NIOBIUM SPUTTERED QWRS

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Abstract

Nb sputtered QWRs are a valid alternative to bulk Nb resonators. The reduced cost of the cavity is only one of the possible benefits. In ALPI, the superconducting linac for heavy ions operating at Legnaro [1], where 54 cavities of this type are operating, we can also appreciate the insensitivity of their resonant frequency to pressure fluctuations over the liquid He bath. This leads to a very stable resonant frequency making unnecessary both the continuous cavity tuning by fast or "soft" tuner devices and the big enlargement of resonant bandwidth by strong over-coupling. The cavities are very reliable, easy to be put into operation and do not show any deterioration in performance with time. We have resonators that can operate (locked in phase and amplitude) at fields exceeding 7 MV/m, even though the operational average field is limited to 4.4 MV/m, since most of the resonators have been obtained by the refurbishing of the previously installed Pb/Cu QWRs, whose characteristics did not allow to take full advantage of the Nb sputtering process.

SUPERCONDUCTING QW RESONATORS

The first SC QWR was developed around 1970, to build an independent phased superconducting linac for heavy ions to boost the energy of Tandem beams [2]. Such cavities presented many advantages with respect to previously developed resonators: a very broad acceptance in velocity connected to the two-gap structure, an excellent mechanical stability which makes them insensitive to deformation and mechanical vibrations, a shape simple to build, treat and clean and the absence of joints in high current regions. The first SC QWRs were obtained by electroplating Pb on OFHC Cu substrates [3]. The resonator performance was limited to accelerating fields around 3 MV/m. However such cavities have operated reliably in superconducting linac for heavy ions for many years. Higher accelerating fields were obtained in QWRs when Nb was used as superconductor. In the first built resonators only the empty inner conductor, filled with liquid He, was realized in full Nb being both the outer conductor and the shorting plate built in Nb explosively bonded on Cu [4, 5]. The Nb QWR performance, as measured in laboratory, were higher than in Pb cavities, but the operational fields on line could not usually take full advantage of the better superconductor characteristics because of the more difficult resonator locking. A further development came enclosing the QWR structure by a second wall, allowing to the liquid He to assure convenient cooling to the whole resonator body. In this way the cavity could be realized wholly in Nb, thus allowing resonator baking also at high temperature [6]. To reduce the resonator cost, the cavity outer walls have been alternatively realized in SS [7].

Nb QWRs ask for continuous resonator tuning to compensate slow frequency drifts. Various tuning devices were developed in different laboratories and their good performance is determinant in allowing reliable resonator phase locking. Nb resonators used to be equipped with fast tuners to compensate fast frequency changes due to mechanical resonances [8]. Recently the development of mechanical dampers, which reduce the cavity sensitivity to mechanical vibration, allowed the locking of QW resonators also without using fast tuner devices [9].

Continuous tuning is not instead required in Nb sputtered cavities, which are described in the next paragraph. They can be reliably locked at high accelerating fields also without any fast tuner devices, simplifying in this way the resonator control.

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QWR SPUTTERING DEVELOPMENT

The first laboratory, aimed at applying to SC QWR production the Nb sputtered technology developed at CERN, was set up in Legnaro in 1987. The goal was to develop a method for a future replacing of the Pb superconducting layer, conservatively foreseen for the ALPI cavities, with Nb. The chosen technology was DC bias sputtering, the easier way to obtain a Nb film with good superconducting characteristics in the complex QWR shape [10]. It took a few years to obtain a prototype exceeding 7 MV/m at 7 W dissipated power [11]. The first cryostat equipped with sputtered QWRs (160 MHz, β=0.13) was installed in ALPI in 1995 [12]. In between 1999 and 2003 all the 44 resonators of ALPI medium β section (160 MHz, β=0.11) had their Pb superconducting layer replaced by Nb [13]. A further cryostat of high β type was also installed in ALPI. The ALPI medium β QWR is presented in fig. 1.

Figure 1: ALPI medium β resonator with its plate.

