

OPERATIONAL EXPERIENCE IN PIAVE-ALPI COMPLEX

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PIAVE-ALPI is the INFN-LNL superconducting heavy ion linac, composed by an SRFQ (superconducting RFQ) section and three QWR sections for a total of 80 cavities installed and an equivalent voltage exceeding 70 MV. In the last years the SRFQ and the bulk niobium QWR came into routine operation, the medium energy QWR section was upgraded with a new Nb sputtered coating, ECR source was firstly improved by using water cooled plasma chamber and then replaced with a new one. The operation of the accelerator complex allowed acquiring a strong experience on many operational issues related to ECRIS, superconducting cavities and cryogenics, beam control and manipulation (with the new and higher accelerating gradient). The paper reports about operational experience, the present limitations and the future perspectives of the facility in view of the experimental campaign with the EU detector AGATA and of the use of PIAVE ALPI as RIB post-accelerator for SPES radioactive ion beam facility.

INTRODUCTION

The superconducting linac complex at LNL is composed by the PIAVE injector [1][2] and by the ALPI booster [3]. PIAVE injector is based on superconducting RFQs (SRFQs) [4][5], the first superconducting ones operational in the world. The SRFQs are followed by two cryostats of bulk Nb 80 MHz Quarter Wave Resonators ($\beta_0 = 0.047$). The beam, received from an ECR source on a 350kV platform [6], is first bunched between the ECR and the SRFQs and then re-bunched between PIAVE and ALPI by two normal conducting cavities [7]. The present PIAVE layout (figure 1) is very compact, with the SRFQ cryostat immediately followed by the two QWR cryostat periods with external doublet focusing. The period is kept as short as possible, especially to reduce the longitudinal phase advance.

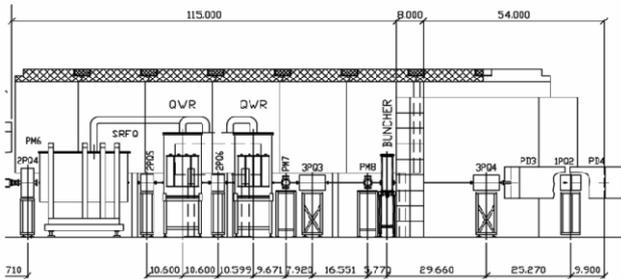


Figure 1: PIAVE layout.

ALPI booster consists, at the moment, in 3 cryostats of bulk Nb 80 MHz cavities ($\beta_0 = 0.056$) and 13 cryostats of Nb sputtered on copper base 160 MHz cavities ($\beta_0 = 0.11$

and $\beta_0 = 0.13$). The linac is composed by two branches connected by an achromatic and isochronous U-bend (figure 2). The linac period consists of one triplet and two cryostats (4 cavities per cryostat) with a diagnostic box in between.

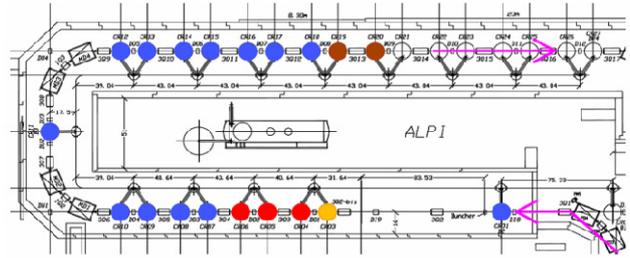


Figure 2: ALPI plan for 2009. The beam coming from PIAVE injector passes through the low- β (in orange and red), medium- β (blue) and high- β (brown) cavities.

In the total complex, there are 74 accelerating cavities and 6 bunchers with a maximum equivalent voltage of more than 70MV (12MV and 58 MV for PIAVE and ALPI respectively). However, the low beta cavities, can be maintained at high gradient during operation, only in exceptionally stable conditions of the Helium pressure. Practically, the maximum equivalent voltage reachable is limited to 64 MV (12MV + 52MV).

