REVIEW OF ALPI

L. Badan, G. Bassato, A. Battistella, M. Bellato, A. Beltramin, L. Bertazzo, G. Bezzon, G. Bisoffi, G.P. Buso, S. Canella, M. Cavenago, F. Cervellera, F. Chiurlotto, T. Contran, A. Dainelli, M. De Lazzari, A. Facco, P. Favaron, G. Fortuna, S. Gustafsson, M. Lollo, A. Lombardi, S. Marigo, M.F. Moisio, V. Palmieri, R. Pegoraro, R. Pengo, A. Pisent, F. Poletto, M. Poggi, A.M. Porcellato, R. Preciso, F. Scarpa, B. Tiveron, J.S. Sokolowski[1], V.L. Ruzinov, S.Y. Stark[2] and S. Dong[3]

INFN-Laboratori Nazionali di Legnaro, Legnaro (Padova) Italy;
[1] The Weizmann Institute of Science, Department of Nuclear Physics, Rehovot, Israel.
[2] Moscow Steel and Alloys Institute, Moscow, Russia
[3] Institute of Nuclear Research, Academia Sinica, Shanghai, China.

Abstract

The installation of the medium beta section ($\beta = 0.11$) of ALPI has been completed and a description of the status of the whole complex is given. The beam test results are described together with the statistics concerning the operation of all the subsystems involved, such as the magnetic lattice, the diagnostics, the control system, the rf cavities, the pulsing system and the cryogenics. The status of the niobium sputtered QW resonators and their installation in the accelerating chain are discussed. Experimental results of the bulk niobium cavities for the low beta section ($\beta = 0.05$) operating at 80 MHz, and niobium sputter-coated, are presented. Studies and status of the installation of the new positive ion injector for ALPI, consisting in an ECR source and a SC-RFQ, are reported.

1 INTRODUCTION

The ALPI (Acceleratore Lineare Per Ioni) complex consists in a series of 93 indipendently phased superconducting accelerating cavities that operate at two different frequencies, namely 80 and 160 MHz. It will be able, when completed, to deliver ion beams ranging from 6 up to 20 MeV/u.

The project, funded in 1989 within the five year plan of the INFN (Istituto Nazionale di Fisica Nucleare), has been divided in two phases [1]. The first phase was intended to allow the acceleration of the intermediate ion mass range, from Si up to I, and it is based on 160 MHz Lead plated resonators with an optimum velocity of β_o=0.11. The accelerating cavities are OFHC Copper lead plated Quarter Wave Resonators (QWR). The second phase foresees 21 bulk niobium resonators with β_o=0.055 operating at 80 MHz, as a low-β section, and 21 high-β section operating at 160 MHz with β_o=0.15. In this phase is also foreseen a new injector consisting in an ECR source sitting on a high voltage platform followed by a Superconducting-RFQ. This new injector will allow ALPI, in the final state of the machine, to accelerate all ion species above the interaction barrier for any Beam-target system.

The first phase of ALPI has been completed and the first beam has been delivered to the experimental hall. At present 44 accelerating QWR and 3 superconducting bunchers are installed and under commissioning.

2 DESCRIPTION OF ALPI

2.1 Layout

In order to use the existing experimental halls ALPI has been, folded in two parallel line connected with a U-bend. Two long connection lines have been built to inject the beam from the TANDEM and to bring the beam back to the experimental set-ups (fig. 1).

The magnetic lattice contains two 90° dipoles, which bend the beam coming from the TANDEM into the low energy part of ALPI, four 45° dipoles, for the U-bend, and two more 45° dipoles to bend rightward to return to the experimental halls.

In order to simplify the shielding of the machine ALPI is placed 4 m below the TANDEM level. To overcome this displacement the two 90° magnets are tilted by an angle of ~7° and in the return line there are two 6° vertical dipoles that bring back the beam to the level of the TANDEM vault.

