ALPI QWR AND S-RFQ OPERATING EXPERIENCE

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Abstract

The operation of ALPI at INFN-LNL allowed acquiring more than a decade of experience on the operational issues of quarter wave resonators (QWRs), built with the three technologies of Pb/Cu electroplating , Nb/Cu sputtering and full Nb. More recently, with the commissioning of the superconducting injector PIAVE, a 2-year long operational experience with superconducting RFQs was acquired.

The paper reports off and on line performances of all INFN-LNL superconducting resonators and the most relevant issues in their setup for reliable accelerator operation.

Future perspectives, opened by the experimental campaign with the EU detector AGATA and by the proposed use of ALPI as the radioactive nuclei beam (RNB) accelerator of the SPES facility, are discussed.

INTRODUCTION

INFN-LNL is engaged with the continuous development and operation of superconducting resonators since 1987, when the first prototypes of Pb-plated copper-based QWRs for ALPI were built and tested [1]. Since then large experience was acquired in the R&D and in the operation of QWRs, built with three different technologies: Pb electroplated onto Cu, Nb sputtered onto Cu and full Nb.

The SC linac ALPI was first used as Tandem booster in 1994 [2]. By the addition or the replacement of QWRs, its acceleration performance greatly increased since then. The most significant milestones were the installation of Nb-sputtered QWRs for its higher β_0 section (two cryostats mounted in 1995 and 2001), the replacement of Pb with sputtered Nb on all medium β_0 resonators (from 1999 to 2003), the regular operation of full Nb lower β_0 QWRs in 2005.

The steady-state operation of PIAVE, the heavy ion injector based on superconducting RFQs, completed the layout of the Heavy Ion Accelerator Complex [3]. PIAVE commissioning, started in November 2005, was completed in April 2006, when a number of acceleration tests from the ECR ion source through the injector and the booster were successfully completed. Regular operation of PIAVE+ALPI, albeit only with noble gases, was proposed to the Programme Advisory Committee in July 2006 and started in November 2006.

The ALPI booster is presently working with either the XTU-Tandem (14.4 MV is the current terminal voltage) or PIAVE as injectors. The recent successful cryogenic operation of the low beta resonators, which made it possible to operate them regularly at $E_a \sim 3$ MV/m, added further contribution to the linac full equivalent voltage, which is now of ~ 48 MV.

Tandem-ALPI accelerates beams from ^{12}C to ^{104}Ru, while PIAVE-ALPI accelerates noble gases, up to $^{132\div136}$Xe. Fig.2 shows the performance, in terms of final energies and currents, of all PIAVE-ALPI accelerated beams and a representative list of Tandem-ALPI beams.

It is worth noting that, while ALPI was used in the past for around ~ 30% of the yearly amount of beam-on-target time, this percentage significantly increased, recently, to reach 70% in the last year, of which 17% use PIAVE as injector.

Beam	E [MeV] - (1 foil)	Beam current [pnA]	E [MeV] - (2 foils)
^{12}C	240	10	250
^{16}O	290	30	320
^{32}S	440	18	550
^{48}Ca	440	1	610
^{58}Ni	540	5	750
^{65}Cu	530	2	750
^{74}Ge	515	2	800
^{82}Se	560	1	800
^{90}Zr	530	1.5	
^{104}Ru	550	1	

Beam	E [MeV]	Beam Current [pnA]
^{22}Ne^{4+}	150	10
^{40}Ar^{9+}	350	4÷10
^{84}Kr^{15+}	600	5÷10
^{132}Xe^{18+}	720	5÷10
^{132}Xe^{22+}	920	3÷5

Table 1: maximum energy and current values of some representative Tandem-ALPI beams (above) and of noble gas beams with PIAVE-ALPI (below) [4].

COPPER-BASED RESONATORS

Pb/Cu resonators

ALPI was proposed in the late eighties as the INFN-LNL superconducting booster. At that time it was decided that the electroplating of a Pb superconductor layer onto a Cu substrate would be the "working horse" technology for the first period of the linac operation. The plan foresaw the construction of 95 Nb Pb/Cu resonators [5], with a target accelerating field of 3 MV/m (corresponding to a peak surface field $E_{s,p} \sim 15$ MV/m), indeed a rather optimistic value, to achieve a final beam energy in the range 6÷20 MeV/u (from the heavier nuclei like ^{90}Zr to the lighter ones, such as ^{12}C). These resonators would be contained in 27 cryostats, including 3 couples of buncher resonators.