PIAVE injector commissioning started in November 2004 with a $^{16}\text{O}^{3+}$ pilot beam. In December 2005, after a long shutdown of the ALPI booster cryogenic plant, a very first ^{22}Ne test beam was accelerated by PIAVE and ALPI to the experimental apparatus PRISMA-Clara (final energy $\sim 6\text{MeV/A}$), where it provided stable beam-on target conditions for around 50 hours, before the scheduled conclusion. In the period January-April 2006, tests with ^{22}Ne , ^{132}Xe , ^{40}Ar and ^{84}Kr beams were conducted. Final energy on target ranged between 5 and 8.25MeV/A and beam currents extended between 5 and 15pnA . The required typical time for driving the beam through injector and booster to the experimental station was $\sim 2\text{-}3$ days. The period May-July 2006 was dedicated to maintenance on the SRFQ cryostat and the TCF50 cryogenic system. During the special maintenance, both fast and slow tuners of the superconducting RFQs were repaired and the distribution of temperature diodes was rationalized. By the end of July, the cryostat was closed and in September-October it was again prepared for beam operation. In November, the first official experiments with the PIAVE-ALPI combination started.

The ECR ion source Alice was also subject to a small but important upgrade at the end of 2006: the source

vacuum chamber was replaced with a water-cooled one. The immediate consequence of this operation was the shift of the distribution of the source charge state towards higher values. As an example, in the case of Xe beam, this allowed a 30% increase of the final energy on target.

In January 2007 a stripping station, equipped with carbon foils of different thickness, was placed before the ALPI U-bend, to test both the feasibility of acceleration and the transport of a charge enhanced beam. The acceleration was successful for Xe and Ar [8]. $^{136}\text{Xe}^{30+}$ was easily transported to the experiment with final energy of 1.1 GeV (8.1 MeV/A), a 20% more than the energy of the un-stripped beam (923 MeV). The beam current on target was greater than 1 pA. $^{36}\text{Ar}^{15+}$ was transported to the experiment with a final energy of 450 MeV, whereas the energy without stripping was 300 MeV.

In the mean time, an important upgrade of the ALPI low beta section started aimed to increasing the accelerating field up to 5.5 MV/m. After spring 2007, the overall machine availability was significantly affected by the replacement program of the old ECR ion source Alice with a new one (LEGIS, Supernanogan, Pantecnik S.A.), which was completed at the beginning of this year.

Commissioning of PIAVE injector with the new source was successful. New source guarantees a lower emittance allowing an increase in overall transmission.

PIAVE INJECTOR

The main components of the injector are the ECR ion source, installed on a 350 kV platform, the LEBT (Low Energy Beam Transport), the cryomodule housing two superconducting RFQs, the QWR linac section (two criomodules housing four cavities each) and the HEBT (High Energy Beam Transport) injecting into ALPI. The linac operates at 80 MHz, the bunching frequency is 40MHz.

ALICE Source and Platform

Ion source beam, extracted with a typical $V_s = 11$ kV voltage, is mass separated (resolving power $m/\Delta m \approx 100$) and finally accelerated by an electrostatic column up to the nominal $\beta=0.00892$ for RFQ injection.

Stability of the platform voltage V_p confirmed being excellent (within 17 V_{pp}) even at higher voltages. V_p was limited to 350 kV, but rarely more than 270 kV ($A/q=7.33$) were used. Injection into PIAVE was consistent with the high beam quality demonstrated by the previous emittance measurement (with a two slit scanner) for all tested beams. It is important to note that beam optics depends from the ratio V_p/V_s where V_s is the constant source voltage.

Among beam delivered to PIAVE, ^{22}Ne was directly separated in the source from the natural gas. Also ^{132}Xe was obtained from natural mixture, while ^{136}Xe was prepared from enriched bottle allowing the proportional increasing of the current so as to obtain the tuning simplification. Other important improvements for ^{136}Xe operation were:

- the development of a new cooled chamber (entirely designed and built in LNL workshop) for Alice which allowed the increasing of microwave power and consequently ion charge state q up to 23+
- the fine tuning of the frequency, from $f=14400$ MHz to $f=14363$ MHz, which increased the $^{136}\text{Xe}^{23+}$ current up to 1200 nA [9] (and up to 740 nA of $^{136}\text{Xe}^{24+}$). Frequency tuning is a laborious procedure since other source tunings must be optimized again at each f . A clear theoretical explanation of its effectiveness is missing, even if several mechanisms were proposed.

