Status of ALPI and Related Developments of Superconducting Structures

G. Fortuna, G. Bisoffi, A. Facco, A. Lombardi, V. Palmieri, A. Pisent, A.M. Porcellato
INFN, Laboratori Nazionali di Legnaro, via Romea 4 , I35020 Legnaro (PD), Italy

Abstract

This talk treats of three main topics, namely:

I) the status of the Superconducting Linac ALPI;
II) the strategies put into action in order to push up the resonator performances;
III) the design and prototype work directed to the construction of a new positive ion injector for our Linac.

Since the beginning of 1995 several beams have been successfully accelerated with the ALPI Linac injected by the XTU-Tandem, especially in the medium-light mass region using Pb-plated and Nb-coated resonators.

The machine, warmed up several times since 1993, does not exhibit significant Q-degradation at high field. The difficulty of transferring the high Q-performances of the Nb based resonators from test bench conditions into the machine environment is discussed with some detail. The most challenging work now under way in Legnaro is the construction of two Superconducting RFQ's which will boost the velocity of the ions produced by an ECR source and pre-accelerated through a 350 kV platform from beta 0.01 up to beta 0.035. The design work and the key choices of the manufacturing process will be presented.

Introduction

In 1989, after a couple of years of preliminary R&D in RF superconductivity, a long term project, named ALPI was initiated at the Laboratori Nazionali di Legnaro (LNL) aiming at extending the nuclear physics activities grown in the eighties around the 16 MV XTU tandem. The goal of the programme was to design and construct, through the development of the necessary expertise, heavy ion machines based on superconducting technologies which would allow to reach and overcome the nucleus-nucleus interaction barrier of any stable beam-target nuclear system.

Following the pioneering work at ANL [1](Argonne, USA), SUNY at Stony Brook [2](New York, USA), Weizmann Institute of Science [3](Rehovot, Israel) and later at Seattle[4], we decided to construct and install a superconducting linac based on a large number (initially 93) of independently phased lead plated Quarter Wave Resonators (QWR's), thus boosting the energies of the XTU tandem beams up to 20 MeV/A (for sulphur isotopes)[5].

The availability of a 16 MV tandem with single and double stripping capability makes the use of a superconducting linac as a post accelerator extremely effective, allowing high intensities (10÷30 pnA) onto the target for medium-light beams like e.g. sulphur, chlorine and nickel and a reliable use of medium-heavy ions up to iodine with intensities of few pnA.

A positive ion CW-mode injector for ALPI linac has been designed in order to produce heavy ion beams of convenient energy and intensity. Beside improving the performance of the LNL accelerator complex for the light and medium heavy ion species, the new machine will allow to produce and accelerate also isotopes which are either rare or inadequate for typical tandem negative ion sources (see fig. 1. and fig. 2).

The new injector, named PIAVE [6], includes a 14.4 GHz ECR source installed on a high voltage platform (350 kV), two 80 MHz superconducting RFQ's and two ALPI-like cryostats containing 8 bulk niobium 80 MHz QWR's. The particular configuration of LNL accelerator complex (XTU tandem, PIAVE and ALPI) will then allow to feed two out of the three experimental halls with completely independent beams at the same time bringing, in the near future, the total amount of available beam time over 6000 hours per year.

Experience with ALPI

Although the machine is prepared to host up to 93 QWR's, our present operating experience is limited to forty-eight 160 MHz accelerating cavities and three out of the five buncher stations[7]. Two more cryostats housing "medium β" type resonators (β=0.11) are ready for the installation.

The whole linac was meant, originally to consist only of lead plated QWR's. The development of bulk Nb (β=0.055) and Nb sputtered (β=0.14) QWR's reduced the number of cavities needed to reach the design performances of the linac to 74.

The "low β" section (β=0.055) of the machine already in an advanced stage of construction was delayed because of unexpected problems connected with the resonator unlocking induced by pressure fluctuations in the liquid helium reservoir of the cryostats. We believe the problems to be now fixed(see later on).

According to the experiment requirements, the accelerated ion species cover the mass range between 30 and 90 with specific energies up to 13.4 MeV/A. The corresponding maximum accelerating voltage reached by the linac is 20.5 MeV/q with an average resonator gradient of 2.65 MV/m. The beam intensity onto the target in most cases ranges between 1 and 3 pnA (up to 5 pnA on the case of ^{32}S).