To complete the machine there are 3 quadrupole doublets and 23 triplets providing proper transverse focussing and 6 quadrupoles to make all the bendings isochronous and achromatic.

The basic unit of the machine is the module, made of two cryostats, one triplet and a diagnostic box.

2.2 Diagnostic system

Every module contains a diagnostic box which can monitor the two transverse planes profiles, the longitudinal phase

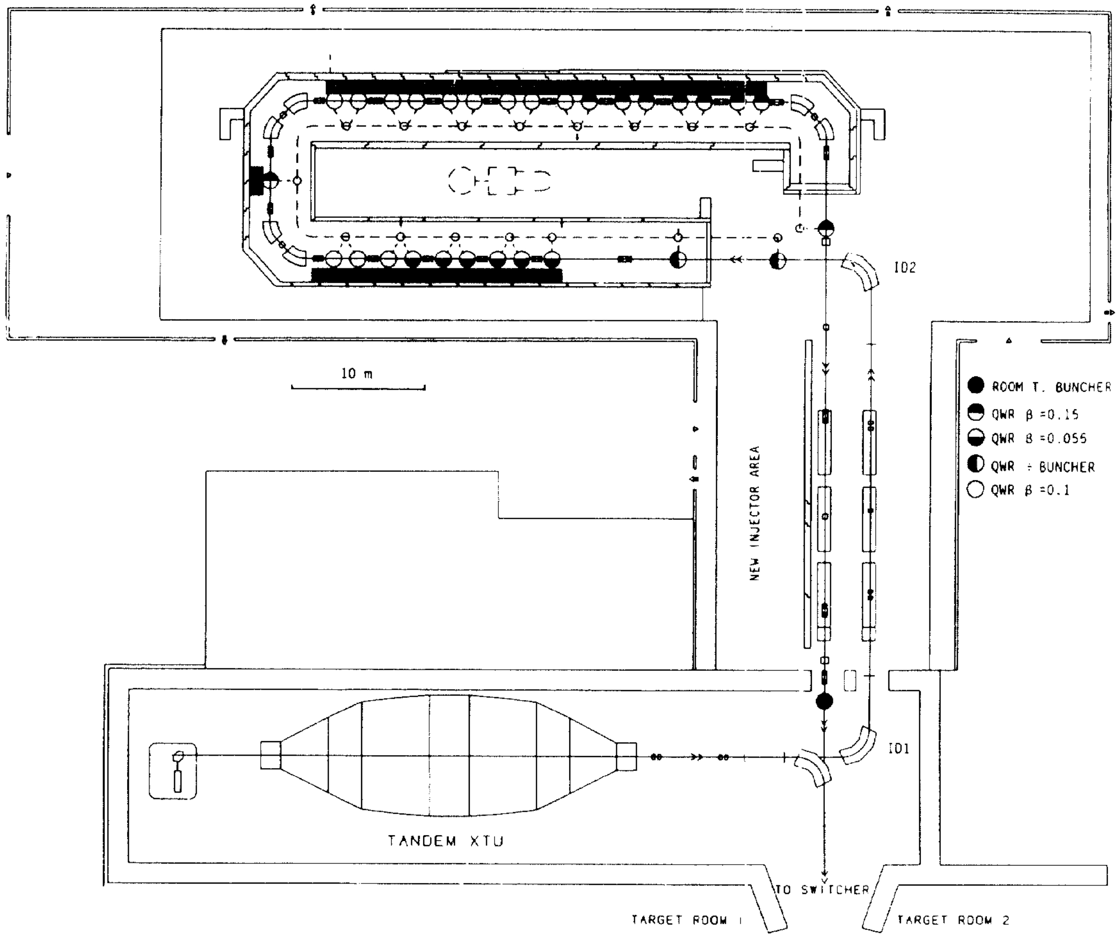

Figure 1: ALPI phase 1 layout

space and the beam current intensity [2]. Other diagnostic boxes are placed along the injection and extraction line that allow to check the beam transport at every beam waist. Not all the equipments are housed in each box but only that which are necessary for the machine operation e.g. the longitudinal phase plane is checked at the input of ALPI and just after the U-bend.

