OPERATION EXPERIENCE WITH ALPI RESONATORS

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Abstract

Seven cryostats, each housing 4 sputtered Nb/Cu QWR resonators, are now in the ALPI beam line; two others will be installed by the end of the year. Pb/Cu resonators are now still mounted only in four cryostats and will have their superconducting layer replaced by sputtered Nb soon. The substitution of the Pb superconducting layer in ALPI medium β resonators did not interfere with ALPI operation; the resonators' upgrading went on in parallel with 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 superconducting characteristics of Nb with the conductivity and 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. Three other cryostats, housing Nb bulk resonators, are installed in ALPI. Their average accelerating field, at 7 W dissipated power, overcomes 6 MV/m. Their equipment with mechanical dampers and software tuners made it possible to lock them in frequency even at such high fields.

1 INTRODUCTION

ALPI is an accelerator complex that includes a 15 MV XTU TANDEM and its SC booster [1, 13]. It is in operation since 1994 at LNL and allowed to accelerate heavy ions for nuclear physics experiment up to 12.3 MeV/u, in case of ^{28}Si, and up to 7.6 MeV/u in case of ^{83}Se.

A positive ion injector, PIAVE, now in advanced stage of construction [2,4], will allow to extend the mass range of the accelerated beams up to U, reaching 6 MeV/u energy.

2 ALPI PRESENT LAYOUT

Taking advantage from the technological development of the resonator construction, the SC linac structure (fig.1) has been heavily modified with respect to the original design, which foresaw 85 Pb/Cu QWR accelerating cavities, working at an accelerating field of 3 MV/m at 7W of dissipated power, and 6 superconducting bunching resonators [1].

The present ALPI structure is summed up in table 1.

Cryostat	N. of cavities	β	SC
B2	2	0.11	Pb
B1→CR3	1, up to 4	0.056	Nb
CR4	4	0.056	Nb
CR5	4	0.056	Nb
CR6	4	0.056	Nb
CR7	4	0.11	Nb/Cu
CR8	4	0.11	Pb→Nb/Cu
CR9	4	0.11	Pb→ Nb/Cu
CR10	4	0.11	Pb→ Nb/Cu
B3	2	0.11	Pb
CR12	4	0.11	Pb
CR13	4	0.11	Pb
CR14	4	0.11	Pb
CR15	4	0.11	Pb→ Nb/Cu
CR16	4	0.11	Pb→ Nb/Cu
CR17	4	0.11	Pb→Nb/Cu
CR18	4	0.11	Pb
CR19	4	0.11→0.13	Pb→ Nb/Cu
CR20	4	0.13	Nb/Cu
B4	2	0.11	Pb

Table 1. Number of resonators, optimum β of the cavities and type of superconductors used in the ALPI cryostats. In some cryostats, sputtered Nb film replaced the previous Pb layer.

The excellent performance obtained by Nb low β resonators, which reached in laboratory an average accelerating field value of 7 MV/m, always at 7 W dissipated power, allowed to limit to three the number of cryostats of the low β section [3].

While it is not possible to set the accelerating field of such resonators at such high level (the rf defocusing is not compatible with the existing beam transport line), an accelerating field of 4 MV/m allows most of beams to reach the medium-β ALPI section with the foreseen velocity. The two exceeding cryostats will be used in the PIAVE injector line.

The cryostat B1, substituted by two normal conducting resonators located in the beam line coming from PIAVE, and which is a standard low β cryostat, can be equipped with 4 low β resonators and inserted in the beam line in the position foreseen for CR3.

