacuum brazed joint located in the outer conductor, 14 cm away from the shorting plate. Only 7 cavities do not have this joint but were directly milled from an OFHC copper rod.

The 60 mm diameter beam ports penetrate inside the resonator body creating approximately 38 mm beam accelerating gaps (the precise length of them being adjusted in order to reach the wanted resonator frequency). They are connected to the resonator by vacuum brazing joints. The beam bore drilled in their axis is 20 mm in diameter. The base facing the resonator inside is rounded.

The inner conductor, which is excavated inside, is the only resonator part in contact with LHe, the remaining resonator body being cooled down by conduction. A stainless steel transition, brazed on the outer cavity body, allows the connection between the empty space inside the inner conductor and the cryostat LHe reservoir.

Three holes penetrate in the resonator body: the coupler and the pick-up ports in the outer conductor and an outlet used during the Pb electroplating on the shorting plate.

The cavity is closed by a 1 mm thick bottom plate whose deformation, driven by an eccentric stepper motor movement, allows the resonator frequency tuning.

Most of the cavities have the inner part (mushroom) in Se–Cu 99.95%, while the outer cylinder is realized in OFHC copper. Few others (less than 10) have instead the inner part

Figure 1. A medium β Pb on Cu resonator after being removed from the cryostat.

in OHFC copper and the outer part in Se–Cu 99.95% copper. Six out of seven cavities produced by a copper rod have an extra coupler hole drilled by mistake on the outer conductor at coupler level, but rotated of 90°.

The medium β cavity resonates at 160 MHz and have a stored energy of 64 mJ/(MV/m)^2. The active resonator length is conventionally defined as the inner resonator diameter (180 mm). The ratio between peak surface electric field and accelerating field ($E_{\text{pick}}/E_{\text{a}}$) is 4.6, while the peak magnetic field ($B_{\text{pick}}/E_{\text{a}}$) is 104 G/(MV/m) respectively; 48 cavities have been used as accelerating structures in 12 cryostats; six others worked as buncher in three other cryostats.

The average accelerating field of the installed Pb/Cu resonators could reach an average value of 2.7 MV/m at the reference power value of 7 W, i.e., an energy gain per cavity and per state of charge of 420 kV [5]. The cavities proved to be very reliable. Their performance deteriorated only by a few % from installation and mainly because less time devoted to their conditioning.

They were generally operated at the accelerating field reachable at the available cryogenic power (7 W per cavity) and their robustness with respect to mechanical vibrations or fluctuations of the He bath pressure made the locking to the LINAC reference phase easy and reliable, without any fast tuning devices or need of adjusting the resonant frequency continuously [6].

3. Development of QWR Nb sputtering at LNL

The method developed in Legnaro for producing good SC Nb film in the complex QWR shape is DC biased Nb sputtering [7]. This technique allows reaching good thickness uniformity by using a relatively simple cathode configuration. DC sputtering has lower deposition rate than other techniques, as for example the magnetron-sputtering process, and asks for a higher argon pressure, but it does not need the development of a plasma magnetic confinement structure. Moreover, the higher probability of trapping impurities in the SC layer, due to the lower deposition rate, is effectively balanced by the use of the bias. This allows the bombardment of the growing film by low energy Ar atom and ions, which promote the desorption of impurities weakly bound to it.

A first Nb-on-Cu prototype was produced in 1991 [8]. A jump in resonator performance (accelerating fields exceeding 7 MV/m at 7 W dissipated power) followed the decision to round the flat shorting plate, typical of QWR, and to connect outer and inner conductors by 30 mm curvature radius. Moreover, the resonator beam ports were external to the resonator body, jointed by indium gaskets [9].

In 1995 the first cryostat, housing sputtered resonators, was installed in ALPI. The performance, measured on the beam line, was limited by field emission to 4 MV/m at 7 W. This process was connected to power produced while cutting and re-welding a leaking bellow after having installed the resonators in the cryostat [10].

An important issue in reaching a good quality film was found to be the copper substrate quality. The four sputtered resonators, produced in 1997 by OFHC 99.99% copper (certificate grade), could reach on line 6 MV/m at 7 W dissipated power. Improvement in sputtering procedure and absence of brazed joints helped in reaching such a result. In 1998 these resonators replaced the sputtered cavities installed in 1995 in the cryostat CR20 [11].

Other four resonators produced with the same shape, but by the standard quality copper of medium β resonator (Copper Se Cu 99.95%) and with brazed joints, were sputtered and installed in 2001 in the cryostat CR19. Their performance is lower, however their average accelerating field is higher than 4 MV/m.

The sputtered resonators are routinely used for beam acceleration at the accelerating fields sustained at 7 W dissipated power without showing any deterioration since the installation.

