A COST-EFFECTIVE ENERGY UPGRADE OF THE ALPI LINAC AT INFN-LEGNARO*

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Abstract

The ALPI SC linac at INFN-LNL is being constantly upgraded in terms of maximum beam energy (E_f) and current, made available for experiments. Presently, a liquid-N cooling scheme is being applied to the RF power couplers of the 16 full Nb resonators, to keep them locked at 5 MV/m, vs. present 3 MV/m. A further upgrade of the 44 "medium beta section" cavities, changing the cavity Cu substrates, was prototyped and is reported at this conference: however it is not fully funded yet and is extremely time-consuming. A cost-effective E_f upgrade is proposed here: to move 2 SC buncher cryostats, which house a single working SC QWR but were designed for 4, at the end of ALPI, equipping them with 4 Nb/Cu QWRs each (new bunchers would either be NC QWRs or a single SC cavity cryostat). The contribution of these cryostats to E_f would be extremely effective: e.g. a E_f~10 MeV/A ($I_{beam} \geq 1$ pnA) Pb beam, a very attractive tool for the nuclear physics community, is achievable. A being performed upgrade of ALPI cryoplant, expected to increase the refrigeration capability by ~25%, makes this change possible today. Details of this solution, as well as its limits, will be presented and discussed

INTRODUCTION

The heavy ion accelerator complex at INFN-LNL is based on the superconducting (SC) linac ALPI, which may be alternatively fed by the 15 MV XTU Tandem or by the SC injector PIAVE (V_{eq} = 8 MV), based on superconducting RFQs. For masses heavier than A ~ 100 the use of the Tandem tends to become unpractical due to the limited life-time of the terminal stripper foils and PIAVE is left as the only option.

At present, for masses beyond A~150, the maximum available energy with PIAVE-ALPI ranges between 7,5 and 8,5 MeV/A. In addition, the development of new heavy mass ions with the ECR ion source is not always straightforward nor particularly swift, having to be carried out only in those periods when the accelerators are not delivering beams to users (30% of the year time, without considering the time necessary for periodic maintenance), since an ECR test bench is not available.

The quest for the heaviest masses is indeed increasing: a large fraction of the proposed experiments at INFN-LNL aims at populating neutron-rich nuclei via multinucleon transfer or deep inelastic reactions with stable beams, as an alternative tool to fragmentation or the use of exotic beams. With very heavy stable projectiles (e.g. Pb), one could populate, in particular, nuclei in the regions of shell closures N=82 or N=126, which are beyond reach, incidentally, with fission or fragmentation.

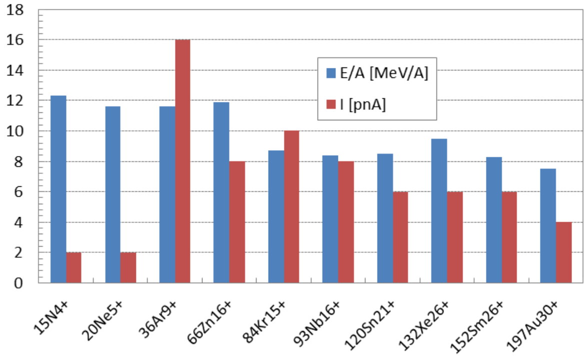
This quest determines the need to increase the final energy of PIAVE-ALPI, so as to go beyond the Coulomb barrier for nuclear reactions involving heavy projectiles and targets. For the Pb-onto-Pb case, for instance, the requested energy is 9,5÷10 MeV/A.

The paper deals with the status of beam developments with the PIAVE-ALPI linac; covers the recent and present upgrades in the SC QWR performance; describes the being performed upgrade of the cryoplant which, for the first time, gives that minimum redundancy in refrigeration power which makes it possible to add two cryostats with accelerating cavities at the end of ALPI. The reuse of the two "bunching" cryostats CRB2 and CRB4 as "accelerating" ones is finally discussed, together with proposal for new bunching units in their place.