The Pb/Cu electroplating technology was validated in 1990, when the first Q-vs-E_a tests showed that an accelerating field in the range 2,3÷2,7 MV/m was achieved on a series of tests [2]. The construction of these resonators was carried out, together with the construction and assembly of the entire accelerator, in the following 4 years. Operation started in 1992 with 16 resonators (including 4 bunching units) and the installation of additional units followed (28 in 1993 and 4 in 1994).

Pb/Cu resonators proved to be reliable for accelerator operation for a number of years. In particular, their excellent mechanical stability made it very easy to lock them in amplitude and phase to their reference values by means of a controller based on SEL scheme; moreover, the high thermal conductivity of Cu made them less susceptible to quench with respect to full Nb resonators. On the other hand, however, their performance was rather limited, since their accelerating field rarely exceeded 3 MV/m (the specified value), averaging at about 2,6 MV/m as an operational number, reduced to 2,4 MV/m after a couple of years. Moreover, the handling of these cavities was somewhat complicated by the fact that the electroplated Pb surface was particularly prone to degradation when accidentally exposed to air, therefore a strict handling of Pb-plated resonators in a N atmosphere was mandatory at all times.

Aiming at a possible upgrade of the resonators accelerating voltage, since the very beginning of the ALPI project two R&D programmes were launched, one on the sputtering of Cu bases with Nb and the other on the realization of full Nb cavities [2]. These programmes proceeded in parallel, reaching in the same year (1993), the outstanding result of an accelerating field of ~ 6 MV/m. At that time the construction of ALPI medium β_0 section (first ALPI construction phase) with Pb/Cu resonators was already nearly completed and the construction technology could not be changed. Given the success of the R&D phases, it was decided nevertheless to continue investing in both the Nb-sputtered and full-Nb technologies and, in the second phase of ALPI, to build the higher β_0 section with the former and the lower β_0 section with the latter [6].

High beta Nb/Cu cavities

The QWR Cu bases for the Nb sputtering technology were soon shaped in a geometry which would be best suited for the deposition of a Nb layer of uniform thickness (see fig.1).

The main differences with respect to the bases for Pb/Cu cavities were:

- Retracted beam ports: the higher β_0 value (0.13 vs 0.11) allowed the beam ports to be shaped as plain holes in the outer conductor, making them easier to sputter in a uniform way
- Rounded shorting plate between the central and the outer conductor
- Use of a capacitive rather than inductive coupler means that no hole is drilled in the region of higher current density close to the shorting plate
- The material was chosen to be 99,95% OFHC Cu, without any brazed joints on the cavity body (thus avoiding that brazing junk might pollute the internal surface during the high T sputtering process)

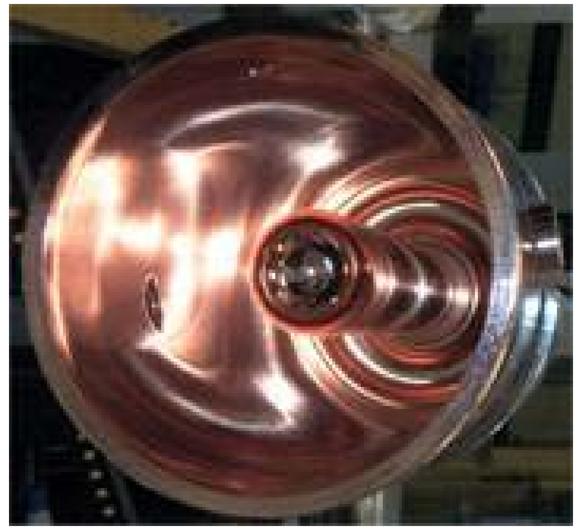

Fig.1: Cu base for Nb sputtered higher β_0 resonators; the geometry is designed to be best suited to the deposition of a uniform Nb layer.

By means of these design details, along with a careful and long setup of the delicate sputtering procedure, the first results were confirmed and exceeded in a number of tests, showing an average accelerating field off-line E_a ~ 6÷8 MV/m at P_d = 7 W (with $Q_0 \sim 6 \div 7 \times 10^8$ at the high field values) [7]. The technology was clearly mature to be applied to on-line resonators.