Even if operation of the ECR ion source Alice in the last years (up to 2008) was mainly devoted to produce beam for RFQ injection (up to ^{136}Xe), several test of induction ovens [10] for metallic beams up to element as refractory as vanadium and of other accessories, like sputter probes, were performed. Current in the order of 1 mA of V^{8+} was maintained for 3 days, after which the experiment was stopped because others was scheduled. Oven was operated up to about 2300 K for three weeks outside the ECRIS, with a gradual decay of the emitted flow. Results with Cr and Ti were similar. Experience proved that a very careful alignment of crucible and rf coil is necessary for reliable operation; moreover, some metals (for example tin) are much more difficult to maintain in the crucible than others (vanadium, silver, etc). For some material, like iron, self consumable crucibles were also designed [10].

Superconducting RFQs

The RFQ part of PIAVE consists in two superconducting RFQ resonators. This original choice allows a very efficient acceleration (more than 2 MV/m for $A/q=8.5$) employing an innovative beam dynamics design [11]. The main specificity of a superconducting RFQ (SRFQ) is the possibility to employ an intense inter-vane voltage that allows achieving a large acceptance and acceleration. Moreover, in this case, the use of two separate structures, beside having clear construction advantages, allowed to further increase the voltage in the second SRFQ; the inter-vane voltage is 148 kV in SRFQ1 and 280 kV in SRFQ2 for $A/q=8.5$.

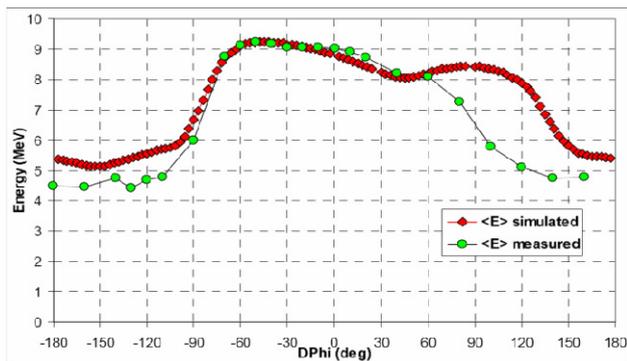


Figure 3: Average spectrum energy at RFQ exit as a function of phase difference between cavities.

The first tuning of the two PIAVE SRFQs was done with O^{3+} beam and the external buncher off, recording beam transmission (on FC) and energy spectrum (on Si detector) for different phases of SRFQ2 (figure 3). The nominal energies for oxygen are 5.45 MeV for SRFQ1 and 9.4 MeV for SRFQ2. Energy selection due to chromaticity effects of the doublet magnet next to RFQ are taken into account in the PAMTEQM [12] - PARMILA [13] simulations superimposed to the measurements in figure 3. Simulations and measurements match very well in the phase range in which the SRFQ1 beam falls within the separatrix SRFQ2, allowing a precise determination of the nominal SRFQ2 phase.

After this, the buncher was switched on to the nominal voltages and adjusted in phase so to reach the maximum transmission. Transmission reached after a fast realignment of the LEBT respect to SRFQ was 68%, as predicted by simulations.