The transverse plane detectors are Beam Profile Monitors made of two grids of 39 thin tungsten-rhenium wires, 20 μm in diameter and a pitch of 250 μm which give a beam transmission of the order of 90%. The signals, coming from an array of preamplifiers, through an analog board for the current to voltage conversion and a logic board for multiplexer scanning, are sampled by a remote VME ADC board and the output is sent to the graphical workstation. In the same display one can see the value of the current on the Faraday cup also housed in it. The interactive display allows also to operate the grids and the Faraday cups.

Concerning the longitudinal phase space the average energy spread and the average time length are measured using a Silicon Surface Barrier Detector (SSBD) which detects the particles scattered by a gold foil. In alternative, for a non destructive measurement, the time structure can also be detected by a Micro Channel Plate, collecting the secondary electrons emitted by a single biased wire located on the beam path.

Another device for the bunch length detections is now under investigation. It is based on a Coaxial Fast Faraday Cup and an oscilloscope with a very large bandwidth (of the order of 10 GHz) [3].

A room temperature 5 MHz resonator has been used in the stabilization of the pulsing system. This device is also a very sensitive non destructive beam current monitor capable of detecting currents from 0.3 to 140 nA [4].

2.3 *Cryogenic system*

The refrigeration system is completely installed and it is under commissioning since september 1993. The complete scenario of ALPI [5], apart from the new positive ion injector, foresees the operation of 98 rf cavities at 4.5 K, located in 29 cryostats. Each cryostat has also a 60 K shield, cooled with the He gas, that screens the cavities and the liquid He reservoir. The capability of the system is now 1300 W at 4.5 K plus 3900 W at 60 K. The liquid He produced is stored in a 2000 l dewar and then distributed along the cryogenic lines to the cryostats. The cryostats are fed either by single or double distribution boxes with the automatic control of the proportional input valves.

2.4 *Pulsing system*

To inject properly into the accelerating cavities of ALPI, the dc beam produced by the ion source in front of the TANDEM has to be bunched and the bunch length at the injection has to be of the order of a few hundreds of picoseconds.

The bunching is achieved with a pulsing system [6] based on a low energy double drift double frequency buncher, working at the fundamental frequency of 5 MHz, which compresses the beam to the nanoseconds range with an efficiency up to 70%. After the TANDEM there are two choppers operating at 5 and 10 MHz and a phase detector based on a 5 MHz resonant cavity.

In the final configuration two superconducting bunchers,one operating at 80 MHz and the other at 160 MHz, will be used to achieve the necessary bunch length of about 200 ps. The 160 MHz buncher is already in operation and the second one will be installed during the second phase of the project.

2.5 *RF system*

The accelerating complex is made of an array of superconducting QWR's [7] indipendently phased and working in a self exciting loop mode[8]. They are arranged in group of four per cryostat and are able to sustain, in normal operation, an average accelerating gradient of about 2.5 MV/m at 7 W.

The majority of the resonators installed along the linac (34) were lead plated in 1993, after the optimization of the plating procedure (only three cavities were rejected at this stage). A preliminary laboratory test of their performance was possible for only three of them; all the others have been tested and conditioned on the beam line. The mean measured Q_0 value was 1.4×10^8.

Most of the resonators were RF-conditioned only for 2 or 3 hours each, which did not allow to obtain the reachable performances (about 2.8 MV/m): time had in fact to be shared with assembling and with beam transport tests. Only 12 cavities were He-conditioned since the He-conditioning system is at present completed only for the first three cryostats.

In well conditioned lead-plated cavities the Q-curve is flat up to the field emission threshold (about 3 MV/m). On the other hand, in the case of the two tin-lead-plated resonators the quality factor is decreasing since the very low fields.