It must be noted that their operation, despite the higher field, was indeed very similar to that of Pb/Cu resonators. The thick Cu base makes them in fact particularly stable to both mechanical vibrations and changes of the liquid He pressure (P_{He}). The sensitivity of the Cu-based resonator frequency to variations of P_{He} is as low as $\Delta f/\Delta P_{He}$ ~ 0,01 Hz/mbar. Even large variations of P_{He}, which in ALPI can change even at a rate of 100 mbar/min, reflect in a rate of frequency variations in the order of 1 Hz/min, so small a value that it does not even need to be controlled via the mechanical tuners.

Medium beta Nb/Cu resonators

The success of the development of higher β_0 cavities opened the possibility to apply the sputtering technique to the medium β_0 section as well. With the aim of a cheap and quick process, sputtering of the same Cu bases which had been previously Pb-electroplated was attempted.

The impulse to the medium β_0 resonator upgrade was given by a serious problem which started affecting a large number of cryostats in a close sequence: the leaking of a cryogenic valve, actuated by cold He gas in the common vacuum of the cryostat. A maintenance team was setup, with the main objective of fixing the problem of the leaking cryostats. At the same time, the old Pb/Cu cavities were upgraded with a newly sputtered Nb film. This process, being conducted with a schedule which should have no interference with the approved physics programme of the LNL facilities, lasted from 1999 to

2003, when the latest medium beta cryostat with mid β_0 resonators was upgraded. In spite of the less favourable geometry (presence of beam ports, large radii on these and on the shorting plate, holes in the high current density region), the average accelerating field obtained increased by more than 60% (from 2,7 to 4,4 MV/m) [8], as shown in fig. 2.

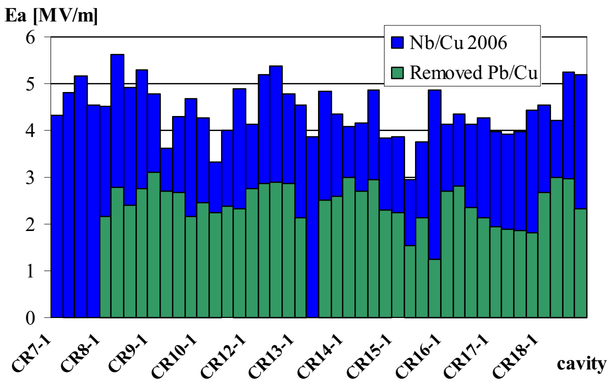

Fig.2: distribution of medium β_0 E_a values before (green bars) and after (blue bars) replacement of Pb with Nb as SC layer. The average value increased by more than 60%.

It is noted, incidentally, that cryostats CRB3 and CRB4 (containing bunching resonators) still contain Pb/Cu cavities, which should be replaced in a near future.

The noteworthy success of the medium β_0 resonator upgrade triggered an R&D program, aimed at a further increase of the accelerating field of these resonators to be obtained by optimization of the shape of the Cu bases. At present 4 new resonators, with β_0=0,11, are being fabricated and sputtered (fig.3). With respect to the base Cu geometry of presently inslatted resonators, they are characterized by:

- Beam ports obtained by mechanical extrusion of the outer conductor (rounded edges)
- Rounded shorting plate
- Capacitive coupler
- No holes in high current regions
- No brazed joints in the outer resonator body

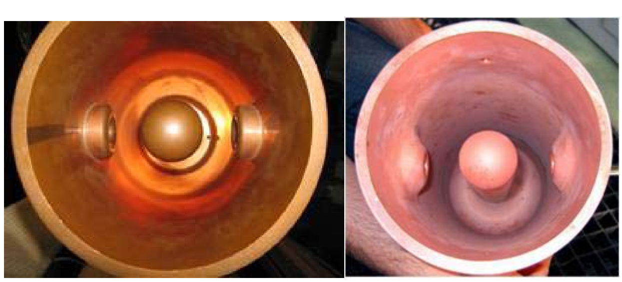

Fig.3: the figure shows the improvements, introduced in the upgraded prototype Cu-base of medium β_0 resonators, so as to improve the quality of the Nb layer and hence the Q-vs-E_a curve.