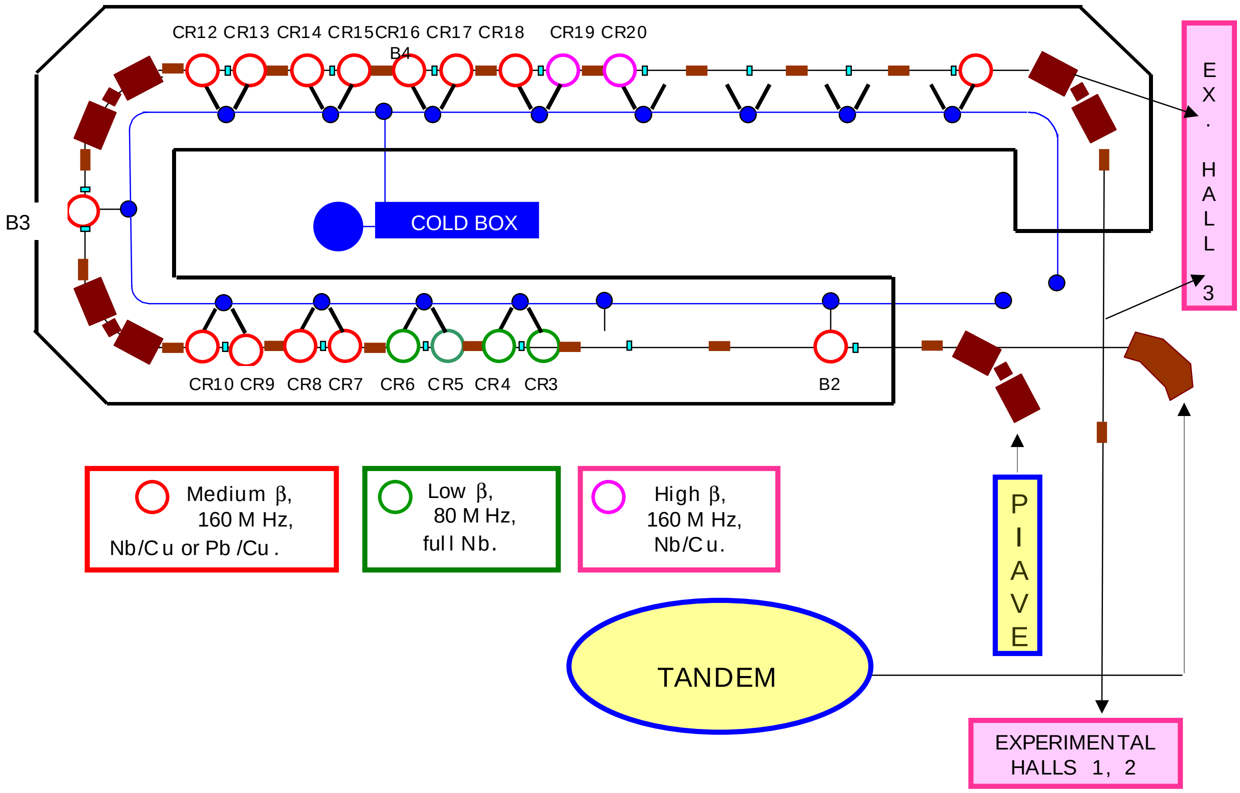

Figure 1: Layout of the ALPI complex. The linac can be injected by the XTU tandem or by PIAVE, a positive ion injector having an ECR source, two superconducting RFQ and eight full Nb resonators of $\beta = 0.047$,. The tandem and the linac can deliver beams to three different experimental halls. In ALPI there are cryostats equipped with low ($\beta=0.056$), medium ($\beta=0.11$) and high ($\beta=0.13$) beta resonators made of full Nb, Nb/Cu, Pb/Cu.

The linac medium-β section includes 4 cryostats in the low energy branch and other 8 units downstream the U bend in which the rebunching cryostat (B3) is located. These cryostats, but CR7, were installed in 1992-1993 and equipped with electroplated Pb on Cu, 160 MHz resonators [5]. The replacement of the Pb layer by a sputtered Nb film showed to be a very effective and low cost way of increasing the cavity performance with minimal interference with accelerator operation [6].

It was not necessary to develop high β cryostats since it was possible to design sputtered Nb-on-Cu resonators having $\beta = 0.13$ which could be accommodated in a standard medium β cryostats [7]. Only two cryostats, housing four resonators each, instead of the foreseen seven, are now in ALPI high β sections.

Three cryostats complete the ALPI layout: B2, B3, B4, the buncher, rebuncher and phase space rotator (such as to reduce energy dispersion) units respectively, housing two Pb on Cu resonators each. They do not need to operate at high accelerating fields, but the equipment with Nb sputtered cavities surely would make maintenance operations easier (Nb does not requires nitrogen atmosphere as Pb does) so we plan to replace the superconducting layer in these resonators too.

The specific energy reachable by ions coming from the Tandem with the terminal set at 15 MV and with the present linac configuration are shown in fig. 3.

Figure 2: A view of ALPI high-energy branch. At centre one cryostat is missing for maintenance.

