PIAVE THE LEGNARO NEW POSITIVE ION INJECTOR BASED ON SUPERCONDUCTING RFQS

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Abstract

The construction of a positive ion injector for the linac ALPI, named PIAVE, at Laboratori Nazionali di Legnaro started in 1996 and the commissioning with beam on target is scheduled for the second half of 2001. The injector consists of two Superconducting Radio Frequency Quadrupole accelerators (SRFQ) and eight Superconducting Quarter Wave Resonators (QWR). The equivalent accelerating voltage of the machine is of about 8 MV and the design ion beam is $^{238}U^{28+}$. The SRFQ resonators, as well as the QWR's, are made of niobium sheets formed and electron beam welded and a particular care has been put in the mechanical design of the structure to avoid low frequency mechanical modes. The paper presents the status of the project describing: the novelties related to the SRFQ design to fulfil the radio frequency and the beam dynamics requirements: the first results of the low energy beam transport commissioning; the experimental performances of the SRFQ2 resonator; the full set of measured performance of the QWR's.

1 INTRODUCTION

The PIAVE injector was planned since the design of the superconducting heavy ion accelerator ALPI presently in operation at the Legnaro National Laboratories. The motivations for the realization of such a positive ion injector are the request of ion beams with masses above 100 amu, which are very difficult if not impossible to deliver using the XTU Tandem electrostatic accelerator.

The difficulties for the Tandem come from the presence of a negative ion source from one side and the necessity of the stripping in the Tandem terminal on the other. These two aspects limit the ion species and the beam intensity available for the experiments respectively.

Consequently PIAVE is made of a positive ion source and of a superconducting rf accelerator in order to fully use the capabilities of the booster in terms of duty cycle.

As far as the main components of the complex the choices of the source type and of the very low energy side of the injector was dictated by the presence on site of the ECR source [1], the very well established know how concerning the Superconducting Quarter Wave Resonator for the heavy ion accelerator [2] and by the feasibility studies of a Superconducting RFQ (SRFQ) made in collaboration with the SUNY at Stony Brook [3,4].

PIAVE is the combination of the ECR source, a pre-injector, a three harmonic buncher, two SRFQ resonators housed in a single cryostat, eight QWR's housed in two cryostats and two beam transport and matching line including two room temperature bunchers.

The source is placed on the 350 kV high voltage platform in order to have the proper injection velocity inside the SRFQ (β= 0.0089). Downstream of the accelerating column there is a quite long Low Energy Beam Transfer line (LEBT), which carries the beams approximately 4 m below the ground level, following the topology of the PIAVE vault, and matches the beam inside the SRFQ in the six dimensions phase space.

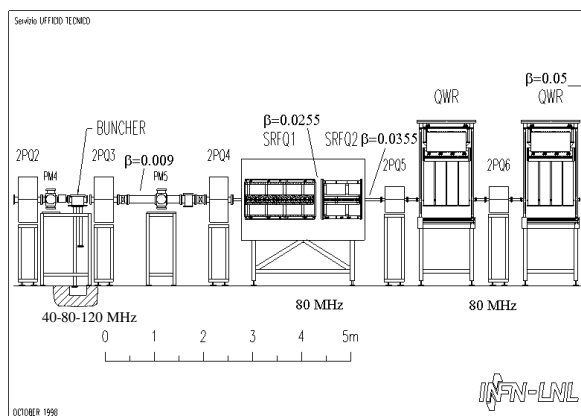Figure 1 shows the accelerating structures of PIAVE.

Figure 1: The PIAVE accelerating structures

The novelty of the project being the SRFQ structure all the other components of the machine were kept as much as similar to the ALPI components and ancillary apparatus. For this reason the rf control system, the beam diagnostics, the vacuum control system, the QWR cryostats, the magnets control system are a reviewed and upgraded version of the ALPI systems.

The PIAVE project was approved by INFN in July 1996 following the commissioning of ALPI.