2.6 *Control system*

The ALPI control system is based on a network distributed architecture [9] operating at three different levels: Unix based workstations for the operators interfaces, Ethernet and TCP/IP for the communications and the interconnections, and VME hardware loaded with VxWorks together with some dedicated processors for the control of the physical devices. The whole control system has been designed and built in house following the request of the machine designers.

2.7 *Vacuum system*

The vacuum system is based on indipendent pumping stations for each cryostat and for each diagnostic box. The system is ruled, indipendently from the central control system, via local controller installed in each module of the machine. The informations coming from the readout of the vacuum gauges are then shared with the cryogenic system controller.

3 COMMISSIONING AND BEAM TEST RESULTS

The testing of the various systems in the ALPI vault is going on since the first half of 1992 when there was the installation of the first group of cryostats in the low energy section of the machine. Since than the assembling and the testing of the apparatus have been proceeding in parallel.

The ALPI beam tests are going on in parallel with the TANDEM operation for experiments. This choice has been dictated by the strong user pressure on the machine.

During 1993 it was decided to stop the beam tests in ALPI, including the rf conditioning 'in situ' of the cavities, for a period of 5 months in order to complete the installation of the cryogenic system which was designed and built in two stages following the ALPI project philosophy.

By the end of 1993 twelve cryostats were assembled, put on the beam line and aligned. Ten of them contain four resonators and the remaining two host two resonators each used as bunchers. During the first two months of 1994 one more cryostat has been added to the machine which completed the first phase.

The most time consuming procedure, to set up the machine, is the conditioning of the QWR's once they are on the beam line. This setting and operation strongly depend on the reliability of the cryogenic and the vacuum systems.

The operation has been carried out in parallel with the completion of other ancillary systems, such as the safety control system. By May 1994 there were thirteen cryostats ready for acceleration.

For the beam test a $^{12+}NI^{58}$ beam was injected from the TANDEM, operating at 15 MV, with a total energy of 195.15 MeV.

The pulsing system described above provided a beam of 2.8 ns at the input of ALPI, and the superconducting buncher compressed the bunch to the measured value of about 300 ps.

As mentioned above the QWR's are phased one by one, at the nominal phase value of ϕ_s=-20°, in sequence. Two methods have been used to set the right phase in two successive beam runs.

The first is based on the energy gain measurement made with a SSBD to set the phase shifter. The energy gain is measured versus the phase (referred to a master oscillator)and the data are fitted with a sine wave.

With this method the first three cryostats in the low energy branch of the machine have been phased in March 1993, for a total of 11 accelerating QWR's and the superconducting buncher.

The second technique uses the 90° bending in a dispersive operation mode, for both the lower energy and the upper energy side. This method consists in making a scan with the phase shifter of each cavity and look at the beam profile center in the nearest diagnostic box after the bending and then set the correct phase value (ϕ_s= -20). The operation in ALPI is complicated by the presence of two 45° bending magnets that have to be operated both at the same time.

With this second technique 36 accelerating cavities have been setted in May 1994 delivering a beam in the experimental apparatus GASP [10] with an energy of 346.5 MeV and and intensity of about 1 p-nA. The average accelerating field was 2.18 MV/m. with a dissipation of about 7 W per cavity.

The U-bend, that connects the low energy side to the high energy one, is required to be isochronous and achromatic. The other main feature of the U-bend is that it has to rebunch the beam down to a few hundred picoseconds in order to inject properly to the following QWR's. The cryostat placed in the middle of the U-bend hosts two QWR's and, with a field of 825 kV/m, they refocussed a 620 ps bunch down to 360 ps.

The setting up of the machine took ~24 hours, from forming the beam with the low energy pulsing system to the delivery to the experimental site. This has been possible because 40 resonators were prepared in advance (regarding frequency adjustment and conditioning) during the three months before the beam time.