The ALPI high β resonator is very similar to that, but does not have beam ports protruding inside the resonators and has a rounded shorting plate (fig. 2).

Figure 2: ALPI high β resonator.

The sputtering technology was later on developed by the Institute of Heavy Ion Physics in Peking, where a prototype for the accelerating structure of the booster of the Beijing Radioactive Nuclear Beam Facility was produced in 1996 [14]. The obtained accelerating field exceeded 5 MV/m, in spite of a not satisfactory coating in correspondence of a substrate brazing joint in the resonator outer conductor. Further development is foreseen once new substrates without brazing joints will be available. The possibility to produce Nb/Cu QWRs by a DC magnetron-sputtering configuration was instead investigated at the Australian National University [15]. A systematic search for determining the most suitable sputtering parameters was carried out and two resonators were produced and installed. At present this technology is planned to be applied to the new accelerating structures developed for the ANU booster [16].

NB SPUTTERING ADVANTAGES

The will to combine the better superconducting characteristics of Nb with the stiffness of Cu based cavities, motivated the search for producing Nb sputtered QWRs. The mechanical stability, which made the cavity less prone to mechanical resonance and insensitive to deformation due to the drift of He cooling bath pressure, is a very great advantage in simplifying the resonator control system and in allowing to operate the cavity up to the accelerating field reachable at the available cryogenic power. The reduced frequency excursions avoid the necessity of strong over-coupling, limiting the amplifier power request, at least in the case where the power transferred to the beam is low. Having to manage a reduced power, the feeding rf line can also be simplified and does not need to be cooled. The resonator high thermal stability, which allows convenient resonator RF processing, is also important in reaching and maintaining high accelerating fields. The multipactoring conditioning is also simplified because the relatively high Q of the normal conducting cavity (the rf currents penetrate also into Cu) allows reaching critical coupling also at room temperature without having a big excursion in the coupler movement. The rf available power of the installed amplifier is sufficient to reach the highest multipactoring level without cooling the resonators at 4 K.

The Nb/Cu cavities are not affected by Q-disease, so they do not need fast cooling through the critical temperature range and do not need to be kept continuously at 4 K to maintain the original performance. They are moreover not sensitive to small magnetic fields, so they do not need magnetic shields for attenuating earth magnetic field. A further advantage is the absence of vacuum joints sealed by In and the related risk of leakage after repeated thermal cycles. Moreover a serious vacuum accident involving a Nb/Cu QWRs is certainly less risky than a similar event happening in a double wall Nb QWR.

The best performance at high field reached up to now in Nb/Cu resonators is however lower than the one obtained in the full Nb resonators, due to the more pronounced Q-curve slope present in sputtered resonators. This problem is not as important in QWR as it is in high β cavities, because beam dynamic constraints ask for limiting the accelerating gradient cavities in the low β section of linacs to values for which the Nb sputtered cavities well compete.

QWR NB SPUTTERING TECNOLOGY

At present DC bias sputtering showed to be the most consolidated technology for sputtered QWR production [17]. The slower deposition rate of the DC diode configuration with respect to the magnetron-sputtering was compensated by the use of bias, which, promoting impurity release during the film growth, allows reducing film contamination, thus improving the film quality. The crucial steps for producing good resonators are briefly discussed.

Resonator design

The impingement rate of sputtered atoms is reduced in location were angles are present, thus leading to a thinner and less clean film in that area. Consequently the resonator design should avoid, especially in the high current region, any recess or sharp angles. In our case we obtained a substantial improvement in the resonator performance by blending QWR inner and outer conductors by a rounded surface instead of having the previous flat shorting plate. It is moreover important to avoid any hole in high current regions, both to reduce contamination possibility and to avoid regions with poor film characteristics. Some constraints are moreover mandatory for designing a resonator to be sputtered. It is necessary to have the possibility of inserting both the cathode and the grounding electrode inside the resonators assuring a minimum distance between cathode and resonator surface in order to allow the plasma discharge to take place. An optimum cavity shape, suitable to be sputtered, can be find if the necessary constraints are kept in mind since the beginning of the cavity design.