BEAM DEVELOPMENTS WITH THE ECR ION SOURCE

Albeit affected by the limited time left available by nuclear physics experiments, the development of new beam species with the ECR ion source made some progress lately. The original Alice ion source was replaced in 2008 by a Supernanogan type ECRIS (Pantechnik), a source which – though not being top rated in terms of performance - was particularly suitable for use on the PIAVE HV platform thanks to its whole-permanent-magnet structure. Beams of noble gases were tested and made available pretty soon (Ar, Kr, Xe), together with a number of species which had already been developed by the company itself (Ag, Ta, Au).

Table 1: Present Performance of PIAVE-ALPI Beams, in Terms of Final Energy (MeV/A) and Current (pnA)



Nuclear physics experiments required additional ion species, for each one of which a dedicated development effort was necessary, up to the level where both performance (beam current and charge state distribution) and stability over a time of a few days at least had to be verified.

Table 1 represents the achievement, in terms of final beam energy and currents, of typical ion species available at present on the PIAVE injector ECR ion source, where only the most abundant charge state is reported for each case.

In Spring 2012, we proved that the maximum current which can be transported through PIAVE SRFQs could exceed 2 euA, as the consequence of dedicated beam tests with a $^{16}O^{3+}$ beam. Such current limit could be easily pushed at least to 5 euA, since temperature diagnostics on all SC resonators did not show any deviations from their normal behavior and no locking problems were observed. However, beam diagnostics instrumentation in ALPI must be upgraded in order to safely withstand such current, therefore we set 2 euA as a practical limit for the moment.

At the request of the INFN-LNL nuclear physics community, the next elements in the development list are (more or less in chronological order of development): Ca, Mo, Pb, Dy and Pd.

As reported in the introduction, beams of the heavier masses bear a special interest. A Pb beam, though not formally developed yet, seems to be feasible looking at the performances obtained with Au (the element of closest mass produced up to now): by using the frequency tuning technique as a first step and then the double frequency heating one can reasonably expect to obtain a final current with a $^{208}Pb^{30+}$ beam (and perhaps $^{208}Pb^{31+}$), useful for experiments.

RUNNING PROGRESS IN THE FINAL BEAM ENERGY ACHIEVABLE WITH ALPI

The ALPI linac has seen a continuous upgrade in the number and performance of its accelerating cavities, and consequently of the maximum achievable beam energy. In the early nineties, the 160 MHz QWR resonators (medium β_{opt} section) originally featured a superconducting Pb layer, electrodeposited onto a bulk Cu substrate, with the rather modest average accelerating field $E_{a,av}$~2,4 MV/m at 7W. Once the Nb sputtering technology was mature, it was successfully applied to the higher β_{opt} section resonators (also at 160 MHz), the Cu substrate of which had been optimized for the sputtering deposition, achieving $E_{a,av}$~6 MV/m. Later on all resonators were stripped of the Pb layer and equipped with a Nb one, onto the same Cu substrates (not optimized for sputtering): the average accelerating field of the medium β_{opt} section thus increased from 2,4 to 4,8 MV/m at 7W. The increase of ALPI equivalent voltage in the period 2000-2006 is shown in fig.1, where the contribution of full Nb lower beta resonators (see relevant paragraph below) is also shown.

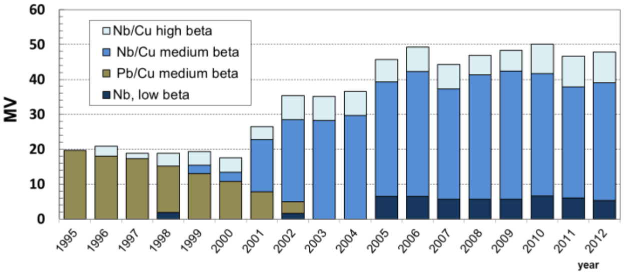


Fig. 1: Previous upgrades of the accelerating field of ALPI resonators ended up in more than doubling the linac overall equivalent voltage.

