FIRST OPERATION OF PIAVE, THE HEAVY ION INJECTOR BASED ON SUPERCONDUCTING RFQs

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Abstract

The Positive Ion Accelerator for low-Velocity Ions (PIAVE [1], see Fig. 1), based on superconducting RFQs (SRFQs), has been completed in Fall 2004 with the first acceleration of beams from the ECR ion source. Superconducting RFQs were used, for the first time, for beam acceleration on a user-oriented accelerator complex. A general status of the injector performances is here given: it includes, besides the SRFQs, eight superconducting (SC) Quarter Wave Resonators (QWRs) and three bunchers; the beam is received from an ECR source on a HV platform and is delivered, through the SC accelerator ALPI, to nuclear physics experimental apparatuses. The paper is specially focused on the technological challenges related to the operation of the SC cavities, the cryogenics, control, diagnostics and vacuum systems.

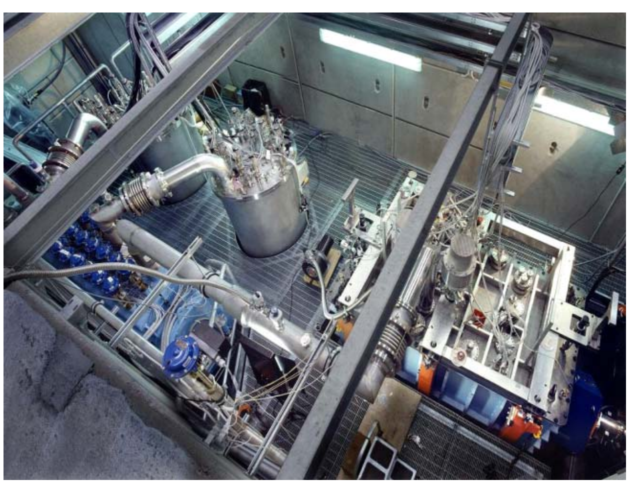

Figure 1: Photo of the completed injector PIAVE.

INTRODUCTION

In November and December 2004, beam tests were conducted first of all through the superconducting RFQ's and later through the whole PIAVE injector. A pilot beam of $^{16}O^{3+}$, with a current up to 1.3 μA, was transported through PIAVE. Initial tests with a $^{132}Xe^{18+}$ beam (100 nA) were encouraging.

In April 2005, after some maintenance on the refrigerator and finer adjustment between the injection line and the RFQs, values of transmission and emittances very close to the specifications were achieved, again with the oxygen pilot beam, with typically 500 nA current, occasionally up to 2 μA.

A separate contribution to this conference [2] is dedicated to a report on the beam tests.

SUPERCONDUCTING RFQS

Two superconducting (SC) RFQs [3] (SRFQ1 and SRFQ2, resonating at 80 MHz, 0.8 m in diameter and 1.34 m and 0.74 m long), are the first accelerating elements in the PIAVE linac. The SRFQs follow an ECR source on a 350 kV platform and an external buncher, and precede 8 SC QWRs. After thorough "off-line" resonator testing was completed and dealt with on previous publications ($E_{sp,n}$> 25.5 MV/m – the design value, Q-values between 5 and 8 x10^8, stability issues in He-to-recovery mode), successful RF tests were conducted on the final setup in June and October 2004. The Q-curves [4] exceeded specifications, i.e. a peak surface field of 25.5 MV/m at 10 W dissipated power at 4.2 K temperature: this will allow the acceleration of the beams now available from the ECR ion source.

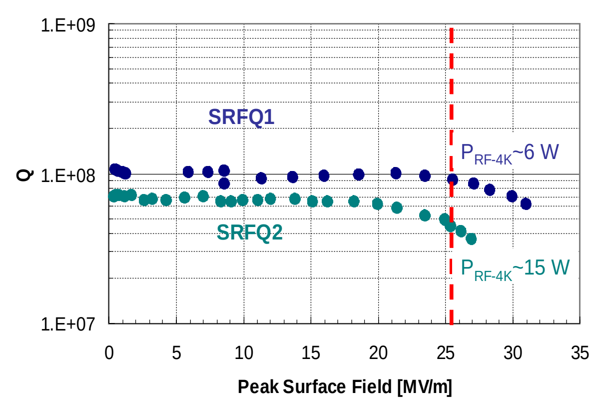

Figure 2: SRFQ1 and SRFQ2 Q performance. The curve is lowered by the presence of the normal conducting loop of the VCX fast tuner, which provides good phase stability of the resonators.