Substrate choice

The substrate has to assure proper and uniform film cooling. It also plays an important role in determining both the sputtering chamber residual atmosphere and in transferring contaminants into the film growing on it.

Usually Cu is used as substrate and its purity, thermal conductivity, microstructure and porosity are crucial in reaching high resonator performance. We got the best results using OFHC certificate grade Cu. Al can also be used as substrate offering many advantages, such as better thermal conductivity, reduced cost, easy construction technology, and reduced activation risk due to a shorter life time of activated radioisotopes. A cavity having Q_0 of $2.5x10^9$ has been produced, but the necessity to cool down the substrate during the sputtering process delayed the use of this material.

Construction technology

We had the best performance in cavities milled out from Cu rod built without any joint. Quite good results were also obtained in substrates having a brazed circumferential joint in the outer conductor and other brazed connections to equip the cavity whit beam ports, connection flange, and cavity supports. The difficulties in this case did not come from the joints facing the inner cavity surface that are practically not visible even after repeated chemical processing, but from empty spaces present between other jointed surfaces, especially under fixing screws. During the sputtering process, when the resonator temperature increases, the enclaves can open delivering impurities which deteriorate the film quality. We systematically open all the hidden volumes, but in some cases vacuum oscillations during the sputtering process indicated the opening of a remaining one.

Surface finishing and chemical treatments

The sputtered film quality is strongly dependent on the smoothness and cleanness of the substrate inner surfaces. The Legnaro procedure for Cu surface finishing includes:

- Resonator tumbling with abrasive for a few days (2-7 days depending on previous processes)
- Electro-polishing, which is performed at room temperature in a solution of 55% phosphoric acid and 45% butanol. By measuring the process current and computing its derivative as a function of the applied voltage, it is possible to set the working point at the derivative minimum (minimum differential conductance) assuring in this way a smooth surface free from defects. The process removes about 20 micron from the cavity inner surface in about two hours.
- Chemical polishing is made in a sulphamic acid based solution, called SUBU5, which has to be renewed after the treatment of 3 resonators; the process removes further 10 micron from the resonator surface.
- Passivation by a sulphamic acid solution to prevent the bare surface oxidation.

Each step is followed by High Pressure Water Rinsing with de-ionized filtered water (HPWR). After the final HPWR, the resonator is sprayed with alcohol and dried with nitrogen and then installed into the sputtering chamber.

Sputtering

The sputtering configuration is sketched in fig. 3.

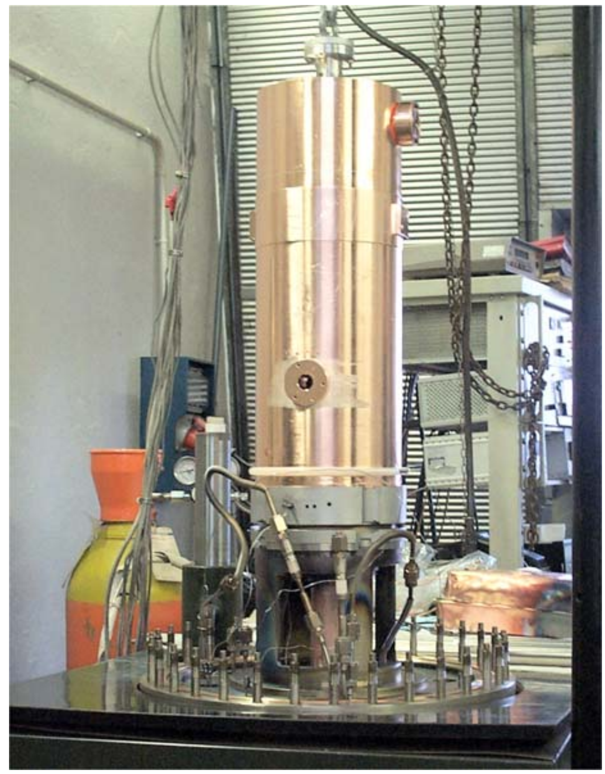

Figure 3: ALPI medium β resonator mounted into the Legnaro sputtering system.