The first prototype was tested in July 2007 at 4 K [9]. At present the Q-vs-E_a curve cannot exceed 3 MV/m (radioprotection authorization limit), however the curve shape, together with previous experience, let an operational field E_a ~ 5,5 MV/m be extrapolated.

NIOBIUM-BASED RESONATORS (QWRS AND SRFQS)

The development of full Nb QWRs started in 1987 [10], with the construction of prototypes of 80, 160 and 240 MHz resonators till 1993. Then the production of 12 80 MHz β_0=0,055 cavities began [11] and a first cryostat was installed in 1995.

Lower β_0 cavities are required by beams injected from the Tandem and with A>80 and by beams injected by PIAVE (the last cavities of which have a β_0 value of 0,047).

By 1998 12 such resonators had been installed in ALPI [12]. Their off-line Q-curves are shown in fig.4, which shows that their average E_a at P_{cav} = 7 W is around 7 MV/m: the higher resonator performance, with respect to the specified 3 MV/m, allowed installing 12, out of the originally foreseen 20, such resonators.

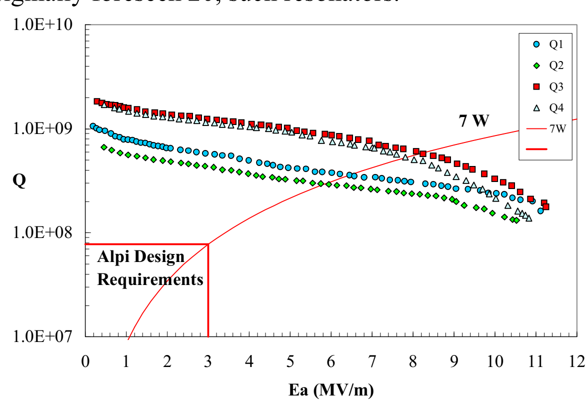

Fig.4: Q-curves of 4 out of the 12 80 MHz full Nb resonators, which were installed in ALPI in 1998.

Eight further full Nb QWRs are installed in PIAVE [13], with similar off-line performance [14], downstream two superconducting RFQs.

A photo of the superconducting RFQs [15] is shown in fig. 5. The classical RFQ is here split into 2 structures, with external bunching (which imposes to find their relative phase for acceleration): they are two four-rod structures, 1,46 m and 0,79 m long respectively, resonating at 80 MHz. Their geometry was designed to be suitable to the operation of a SC resonator.

Their off-line Q-vs-E_a curve exceeded the specifications. The main operational issues of SRFQs were [3]:

1. Frequency locking with respect to mechanical vibrations and changes of the liquid He pressure (obtained by means of VCX fast tuners, mechanical tuners and gentle cryogenics conditions)
2. ± 0,2 mm alignment between cavity and beam axis so as to obtain good beam transmission

Fig.5: photo of one SRFQ in the on-line cryostat; the resonator is surrounded by its own liquid He dewar; the Cu thermal shield at 77 K can be seen

Fig. 6 shows the Q-vs-E_a curves for SRFQ1 and SRFQ2. The very large $E_{s,p}/E_a$ ratio of the two structures is given by the peculiar feature of EM fields in RFQs, in which the main component of the electric field is transverse to the main axis to ensure proper transverse focusing.

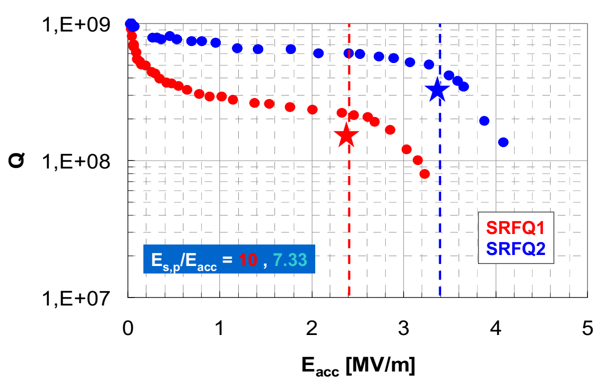

Fig.6: Q vs E_a curves of superconducting RFQs (SRFQ1 and SRFQ2); the figures shows the specified working point (at P_{diss} = 10 W) (red and blue star), as well as the $E_{s,p}/E_a$ ratios.