The majority of the experiments was devoted to the spectroscopy of very exotic nuclear states by means of the 4π multi-array detector named GASP, which needs a quasi-dc time structure of the beam. Only in few cases the beam was injected with a 5 MHz prebunched structure obtained with the double-drift double-frequency buncher (5÷10 MHz), chopper and phase detector assembly[8]. In those cases where neutrons and γ-rays were discriminated through time of flight techniques, a direct measurement of the dark current between pulses less than 10^{-4} with respect to the bunched portion of the beam was obtained.

In our experience the quasi-dc operation mode (160 MHz bunching) even proved to speed up the setting up of the machine, to require no interventions on accelerator components for days and to preserve the usual transmission and final quality of the beam. In fact once the resonators of the low energy leg of the machine are correctly phased, the particles outside the separatrix are mainly lost in the internal "U-bend".

In routine operation about 30% of the dc-beam injected in the machine is transported to the target. This average value results from the bunching efficiency (45%) and the total transmission of the machine including injection and extraction lines (70%).

The periodicity adopted for our machine (triplet-cryostat-diagnostics-cryostat) which allows us to monitor the beam every two cryostats, has been found very effective for the setting up of the periodical focussing Therefore we are confident to routinely reach 90% transmission, as demonstrated in some cases with sulphur and nickel beams.

The availability of beams for experiments strongly depends on the reliability of the cryogenic system. In the last eighteen months, in fact, 19% of the scheduled beam time was lost because of faults of the screw-compressors and damages of "cold box" turbines caused by power failures in occasion of strong storms. Faults occurring to other linac subsystems (pulsing, diagnostics) caused another 6% of machine shutdowns.