All coupling and tuning devices worked properly and only one resonator was found to be 400 Hz out of frequency.

The beam was stable on the target for longer than two days whereafter an interruption of liquid He production stopped the test. The beam was recovered after ~24 hours and sent to a second experimental stand for few hours. The resetting of the machine took ~6 hours.

The most delicate ALPI subsystem, because of its complexity, was proved to be the cryogenic one.

4 STATUS OF PROTOTYPES AND STUDIES FOR THE UPGRADING OF ALPI

The second step in the project is the accomplishment of the ALPI phase 2 which consists in the low-β section, the high-β section and the new positive ion injector to flank the XTU TANDEM with an ECR source and a superconducting Radio Frequency Quadrupole chain.

The effort is mainly devoted to the design and construction of the superconducting resonators. Apart from the superconducting RFQ, all the cavities under investigation are of QWR type.

Two different technologies are involved in this studies. One is the bulk niobium and the second is the sputtering of Niobium on OFHC Copper substrates.

4.1 Superconducting resonators

Since the beginning of ALPI, studies have been carried on concerning the bulk niobium QWR's [11] with different resonant frequencies ranging from 80 to 240 MHz.

As mentioned above, the accelerating resonators for the low-β section of ALPI will be bulk niobium QWR's. Recently one prototype of a series of 6 cavities, working at 80 MHz and fabricated by an italian company, was successfully tested at the Laboratori Nazionali di Legnaro (LNL). The results of the Q value measurements are shown in figure 2.

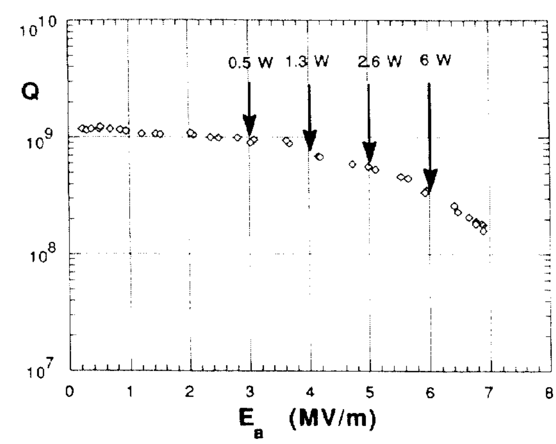

Figure 2: Low-β 80 MHz bulk niobium resonator Q-curve

A Niobium coating technique has been developed at the LNL by means of the sputtering deposition [12]. Minor changes of the 160 MHz medium-β reasonator geometry were made to realize a Niobium sputtered cavity characterized by a β_{opt}=0.14 which can be used in the high-β linac section.

The Q curve versus the accelerating field for a cavity ready to be placed on the beam line is shown in figure 3.

Four Niobium sputtered QWR's will be assembled in the next cryostat to be put in the linac.

4.2 The positive ion injector

The first part of the new injector, namely the ECR source, was already built and tested [13]. At present the high voltage platform which will house the source, together with its

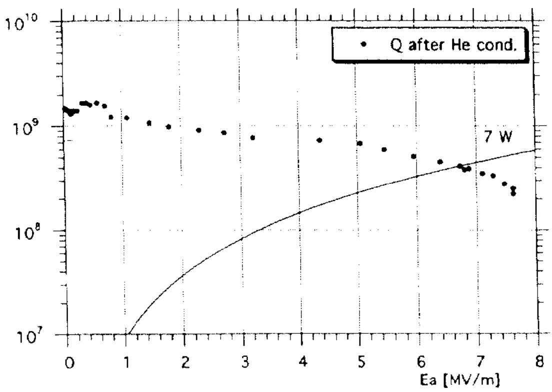

Figure 3: 160 MHz sputtered Niobium resonator Q-curve

analysing magnet and the bunching system, is under construction. In the near future the ECR will be placed in its final position in the ALPI vault and the commissioning, together with studies of metallic ion extraction [14], will start again after a long shutdown due to necessity of removing the source from its present place. Measurements of source alignement were performed [15].