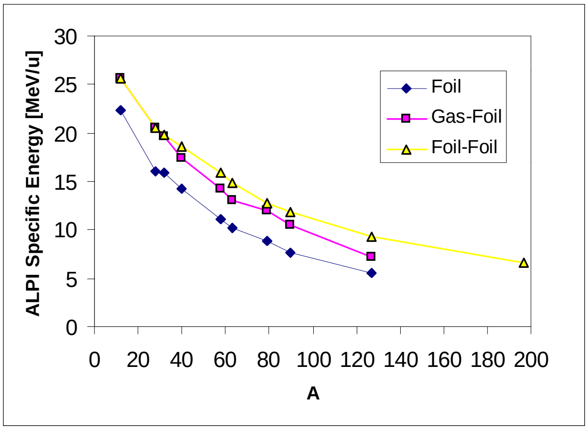

Fig.3: Beam specific energies in the present ALPI configuration once the program of replacement of Pb by sputtered Nb will be completed.

The three curves refer to a foil-foil stripper, a gas-foil stripper and only a foil stripper respectively; in all cases the most probable charge states were used. The accelerating fields were set at 4 MV/m, which has been shown to be a conservative value for Nb and Nb/Cu resonators. Even though there are seven less cryostats than the foreseen number, the energy is lower than the originally designed value only for very heavy beams (A>100), for which, because of the restriction due to lifetime of the foil strippers, it is anyway convenient to use the new being built positive ion injector PIAVE instead of the XTU Tandem.

The linac structure is optimised for A = 100. As an example the acceleration profile in the case of a ^{90}Zn beam, coming from the Tandem at 15 MV with a charge state of +17, is shown in fig.4. The average normalised Transit Time Factor [TTFn] is higher than 95% and the beam energy is increasing linearly along the linac.

The acceleration is less efficient in the case of very light ions, because the very fast beams ask for a higher number of high β resonators (a higher β value would be more convenient in the last resonators).

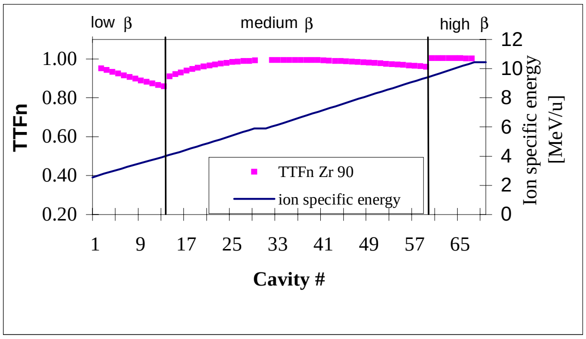

Fig. 4. Beam energy per nucleon and TTFn for a ^{90}Zr^{+17} beam following the cavity along the linac. The ion injection β at the first resonator is 0.074.

3 ACCELERATED BEAMS

The Tandem ALPI complex generally provides beams for nuclear physics experiments, even though about one month per year being reserved to applied physics. Only some experiments need to use the superconducting linac to reach the energy required. In 1999 a total of 3700 hours of beam time were delivered to users, 25% of which using the linac as booster. The delivered beam time was 5000 hours in 2000, 22% of which using the booster. The percentage has been larger than 30% in 2001 so far. In table 2 the beams provided to the users since the last SRF workshop are shown. The number of cavities used (N), the input and output β and the average energy delivered per charge state and per cavity to the ions are also shown. The number of the resonators used in each run is determined by the beam energy required by the users. The cavities were sequentially turned on, at 7 W cavity dissipated power, up to the required beam energy.

It is possible to notice that the energy gain per cavity and per charge is now around 0.5 MeV, value that was overcome in case of the acceleration of an ^{82}Se beam when all the available medium and high β resonators were used. The best performing cavities are not always in operation: generally, if the required energy made it possible, it was preferred to use only those resonators located downstream the isochronous and achromatic U bend [8], thus making the setting time of resonators faster.

The resonators of this branch are not yet upgraded and this explains the reduction in energy gain in some cases.

Table 2: ALPI accelerated beams since the last workshop. The day of experiment, the ion specie, the number of cavities used for acceleration, and the beam velocities at the linac input and output ($\beta = v_{ion}/c$) are presented. In the last column the average energy gain per cavity and per charge unit is given.