QWRs and Bunchers

The PIAVE QWR section includes, two cryostats, each containing 4 bulk niobium QWRs with $\beta=0.047$ working at 80 MHz. These large cavities, powered by 1 kW RF amplifiers, are equipped with mechanical dampers to reduce their sensitivity to ambient mechanical noise. QWRs reached off-line accelerating field of ~ 7 MV/m ($E_s/E_a \sim 5$), while their nominal accelerating field in PIAVE is 5 MV/m. Beam dynamics considerations suggest scaling the accelerating field of QWRs with the A/q ratio as for the RFQ. Therefore, the maximum accelerating field used in operation is as high as 4.3 MV/m. Phase and amplitude locking asks for an enlargement of the resonant bandwidth on all cavities. This was achieved by over-coupling the SC cavity in a self-excited loop (SEL) mode (1 kW amplifiers were used). In addition to the QWRs, two room temperature bunchers are installed: the triple-harmonic low energy buncher and the high energy buncher, a high power, water-cooled $\beta=0.05$ QWR (a similar cavity was installed also in ALPI). The triple harmonic buncher, located upstream the first SRFQ, is used to match the beam in the SRFQ longitudinal acceptance ellipse. It guarantees a capture of 68 % in nominal conditions. The room temperature high energy buncher, together with the twin cavity located in ALPI, has the function to match the PIAVE 1.3 MeV/A beam to the ALPI line. A 10 kW amplifier powers this resonator.

ALPI BOOSTER

Low Beta Section

The ALPI low- β section includes, at present, three cryostats, each containing 4 bulk niobium QWR's with $\beta=0.055$ working at 80 MHz. Room for one more cryostat, named CR3, was left in the beginning of the line.

Resonators have an average gradient which is around 6 MV/m with the nominal 7 W power dissipation; this gradient, however, cannot be maintained in operation due to a too high sensitivity to the Helium pressure fluctuation. The frequency sensitivity to pressure changes,

in full Nb QWRs, is about 1 Hz/mbar even though P_{He} occasionally fluctuates in ALPI at a rate of up to 100 mbar/min or more.

For long-term operation, to avoid cavity unlocking, the gradient is usually set within 3.5 MV/m. The RF system, originally dimensioned for this gradient, allows a steady forward power of about 50 W per cavity. The resulting value of the P/E_a^2 ratio gives the minimum RF bandwidth for safe operation in ALPI, i.e. about ± 15 Hz.

This limitation in accelerating fields together with the frequency jump after low beta section, make the transport in the ALPI U-bend extremely difficult especially for beam with high A/q . The beam behavior after frequency jump is highly non-linear due to the high gradients and strong Bessel components of the fields inside the medium beta cavities.

Medium Beta Section

ALPI medium beta section includes 44 superconducting resonators housed in 11 cryostats. The cavities are 160 MHz QWR with 0.11 optimum beta. Their original Pb superconductor layer was replaced with a sputtered Nb film in between 1999 and 2003 when a maintenance cryostat programme was set up for repairing cryogenic leaks developed in the cryostat cryogenic circuits. The cavity upgrading resulted in a substantial increase of ALPI average accelerating field, which rose from 2.7 MV/m (the best average value obtained with Pb) to 4.8 MV/m, at the available power of @ 7W. The performance is still improving due to longer conditioning. The new performance was obtained without any further upgrading of both cavity equipment and control software.

Due to the mechanical stiffness, cavities are insensitive to changes in liquid He bath pressure. For this reason, they can be reliably phase locked at the accelerating field sustained by the available cryogenic power, fed by 100 W amplifier and without the necessity of continuous frequency tracking.

There are further 6 medium beta cavities in the bunching cryostats; only two of them, housed in the re-bunching unit, still maintain their original Pb layer.

All the medium beta cavities are operational, but one (CR14-2) which has the rf input line damaged during high power conditioning.

The high beta section consists of two cryostats only. The cavities maintain the medium beta frequency of 160 MHz. The increase in their optimum beta ($\beta_0=0.13$) is obtained by moving the resonator beam port outside the resonator body. The cavities, housed in the two medium beta cryostats, have the same inner shape, but different construction technology and copper quality. Cavities in CR20, designed to be sputtered and installed in 1998, reach 6 MV/m @ 7 W in average, while the ones in CR19, which were later built similarly to the medium beta ones, present accelerating fields around 5.5 MV/m. Now, two of these cavities are out of operation because of an rf line failure and a tuner stuck respectively. The high beta cavity behavior is quite similar to the medium beta one; they maintain the same reliability and facility of setting [14].