In the PIAVE cryostat the two SRFQs are equipped with VCX fast tuners [5], which lower the resonator Q-curves with respect to those measured in the test cryostat (where the fast tuners were not installed).

In order to achieve phase stability, the pressure variations of the liquid He bath, in which the SRFQs are immersed, had to be reduced to below 5 mbar/min. A significant effort was dedicated, in Fall 2004, to achieving these conditions on the TCF50 refrigerator and values mostly lower than 2 mbar/min were obtained.

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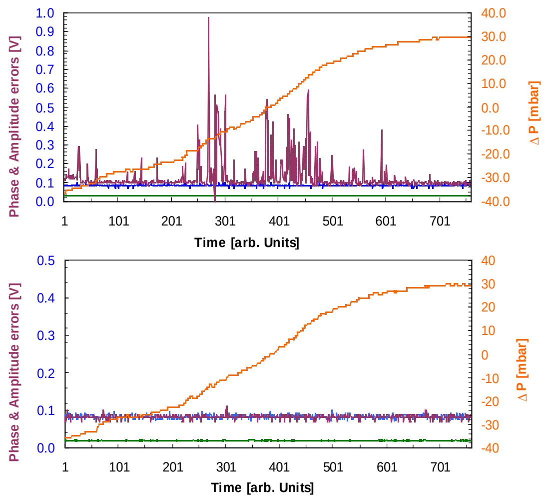

Figure 3: A 40 min sample of the stability behaviour (in phase and amplitude) of the SRFQs is shown. The pressure variation (orange curve) shows that $\Delta P/\Delta t \leq 2$ mbar/min, i.e., better than specified.

With the use of the fast tuners SRFQ2 could be reliably kept phase locked during all RF and beam tests as its fast tuner frequency window is ±100 Hz (design value). SRFQ1 is less stable, probably because of the smaller fast tuner frequency window (±40 Hz), which will be increased at next cryostat disassembly. Nevertheless the overall ϕ&A stability of the SRFQs was sufficient for beam tests and acceleration.

Fig. 3 shows a particularly "noisy" sample, taken during the beam tests, of the phase and amplitude error signals of SRFQ1 and SRFQ2. Despite SRFQ1 is somewhat less stable, none of the two cavities however lose the lock during the period to which the plot refers. Indeed, during beam tests of 10 hours or more each, SRFQ2 never lost the lock, while SRFQ1 did on very rare occasions.

QWRS AND BUNCHERS

Initially, PIAVE QWRs [6] were all equipped with the standard cam-shaft ALPI mechanical tuners; this old mechanism works well statically but has a slow and unpredictable dynamical response. So during a stop in the PIAVE installation schedule before the tests of Fall 2004, the tuners of 4 (out of 8) QWRs were replaced with the new ones (much more precise and reliable) developed for ALPI niobium bulk QWRs [7]. Despite the short time available for RF conditioning, all PIAVE QWRs performed reliably during the beam tests in December 2004 at the required field E_a ~ 4.2 MV/m.

The normal conducting (NC) three-harmonic buncher, located along the LEBT line between the ion source and the SC cavities, already worked well several times; HEB1, the first of the two NC Higher Energy Bunchers (HEB) was tested and prepared for beam operation in December but not yet used; HEB2, now at the beginning of ALPI linac, was installed in late 2004 and successfully tested in March 2005.

CRYOGENICS AND VACUUM

The main component of PIAVE cryogenic plant is a LINDE TCF 50 refrigerator (see the Cold Box in Fig. 2). It can supply a power of 410 W @ 4.2 K, 1000 W @ 80K with liquid nitrogen pre-cooling. Its maximum power is around 30% larger than the foreseen cryogenic injector average load. 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, used to refill the buffer with pure helium gas. In Fall 2004 automatic refrigeration of all PIAVE cryostats marked the end of the cryogenic plant installation and test phase.

Figure 4: Photo of TCF 50 Cold Box.

The good operation of the refrigerator is one of main conditions for an easier beam transport because 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 to achieve pressure variations smaller than 2 mbar/min, a slow enough drift to be compensated by the resonator mechanical tuners of SRFQs and QWRs.