DIFFICULTIES AND CHALLENGES OF FULL NB RESONATORS

Operation of full Nb resonators is more critical than operation of Cu-based resonators. The main challenge is to ensure the resonator phase stability with respect to slow changes of the liquid He pressure (time scale of s or slower) and to mechanical vibrations (time scale of 10÷100 ms).

As it will be shown in the next paragraph, the phase stability issue was faced in QWRs by means of: continuous frequency adjustment with an improved mechanical tuner [16]; the development of mechanical dampers [17]; an upgraded RF system (the latter improvement is ongoing at present) [18]. In SRFQs it was solved by implementing two large range tuners on each resonator and VCX Fast Tuners (design of Argonne National Laboratory) [19].

Problem in feeding low β_0 resonators with He

Since their very first installation in 1995, ALPI QWRs have encountered a serious cryogenic problem. The layout of the ALPI cryogenic lines caused inefficient cooling of the cryostat thermal shields (provided by 7 bar He gas). Consequently, in the lower β_0 branch of ALPI the shields temperature exceeded 100 K on the far end cryostats. The anomalous evaporation of liquid He in the cryostat dewar stopped the liquid He transfer. Therefore lower β_0 cryostats (CR04÷CR06) could never be efficiently refrigerated while the rest of ALPI was kept cold (with a couple of exceptions such as a single lower β_0 cryostat cooled for very short beam times).

Only in 2004 a long maintenance shutdown of ALPI was planned, in order to perform a complete reshaping of cryogenic lines layout: by implementing the condition of constant pressure drop on each cryostat, the distribution of the shields temperature was far better balanced all along the linac [20]. Fig. 7 shows this distribution before and after the upgrade of the cryogenic lines.

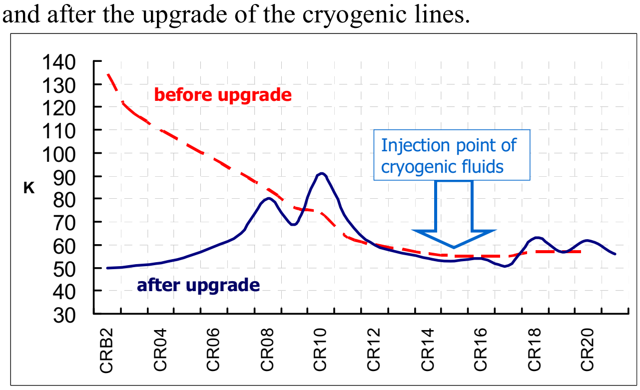

Fig.7: distribution of the gas He shield temperatures of ALPI cryostats, with respect to the injection point, before and after the cryogenic lines upgrade

In order to monitor the experimental conditions in a better way, additional gauges were mounted in the 4 additional valve boxes, which were installed during the cryogenic lines upgrade (P and T sensors and 2 mass flow meters).

As a result, the cryogenic operation of cryostats CR04÷CR06 is working successfully since 2005.

Phase locking of full Nb QWRs

The advantage of using Cu-based resonators is that the phase stability towards slow He pressure (P_{He}) changes or mechanical vibrations is not an issue. The structure of such a cavity is mechanically very stiff and the sensitivity to changes of the liquid He pressure is as small as 0,01 Hz/mbar. This means that the Cu-based cavity frequency change is never larger than 1÷2 Hz (within its bandwidth) even though P_{He} occasionally fluctuates in ALPI at a rate of up to 100 mbar/min or more. The resonator can be operated, therefore, in a moderately overcoupled mode.

On the other side, the frequency sensitivity to pressure changes in full Nb QWRs is ~100 times larger ($\Delta f/\Delta P \sim 1$ Hz/mbar) and mechanical vibration modes as low as 22 and 42 Hz were measured in operation.

This low frequency mechanical resonances motivated the development of a mechanical damper of the inner conductor [17], in order to lower Q_{mech} of these modes.

Fig. 8 shows the recorded probability of a certain extent frequency deviation from the central value for all 12 lower β_0 resonators, equipped with mechanical dampers, in ALPI [21].