PIAVE-ALPI UPGRADE

Many upgrades of the PIAVE-ALPI complex are concluded or very near to conclusion. Replacement of the ALICE source with the LEGIS one was completed last year. Injector commissioning with the new source started at the beginning of 2009 and was concluded at the end of May. Extremely good results have been obtained in terms of transmission and beam quality.

In the mean time, an important upgrade of the ALPI low energy cryostats is in progress. This will guarantee an increase of the low beta cavity accelerating fields up to 5.5 MV/m.

The same accelerating field for the medium beta section will be guaranteed by sputtering on new copper bases.

LEGIS Source

The new ECR ion source, named LEGIS (LEGnaro ecrIS), is a product by Pantechnik [15] company. LEGIS is a full permanent magnet source working at 14.5 GHz. Good performance and low power consumption make it well suited for operation on a high voltage platform.

The source and its beam line are controlled via National Instruments FieldPoint modules that acquire all parameters and display them by a LabView interface.

Besides the production of ion beams from noble gases, it will be capable to produce metallic ion beam by two different methods:

- A resistive oven to produce metallic vapors from elements reaching a vapor pressure of 1 Pa for $T < 1500$ °C.
- Plasma sputtering to produce metallic vapors from refractory elements.

Source installation was completed at the end of last year. It was housed in the old high voltage platform. All the line up to the accelerating tube was redesigned in order to have good flexibility and complete beam characterization. To this scope, two independent movable slits for beam selection and an emittance measurement device were installed (figure 4). Each slit consists of two water cooled tantalum plates, moved together by a stepper motor. Each plate has a current pickup for beam loss monitoring.

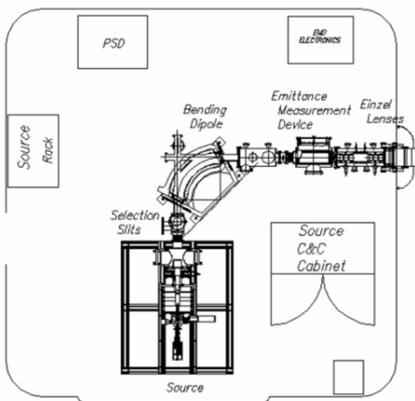


Figure 4: The complete beam line on the high voltage platform and its equipment.

The emittance measurement device consists of a slit-grid system. The maximum stroke of the system is ± 30 mm while the maximum divergence that can be measured is more than 70 mrad.

The proof of good source performances with gaseous and metallic ion beams was given during acceptance tests at Pantechnik site (table 1). For what concerns beam quality, the normalized 4-rms emittance was well below 0.3mm-mrad for oxygen, argon and gold beams.

Table 1: LNL Current Requests

	Ion	Current [μ A]
gaseous beams	O ⁶⁺	200
	Ar ⁹⁺	100
metals with oven	Ag ²¹⁺	3
	Au ²⁶⁺	10
	Au ³⁰⁺	1
metals with sputtering	Ta ²⁴⁺	1

Acceptance tests were partially repeated at LNL at the end of 2008 and will be completed within 2009.

PIAVE injector re-commissioning started in March with ⁴⁰Ar⁹⁺ beam. An important source alignment problem emerged in the first emittance measurements. We solved it, using the multi-polar corrector located on the dipole magnet in dipolar configuration and we added a new steerer to the line next accelerating tube. Emittances (normalized, rms) measured after the solution of the problem remain below 0.075 mm-mrad for all operating conditions. The best values that we measured are 0.059 mm-mrad for the x-plane and 0.048 mm-mrad for the y-plane. These low emittance values together with the use of an electrostatic triplets downstream of the accelerating tube allowed to reach very good performances in terms of transmission (table 2).

Table 2: Comparison of Injector Transmissions (%) with ALICE Source and with LEGIS Source

	Old PIAVE	New PIAVE
Injector input	100	100
Injector output	63.3	70.3
Booster input	56.8	62.4

ALPI Low Beta Section Upgrade

At present, the equivalent voltage of the ALPI low- β section is around 7.5 MV, limited by the resonators RF system. In the view of the ALPI-PIAVE linac upgrade that will lead to acceleration of ions of any mass above the Coulomb barrier energy this value must be doubled.