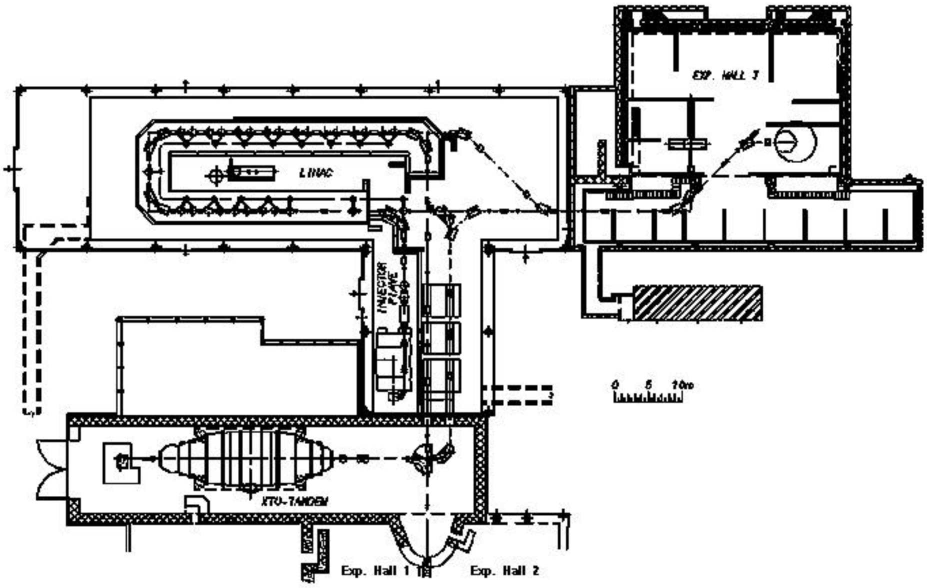

Fig. 1. Layout of the ALPI accelerator complex

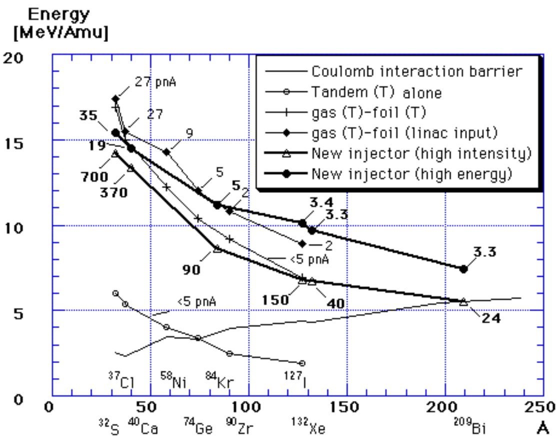

Fig. 2. Performances of the ALPI complex in the configurations XTU-tandem (15MV)-ALPI and new injector(8MV)-ALPI. Two stripping configurations are considered when using the tandem as injector: gas(T)-foil(T) (both inside the tandem) and gas(T)-foil(outside the tandem). For the new injector (high energy curve) stripping is done before injecting ALPI. For comparison the performances of the XTU tandem alone (16 MV) are also plotted. The figures on the plots indicate beam intensities onto the target.

Expertise on Superconducting QWR's at LNL

In 1987, at the beginning of our experience, we decided to develop two gap resonators, geometrically simple, very stable against mechanical vibrations and suitable to cover the ion velocity range of interest for experiments.

Within the R&D program we defined the following priorities:

1. Feasibility studies and tests (dynamics and electrodynamics investigations) of QWR's in which the straight inner conductor ends in a hemisphere [9]. This geometry reduces peak surface electrical fields, facilitates the coating processes (lead plating and Nb sputtering), simplifies the construction of bulk niobium resonators and makes either seamless (by drilling a copper rod) or vacuum brazed OFHC copper cavities feasible[10] (see fig. 3.).
2. Fixing up of a recipe for electroplating with a reduced number of process steps. Electroplating is a low cost treatment which can be used as a first approach in the development of new superconducting structures which exhibit complicate geometries.
3. Transfer of CERN experience in the sputtering process from the 350 MHz e-cavities to the QWR's. This ambitious goal was originally conceived as a long term program aiming at the upgrading of the Lead plated resonators.
4. Improving of the manufacturing technologies of bulk niobium QWR's.

Lead plated resonators

Our experience in lead plated resonators is supported by the high number (120)of successful plating cycles performed so far and by the sixty working resonators produced for the linac [11].

The good reliability and reproducibility of the plating process allowed us to restrict the laboratory quality test during the mass production to only 15% of the total number of resonators in preparation. Normally these resonators do not suffer from severe multipacting.

In the last two years the machine was warmed up three times forcing us to recondition it from scratch. In the worst case (cryostat opening) the cure of the multipacting did not take longer than 6 hours per cavity following twelve hours of baking of the resonators at 350 K with the cryostat shields at 60÷70 K. Through the assistance of a semiautomatic computer control procedure the whole linac multipacting conditioning was performed in about 60 hours.

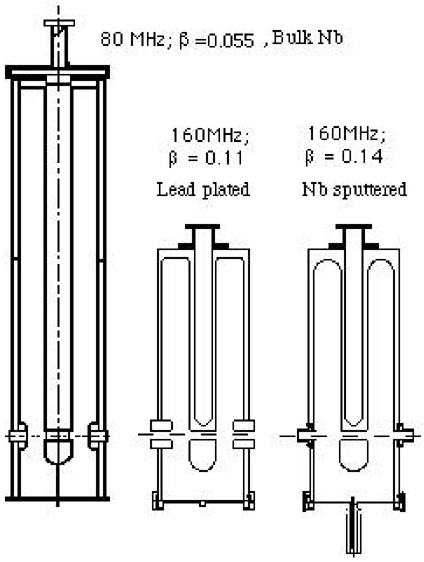

Fig. 3. Three different QWR's installed in the linac

Keeping the linac resonators at 300 K either in high vacuum (range 10^{-7} mbar) or in dry Nitrogen overpressure (1200 mbar) does not affect the multipacting conditioning time. On the contrary a wrong procedure in warming up of the resonators can strongly influence the multipacting phenomenon in the subsequent conditioning. The cavities must be steadily kept at a higher temperature than the cryostat shielding. If the shield temperatures, due to cryogenics faults, drifts over 120 K with the resonators still at a temperature close to 4.5 K, the whole multipacting conditioning has to be repeated.

