COMPLETION OF THE COMMISSIONING OF THE SUPERCONDUCTING HEAVY ION INJECTOR PIAVE AT INFN-LNL

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Abstract

At INFN-LNL the commissioning of the injector PIAVE, based on superconducting (SC) RFQs, has been completed. All the superconducting cavities (two RFQs and 8 quarter wave resonators – QWR) have shown very satisfactory stability with respect to changes of the liquid helium pressure and to microphonics. Beam parameters are very close to the nominal values. The commissioning was completed by accelerating the pilot beam $^{16}O^{3+}$ with the PIAVE injector and the booster linac ALPI (summer 2005). Since December 2005, a number of test beams were accelerated (mainly noble gas species) with PIAVE and ALPI and delivered to user experimental stations. Regular operation will be scheduled from fall 2006 onwards.

PIAVE COMMISSIONING

The commissioning of the superconducting injector PIAVE with various beam species was completed in early spring 2006. Starting from October 2006, the first official nuclear physics experiments making use of the PIAVE Injector will be scheduled, according to the priorities which shall have been set in July 2006 by the international Programme Advisory Committee.

The Positive Ion Accelerator for low-Velocity Ions (PIAVE) [1] is based on SC RFQs (SRFQs) [2,3], which have been used for the first time for beam acceleration on a user-oriented accelerator complex. The SRFQs are followed by eight SC Quarter Wave Resonators (QWRs). The beam, received from an ECR source on a 350kV platform, is bunched between the ECR and the SRFQs and re-bunched between PIAVE and the SC booster ALPI by normal conducting cavities [4].

The injector setup was done in 2005 with a $^{16}O^{3+}$ pilot beam. In December 2005, after a long shutdown of the ALPI booster cryogenic plant, a very first ^{22}Ne test beam was accelerated by PIAVE and ALPI to the experimental apparatus PRISMA-Clara (final energy ~ 6 MeV/A), where it provided stable beam-on-target conditions for around 50 hours, before scheduled conclusion.

In the period January-April 2006, the LNL tandem-ALPI operation programme allotted around 5 days/month for PIAVE+ALPI beam tests. In this period, tests with ^{22}Ne, ^{132}Xe, ^{40}Ar and ^{84}Kr beams were conducted. Final energy on target ranged between 5 and 8.25 MeV/A and currents between 5 and 15 pnA.

The typical time required driving the beam through injector and booster to the experimental station was ~36 hours.

The period May-July 2006 is being dedicated to maintenance on the SRFQ cryostat and the TCF50 cryogenic system. The tandem-ALPI complex provided meanwhile ion beams to user stations, allowing recovering most of the shifts lost during the long shutdown of ALPI in 2005.

PERFORMANCE OF MAIN SUBSYSTEMS

The beam was kept on target for 2÷3 days in all test experiments with PIAVE + ALPI (conducted between December 2005 and April 2006), so as to check the long term stability of all components. The overall result was indeed very good.

We shall analyze, in the following, the performance of the main accelerator sub-systems, namely the ECR ion source, the refrigerator and the superconducting cavities.

Alice ECR Ion Source

As mentioned above, characterization of the ECR ion source with noble gas beams was completed and, more recently, production of beams from metallic elements ($^{63}Cu^{11+}$, $^{107}Ag^{18+}$, $^{120}Sn^{19+}$, $^{141}Pr^{18+}$, $^{48}Ti^{10+}$) was demonstrated.

To improve the source performance, gas-mixing and biased-disk methods were used. The first beam extracted and delivered, through PIAVE and ALPI, to an experimental area was $^{22}Ne^{4+}$ (12/2005): the mixing gas was He, the microwave power was P_{MW} = 83 W while the bias voltage was V_B ~ -500 V. The neon current extracted from the source was 1 μA (not at the maximum source performance) from a bottle with natural abundance (i.e. 10% abundance for isotope ^{22}Ne) and the transmission to the first diagnostics station after the accelerating tube was very close to 100%. The beam current was stable for all the shift duration (several days), with minor adjustments of the helium flow into the source.

The second beam, delivered to the experiments, was $^{40}Ar^{9+}$: the quite high q/A ratio allowed using a fairly low platform voltage (about 159 KV). The tests were performed, alternatively, with N_2 and O_2 as mixing gases, with no much difference between the two. With $P_{MW} \leq$ 90W and $V_B \leq$ -500V, the beam current on the platform was I_B ~ 8 μA (with 5 μA being a value that can be maintained for a long time): anyway, the current required by the experiment implied no more than 3 μA at injection.