The main machine parameters characterizing PIAVE are summarized in table 1

Table 1: Main PIAVE parameters

Ion species	All elements	

Mass to charge ratio	8.5÷2	
RF Frequency	80	MHz
Input energy*	37.1 (β=.0089)	keV/u
Output energy*	1.2 (β=.051)	MeV/u
Equivalent voltage*	9.9	MV
Trans. Emittance	0.5 (5*ε_{rms}norm)	mm*mrad
Long. Emittance	3.5 (.95 Mev/u)	deg*MeV

* The values are referred to a mass to charge ratio of 8.5 ($^{+28}U^{238}$)

2 ACCELERATOR DESCRIPTION

2.1 LEBT

The beam coming out of the source is accelerated by the accelerating column and it is displaced 5.2 m in height and 1.7 m in the horizontal plane respect to PIAVE beam axis. The displacement is done by a magnetic U-bend, made of two 90° bending magnets, two triplets and a compensating quadrupole in order to have an achromatic transport [5]. To achieve the horizontal displacement, the U-bend is inclined on the vertical of about 18 degrees.

Once the beam is at the ALPI level the LEBT performs the transverse and the longitudinal matching at the input section of the SRFQ structure using 4 quadrupole doublets and a three harmonic buncher [5,6](figure 2).

Figure 2: The PIAVE U-bend (left) and the three harmonics buncher (right)

We decided to have the bunching of the beam outside the SRFQ structure in order to have a shorter SRFQ. The price paid in terms of beam transmission (70% instead of 95%), is allowed by the ECR performances in terms of beam current.

At present the LEBT is operational and under commissioning using the configuration shown in figure 3. In that layout the emittance measurement box is placed instead of the SRFQ and at its entrance.
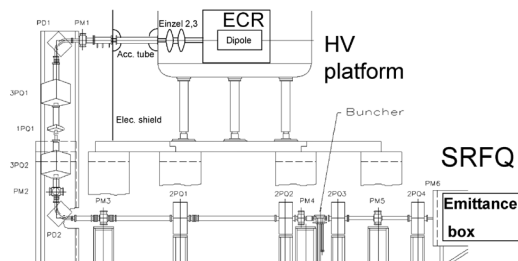

Figure 3: Present configuration of the LEBT for the beam commissioning.

The aim of the LEBT commissioning is to have a complete characterization of the transfer line, in order to operate it using the beam diagnostics available without the necessity of having some beam diagnostic exactly in front of the SRFQ during the normal operations.

The beam tests done up to now consisted in the measurements of the transverse emittances (x and y) Figure 4 shows a picture of the diagnostic used based on slit and grids method [7].

The list of the tested ion species is shown in table 2. The beam characteristics have to be compared with the nominal SRFQ emittance (0.1 mm*mrad rms-normalised) in both x and y planes and with the SRFQ acceptance (0.9 mm*mrad rms- normalised).

There are still problems of beam centring due to the delay in the delivering of the steering magnets

The beam transmission from the accelerating column to the final Faraday cup is of 95% and the optics is very reproducible and stable [8].

The continuation of the LEBT commissioning will include the bunching of the beam using the multi-harmonic buncher, the measurement of the time and energy distributions of the beams at the entrance of the SRFQ and a systematic campaign of measurements with different beams.