Field emission is cured in the machine by using the following complementary methods: "gentle" RF power processing both in high vacuum and controlled He gas atmosphere (4÷5 10^{-5} mbar) and the usual RF high power processing by means of 1 kW RF amplifiers. While the later method is manually applied to single resonators exhibiting severe electron loading, "gentle" RF processing is managed by the RF control program, pulsing the 100 W amplifier output signal for a duration of 400 ns with a duty cycle of 20%.

The results of such field emission treatment are very encouraging. After every warming up of the machine the previous Q-performances were promptly recovered for all the resonators.

The accelerating field at 7 W dissipated power was improving with time through subsequent conditioning stages, from the initial average value of 2.4 MV/m to the present 2.7 MV/m.

More in details, 62% of the resonators exceeds the average field value of 2.6 MV/m, 27% of them exhibits a value in the range 2÷2.6 MV/m and the remaining 11% shows values slightly lower than 2 MV/m.

Lead-tin plated resonators have been preferred in some laboratories because of their stability against oxidation and hydrossidation processes which makes even air storage possible [12]. As an alternative, since approximately same BCS losses are expected for both lead and lead-tin coatings, we pursued the goal of making lead films oxygen and humidity resistant through passivation processes [13].

QW-Niobium sputtered resonators

In June 1995, the first cryostat housing four Nb coated QWR's produced via DC biased diode sputtering was installed in the machine. This represented the final goal of a very intense prototyping work which allowed us to fix a reliable recipe for the sputtering process [14]. The guidelines of the prototyping work were:

1. Optimization of the resonator copper base avoiding sharp corners in the internal surfaces and any hole in the outer conductor with the exception of the beam ports. Coupler and pick-up antennas were moved to the tuning plate placed at the bottom of the resonators.
2. Careful design of the Nb cathode in order to get a uniform deposition rate in every area of the resonator with particular attention to the high current zone.
3. Fixing up of the polishing of the OFHC copper substrate and its best vacuum conditions before sputtering.
4. Definition of the cathode preparation ("cathode training").
5. Fixing up of the multiple stages sputtering procedure.

The best results on test bench show high Q performances ($2x10^9$) at low field level and accelerating gradients of 6.9 MV/m at 7 W of dissipated power (see fig. 4).

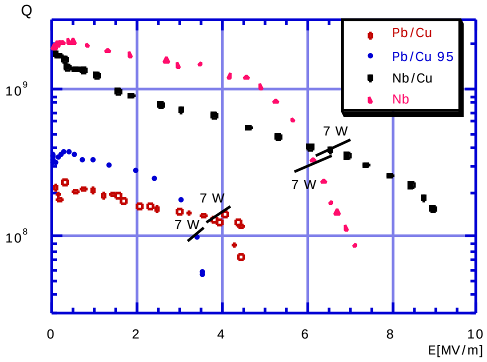

Fig. 4. The best Q performances reached at LNL on bench test with the different QWR's installed in the linac.

These resonators are nearly multipacting free (1÷2 hours of conditioning is enough) and with clean assembly conditions they exhibit weak field emission. When field emission appears too strong a rinsing with high pressure (200 bar) de-ionized water is sufficient to reduce the x-ray emission at the usual level.

The resonators installed in the accelerator sustain accelerating fields in excess of 4 MV/m at 7 W of dissipated power. It should be noticed that such resonators were produced with an anomalous sputtering process (at floating bias voltage), and suffered from vacuum leaks and dust contamination during installation [15].

Bulk-Nb QWR's

Prototypes of QWR's with β=0.055 (f=80 MHz), β=0.11 (f=160 MHz) and β=0.165 (f=240 MHz) have been developed in these years at LNL [16]. Extensive bench tests showed the excellent Q-performance of such cavities (Q_0 in excess of 10^9) which sustain accelerating fields of 5 MV/m with a power dissipation of 1 W (see fig. 4).

The 80 MHz resonators were chosen for the "low-β" section of the linac and for the high velocity part of the new injector (β≥ 0.035). The weight of such 1 m long resonators is very close to that of the β=0.11, f=160 MHz copper bases allowing the use, for the cryostats, of the same basic design as in the medium and high β sections of the machine.