Further Upgrade of the Medium Beta Resonators

As anticipated above, a further optimization of the accelerating field of the medium beta resonators can be achieved, if the geometry of their Cu substrate is modified, and made more appropriate for the deposition of a Nb layer per sputtering. A specific paper is presented in these proceedings on this topic, which is just briefly recalled hereinafter [1,2].

Similarly to higher beta resonators, the high-H field region in the medium β_{opt} QWR resonator (connecting the central stem to the outer conductor) of a prototype ALPI cryostat (CR15) was much better rounded off mechanically, allowing for an improved quality of the SC layer there. Moreover, while higher beta resonators require large accelerating gaps and therefore their beam ports are simple rounded off holes in the outer conductor, the smaller accelerating gap of medium beta resonators asks for a new shape of the beam port, which is no longer brazed (with a sharp corner) but rather extruded from the Cu outer conductor itself (with a rounded-off corner), as shown in fig.2.

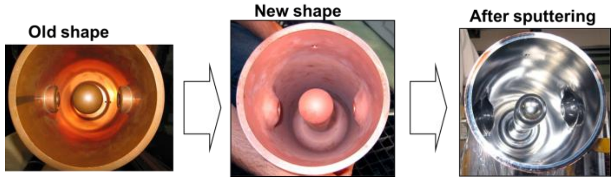


Fig. 2: The change in shape of the interior of medium beta resonators, tested on cryostat CR15 on ALPI linac in 2012, is shown. See a detailed report in ref. 1.

As shown in [1], the results obtained on the prototype cryostat CR15 are promising ($E_{a,av}$ = 5,5 MV/m at 7W), and susceptible of significant improvement, due to the long storage time that these cavities had to suffer since they were sputtered, before being assembled on ALPI.

Such upgrade, which is certainly cost-effective, is however significantly time consuming since it requires dismantling operational cryostats – one by one – while keeping all others operational for the scheduled experimental campaigns. It will be applied, in the future, for any cryostats requiring special maintenance, but for a swifter energy upgrade of ALPI the preferred option is different (described in the following).

Upgrade of the Full Nb Lower Beta Resonators

Last not least, four additional cryostats were added at the beginning of the linac, housing 80 MHz full Nb QW resonators. The performance of these cavities, exceeding 6,5 MV/m at 7W in the laboratory tests, could hardly exceed 3 MV/m in operation: in fact they are 100 times more sensitive to He pressure variations than Cu-based cavities are (1 Hz/mbar vs. 0,01 Hz/mbar); in addition, they are less stiff and hence more susceptible to mechanical vibrations. The use of mechanical dampers, originally developed at INFN-LNL and then successfully employed in other labs [3,4], turned out to be a very effective cure but not sufficient to exceed $E_{a,av}$~3,5 MV/m values in operation. A factor 10 higher RF power (from 150 to 1000 W) proved necessary to exceed 5 MV/m, but this required substantial changes in the design of the input power coupler which had to be cooled with liquid nitrogen. This upgrade is being presently carried out and is expected to be completed in the first half of 2013.

Out of the four cryostats with lower beta full Nb resonators (CR03-CR06): one (CR03) has been fully upgraded and is now operational since 2010; another one has been upgraded but not tested yet (CR05); a third cryostat is being maintained in 2012 (CR04), while the intervention on CR06 is foreseen to take place in Spring 2013.

Fig. 3 shows a photo of the liquid nitrogen refrigeration system of the resonators in the CR03 cryostat. Extended tests carried out in 2010 on cryostat CR03 [5] showed that an accelerating field of 5 MV/m (at a forward power of P_f=200 W) could be sustained (phase-amplitude locked conditions) during 5 days. Cavities were locked even at 6 MV/m for shorter periods.

Fig. 3: Photo of the N-cooling scheme of full Nb 80 MHz QWRs of ALPI.