Table 2: Beam size σ, currents and normalised rms emittances

Ion	I1 [nA]	σ [mm]	I5 [nA]	εx [mm*mrad]	εy [mm*mrad]
$^{40}Ar^{6+}$	2760	3.1	2600	0.10 ± 0.0067	0.14 ± 0.031
$^{40}Ar^{8+}$	1320	3.4	1210	0.086 ± 0.011	0.16 ± 0.011
$^{40}Ar^{9+}$	720	3.7	630	0.071 ± 0.010	0.11 ± 0.016
$^{129}Xe^{14+}$	120	3.0	110	0.047 ± 0.011	0.074 ± 0.024
$^{129}Xe^{17+}$	270	6.3	238	0.059 ± 0.0086	0.11 ± 0.012
$^{129}Xe^{18+}$	410	3.9	380	0.036 ± 0.0063	0.065 ± 0.030

Figure 4: Beam emittance meter

2.2 The SRFQ's

As mentioned above the most challenging part of the project was the construction of the SRFQ's resonators where a new technology had to be proved. Now, with the recent results, other applications are possible for this type of structure [9]

PIAVE foresees two SRFQ's to accelerate the beam from the velocity coming out of the high voltage platform (β=0.0089) to a suitable velocity for the double gap QWR resonators optimised for a velocity of β=0.047.

We decided to split the SRFQ into two resonators to keep the energy content of a single cavity less than 4 J in order to be able to use a 1 kW amplifier and having a feedback control bandwidth of 20 Hz ($P_a=2\pi U*\Delta f$) [5].

The main design parameters of the SRFQ's are shown in table 3 [5]. The value of 315 kV for the ECR platform and the ion species $^{238}U^{28+}$ are the design specifications coming from the state of the art of the ECR source as far as the charge over mass capability.

The first resonator to be built was the SRFQ2 because it is the most demanding in terms of peak field and energy content.

The technology chosen for the construction of this resonator is bulk niobium sheets formed and eb-welded, making use of the large experience acquired for the QWR's by LNL. Almost all the parts forming and the machining of the pieces were done in house at LNL.

The end plates of the structures, used as tuning plates, are made in niobium sputtered copper.

The aspects studied in very deep details are related to the electromechanical design of the resonator. In effect the larger effort has been placed in the studies of the stiffening of the niobium structure with titanium ribs in order to push the lowest mechanical eigenmode frequency over 120 Hz [10].

The resonator, shown in figure 5, was constructed after a period of R&D made with the realisation of a stainless steel full scale model.

The heat treatment of the SRFQ2 internal parts was done at DESY HV-furnace prior to their eb-welding.

The chemical polishing was done at CERN.

The resonator underwent to room temperature rf measurements with the bead pulling technique in order to check the mechanical precision of the structure and the rf mode separation. The measured unbalance of the four quadrants is less than 0.4%, with a relative dipole mode splitting of 0.8% [10].

Table 3: SRFQ design parameters

	SRFQ1		SRF2		
	In	Out	In	Out	
Energy	37.1	351.3		585.4	**KeV/u**
	8.82	83.61		139.3	MeV
Beta	0.0089	0.027		0.035	
Voltage	148.0	148.0	280.0	280.0	kV
Length		138.9		74.4	cm
N of cells		43		13	
m	1.2	2.8	2.7	2.8	
a	0.7	0.4	0.8	0.8	cm
R_0	0.80	0.80	1.53	1.53	cm
ϕ_s	40.0	18.0	12.0	12.0	deg
$E_{p.s}$		24.		25.5	**MV/m**
U		1.8		3.5	J

The 4 K measurements showed and even better situation than the room temperature one and we can say that the cold mechanical precision of the electrode relative positions in within ±75 µm.

The superconducting rf test performed on the SRFQ2 resonator gave very good results in terms of: accelerating field, Q-value and mechanical precision [10].

A quality factor Q = $5\div8\times10^8$ stays basically constant up to E_s=$21\div22$ MV/m, where it starts to drop because of residual field emission (the drop is correlated with X ray emission). A maximum value of 29 MV/m can still be reached in CW operations, at the expense of a much higher dissipated power. A peak surface field exceeding 40 MV/m could be reached feeding the resonator by 10 ms pulses at a repetition rate of 1 Hz.

The phase and amplitude locking of the resonators has been tested up to E_s=12 MV/m with a 700 W class A amplifier and with a rf controller similar to the ALPI QWR's one [11].