Up to now we have not had the opportunity to continue to produce more resonators of this type, for lack of available cryostats where to install them. Instead of searching for the best performance reachable by the sputtering technology in suitably designed resonators, we decided to investigate the way of obtaining the best performance by refurbishing the existing copper bases of medium β cavities.

Minor changes in resonator shape and the adjustment of the sputtering parameters allowed production of resonators reaching an average accelerating field larger than 4.1 MV/m, as described in the following paragraph. This allowed a substantial increase of ALPI performance with practically no additional investment. It is important, however, to point out that the accelerating fields obtained in these renewed resonators are not the limit of the sputtering technology. Accelerating fields exceeding 7 MV/m can be obtained when suitably shaped copper bases are used. Further scope for improvement could be there from the use of other substrate materials (i.e. aluminum).

4. Sputtering of medium β resonator

4.1 *Mechanical adjustments in the copper bases*

The impurity release promoted by the bias during the sputtring process is not much effective at the borders of the flat shorting plate and in the area around the beam ports of the

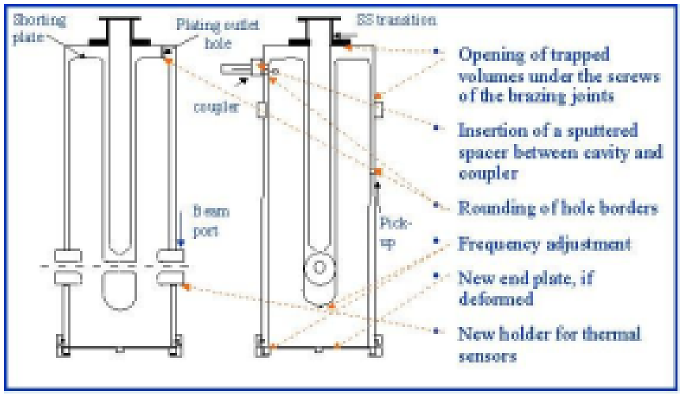

Figure 2. Mechanical adjustments of the resonator substrate before the sputtering process.

existing substrates. Unfortunately, their shape cannot be modified, thus resulting in a lower quality film in those areas. Other minor mechanical adjustments can, however, help in improving the resonator performance. For example we drill small holes in the outer resonator surface to open the trapped volume located under screws used to fix parts for brazing, thus avoiding their opening during the sputtering process, when the trapped gas release can deteriorate the film quality. We also rounded the sharp inner edges of the holes penetrating inside the resonator (antennas) thereby improving both the adhesion on the edge and the film quality inside them. If Cu defects are visible in the inner resonator surface, they are broken-up and smoothed mechanically to allow uniform film deposit on them. In correspondence of the coupler hole, the resonator wall is very thin and we screw to the resonator a 20 mm Cu tube, which is sputtered together with the cavity. In this way we give the possibility to the electromagnetic field to decay before meeting a normal conducting coupler body surface, reducing in this way the associated rf losses.

The main modifications of the resonator substrate for adapting it to the sputtering technique are summed up in figure 2. We have to modify the resonators at home in order to speed up the time between cryostat dismounting and its new installation on line, not having spare substrates to replace those dismounted from the cryostat. The situation became better at the end of 2001, because the increasing of ALPI performance allowed installing in CR19, previously equipped with medium β generators, high β cavities. This allows from then onwards to have 4 medium β to be prepared in advance, thus making the cryostat replacement faster.

4.2 *Surface finishing and chemical treatment*

Once the resonator shape is modified, the first steps in resonator treatment are the removal of indium, used as thermal and rf gasket between the resonator body and the end plate and the stripping of Pb layer.

The resonator mechanical finishing is done by two days of resonator tumbling.

After a preliminary degreasing in an ultrasonic bath, the resonator is suspended by an automatic travelling crane and automatically carried in a sequence of stations where it

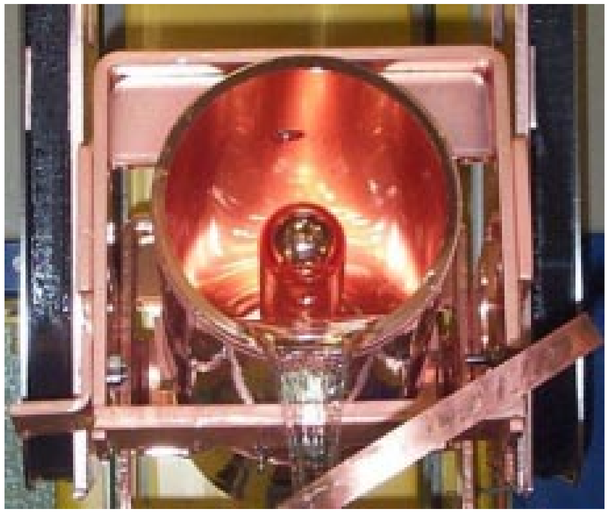

Figure 3. The resonator copper base after chemical polishing: the surface is mirror-like.

is electro-chemically and chemically polished and has its surface passivated. In between treatment cycles the resonator is rinsed by high pressure de-ionized filtered water (HPWR).