Date	**Ion**	**N**	**βin**	**βout**	**Energy gain /charge /cavity [MeV/ch./cav.]**
3Nov 99	$^{32}S^{13+}$	32	0.109	0.154	0.429
21Feb00	$^{32}S^{12+}$	25	0.107	0.142	0.435
27Feb00	$^{36}S^{12+}$	29	0.101	0.140	0.449
02Mar00	$^{62}Ni^{11+}$	14	0.088	0.105	0.428
14Mar00	$^{48}Ca^{9+}$	18	0.079	0.097	0.436
14Nov00	$^{32}S^{9,12+}$	31	0.107	0.153	0.477
22Nov00	$^{58}Ni^{6,15+}$	29	0.084	0.114	0.340
30Nov00	$^{80}Se^{11,17+}$	31	0.079	0.112	0.453
04Feb01	$^{58}Ni^{13+}$	13	0.087	0.100	0.395
14Feb01	$^{58}Ni^{13+}$	29	0.087	0.118	0.456
22Feb01	$^{82}Se^{11,17+}$	41	0.079	0.123	0.502
03Mar01	$^{82}Se^{11,17+}$	44	0.079	0.128	0.537
15Jun01	$^{36}S^{9+}$	22	0.093	0.117	0.429
29Jun01	$^{74}Se^{18+}$	22	0.085	0.111	0.439
07Jul01	$^{83}Se^{6,16+}$	32	0.074	0.110	0.487

4 ON LINE OPERATING EXPERIENCE WITH RESONATORS

4.1 Pb/Cu and Nb/Cu resonators

Only 16 out of the 44 previously installed accelerating Pb/Cu resonators are still in place [5]. They are working at an average field of 2.7 MeV/m at 7 W, the average field of the removed ones being 2.3 MV/m. The average value of all of them was 2.5 MeV/m in 1995, so their performance was slightly decreased [9].

In most cases, however, the lower value can be due to the shorter conditioning time devoted to them.

While the performances were rather limited, due to the lower superconducting characteristics of Pb, these resonators worked very reliably: practically we registered no beam time loss because of the resonators.

The first sputtered resonators now in place were installed in 1998 [5]. Up to now we installed 28 of them, 23 having been used for beam acceleration, four being mounted on the beam line after the last beam time, while the remaining one needs to change its bottom plate to reach the linac frequency.

The sputtered resonators are working at an average field of 4.3 MV/m without showing any decrease in performance since the installation.

There is practically no difference between Pb/Cu and Nb/Cu resonators regarding conditioning and setting procedure both for medium and high β resonators. The resonators have both the same rf and stepping motor controllers, the same 100 W amplifiers and the same control program [10].

The only difference between high β and medium β resonators is that the first are equipped with a capacitive coupler, while the later, as well as the low β cavities, have an inductive coupler. In both cases it is possible to reach critical coupling condition both in normal and in superconduting state.

Frequency of both Nb sputtered and Pb plated resonators does not change with He bath pressure drifts, therefore the resonators do not need fast tuners or frequency adjustment during operation, thus making the resonator setting very fast and reliable.

4.1.1 Preparation of resonators for beam time

We typically warm up the linac resonators up to room temperature at least two-three times a year, either for scheduled maintenance, or summer shut down (we have not enough personnel to keep the cryogenic plant in operation in this period).

After a thermal cycle we cool down the cryostat shields by 60 K He gas at 7 bar [11].

Baking is performed only on newly installed resonators while multipactoring conditioning is necessary after each thermal cycle.

Fig.5: 160 MHz, medium β cryostat equipped with four Nb/Cu sputtered resonators.

This process is usually performed before cooling the resonators at 4 K by means of a computer program that modulates gradually the power sent to the cavities, thus allowing to work sequentially on all the resonant levels [12]. The method might not be the most time efficient, but in one day all the resonators are free from multipactoring without needing manpower to control the process.

Two-three cryostats per day can then be cooled to 4 K. Field emission conditioning is performed in parallel on several cryostats (even all of them, depending on the conditions of the cryogenic plant) using the installed amplifiers, in a He gas atmosphere at about $4x10^{-5}$ mbar; the gas inlet is performed by a computer controlled automatic procedure.

The resonator control allow to pulse, with a duty factor of 25% and pulse length 250 msec, the power which feeds the cavity, This gives the possibility to reach 100 W peak power per cavity, limiting however to 30 W the total power dissipated in the four cavities of each cryostat.

The process is very efficient: two-three cycles, of three hours each, are generally sufficient to restore and stabilize the performance. In the last two years high power (1kW) conditioning was used only once in one resonator after its cryostat was vented for maintenance: a couple of hours of

Helium conditioning allowed to recover the accelerating field obtained before demounting it.