To set up the low- β section upgrade plan we took profit of the experience developed at TRIUMF, where similar resonators [16] are operated above 7 MV/m by means of a more powerful RF system and cooled RF couplers [17]. The upgrade actions are the following:

- replacement of all the 150 W RF amplifiers with 1 kW units;

- replacement of all existing 80 MHz RF couplers with new ones cooled with liquid Nitrogen;
- modification of all low- β cryostats to allow use of the new couplers;
- replacement of cryostat rf input line;
- construction and installation in ALPI of one more cryostat hosting 4, $\beta=0.047$ resonators;
- installation of a liquid nitrogen distribution system in ALPI-PIAVE.

The upgraded cavities are expected to operate at least at 5 MV/m, giving an equivalent voltage of around 14.4 MV, as required. The average forward RF power required guaranteeing ± 15 Hz RF bandwidth at 6 MV/m is about 200 W, but up to 600 W are needed for safe long term operation and for pulsed power RF processing. At present, the new amplifiers are installed in the old cryostats. Before summer, the new cryostat, equipped with the new RF system and with the cooled couplers, will be installed in ALPI, becoming the test bench for the new equipment. In the next phase, all the cryostats will be modified and upgraded for coupler cooling.

ALPI Medium Beta Section Upgrade

The average accelerating field of cavities of medium beta section is still lower than the one of high beta section, due to the characteristics of recovered substrates. We expect to reach in medium beta cavities the same performance obtained in high beta cavities by sputtering on new, suitable built, bases.

Four cavities, produced by new substrates, were sputtered up to now. The laboratory test confirmed they can reach in operation accelerating field in between 5.5 and 6 MV/m [14]. We plan they will substitute the cavities presently housed in CR15 by this fall. The substitution of cavities in other cryostats will further increase ALPI energy, but it asks for devoted funding.

CONCLUSION

PIAVE and ALPI are working reliably, at present, fulfilling the experimental programme of INFN-LNL.

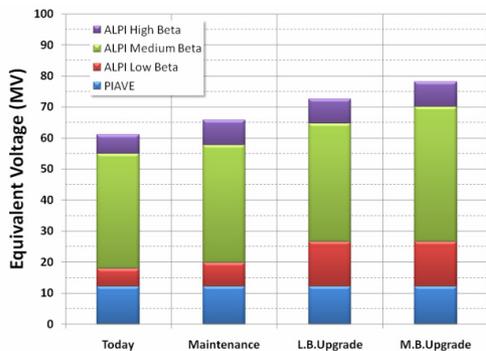


Figure 5: Equivalent Voltage increase with PIAVE-ALPI upgrade.

With maintenance of six cavities, (2 low- β , 1 medium- β and 2 high- β) and the completion of the low beta upgrade, the accelerator will reach an equivalent voltage of more than 70 MV. The funding of the medium beta upgrade will further pump up the equivalent voltage up to 78 MV (figure 5 and figure 6).

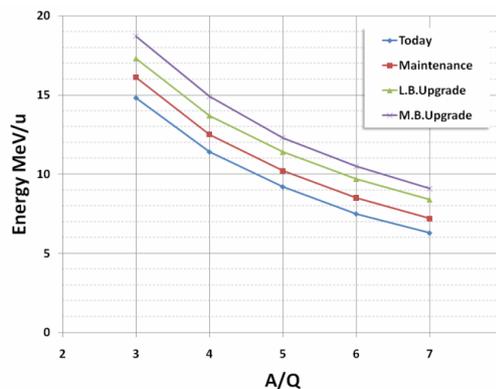


Figure 6: Expected final energies for the PIAVE-ALPI complex. Final energies for $A/Q=3$ could be a bit overestimated (Beam dynamics imposes a decrease in the accelerating fields of low beta section cavities.)

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