It needs to be emphasized that all changes on these cryostats too proceed at the low pace dictated by the priority use of the facility to deliver beams to the experimental stations for a large fraction of the time.

ALPI REFRIGERATOR UPGRADE

The helium refrigerator of the superconducting ALPI accelerator was commissioned in 1991. It is manufactured by Air Liquide, it uses a Claude cycle processing up to 150 g/s of helium. It consisted of a Brayton cycle with two gas bearing turbines, also used to cool the thermal shields of the cryostats, and Joule-Thomson (JT) expansion valve or, as an alternative, a reciprocating wet expander (WE) for the liquid helium production. In 1991 the refrigerator was accepted, with the WE in operation, giving a refrigeration power of 3900 W at 60-70 K plus 1180 W at 4.5 K. The use of the wet expander was abandoned soon due to its discontinuous stability of operation. The subsequent continuous operation with only the JT valve was just enough, in terms of refrigeration capacity to comply both for the shields and at 4.5K with the number of cavities and cryostats installed (~ 700 W).

In 2008 it was proposed by LNL to install on the JT circuit, in order to increase the refrigeration capacity at 4.5 K with respect to the use of only the JT expansion valve, a third helium turbine as an alternative to the WE. The design of the supercritical turbine was assigned to Air Liquide. According to the calculation carried out the third turbine, processing up to 70 g/s of helium, between 300 and 400 W at 4.5 K can be added to the existing refrigeration capacity.

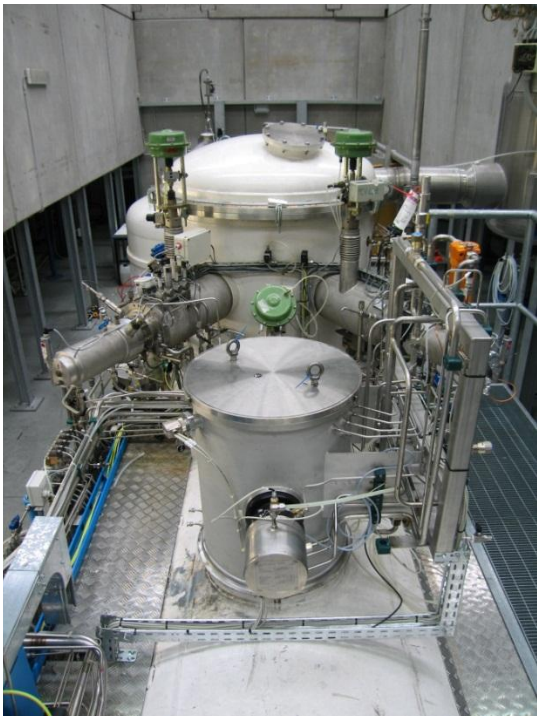


Fig. 4: Photo of ALPI Cold Box, recently upgraded with a 3rd turbine.

Due to impossibility to stop the ALPI accelerator and as a consequence the refrigerator in the past years, the upgrade was postponed to March 2012 and has just been completed. Fig. 4 shows ALPI cold box after the installation of the third turbine. In Fig. 5 the results in terms of refrigeration capacity at 4.5 K after the upgrade are shown. A measured increase of 360 W, with respect to the previous JT configuration, can be observed. Furthermore the refrigerator can process more helium gas, thus exceeding the 1100 W refrigeration capacity at 4.5K as shown.