When the 80 MHz resonator is working inside a normally noisy environment, its amplitude and phase are easily locked up to field levels of 6 MV/m within the usual self excited loop configuration by widening the resonant bandwidth (resonator overcoupling). On the contrary, if the pressure in the liquid helium reservoir of the cryostat feeding the resonator, is oscillating, as in our case, by ±50 mbar, this locking method is not longer efficiently applicable, because of frequency drifts up to 50 Hz. These drifts are normally in the range of 1÷2 Hz per minute and can be recovered within a window of few Hz by means of a computer program which, in response to the phase error signal, drives the fine tuning mechanism.

In order to respond essentially to the excitation of the 42 Hz mechanical resonant mode of the cavity, a fast tuner (an externally controlled reactance VCX) is going to be used in combination with the slow tuner. The fast tuner consists of an inductive coupler connected by means of a 50Ω coaxial line to a variable capacitance located outside the cryostat. The system is designed in such a way that a tuning range of 400 Hz MV^2 m^{-2} (i.e. 25 Hz at 4 MV/m accelerating field, which appear to be more than needed in our case) can be obtained with only 1 W dissipated by the tuner at 4.2 K, and about 8 W dissipated at 100 K. The advantage of having easy access to the electronic components is clear, as well as the fact that relatively low power lines and feed-throughs are needed.

Furthermore, in order to lower the Q of the 42 Hz mechanical resonance, minor and simple mechanical modifications, mainly involving the flange holding the resonator, are still under development.

The new injector PIAVE

The energy plots as function of the beam mass number (see fig. 2) well illustrates the specific function of the new injector in the ALPI complex:

1. It makes acceleration of heavy nuclei (A≥130) feasible.
2. It increases the beam intensity onto target by a factor 10 or more for medium-heavy and medium-light nuclei. For heavy beams intensities are estimated to be around some pnA.
3. It extends the use of ALPI to the rare and costly isotopes.

The new injector preserves the CW operation mode of the ALPI linac and the beam qualities typical of the tandem accelerators.

The crucial requirement of high beam quality is already fulfilled at Argonne National Laboratory where a superconducting linac capable of accelerating very slow ions ($\beta \approx 0.009$) is in full operation since few years [17].

The novelty of our design consists in employing for the first acceleration stage ($0.009 \leq \beta \leq 0.035$) two superconducting RFQ's resonating at 80 MHz following the original idea of I. BenZvi [18]. The rest of the acceleration up to β 0.045 is provided by eight 80 MHz bulk Niobium QWR's ($\beta_{opt}=0.05$) housed in two cryostats.

The layout of PIAVE injector is shown in fig 4

The beam, produced by a 14.4 GHz ECR source standing on a 350 kV high voltage platform [19] is analyzed and transported to the new injector through a matching line which contains an achromatic "U-bend" vertically tilted by 20 deg. The beam emerging from the pre-accelerating column is, in fact, 5 m higher and horizontally displaced by 1.8 m with respect to the new injector beam axis.

The longitudinal phase space matching at the SRFQ input is met by means of a room temperature double drift and double frequency (80÷160 MHz) buncher operating at moderate voltage (V<4 kV) with an efficiency close to 60%. To increase the pulse to pulse time interval to 200 ns for time-of-flight experiments and isomeric nuclear state investigations, a 5 MHz buncher is foreseen on the high voltage platform downstream the source extraction voltage.

Dowstream the RFQ transverse focussing in the QWR accelerating section is accomplished with two quadrupole doublets to compensate for the strong RF defocussing forces active at these low β values. Then the beam enters the linac through an achromatic "L-bend" of the ALPI type and the longitudinal matching is obtained with two room temperature bunchers placed in the beam waists before and after the "L-bend".

The design parameters of the RFQ's are presented in table 1.

The frequency is fixed at 80 MHz which seems the best compromise between beam dynamics and resonator size requirements.

The major constraints for the RFQ design, dictated by the superconducting nature of the cavities, are: the maximum electric surface field E_s (25 MV/m) and the maximum stored energy U (5 J). This last value is imposed by the RF power needed to keep the resonator locked within the required frequency window of ±10 Hz.

Due to the high costs of a superconducting structure and associated cryostat, big emphasis was given to the maximization of the average acceleration E_a; this was pursued bunching the beam outside the SRFQ's and keeping the modulation factor m, kR_0 (average aperture over modulation wavelength) and intervane voltage V relatively large [20].