Locking of resonators takes some hours; it includes the determination of resonant frequency and of the acceleration field reachable at 7 W dissipated power, setting of the coupling conditions, frequency adjustment, phase lock to the linac frequency.

After that, if time is left before beam scheduled time, the cavities are kept locked in amplitude and phase for 24 hours to monitor their long-term behaviour.

Their conditions are readjusted, if necessary, to compensate for both long-term drifts in eigenfrequency and changes in power consumption, then the amplifier is turned off. The cavities are in this way ready for beam acceleration and can be put into operation by simply switching on the amplifier when required. Following this procedure the accelerating field can be maintained for weeks. Only twice in two years we had to stop the beam for a couple of hours to reduce, by He conditioning, the power consumption, in one cavity. Unlocking due to shift in frequency is extremely unusual.

The merit of this stability is not only due to the cavity stiffness, but for the high reliability shown by the rf resonator controllers: we had to change only twice of them during beam. After loading the new controller calibration files the beam could be restored in its original condition without any adjustments.

4.1.2 Setting the phase for acceleration

The determination of the suitable acceleration phase of a resonator is performed in ALPI looking at the bunched beam position in the Beam Profile Monitor (BPM) located downstream the following L-bend (set-up in dispersive mode) [13].

The powering of a phase-and-amplitude locked resonator will vary the beam energy and thus the position of beam profile on the BPM. It is possible to restore the beam in its original position by changing the resonator phase (it happens when the resonator phase is set to 0° or 180°) .It is possible to determine the conventional sign of the phase for full acceleration looking at the direction of the beam movement on the BPM when the phase is slightly changed.

Usually the working point is set at –20° with respect to maximum energy gain (the bunch arrives when the field in the cavity is still increasing, for acceleration phase stability). We find it useful, however, having in some cavities (about one over three) the synchronous phase set at +20°.

The setting of the synchronous phase can be performed using an automatic procedure, which, monitoring the beam profile while changing the resonator phase, suggests the suitable phase to be applied for beam acceleration.

4.2 Bulk Nb resonators

The first low β cryostat, CR6, was properly installed in the beam line in 1998 [14].

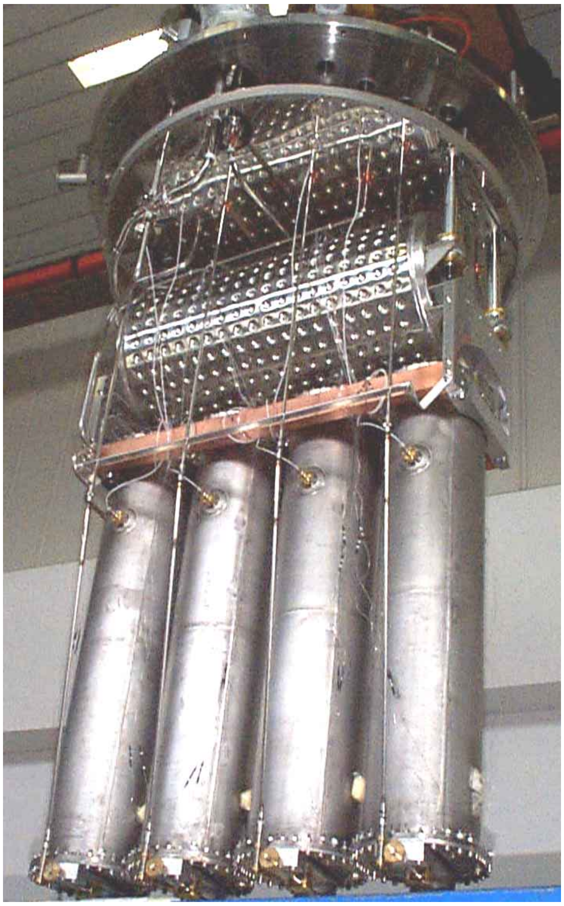

Fig 6: The cryostat top flange with four low β, 80 MHz Bulk Nb resonators.

The resonator performance measured on the beam line, and checked by the beam energy gain, confirmed the accelerating field obtained in laboratory (average value higher than 7 MV/m).

The resonators were equipped with mechanical dampers that reduce their sensitivity to mechanical resonances. These resonators are sensitive to changes in He bath pressure that produce slow fluctuations in eigenfrequency. With the cryostat connected to the refrigeration system the fluctuations are too large at present to kept with in the resonator bandwidth even by overcoupling the resonator to the maximum value allowed by the 180 W feeding amplifiers. This problem was solved by the movement of the tuner plate that can readjust the resonator frequency, through a feedback system provided by the resonator rf controller, looking at the phase error [15]. Once the number of tuner motor steps- producing 1 Hz change of resonant frequency and the tuner mechanism backlash were precisely determined, it was possible to lock reliably the resonators up to 6 MV/m.