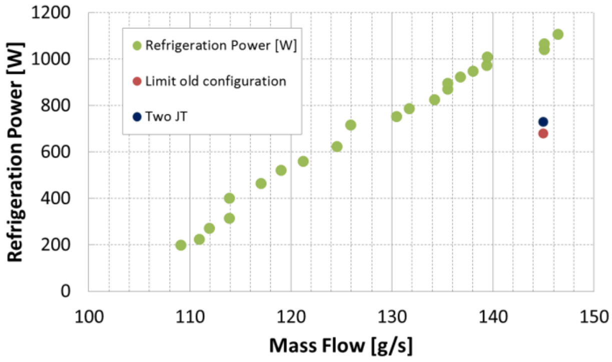


Fig. 5: Refrigeration capacity available at 4.5 K after the installation of the supercritical turbine (green dots). The gain at 145 g/s, with respect to the previous configuration (red dot) is (1040-680) = 360 W. In the actual configuration, without T3, an additional capacity is available, due the by-pass valve of T3 action as an additional isenthalpic expansion in series with the JT valve (blue dot).

The achieved result, in terms of refrigeration capacity, makes it possible to add 100W power dissipation, from the cryostat reshuffling proposed in the next paragraph, while leaving some margin in refrigeration power redundancy.

THE NEXT FRONTIER ON STABLE BEAMS AT LNL: LEAD AT 10 MEV/A

The recent and on-going progress on the on-line performance of SC cavities made it possible to increase the final available energy of medium-A (^{120}Sn, ^{132}Xe, ^{152}Sm) nuclei to 8,5÷9,5 MeV/A and of heavier nuclei (^{197}Au) to 7,5 MeV/A. Further upgrade is necessary to reach 9,5 MeV/A for heavier species and more than 11 MeV/A for medium-A ones.

It is easy to calculate with an Excel spread-sheet that approximately the same improvement in final energy, which is achievable by the further upgrade of medium beta resonators described above, can be obtained adding two additional cryostats (CR21 and CR22) with high beta resonators at the end of ALPI. The final beam energy for the reference ^{208}Pb beam would be 9,5 MeV/m with a charge state q=30+, and 10 MeV/A with charge state q=31+ (see next paragraph).

It is proposed to promote cryostats CRB2 and CRB4 to positions CR21 and CR22. CRB2 and CRB4 are identical to all other cryostats and perfectly suited to house four accelerating cavities each but, as a matter of fact, they presently house only two SC cavities each, which are used as beam bunchers. Beams injected from PIAVE (housing 80 MHz SC cavities) already by-pass CRB2 (kept off) and are re-bunched by the NC bunchers HEB1 and HEB2, the latter one being placed right after CRB2 on ALPI beam line.

Cryostat CRB2 (housing 2 160 MHz SC QWRs, only one of which is needed, and with the marginal maximum accelerating field of 0,3 MV/m), is used nowadays only with beams injected from the Tandem, when the 80 MHz section is off and the beam is sent directly into the 160 MHz medium β_{opt} section (cryostat CR07 onwards). If possible, the role of CRB2 would be simply taken in the future by HEB2: only simulations can indicate (see next paragraph), whether the smaller longitudinal acceptance of the 80 MHz HEB2 buncher is adequate to this purpose, or whether it would be a bottleneck, causing a drop in beam transmission.

In place of CRB4, at present requiring one cavity working at the maximum field of 0.36 MV/m, either two normal conducting resonators or a SC one will be needed, depending on the maximum field required.

A complete simulation of the beam transport in ALPI, with the addition of the two high β_{opt} cryostats, is described in the next paragraph. The case studied is a ^{208}Pb^{30+} beam from PIAVE.

BEAM DYNAMICS STUDY ON THE MODIFIED LINAC

Multiparticle beam simulations were performed with the code TRACEWIN [6], starting from the exit of the second SC RFQ in the PIAVE injector, down to the linac end where two additional cryostats with accelerating resonators, derived from bunching cryostats CRB2 and CRB4, are added on the beam line. The main purpose was to optimize acceleration efficiency together with overall ion transmission and determine the required field of the rebunching resonator at the end of ALPI.

The maximum value of E_a available in the simulations is consistent with state-of-the-art values on ALPI, per each family of resonators: 5 MV/m for lower β_{opt} cavities, 4,5 MV/m for intermediate β_{opt} and 6,5 MV/m for higher β_{opt} ones, including the newly added resonators. Maximum gradient of the magnetic triplets is the presently available value of 20 T/m.