Once fixed kR_0, and limited m in a certain range, with the reported condition on U and E_s both R_0 and resonator length are determined according to β. Since both V and R_0 are proportional to β, problems in the RFQ design are soon met as β approaches values around 0.035. This velocity is high enough to accelerate with QWR's.

The longitudinal emittance growth during the first stage of acceleration and the transverse mismatch between the to resonators are kept under control constructing a rather long first RFQ, with moderate values of R_0 and V, and a shorter second one with higher R_0, V and E_a values. This configuration allows to shape the first 22 cells of SRFQ 1 as an adiabatic bunch compressor where the synchronous phase ϕ_s decreases linearly from -40 deg down to -18 deg. At the same time the modulation is increased with a law which preserves the specified acceptance.

In the second RFQ ϕ_s is kept constant at -8 deg and both transverse and longitudinal emittances are well within specifications.

The vane shaped four-rods resonators [21] are going to be fabricated in high RRR (250) Nb and will be fully immersed in a liquid He-bath at 4.2 K. Electrodes and stems are hollow structures which allow the liquid-He to get in close contact with all the current loaded surfaces of the resonator. Three mm thick Nb walls are well suited to dissipate the power losses estimated with M.A.F.I.A. code (magnetic field ≤300 Gauss). The present resonator design comes out from the results of extensive M.A.F.I.A. simulations combined with detailed investigation on the mechanical stability of the resonator made with the I.D.E.A.-S code.[1]

Our aim was, in fact, to push the frequency of the lowest vibration mode as high as possible (f>130 Hz) and to try to avoid any environmental perturbation exciting it. In this way we keep the resonator locked in the usual self excited loop scheme by enlarging the bandwidth up to 20 Hz. Any slow frequency drift is corrected by a slow tuner driven by a feedback mechanism which acts in response to the phase error signal.

The SRFQ's are designed to be realized in bulk niobium sheets e-b welded. The problems related to theirs construction are presently tackled with the realization of a stainless steel model. The aim of the prototype construction is to check the required jigs, the rough tuning procedure, the welding feasibility and the mechanical stability of the structure, compared with the computer simulations.

---

[1] IDEAS-S Finite Element Modeling, Structural Dynamics Research Corporation, 2000 Eastman Drive, Milford,OHIO 45150, USA

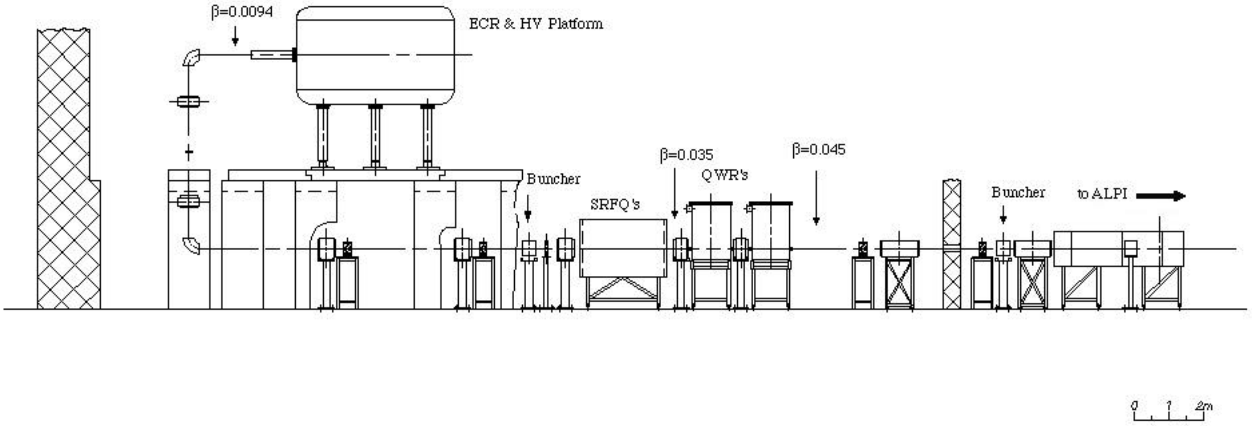

Fig. 5. The technical layout of the new injector PIAVE

Table I SRFQ's parameter list[*]