The resonators were cooled down few times and they did not show any degradation due to Q disease. They were not however oftenly used for accelerations, for various reasons. First of all the beam energy required could often be reached without using these resonators and it was easier and less time consuming to operate only those resonators located in the linac high energy branch, without having to set the isochronous and achromatic U bend; two missing cryostats downstream CR6, as happened in 2000 for cryostat maintenance, would have made the setting even trickier. This option was possible because the output β of the tandem beam was compatible with acceptance of the medium β resonators.

The remaining two low β cryostats, CR5 and CR4, were placed in the beam line in 1999. The cryostat CR5 was cooled down to 4.5 K only in July this year just for a couple of days before the summer shut down, while the CR4 will be cooled down only in Fall this year. The CR5 cavities were measured, without having the possibility of any rf or He conditioning. The average Q_0 values were higher than $2x10^9$. The accelerating fields at 7 W were limited by field emission to an average value of 5.6 MV/m, but they are expected to reach after conditioning the values obtained in laboratory (fig. 7). Unfortunately last year a long shut down of the cryogenic system, one scheduled to replace the cold box control system (that improved a lot its reliability), and an other unscheduled one, to repair an inner purifier of cold box, limited the working period of the linac. The available operation time was devoted to deliver beam as fast as possible to users, leaving no time for extensively on line test of the low β resonators. These cavities are however necessary when PIAVE will be used as an injector: hence a test of their performance and long-term reliability will be a priority this autumn.

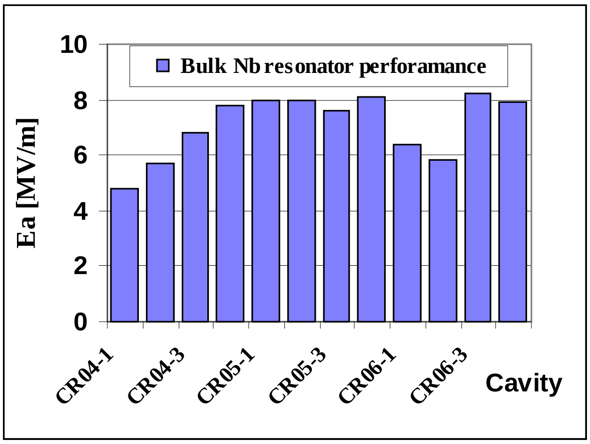

Fig 7: Performance of Nb bulk resonators at 7 W dissipated power

5 CRYOSTAT MAINTENANCE

A critical part in ALPI cryostat design resulted to be the cryogenic immersed valve used to commute between resonator pre-cooling and He tank filling: in four cases it developed leak towards the cryostat vacuum that made the cryostats unusable.

Fig. 8: The cryostat top flange after maintenance: in the centre the newly installed cryogenic valve can be seen.

Fortunately the vacuum deterioration was, on such occasion, enough slow and it did not create fast LHe evaporation [16], but it advised to reconsider the valve choice. A standard type valve which, differently from the originally installed, has bellows operating at room temperature, could fit an existing cryostat top flange feed-through and the corresponding hole of thermal shield. In this way, only by means of minor changes in the connections, it was possible to move the valve actuator mechanism out of the cryostat avoiding bellow movements at 4 K. We changed all leaking valves with this new type and we decided to substitute them in all the cryostats that would go into maintenance in the future.

The repair of the leak gave us the opportunity to perform a complete maintenance program [6] so as to increase the cryostat reliability in the future. Beside the change of the cryogenic valve and the insertion of upgraded resonators, it includes: the change of gaskets of the He circuits and their fixing by means of silver plated screws; the dimensional adjustment and Cu re-plating of the rf input line, the change of viton sealing in the cryostat beam line valves and its shielding from beam halos and from field emission electrons by the insertion of stainless steel rings; the fixing of all the joints of the coupler and tuner line by pins, the shielding of the aluminised mylar that is used to reduce shield emissivity, by tantalum protections around the beam ports. The change of the resonator-superconducting layer made the cryostat assembling easier since Nb resonators do not need to be kept in nitrogen atmosphere during handling.