As anticipated, the studied case is ^{208}Pb^{30+}, i.e. an A/q~7 beam, which – as explained in the introduction – has a vast application interest for the nuclear physics niche at INFN-LNL.

The final energy of the ^{208}Pb^{30+} beam increases up to 9,8 MeV/A, from the 8.5 MeV/A which would be available till cryostat CR20, the last one on ALPI beam line today.

Fig. 6 shows the final result, in terms of transverse envelopes and corresponding beam losses along ALPI.

As can be observed, losses are concentrated along the accelerating sections of the accelerator, the so called low-energy and high-energy branches, which are separated by the achromatic isochronous U-bend. Marginal losses (0.5%) are estimated, as a consequence of the addition of cryostats CR21 and CR22.

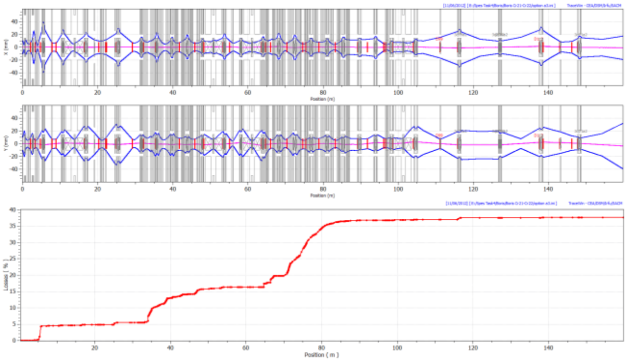


Fig.6: Horizontal and vertical envelopes of the $^{208}Pb^{30+}$ beam along ALPI (above) and the corresponding beam losses (below). Most losses are concentrated along the lower and higher energy branches of ALPI, where the accelerating elements are located

As can be seen in the zoom of fig.7, ions are lost mostly on the entrance cavity of the triplet-cryostat-cryostat-triplet period, both in the low and high energy branches of the linac.

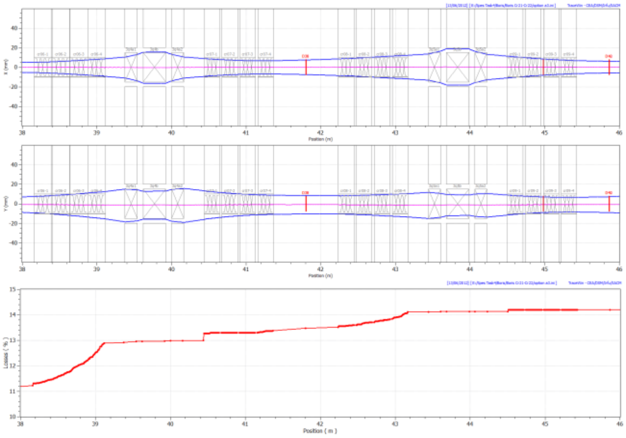


Fig. 7: A zoom of fig.5 is shown, where the detailed location of losses along the linac can be observed.

Those losses which are due to the asymmetry of the magnetic field along the accelerating path in a QWR [8,9] is mitigated by a proper choice of either a +20° or -20° accelerating phase in the resonators.

The simulation result shows an overall beam loss of ~ 37%, due to the above explained effects. It should be recalled that, in practice, losses are in the order of 50÷60% [10]. This is probably to be imputed both to the rather rough present alignment status and to the residual uncertainty in the definition of the amplitude and phase of the accelerating fields on our QWRs, which should be improved thanks to the evolution to more stable digital cavity controllers.

A beneficial effect on the overall beam transmission is expected in Fall 2012, when an overall laser-tracking realignment of the accelerator, in progress on ALPI at present, shall have been completed and, in particular, appropriate displacement of the accelerating cavity axis with respect to the beam axis [9] shall have been applied.