The new accelerating structure, that will cover the velocity range from β=0.01 to β=0.05, is under investigation and prototyping. It will be a superconducting RFQ chain [16] operating at the frequencies of 40 and 80 MHz. It will accept a prebunched beam coming from the 350 kV platform with a charge to mass ratio of 1/8.

5 CONCLUSIONS

The commissioning of the first phase of ALPI is going on at LNL since the begining of 1994 and the preliminary results, with the beam delivered to the experimental hall, are satisfactory. The required reliability of the complex for the normal operation and improvement of the overall transmission efficiency need future work.

All subsystems have been succesfully tested.

The two QWR's construction technologies, bulk niobium and niobium sputtered on copper, gave very good results and cavities to be put in the beam line, for both technologies, are under construction.

The ECR source was constructed and tested and the high voltage platform is being assembled. The accelerating structures of the new positive ion injector are under investigation.

6 ACKNOWLEDGEMENTS

The authors would like to thank all the LNL foreign collaborators that in the different phases helped in the design, construction, assembling and alignment of ALPI. Among them D. J. Larson and I. Ben-Zvi, for the help during the design and the initial technical choices, K. Rudolph, who spent some years at the LNL helping in the rf systems and eletronics, E. A. Togun and T. Zhang, for the beam simulations, V. Kurakin, V. Andreev for their useful suggestions and hard work in the alignment of all the components of the machine and V. Stolbunov for his collaboration in the high voltage platform project.

7 REFERENCES

[1] G. Fortuna *et al.*, Nucl. Instr. and Meth. A287 (1990) 253-256.

[2] M. Bellato, A. Dainelli, M. Poggi, "The beam diagnostic system of the ALPI post-accelerator", EPAC92 Proceedings,1085- 1087.

[3] M. Bellato, A. Dainelli, M. Poggi these Proceedings.

[4] A. Facco *et al.*, A high sensitivity phase stabilizing system and beam current monitor, NIM A 337 (1994), 253-257

[5] R. Pengo *et al.*, Cryogenics and related topicsof the ALPI linac, NIM A328 (1993), 242-250

[6] A. Facco *et al.*, The ALPI pulsing system, EPAC92 Proceedings,1507-1509.

[7] A. M. Porcellato *et al.* On-Beam and Off-Beam Performance of Qarter Wave Resonators for the ALPI Linac, Proceedings of S.N.E.A.P. '90 Kansas State University, 259-277

[8] G. Bassato *et al.*, Automation of procedure for locking ALPI resonators, NIM A328 (1993), 195-198.

[9] G.Bassato, A. Battistella, M. Bellato, S. Canella "The control system of the LNL linac", EPAC92 Proceedings,1145-1147.

[10] D. Bazzacco *et al.*in Proceedings of Iternational Conference on Noclear Structure at High Angular Momentum (Ottawa 1992),vol 2, AECL 10613

[11] A. Facco *et al.*, Bulk niobium Low-, Medium-, and High-β superconducting Quarter Wave Resonator for the ALPI postaccelerator, 1993 Particle Accelerator Conference Proceedings.

[12] V. Palmieri *et al.*, Niobium Sputter-Coated Copper Quarter Wave Resonators, to be published on the proceedings of the 6-th Workshop on RF Superconductivity, october '93, CEBAF Newport News, R. Sudelin ed..

[13] M. Cavenago and G. Bisoffi, Commissioning of the ECR ion Source Alice, NIM A328(1993), 262-265.

[14] M Cavenago *et al.*These Proceedings

[15] V. Balakin *et al.* Magnetic field and beam position measurements for the ECR ion source ALICE, These Proceedings

[16] I. Ben-Zvi, A. Lombardi and P.Paul, Particle Accelerators **35** (1991) 177.