We had to uninstall from the beam line CR10, that was equipped with resonators sputtered in 1998, in order to repair the leak: the resonators did not show any decrease in the performance after repairing the cryostat: the procedure adopted to protect the resonators during the operation of cutting and welding the cryogenic valve and during cryostat alignment seems to prevent any deterioration even though the processes were not done in a clean room.

6 LINAC UPGRADING BY NB SPUTTERING

Only four cryostats housing Pb/Cu accelerating cavity are installed at present (CR12, CR13, CR14, CR18).

Two others (CR16 and CR19, the last housing at present high β resonators) are under maintenance and will be in place by the end of the year. The remaining seven medium β cryostats house now sputtered Nb/Cu resonators.

In fig. 9 the performance reached by Nb/Cu resonators are compared with the previously installed Pb/Cu cavities: while the average accelerating field at 7 W dissipated power reached only 2.7 MV/m when Pb was used as superconductors, the average accelerating field of the same cavities after Nb sputtering is 4.3 MV/m. This value means an energy gain of 0.670 MV per charge state, in case of a beam with $\beta=\beta_{opt}$ and when the synchronous phase is set at –20°. It is necessary anyway to remind that accelerating fields of 7 MV/m at 7W have been reproducibly obtained in suitably designed quarter wave resonators and further improvements, such as Nb sputtering on Al substrates, are under development with encouraging results (Q_0=1.5x10^9).

Holes in high current regions and the beam port shape make it difficult to deposit a Nb layer having the uniformity and quality necessary to take full advantage of the better superconducting properties of Nb in the medium β cavities. The possibility to obtain, by Nb DC-biased sputtering, good performance resonators starting from the existing medium β copper bases was established only in 1998 [6]. The only changes in the resonator shape that were necessary to obtain such results were: the smoothing of the holes for the coupler, pick up and of that, present on the shorting plate that was used for plating; the opening of trapped gas volumes, present in the resonator body under screws used for keeping together resonator parts during the resonator brazing.

Moreover a 20 mm long copper tube, inserted between the cavity coupler hole and the coupler body and sputtered together with the cavity, has to be added to the coupler hole to allow the electromagnetic field to decay before meeting normal conduction surface. In this way it was possible to reduce the associated rf losses, that were negligible for the lower Q resonators, but which have to be avoided in higher Q Nb/Cu version.

The first two medium β cryostats equipped with Nb/Cu resonators was installed in 1999, and then we had to wait for available good copper bases, since the dismounting of operating cryostats was not feasible. When last year we had to dismount three vacuum leaking cryostats, we could restart the production.

As shown by fig.10, since May 2000, a considerable effort has been devoted to establish an efficient cavity production cycle, which allowed the fast replacement and improvement of the cavities dismounted from the cryostats that had to go into maintenance. With the contribution of an external factory (Strumenti Scientifici Cinel, Vigonza (Pd), Italy), in about one year more than 20 cavities were dismounted, stripped of their Pb layer, adjusted in frequency and shape, tumbled, chemically treated, baked and sputtered.