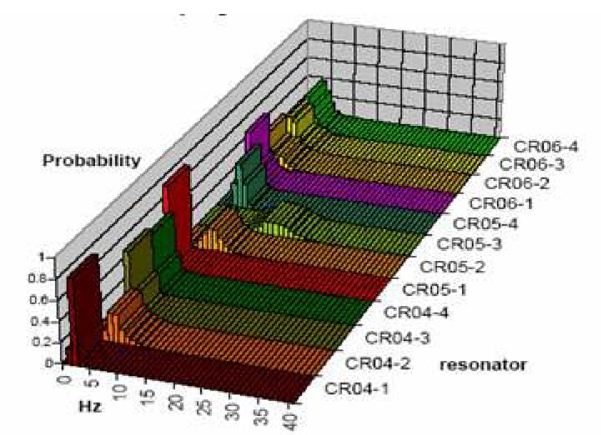

Fig.8: for each lower β_0 QWR, the deviation probability of the actual resonant frequency with respect to 80 MHz was recorded and plotted

Concerning the slow frequency changes, the continuous movement of the mechanical tuner, which keeps track of the frequency change induced by the He pressure variations, motivated an upgrade of its mechanics. The standard cam-shaft tuner was replaced with a much more precise lever tuner, actuated by a standard stepper motor (inspired by the TRIUMF design [22]). The new design, featuring very little magnetic material and no lubricant at all, is capable of a resolution of better than 0.33 mm (equivalent to 1 Hz frequency steps) and has a very small and reproducible backlash.

Thanks to the upgrade of the cryogenic lines and the implementation of mechanical dampers and new slow tuners, at present full Nb QWRs can successfully operate at the ALPI original design field of 3 MV/m.

Their operation at fields closer to their off-line performance (E_a~7 MV/m) is still limited by an inadequate RF system. In fact, it is necessary to over-couple the resonators by means of a 1 kW amplifier instead of the presently used 150 W ones. These higher power amplifiers were purchased in 2007 and the needed related upgrade of the RF lines and couplers (i.e. their refrigeration with liquid nitrogen) is being carried out on CR03, a fourth lower β_0 cryostat which is being prototyped with this purpose and which will be added in ALPI in 2008 [18].

Following the successful test of CR03 cavities, all the remaining full Nb QWRs will be upgraded similarly, with the aim of reaching an accelerating field of at least 5 MV/m for ALPI operation.

It is also planned to upgrade in the same way PIAVE β_0=0.047 QWRs. Thanks to the gentler behaviour of the injector cryogenics, PIAVE QWRs can already be locked up to 4.1 MV/m.

Phase locking of full Nb SRFQs

As reported more extensively in ref.3, the development of VCX fast tuners in collaboration with Argonne National Laboratory [19] and a particularly stable cryogenic system ($\Delta P/\Delta t \leq 5$ mbar/min) granted reliable phase locking of SRFQs.

The PID parameters of the cryogenic plant were carefully setup together with engineers of its building company, and a working condition providing very slow variations of the liquid He pressure in time ($\Delta P/\Delta t$ usually as low as 2 mbar/min or less) was achieved.

Under these conditions VCX fast tuners were able to provide very stable working conditions to SRFQs, whose f_{res}-sensitivity to changes of the liquid He pressure is as high as 40 Hz/mbar (i.e. ~40 times that of full Nb QWRs and ~4000 times that of Cu-based QWRs). The rate of unlock events, which be not spontaneously recovered by the system itself, is of 0÷5 per day, mostly depending on the stability state of the cryogenic system: the machine operator is able to rapidly fix the problem in nearly all such cases.

OVERALL LINAC OPERATION ISSUES

ALPI features nowadays 64 accelerating QWRs, either in sputtered Nb/Cu or in full Nb.

As far as the impact of the accelerating field on the linac performance is concerned, the increase of the linac accelerating voltage in the last decade is shown in fig. 9, where the relative contributions of the replaced SC layer of the medium β_0 section, the high β_0 sputtered resonators and the lower β_0 sections are emphasized.

The present value of the equivalent voltage, related to an average accelerating field $E_a \sim 4{,}4$ MV/m, is very close to 50 MV.

Concerning the main operational parameters, table 2 compares the three main resonators families in ALPI: Nb sputtered QWRs (medium and higher β_0), full Nb QWRs and SRFQs.

While off-line values of the peak surface electric field range between 22 and 32 MV/m, operational field values are very close to off-line values in Cu-based QWRs, while they are somewhat lower for SRFQs (87%) and full Nb QWRs (45÷65%, waiting for the presently on-going upgrade of the RF lines).