In ref.7 a denser lattice is considered as a possible future upgrade option, in the SPES project framework, with one doublet lens every single cryostat instead of the present triplet lenses every two cryostats. It remains to be seen if such layout change is worth the non-negligible investment, i.e. if the resulting enhancement in the longitudinal acceptance is likely to substantially reduce the gap between the theoretically predicted beam losses and the actual ones.

For the case considered herein, where a $^{208}Pb^{30+}$ beam is injected from PIAVE into the 80 MHz full Nb cavities of cryostat CR03, the existing 80 MHz NC bunchers HEB1 and HEB2 are fully appropriate ($E_a \leq 0.54$ MV/m).

The addition of CR21 and CR22, on the other hand, will increase the final beam energy and, moreover, significantly reduce the distance to the rebunching resonator, which will be still conveniently located in the same place as today, i.e. upstreams of the final L-bend leading to the experimental halls. Both these factors make the required field of this resonator to increase, from the present 1,8 to 3,8 MV/m. This means that a single, but superconducting, cavity must undertake the bunching function when cryostats CR21 and CR22 shall have been added.

It is to be noted, incidentally, that 9,8 MeV/A of an A/q=7 ($^{208}Pb^{30+}$) beam corresponds to a 1,64 T field in the final dipoles, which is 2,5% more that the dipole rated values: however, both the power supply and the magnets should be able to achieve such value reliably, provided that appropriate refrigeration flux is guaranteed.

The remaining issue is to check whether, for lighter beams injected by the Tandem directly into the 160 MHz medium-β_{opt} Nb accelerating cavities, the use of the PIAVE ALPI 80 MHz buncher HEB2, in place of the 160 MHz SC buncher housed in the to-be-removed cryostat CRB2, would contribute to any additional beam loss downstreams, i.e. if it would act as a bottleneck for the longitudinal acceptance of the machine. Simulations with $^{65}Cu^{11+}$, i.e. one of the most critical – in terms of A/q (~7) – injected into ALPI from the tandem ion source (worst case) are on-going at the present date. This beam – because of its initial relatively high values of β=v/c (7,7%) and TTF_n (0.8)– would be conveniently accelerated only by ALPI medium-and-high β_{opt} sections, i.e. from cryostat CR07 onwards.

NEW ACCELERATING CAVITIES

The 8 new accelerating cavities, to be installed in refurbished cryostats CR21 and CR22, shall be of the high-β_{opt} Nb-Sputtered type, as well as the new one which must be dedicated to beam bunching.

It is proposed that this resonator be housed in a single-QWR rebunching cryostat. For homogeneity with the rest of the plant, this cryostat shall have a gaseous He thermal shield and common vacuum for thermal insulation and the beam transport.

CONCLUSIONS

The just accomplished upgrade of ALPI cryogenic plant has provided an increase in the refrigeration power by more than 300 W (from 800 to more than 1100 W), thus providing adequate redundancy and leaving ~ 100W available for new cryogenic installations.

In this framework, it has been proposed to promote the presently “bunching” cryostats CRB2 and CRB4 (at the beginning and end of ALPI) to the role of “accelerating” cryostats CR21 and CR22, equipping them with 8 additional Nb-sputtered QWRs.

As a consequence, with no further cost in beam transmission, the final energy of a very heavy stable beam as ^{208}Pb would increase from 8,8 to 9,8 MV/m, thus exceeding the Coulomb barrier for Pb-Pb reactions by a large enough amount to make it appealing for the nuclear physics experimental campaign at INFN-LNL.

The role of the 160 MHz buncher CRB2 can be probably taken by the already existing 80 MHz NC buncher HEB2 for relatively light beams injected by the Tandem directly into the 160 MHz medium β_{opt} section, with negligible beam loss: dedicated simulations are in progress.

The whole project requires modest investment, since it exploits most of the existing equipment, conveniently reshuffled: a limited readjustment of the cryogenic lines and the addition of a single-QWR rebunching cryostat would be the higher cost components required.

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