Clean vacuum in the cryostats (10^{-9} mbar) is assured by turbomolecolar pumps (1500 l/s for SRFQ an 450 l/s for QWR) coupled with turbo drags and membrane pumps. The cryostats are equipped with Pirani, Penning and Bayard-Alpert vacuum gauges, which are automatically selected according to the vacuum level. The control System based on PLCs allows remote safe control of pumps and valves and data recording. The processes of vacuum production, venting and He conditioning are completely automated. Vacuum data are acquired through two RS232 links and transferred via RS485 to Window2000 vacuum servers. Two more Window2000 PCs are connected to the servers by a dedicated network branch where the whole vacuum system may be monitored in real-time.

PIAVE CONTROL SYSTEM

The control system of PIAVE has a three-level structure. Many of its control components are the same that were used in the RF Linac ALPI (in operation at

L.N.L. since 1993), or very similar to them, while others were re-designed or changed to adapt them to the different needs of PIAVE or because of technological evolution.

Here some general features of PIAVE control system are given.

Local VME disk-less systems are used for diagnostics and RF; for diagnostics they are identycal to those used in ALPI while for RF two new systems with PPC CPU boards (MVME2100) running VxWorks 5.4.2 were installed in a configuration including RS232 controllers (16 channels on a single board, by Tews TIP866 IP over SBS, VIP616 carriers), VME step-motor control boards and VME digital and analog I/O boards.

The data network from the VME systems to the remote control PCs is a 100 Mbit/s link for RF, while the other network branches, (common to the ALPI Linac control systems), are still at 10 Mbits/s.

For PIAVE magnets, whose remote control make use only of RS232 connections, an Equinox terminal hub (16 ports) is used in association with a control PC through TCP/IP protocol on the network.

The remote operator interface of the magnets and RF control of PIAVE (originally on Alpha or Sun workstations) were moved to Linux PCs while the diagnostics system is still on a Sun Solaris workstation.

The remote control of PIAVE ECR ion source is based on two Linux PCs, the first being an industrial unit installed on the high voltage platform and here directly connected to the ECR devices, the second being the remote control computer connected to the previous through a network branch on optical fiber.

RF CONTROL FOR SRFQS

The main challenging feature in the PIAVE RF control system was the installation of VCX tuners for the two SRFQs [5]. These phase lock systems were specially designed for PIAVE SRFQs in collaboration with Argonne National Laboratory and consists of three modules: the internal power unit (mounted at the bottom of each SRFQ and cooled by liquid nitrogen), the external pulser unit and an external separated PWM modulator.

The VCX power unit is in an array of pin diode switches dynamically connecting a capacitor to a dedicated coupler in the resonator; the switching rate is 25 kHz and the switched power is about 20KVA at the maximum operating field.

The VCX pulser is a high voltage driver using power mosfets that switch on/off the pin diodes with a slew rate of 7000 V/ms (the high speed reduces the pin diode power dissipation during the commutation).

VCX phase locking is obtained by the external PWM modulators varying the on/off pulse width proportionally to the phase error signal coming from RF controller where the resonators pickup and phase-reference signals are comparedand the error signal produced. In RF controllers for the SRFQs the VCX phase lock system is integrated with the standard phase control technique using a CPM vector modulator (when used it modulates the reactive power from the amplifier to the resonator coupler proportionally to the phase error); on the SRFQs both the phase lock methods (VCX and CPM) may be activated and the selection of one or the other is made from the user interface. Amplitude field stabilization is always performed by the CPM modulator.

The remote control interface on the VCX allows to adjust the setting of the feedback gain in the fast tuner phase control loop (through a DAC) and send set/reset commands to the switches that enable the modulation (to lock the resonator phase) or allow to check the VCX behaviour by setting all diodes in the status ON or OFF, to verify the frequency control windows. A group of read-only status bits are also available to the remote control interface to check the VCX status on line in response to the setting commands and interlock conditions.

Special software tasks had to be added (for SRFQs) for the VCX management and to read the absolute position through encoders connected to the tuners' motor shafts, while other tasks had to be adapted to the new hardware configuration. An almost completed re-design was required for software automatic retuning of SRFQs through the mechanical tuners (to compensate pressure slow pressure drifts on the liquid He baths), each cavity being equipped with 2 tuners (and associated encoders) and because two different possible technique of phase locking (CPM or VCX) are available for them.

As both mechanical tuners of each SRFQ may move in two opposite directions and there is a wide but limited travel length for them, a routine for automatic motion inversion and phase re-lock near the travel end points was also added and is currently under test.

The control task for RF alarm detection and automatic amplifiers shutdown had to be specialized to add software interlocks between VCX pulser alarms and RF power amplifier enable switch. In fact RF power to SRFQs has to be automatically stopped when VCX diodes are not properly powered by the high voltage generator.

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