A current I_B ~ 700 nA of $^{84}Kr^{15+}$ (54% isotope abundance), was then obtained, starting from a natural Kr bottle. In this case N_2 had to be used as mixing gas, since the use of O would have caused overlapping of its charge states with the relevant Kr one at the Faraday cup. A slow tuning of the source (~ half day) was needed in this case.

Concerning xenon beams, isotope $^{132}Xe^{18+}$ was successfully injected into PIAVE ($^{22}Ne^{3+}$, having the same q/A ratio, was an excellent pilot beam). I_B is, at the moment, limited to 400 nA, because of both the relatively low P_{MW} used and the use of a bottle with natural abundance (several isotopes have comparable abundances). I_B shall clearly increase, as soon as we shall use a bottle of ^{136}Xe (enriched isotope) and implement a cooled plasma chamber, so as to take advantage of the maximum performances of the microwave generator (400 W).

PIAVE Refrigerator

The main component of PIAVE cryogenic plant is a LINDE TCF 50 refrigerator. It can supply a power of 410 W at 4.2 K, and 1000 W at 80K (with liquid nitrogen pre-cooling). Its maximum power exceeds, by ~ 30%, the average cryogenic load of the injector, ensuring thereby the necessary redundancy. The cold-box and the dewar are placed above the beam-line tunnel in which the cryostats are located. An external purifier is sited near the cold-box, and it is used to refill the buffer with pure He gas. In fall 2004, automatic refrigeration of all PIAVE cryostats marked the end of the cryogenic plant installation and test phase.

The good operation of the refrigerator is mandatory for a reliable beam transport, since stable phase locking of the resonators is tightly connected to smooth and slow variations of pressure on the liquid He bath. A fine tuning work performed in collaboration with Linde Kr. AG allowed achieving pressure variations smaller than 2 mb/min. Such a drift is enough slow, to allow compensating the related frequency drifts of all SC resonators by means of their mechanical tuners.

Superconducting RFQ and QW Resonators

SC RFQs were conditioned up to the design surface field required by the reference $^{238}U^{28+}$ beam, i.e. 25.5 MV/m, (E_s/E_a ~ 10 and 7.33 for SRFQ1 and SRFQ2 respectively). The field value for different ion beams scales with the q/A ratio. Setting a field of 25.5 MV/m requires a dissipated power of ~ 10 W at 4.5 K. Residual field emission is present in SRFQ2 at this field level. However, E_s = 22 MV/m (i.e. 86 % of the nominal value) was reliably used, for time spans of around 5 days, for the above mentioned $^{22}Ne^{3+}$ and $^{132}Xe^{18+}$ beam tests.

Superconducting Quarter Wave Resonators (QWR) reached off-line accelerating field of ~ 7 MV/m (E_s/E_a~5), while their nominal accelerating field in PIAVE is 5 MV/m. Beam dynamics considerations suggest scaling the nominal field of QW resonators with the q/A ratio as well. Therefore, we used in operation a field as high as 4.3 MV/m on the 8 QW resonators of PIAVE, also with several days of stable conditions.

Phase and amplitude locking asks for an enlargement of the resonant bandwidth on all cavities. This is achieved: on QWRs, by over-coupling the SC cavity in a self-excited loop (SEL) mode (100÷300 kW amplifiers are used); on SRFQs, using VCX fast tuners [5].

Two different systems were adopted, in SRFQ and QW resonators, to compensate for the cavity frequency changes due the variation of the liquid helium pressure, maintaining their actual frequency in the resonator bandwidth.

Figure 1: SRFQ resonators in their cryostat.

For SRFQs, where the frequency sensitivity to pressure variation is $\Delta f/\Delta P$ = -48 Hz/mbar for SRFQ1 and -39 Hz/mbar for SRFQ2, a double system is adopted: pushing or pulling either end plate with respect to the quadrupole vanes (capacitive tuning) allows recovering positive or negative frequency changes, with virtually no back lash. Variations of the liquid He pressure smaller than 2 mb/min are consistent with the maximum frequency change rate of each tuner (~ 2 Hz/s, corresponding to 3 mb/min). At the tuning range end, the direction of motion of both end-plates must be reversed (every 6÷12 hours in the beam tests carried out so far).

QWR resonators (f vs. P sensitivity ~ 1 Hz/mbar) use single end-plate tuners. Half of the 8 QW PIAVE resonators feature new high-resolution tuners [6], capable of providing steps as small as 0.33 μm or smaller, corresponding to frequency steps of 1 Hz and with negligible back lash.