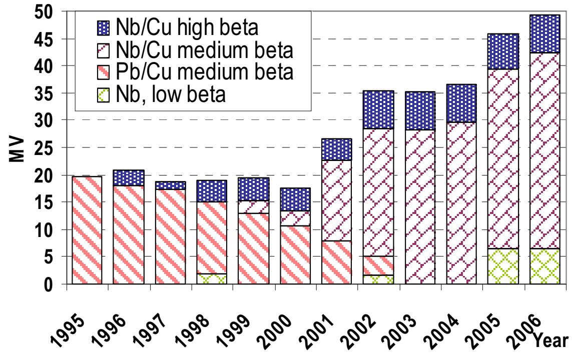

Fig.9: variation of ALPI equivalent voltage in the last 12 years; the relative contributions of the three β_0 sections is highlighted (replacement of Pb with Nb in medium β_0 resonators being the most relevant one)

	Nb/Cu QWR	Full Nb QWR	Full Nb SRFQ
$\bar{E}_a$ [MV/m]	4,5/6,5	6,5	2,2 / 3,2
$\bar{E}_p$ [MV/m]	22,5/32	32	25
$\bar{E}_{a,op}/\bar{E}_a$ [%]	98/92	45÷65	87
RT RFE conditioning [h]	48	96	32
4K RFE conditioning [h]	None	2	20
He conditioning [h]	6	6	20
HPPP [h]	4	None	100
Q-disease	None	Some	None
Deconditioning	None	None	On SRFQ2
Unlock rate [day^{-1}]	0	0÷5	0÷5

Table 2: comparison among different types of PIAVE-ALPI resonators, regarding their main operational parameters (achieved peak and accelerating fields, off line and on-line), conditioning times and others.

While off-line values of the peak surface electric field range between 22 and 32 MV/m, operational field values are very close to off-line values in Cu based QWRs, while they are somewhat lower for SRFQs (87%) and full Nb QWRs (45÷65%, waiting for the presently on-going upgrade of the RF lines).

It can be noted that SRFQs, albeit ensuring very reliable operating conditions in general, require particularly long conditioning time, both for RFE (resonant field emission) and particularly for HPPP (high peak power processing). The HPPP refers here to the pulse-mode use of only $P_{ampl} \leq 1$ kW amplifiers.

After conditioning and locking all resonators in amplitude and phase, the setup of the phase of each ALPI resonator with respect to the master oscillator (reference phase) is computed by the LNL beam dynamics group, in order to maximise beam transmission through ALPI and keep control of beam emittances.

First of all a simple computer code, developed on an Excel spreadsheet, sets the preliminary values of each resonator reference phase, so as to minimize the average phase width of the bunch and to keep its oscillations under control: this is done, normally, by a proper choice of the phase between the two values -20° and +20°. In the particular case of the very first lower β_0 cavities, lower values of E_a than the available ones need to be input for this purpose.

As a second step, this setup for the longitudinal dynamics is inserted into a Trace3D [23] sheet, through which quadrupole gradients are regulated, so as to have a beam which be well enough focused in the cavities and not too large in the magnets. In this step, one has to make sure that the chosen dynamics does not imply quadrupole gradients larger than the available ones: otherwise one needs to go back to the Excel spreadsheet and change resonators reference phase, thus iterating the process.

The last step is a multiparticle simulation with the code PARMELA [24] (fig.10), through which possible longitudinal beam losses (and their causes) are searched and quadrupole gradients are corrected in order to minimize transverse losses.

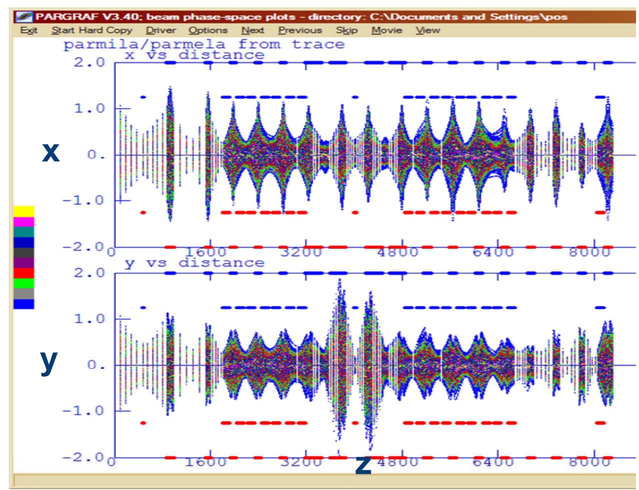

Fig.10: example of a PARMELA multiparticle simulation (transverse phase space envelope), calculated for a $^{70}Zn^{10+}$ beam to be accelerated with Tandem-ALPI