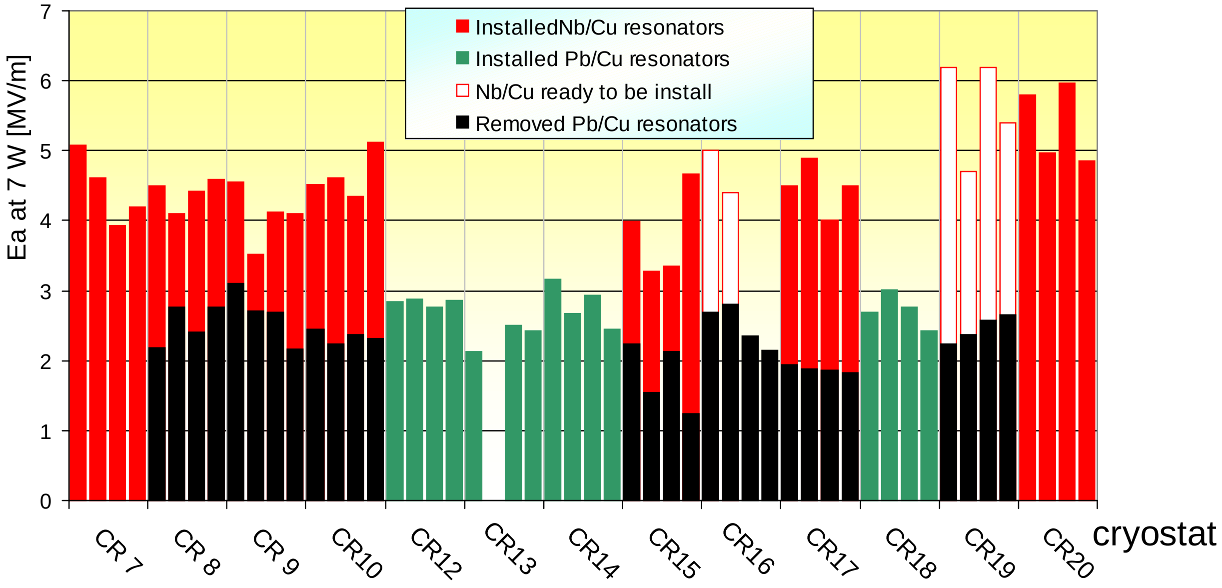

Fig 9: The increasing in Cu resonators performance due to Nb sputtering is shown in this plot where the accelerating fields reached by Pb/Cu resonator at 7 W dissipated power, either still existing on the beam line (green bars) or before being dismounted (black bars), are compared with the accelerating fields obtained by the same resonators after Nb sputtering (red bars). The spotted red bars refer to resonators, which have been sputtered and tested, but not yet installed.

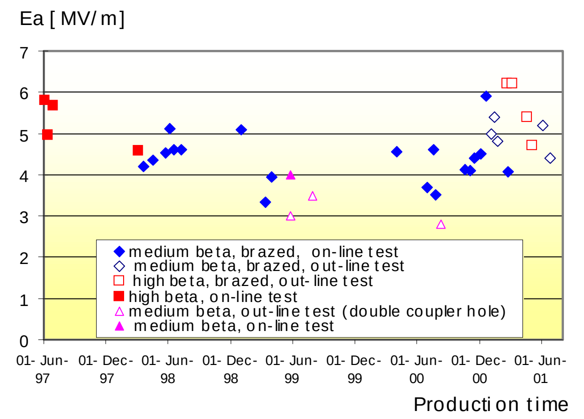

Fig. 10. Performance as a function of the production time for sputtered medium and high β resonators. Beam energy gain confirmed the calibration of the accelerating field in the installed resonators. Most of the resonator substrates have been built by brazed component; the others (where not specify) are machined out of a single copper bar. The Nb sputtering production rate has been accelerated in the last year.

All these cavities were tested at 4.2 K to measure the Q curve, but rf and He conditioning did not necessary. The field emission process is not usually the performance limit phenomenon for these resonators and it can be overcome by He conditioning after installation: this is way we chose to speed up the installation.

Fig.11: A medium β resonator after being stripped by the Pb layer and Nb sputtered. The hole in the shorting plate was used in the Pb electroplating process.

In most cases the sputtering process lead to resonators having accelerating field higher than 4 MV/m; only in few cases this value was not reached, the less performing results being obtained in resonators having problems in the copper bases (like an exceedingly wrong coupler hole).

Beam energy gain confirmed the calibration of the accelerating field in the installed resonators.

The copper substrate quality, that was not an important issue for lead resonators, plays instead an important role in the performance of Nb sputtered resonators. Bubbles in the copper substrate can lead to hot spots if present in high current areas or in any case they can deliver impurities that can contaminate the growing film during the sputtering process. Anyway the rejections rate was smaller then less than 10%: we can hence conclude that the sputtering technology in QWR reached a very good reliability.

It is important to emphasize that the substitution of the superconducting layer did not interfere with ALPI operation; the improvement of resonators went on in parallel with the cryostat maintenance; in most cases the latter could not be postponed because leaks made the cryostats unusable.

After having showed the reliability of the cavity production and having tested that it was possible to run the linac even with a missing cryostat, we made the cavity substitution to coincide with the scheduled cryostat maintenance, this makes the upgrading programme faster.

With the present rate we could refurbish all the remaining accelerating cryostats in one year; probably the process will take some longer time because the activity has to share personnel with the PIAVE installation programme.

7 CONCLUSIONS

The performance of ALPI has been substantially increased in the last two years.

The reliability of the cryogenic plant is improving and this allowed to complete all the scheduled experiments.

The renewing process of the old Pb/Cu resonators by Nb sputtering showed to be reliable. When PIAVE will enter into operation we should have the ALPI equipped only with Nb resonators, both sputtered or bulk.

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