Figure 6 shows the final Q versus electrical peak surface field with the corresponding rf dissipated power. On the same picture the design specifications of the resonator are shown (7 W @ E_s=25 MV/m, 280 kV between the electrodes). Finally, it is worth mentioning that the RF-joint between the Nb-sputtered end-plates and the full Nb resonator carries no gasket at all.

The other problem related to the structure was the proper cooling of the electrodes with the liquid helium. The electrodes and the supports are hollow with wall thickness of 3 mm and for a proper cooling one needs that the liquid helium wet all the outer surfaces of the resonators. The only bulk pieces are the electrode tips made in niobium bars. The gas trapping inside the supports and electrodes recesses was avoided using draining tubes as a siphon [12]. The system is very effective up to 40 W average power but it has to be

upgraded for the next test and for the operation in order to give more power margin for the field emission conditioning.
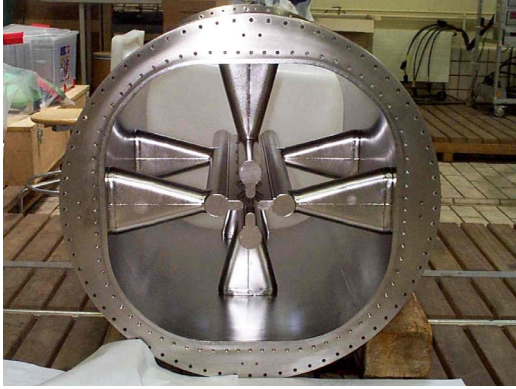

Figure 5: The SRFQ2 niobium-titanium resonator

The SRFQ1 resonator is presently under construction. Its realisation will profit of all the know how acquired in the construction of the previous resonator, having almost the same cross section.

The main difference between the two resonators is the length the electrodes. SRFQ2 electrodes will be cut in two parts to be able to perform the eb-welding of the structure and of the outer shell.
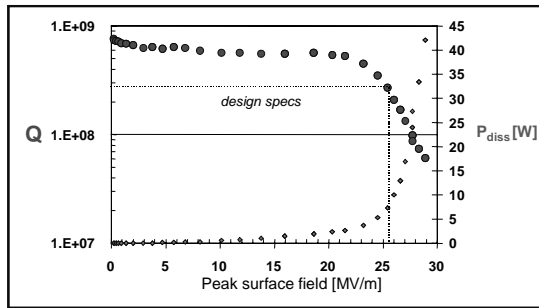

Figure 6: The present performance of SRFQ2 is shown, which exactly matches the design specifications of PIAVE (the inter-electrode voltage at 25.5 MV/m is 280 kV as required for the $^{238}U^{28+}$ reference case).

2.3   QWR's

To accomplish the acceleration of the beam from β=0.035 to β=0.051, to match the optimum velocity at entrance of ALPI, eight bulk niobium QWR's have been designed , built and tested.

The structure of this accelerator section follows the ALPI scheme, four resonators per cryostat, but for the transverse focussing period the lattice is, in this case, made of quardupole doublets and no diagnostic boxes between the two cryostats. Therefore one can use an accelerating gradient of 5 MV/m giving more margins for proper injection in ALPI.

The main difference between these resonators, one of which is shown in figure 7, and the ALPI low β resonators is that the inner conductor is squeezed to decrease the distance between the gaps to optimise the

structure for the lower velocity (PIAVE $β_{opt}$=0.047, ALPI $β_{opt}$=0.055)

Figure 7: View of a PIAVE type bulk niobium cavity.

The required accelerating electric field of PIAVE QWR was increased from 3 MV/m at 7 W to 5 MV/m following the very good results of the first prototype.

The chemical treatment of the QWR's was made at CERN

At present, the average accelerating field of all cavities is 6.8 MV/m with 7 W. The design values of the rf parameters of the PIAVE QWR's are summarised in table 4 [6].