Radio Frequency	80	MHz	
Input Energy	41.2	keV/u	(β=.0094)
Output Energy	578	keV/u	(β=.0352)
Average acceleration*	2.16	MV/m	
Max. Surface E field*	25	MV/m	
Max. surface B field*	295	G	
Max. stored energy/RFQ*	≤4	J	
Acceptance	≥0.9	mmmrad	(norm.)
Output emittance	0.5	mmmrad	(norm.)
	≤0.7	nskeV/u	

Conclusions

In the last few years at LNL have been introduced many innovations in the fabrication of QWR's with the result of obtaining high performing resonators at moderate costs. The SC-ALPI linac is working according to the experiment needs and it is going to reach the expected 35 MV in the near future.

A challenging new injector based on SRFQ's has been recently funded and it is expected to be in operation in three years from now.

Acknowledgments

The results presented in this paper have been possible for the invaluable efforts of the colleagues of the LNL accelerator division.

References

[1] L.M. Bollinger, Annu. Rev. Nucl. Part. Sci. 36 (1986) 475. See for the numerous references concerning ATLAS.
[2] J.N. Noe', Rev. Sci. Instr. 57 (1986) 757.
[3] I. BenZvi, B. V. Elkonin, J. S. Sokolowsky and I. Tserruya, Nucl. Inst. and Meth. **A254**, 306.
[4] D.W. Storm et al., Nucl. Instr. and Meth. **A287** (1990) 247.
[5] G. Fortuna et al, Nucl. Instr. and Meth. **A287** (1990) 253.
[6] A. Lombardi et al., this Conference Proceedings.
[7] A. Dainelli et al., Proc. of the 7th International Heavy Ion Accelerator Technologies Conf., Canberra (1995), to be published on Nucl. Instr. and Meth. **A.**
[8] A. Facco et al., Proc. 3rd Europ. Particle Accel. Conf., Berlin 1992, eds H. Henke, H. Homemayer and Ch. Petit-Jean-Genas (Edition Frontieres, Gif-sur-Yivette) p.1507.
[9] I. BenZvi et al., Proc. of the 2nd Europ. Particle Accel. Conf., Nice, 1990, eds P. Marin, P. Mandrillon, Edition Frontieres, p. 1103.
[10] R. Pengo et al., Nucl. Inst. and Meth. **A238** (1993) 242
[11] G. Fortuna et al., Nucl. Inst. and Meth. **A238** (1993) 236 and references therein.
[12] U. Trinks, P. Schütz, Proc. of the 6th Workshop on rf Superconductivity CEBAF ed. R. M. Sundelin (1993) vol. 1 p. 167.
[13] S. Gustafsson et al., Proc. of the 7th Workshop on rf Superconductivity Gif-sur-Yivette, ed. B. Bonin (1995) vol. 2 p. 589.
[14] V. Palmieri Proc. of the 7th Workshop on rf Superconductivity Gif-sur-Yivette, ed. B. Bonin (1995) vol. 1 p. 237 and references therein.
[15] V. Palmieri et al., Proc. of the 7th International Heavy Ion Accelerator Technologies Conf., Canberra (1995), to be published on Nucl. Instr. and Meth. **A.**
[16] A. Facco, J. S. Sokolowskj, Proc. of the 4th Eur. Part. Acc. Conf., London, eds. V. Suller, Ch. Petit-Jean-Genaz (1994) 2054
[17] L.M. Bollinger et al., Nucl. Instr. and Meth. **A328** (1993) 221.
[18] I. BenZvi, A. Lombardi and P. Paul, Particle Accelerators 35 (1991) 177
[19] M. Cavenago, G. Bisoffi Nucl. Instr. and Meth. **A328** (1993) 262.
[20] A. Pisent, "Beam Dynamics of the new LNL Injector" LNL-INFN (REP) 107/96.
[21] G. Bisoffi, G Algise and A. Lombardi, Proc. of the 7th Workshop on rf Superconductivity Gif-sur-Yivette, ed. B. Bonin (1995) vol. 2 p.677.

---

[*] The values are referred to a mass to charge ratio of 8.5 e.g. $^{+28}U^{238}$.