Once this series of simulations provides reasonable results, the values of the resonator reference phase, together with the quadrupole gradients, are passed to the operation group to be implemented in ALPI for beam transport and acceleration. This procedure, setup around two years ago, had a significant effect in speeding up the linac setup and reducing beam losses.

FUTURE DEVELOPMENTS

PIAVE and ALPI are working reliably, at present, fulfilling the experimental programme of INFN-LNL, prepared with the support of an international Programme Advisory Committee. However, further improvement of these facilities are required (among other upgrades) by the future proposed scenario of the laboratories. The most important challenges that Legnaro is facing are:

1. Experimental campaign with EU-detector AGATA.
2. The use of PIAVE-ALPI as a RNB accelerator in the SPES facility.

		2007	2008	funded	Mid β upgrade	High β extension	
Resonators Upgrade Phases	CR03	0	5	5	5	5	E_{acc} [MV/m]
	CR04→CR06	3.5	3.5	5	5	5	
	CR07→CR20	4.2	4.2	4.5	5.5	5.5	
	CR21→CR27					5.5	
Present ECRIS, *stable beam*	$^{132}Xe^{20+}$	7.5					Energy [MeV/A]
New ECRIS, *stable beam*	$^{132}Xe^{26+}$		10.4	11.4	13.0	15.4	
Charge Breeder, *RNB*	$^{132}Sn^{20+}$			9.0	10.3	12.0	

Table 3: the table shows the upgrade phase of ALPI QWRs and their impact in terms of final ALPI energies of relevant stable (^{132}Xe) and unstable (^{132}Sn) beams; as shown in the table, the increased charge state obtained with the being implemented new ECR ion source also plays a very important role.

AGATA (Advanced GAmma Tracking Array) [25] is a 4π set of 180, large 36-fold segmented Ge detectors, designed to be operational at European Laboratories offering high intensity stable and unstable beams. Its demonstrator will be commissioned and tested for the first time at LNL (I) with PIAVE-ALPI beams (2008-2010), then at GANIL (F) in an upgraded version (2010-2012) and finally at GSI (D) after 2012.

So as to fulfil the experimental specifications of the AGATA demonstrator, higher heavy ion beam currents and energies are required on PIAVE-ALPI.

Moreover the RNB facility SPES [26], presently funded up to ~ 1/3 of its full cost, foresees the use of PIAVE-ALPI, albeit in a slightly modified layout, as accelerator of radioactive species.

In view of these applications, two improvements were already funded and are being implemented: the installation of an ECR Ion Source of higher performance (in terms of charge states and extracted currents) than the present one and the upgrade of the lower β_0 section of ALPI, to make it work at least at E_a ~ 5 MV/m (Improvement A).

In view of farther future upgrades, it is worth recalling that one could, with a very limited budget, further enhance the average E_a (from 4,4 to 5,5 MV/m) of the medium β_0 section by replacing the Cu bases of the sputtered resonators with properly shaped ones (Improvement B).

Last, one could eventually build and install three additional cryostats with higher β_0 sputtered resonators in the already available space at the end of ALPI, still leaving enough drift space for bunching/debunching resonators (Improvement C).

The impact of these three improvements on the final value of beam energy with reference beams of interest (stable ^{132}Xe and unstable ^{132}Sn species) are reported in table 3.

As can be seen in the table, the implementation of the funded programme (new ECRIS and upgraded lower β_0 section) will allow increasing the final energy of the reference ^{132}Xe beam by more than 60% (of interest for stable beam physics, e.g. AGATA demonstrator array), while the final energy of ^{132}Sn, with an assumed value of charge state as given by present state-of-the-art ECR charge breeders, will be close to 9 MeV/u.

Much higher values would be obtained if the further upgrade of the medium and higher β_0 sections were approved and implemented: we believe that these values would provide the maximum possible equivalent accelerating voltage of ALPI with state-of-the-art resonator technologies (close to 80 MV).

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