The resonator electro-polishing which removes 20 micron inner surface, is performed at room temperature in a solution of 55% phosphoric acid and 45% butanol; a computer, which plots both the measured current I, and its derivative dI/dV, as a function of the applied voltage V, controls the process. The working point is set at the minimum of such derivative (minimum differential conductance).

The chemical polishing is made in a sulphamic acid based solution, called SUBU5. The process removes further 10 micron from the resonator surface. Copper passivation in a sulphamic acid solution is crucial for protecting the bare copper surface from oxidation. After the final HPWR, the resonator is sprayed with alcohol and dried with nitrogen.

As it is possible to notice in figure 3, the copper surface is mirror-like after the chemical treatment. Even though the chemical agents attack the alloy used for brazing (NiCuAg and PaCuAg) the chemical etching does not produce any damage to the brazed joints leading to defects on the Nb film.

4.3 *Nb sputtering*

The sputtering configuration used to produce medium β QWRs is sketched in figure 4. The cathode is a cylinder ending with a sharp edge, which, producing high surface electrical fields, promotes the impingement of argon ions on them. In this way there is a higher release of Nb atoms, which can reach and produce a sufficient film thickness even on the resonator shorting plate.

The cavity body has to be negatively polarized to realize the bias condition; cylindrical SS nets produce grounding. The cavity is baked at 500°C for a couple of days. At the end of the process the vacuum reaches the high 10^{-9} mbar scale. Lower quality vacuum,

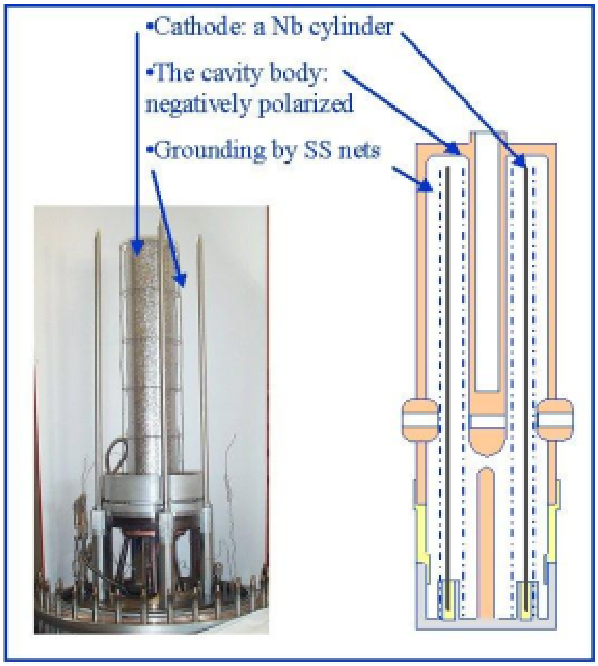

Figure 4. The sputtering configuration.

caused by leaks or opening of the trapped volume, is correlated to a decrease of resonator performance.

The resonator temperature rises fast during the sputtering process. So it is performed in steps, with pauses between in order to maintain the temperature between 300°C and 500°C.

The optimum film thickness is 2 micron, that is thicker than the penetration depth, but which is not thick enough to lead to peeling due to the differential Nb and Copper thermal contraction.

The discharge parameters were found to be 1 kV for cathode voltage and −120 V for bias voltage, while the argon pressure is maintained at 0.2 mbar, the power sustained by the discharge is 5 kW. Avoiding sparks and arcs in the plasma during the discharge is crucial because they can produce defects, which can spoil the film quality. The sputtering cycle of a QWR requires a full week.

4.4 *Test procedure*

Cleanliness is important to avoid enhancing field emission. The resonator is not assembled in a clean room, but we pay attention to maintain it with the shorting plate up and with all the ports closed, to avoid introducing dust inside and closing it as soon as possible.

The laboratory test follows a standard sequence and it takes advantage of a computer controlled procedure [5,12].