The resonators are ready to be assembled in their cryostats [6] and the accelerating performance are shown in figure 8

Table 4: QWR's rf characteristics.

Frequency	f	80	MHz
Optimum velocity	$β$	0.047	
Acceleration length	l	0.18	m
Stored energy	U/E_a^2	0.13	J/(MV/m)
Max H field	H_p/E_a	≈ 100	G/(MV/m)
Max E field	E_p/E_a	≈ 5	
Norm. shunt res.	R'_{sh}	17.7	MΩ/m
Geom. Factor	$\Gamma=Q \times R_s$	15.4	Ω

2.4   MEBT

To transport the beam from the exit of the accelerating structure of PIAVE to the entrance of ALPI a Medium Energy Beam Transport (MEBT) line is foreseen.

This MEBT is about 10 m long and includes two quadrupole triplets, two room temperature bunchers and one magnetic L bend, made of two 45° dipoles separated by one quadrupole singlet for the chromaticity correction.

The magnetic elements are already in place aligned and waiting for the beam. The remaining element to be installed is the final dipole because it has the same ALPI vacuum and we will install it when we are ready for the beam injection.
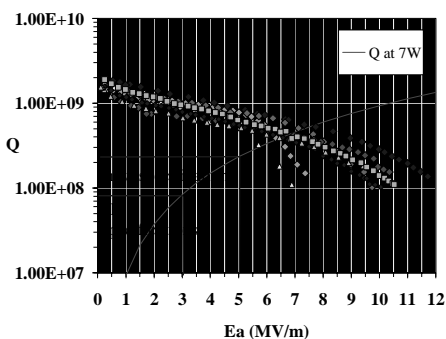
Figure 8: Rf test results of the 80 MHz, low β superconducting cavities. Only cavity n. 8 (square marker) underwent high pressure rinsing.

The distance between PIAVE and the QWR's in ALPI is of the order of 20 m. For this reason we need two re-bunching elements for the longitudinal matching. The buncher technical design is shown in figure 9.

The resonators operate at 80 MHz and they have 100 kV on the gap with 3.9 kW power dissipation. Class AB 10 kW triode amplifiers will feed them and they will be water-cooled.

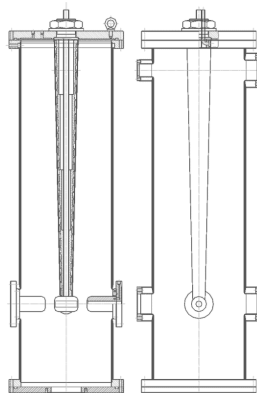The units are presently under construction in the LNL mechanical workshop.

Figure 9: High energy buncher

2.5 *Cryogenics*

PIAVE will be equipped with a separate liquid helium refrigerator capable of about 400 W at 4.5 K cooling power with the nitrogen pre-cooling. It will serve the two existing QWR cryostats, also with helium gas for the thermal radiation shield, and the SRFQ cryostat only with liquid helium. The refrigerator is the old LISA system displaced from Frascati to Legnaro. The SRFQ cryostat is still in its design study stage and it will be constructed by the Budker Institute of Novosibirsk.

3 CONCLUSION

PIAVE is in its final year of construction.

The tests on the SRFQ2 resonator showed the well performances of the resonator in superconducting regime, $Q > 5*10^8$ for $E_s > 22$ MV/m and promising first locking essay. The second resonator, SRFQ1 is under construction.

The other rf structures: QWR's are ready to be installed in the cryostats; the LEBT buncher is installed and ready for beam test; the MEBT buncher is under construction.

The liquid helium refrigerator is undergoing to a special maintenance after is displacement from Frascati and will be ready by the first quarter of 2001.

The QWR's cryostats are almost ready, they need minor modifications in order to be assembled. The SRFQ cryostat order has been placed.

The commissioning of PIAVE is foreseen for the end of 2001.

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