As a conclusion of the several beam tests of the latest months, it is noted that, for all resonators (both SRFQ and QWR), unlocking is an extremely rare event (less than once a day), while one or two times per hour, on average, phase and amplitude errors typically exceed their maximum values (0.4 deg in phase and 0.25 % in amplitude), for a few seconds at most and recover automatically, without any operator actions.

BEAM TRANSPORT RESULTS

Beam tests were carried out first of all through the LEBT (Low Energy Beam Transport) line, then through the SRFQs, later through the entire injector and more recently through the ALPI booster to the target and detector arrays. A beam of $^{16}O^{3+}$, from the ECR ion source on a high voltage platform, was used for the first tests of beam characterization through PIAVE (a current of ~ 1÷3 μA was typically available from the source).

Setting of the relative phase between SRFQ1 and SRFQ2 was achieved by looking at the final beam energy and transmission [7]. As expected, the beam energy at the end of PIAVE was 20.8 MeV.

Beam transmission, between 85% and 100% in the cavity-free regions, turns out to be as high as 68% in the 3H-buncher [2]-to-SRFQ section (expected value 69%).

Transverse emittances are measured using a slit and a grid at fixed distance, moved together by a stepping motor for each plane, either the horizontal or the vertical, at a time. The beam profile monitor "wires" are actually little bars of tungsten, 0.4 mm thick. There are 77 such bars (spaced by 0.6 mm) for each plane. The distance between the slit and the beam profile monitor plane is 300 mm, so that an angular accuracy of 3 mrad is achieved. The whole covered angular divergence is 231 mrad. The slits are made by tungsten, with a 100 μm wide aperture, and they stick to a piece of copper so as to dissipate the beam heat. For beam measurements after the RFQ the effective step size was halved (0.5 mm) by mounting two grids one on top of the other.

Transverse emittance has been measured for different beams. In Table1 results for Ar^{9+} are presented, with all QWR cavities respectively off and on (0.58 and 1.2 MeV/u). The vertical emittance with QWR off is perfectly consistent with LEBT beam measurements, and the 25% increase, with QWRs switched on, is acceptable. As for horizontal measurements, the only-RFQ-on value is again in agreement with simulations, while the increase after switching of the QWRs, probably due to still poor beam alignment, has to be better investigated. The beam is anyway within ALPI transverse acceptance.

Table 1: Transverse Emittance for Ar^{9+} beam

	$\varepsilon_{rms,x}$ [mm-mrad]	$\varepsilon_{rms,y}$ [mm-mrad]
PIAVE QWR OFF	0.100	0.103
PIAVE QWR ON	0.200	0.125

Longitudinal emittance has also been measured in the same position, using a silicon detector intercepting the particles scattered at a 25° angle by a thin golden foil. The data acquisition system allows determining the time-energy correlations with the possibility (in principle) to get a direct plot of the longitudinal emittance. In practice, while the measured bunch length seems correct, we have not yet been able to get an acceptable energy resolution. The silicon detector overestimates the energy spread by one order of magnitude. As a consequence, the rms emittance, measured with the time-energy correlation, is overestimated. We have therefore decided to measure the longitudinal emittance indirectly, following the three gradients method. In Fig.3 we plotted the phase length measurements obtained, by changing the field of the third QWR cavity, which is used as a buncher.

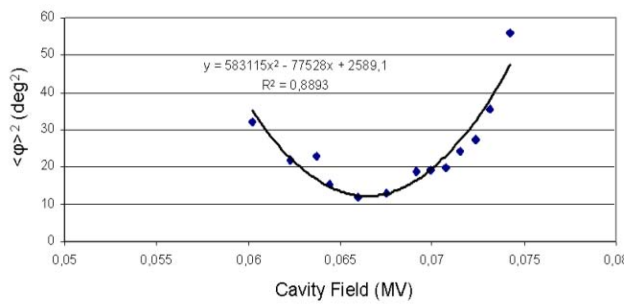

Figure 2: Parabola obtained with the three-gradient method.

Computed emittances are reported in Table 2. Values obtained including the beam tails (w. t.) means that we are using a larger window for the phase spread. The direct measurement means that we use the correlated RMS area of phase and energy spread, that overestimates the emittance as discussed above. The three gradient method gives an emittance value that is, within a factor 2.5, in agreement with what expected from simulations.

Table 2: Longitudinal emittance measured with a $^{40}Ar^{9+}$ beam (see text for details)

	εrms,l [deg-keV/u]	εrms,l [ns-keV/u]
Direct measurement	39±1.6	1.358±0.006
3 Gradient-method	5.5±0.3	0.19±0.01
3 Gradient-meth. w. t.	6.0±0.3	0.21±0.01
Simulation results	2.16	0.075
Simulation results w.t.	15.5	0.54

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