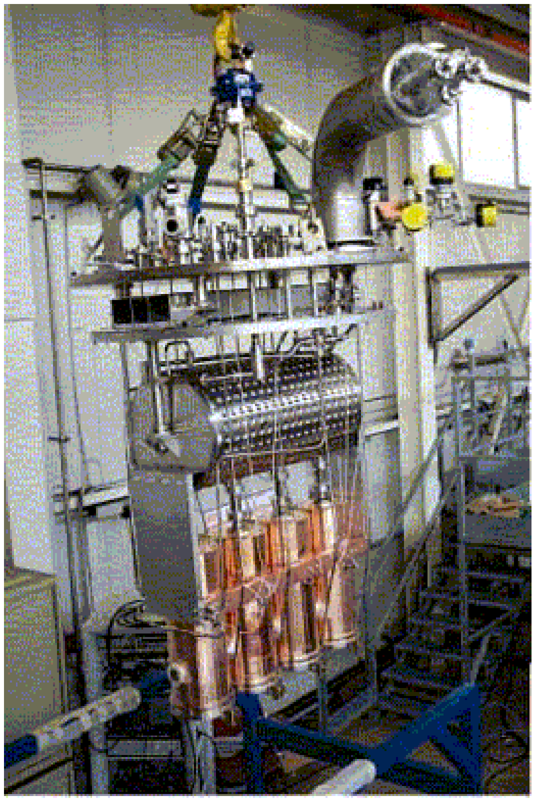

Figure 5. The ALPI cryostat completed with four sputtered resonators during the alignment procedure.

The resonator is baked for 12–24 h at 85°C. Multipactoring conditioning takes about 6 h and it is performed at room temperature, then the cavity is cooled down at 4 K. *Q*-measurement and pick-up calibration are performed at resonance in critical coupling condition, by detecting the decay time of the resonator stored energy.

He conditioning is performed at about 3×10^{-5} mbar cryostat pressure, feeding the cavity with 500 W, in pulsed regime (20 ms $\times$ 5 Hz) We usually do not perform conditioning for more than 1 h because of lack of time and also not to exceed a 100 l LHe consumption. This time is however sufficient to be able to extrapolate from the final *Q* curve measurement, resonator performance on line.

4.5 *LINAC cryostat assembling*

Once dismounted from the ALPI line the cryostat is subjected to a complete maintenance program, described in [13], which not only foresees the substitution of the cryogenic valve or the repairing of other malfunctioning, but it is also devoted to increase its reliability in the future.

The resonators share the cryostat vacuum and the cryostat design foresees the resonator alignment while the resonator beam ports remain open (figure 5). To avoid contamination,

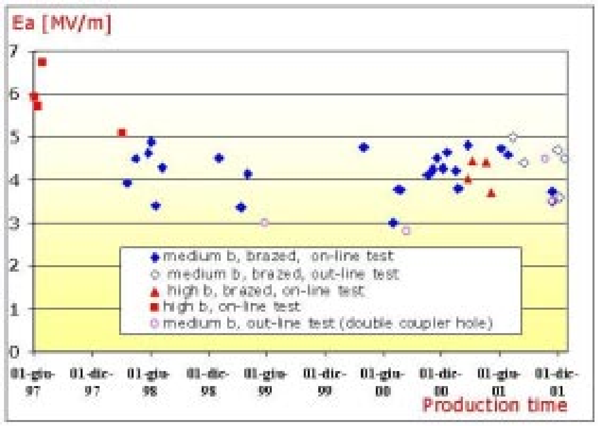

Figure 6. Performance as a function of the production time for sputtered medium and high β resonators. Beam energy gain confirmed the calibration of the accelerating field in the installed resonators.

we always keep the resonator apertures closed when the resonators are moved during the alignment procedure and we try to avoid venting of the cryostat once the resonators are mounted. For the same reasons fore-vacuum in the cryostat is made always slowly to avoid moving dust inside the resonator.

The cryostat is then stored under vacuum untill it is installed in ALPI beam line.

5. Results of ALPI refurbishing

We have produced 41 cavities by Nb sputtering up to now of which 33 are of the medium β type, 8 of the high β. At present, in January 2002, 32 are in operation, 4 are going to be installed in a few days. Other 5 are waiting for their cryostat to be ready.

The performance of the produced resonators obtained (as measured on line, if installed) is presented in figure 6. As it is clear from the figure, in most cases the sputtering process leads to resonators having accelerating fields higher than 4 MV/m; only in few cases this value was not reached, the lower performing results being obtained in resonators having problems in the copper bases.

Taking into account that priority was given to assure ALPI operation, and hence we had to install all the cavities as soon as they were produced even though the performances were lower than expected (we could reject only two cavities), we can say that the sputtering technology in QWR's reached a very good reliability.

The average accelerating field of the sputtered resonators installed up to now is 4.4 MV/m, about 50% higher than the value obtained by Pb/Cu resonators when operating at their best. The sputtered resonators can be controlled and fed by the same controllers and amplifiers used by the previously installed Pb/Cu resonators and maintain the same reliability and easy way of operation [14]. The upgrading of medium β ALPI resonators will continue and in less than two years (the programme has to share the priority with PIAVE installation) we should have all the Pb/Cu resonators replaced by Nb/Cu sputtered resonators.

6. Conclusions

The performance of ALPI has been substantially increased in the last two years by the replacement of Pb with Nb on installed resonators. The upgrading of medium β ALPI resonators will be completed in about two years.

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