The cathode is a simple Nb cylinder ending with a sharp edge, which, creating a high surface electrical field, promotes the impingement of Ar ions on it. In this way there is locally a higher release of Nb atoms, which can produce a sufficient film thickness on the resonator shorting plate simplifying the cathode configuration. The location of the cathode at the right distance from the shorting plate is critical. The cavity body has to be negatively polarized to realize the bias condition; cylindrical SS nets, coaxial to the cathode, produce grounding. The nets have to be substituted after a few sputtering cycles because the film deposited on it can fragmentize and deliver powder. The resonator is then assembled into the sputtering chamber where cathode and grounding system are predisposed in advance. The chamber is then evacuated up to reach 10^{-6} mbar scale and then the cavity is baked at 600° for a couple of days using infrared lamps. At the end of the process the vacuum reaches the high 10^{-9} mbar scale. A lower quality vacuum caused by leaks or opening of the trapped volume is correlated to a decrease of resonator performance. The optimum film thickness was found to be 2-4 micron. The sputtering process is performed in 12 steps of about 15 minutes each, alternated with about 3 hour-pauses in between, thus allowing the resonator temperature not rising too much. High substrate temperature is favorable for obtaining a clean film, but it is mandatory to remain always under the brazing temperature, and it is moreover useful to avoid overcoming the baking temperature, which can lead to Nb film contamination due to vacuum deterioration.

The sputtering parameters found to be most suitable for sputtering are: 0.2 mbar for the Ar pressure, -1 KV for cathode voltage, -120V for the bias voltage and 300÷500°C for the substrate temperature. The power sustained by the discharge is 5 kW. To avoid sparks and arcs in the plasma is crucial during the discharge because they can produce defects, which can spoil the film quality. Once reached the wanted film thickness, the cavity is let to cool down to room temperature in vacuum. The sputtering cycle of a QWR, including the assembling and dismounting of the resonator from the sputtering chamber, takes a full week.

The cavity end plate is also Nb sputtered in a devoted sputtering chamber, which allows processing of many plates together. The system is also used for producing the end plates of the low β, full Nb QWRs and those of the two PIAVE SRFQs [18] Most of the ALPI resonators have the end plate connected by an In joint. It was shown that it is possible to eliminate the In gasket, simplifying assembling and disassembling, if sufficient tightness is assured for the contact between cavity and plate.

Assembling, conditioning and test

The cavities are individually tested in laboratory before being assembled in the line cryostat. In laboratory we can perform conditioning only at low power and measure the resonator performance only up to 5 MV/m (authorization limit). Usually this is sufficient to foresee the final cavity performance. Once completed the cold test, the cavity is opened to air for the final mounting. We could not afford a new HPWR before assembling for most of the cavities installed up to now in the beam line. The line ALPI medium and high β cryostats have 4 cavities each. They share the vacuum with the installed cavities and unfortunately ask to keep the cavities open to air during the alignment procedure. We use some tricks to limit the resonator contamination during venting, assembling and alignment procedures which are not performed in clean room. Some contamination is however unavoidable and the cavities are usually later affected by field emissions and need RF or/and He conditioning. Usually, when we have the possibility to condition them for a few hours using 1 kW peak power, we get rid of it, at least up to the nominal working point which is determined by the cavity accelerating field reached at 7 W dissipated power. We have not yet had the possibility to perform high power conditioning in the last installed cryostats and this still affects the cavities performance. A few hours of He conditioning using the installed amplifier (100 W) are instead sufficient to recover the performance after a thermal cycle at room temperature if the cryostat is not open to air. The cavity movable coupler allows critical coupling both for normal-conducting and super-conducting conditioning. We perform multipactoring conditioning after a few hours resonator baking at 350 K, while keeping the cryostat shield cold. We do not need further multipactoring conditioning once the cavity is at 4K.

SPUTTERED RESONATOR PERFORMANCE

The 160 MHz QWR produced by Nb sputtering on properly designed and built substrates show Q_0 of 1-2x10^9 and reach accelerating fields exceeding of 11 MV/m, as it is possible to notice in fig 4 . The last value corresponds to a peak electric surface field exceeding 50 MV/m and to a peak magnetic field of about 1100 gauss. Such cavities have been operating since 1998 in ALPI at an average accelerating field of 6 MV/m at 7 W of dissipated power.

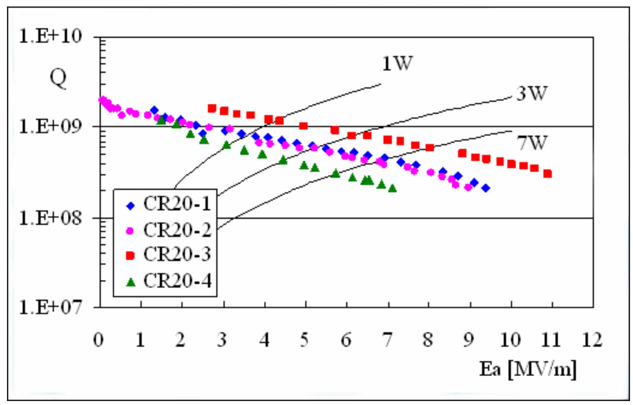

Figure 4: Typical performance of high β ALPI resonators, having substrates suitably designed and built to be sputtered.

The accelerating fields of resonators, upgraded after being previously Pb plated, operated at an average value of 4.4 MV/m at 7 W dissipated power, the reduced value is due to the lower accelerating field of resonators produced in between 2000 and 2001, when we had only bad substrates available and a very tight production schedule. The gap, both in Q and accelerating fields, between the new designed resonators and the recovered substrates has been however improving with time up to reaching Q_0-value of 7x10^8 and accelerating of 6 MV/m at 7 W in the last produced resonators [19]. As it is possible to notice in fig. 5, all such resonators, but one, have a Q_0 value in between 5 and 7x10^8. The lower Q-value in the remaining resonator was connected to discharges in the HV feed-through which forced to interrupt the sputtering process and to vent the vacuum chamber to eliminate the discharge. The sputtering process was later completed without a new chemical treatment. All resonators reached accelerating field in between 4.5 and 6 MV/m, and even better performance are foreseen by further conditioning. The sputtered cavities do not show any sign of degradation with time. There is only a cavity, whose cryostat was opened for maintenance without having the possibility to dismount the resonators, that later showed strong field emission. We could get rid of it by conditioning, but the resonator Q resulted deteriorated limiting the accelerating field to 3.2 MV/m at 7W, instead of the previous operational value of 4.2 MV/m.

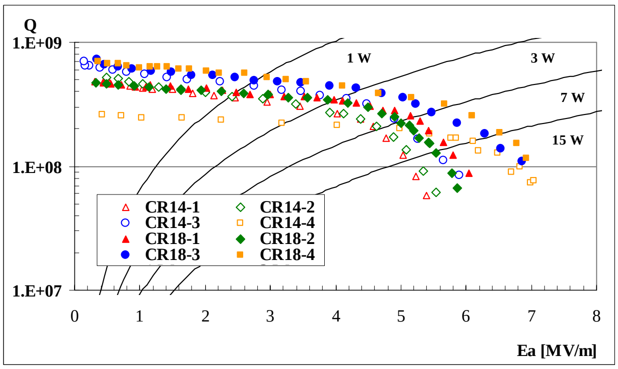

Figure 5: ALPI medium β resonator performance obtained in the resonators installed in 2003.

The upgrading of medium β ALPI resonators gave a substantial increase in ALPI performance being the average accelerating field value of previously installed Pb/Cu resonators limited to 2.4 MV/m [20].

CONCLUSIONS

The Nb sputtering technology shows to be very effective in producing reliable resonators which both have high performance, and are very easy to put into operation. Even better results can be obtained using 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 can be industrially applied.

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