THE CONTROL OF THE NEW PIAVE INJECTOR AT LNL

G. Bassato, S. Canella, A. Battistella
INFN Laboratori Nazionali di Legnaro, Legnaro (PD), Italy

ABSTRACT

The commissioning of the new PIAVE injector for the superconducting linac ALPI is approaching its conclusion. The machine is designed to accelerate ions with masses up to 200 amu from the velocity of $\beta = 0.009$ up to $\beta = 0.055$ and a beam current up to 5 µA.

The machine consists in an ECR source installed on a 350 KV platform followed by two superconducting RFQ resonators operating at 80 MHz. Downstream the RFQs, eigth Quarter Wave Resonators, made in bulk niobium, provide the energy gain necessary to inject the beam into the linac. This paper describes the control of the new injector with a particular emphasis on the RF system that required the most significant changes with respect to the consolidated ALPI scheme, due to the frequency dependency of the RFQs over the pressure of refrigerating helium gas.

INTRODUCTION

The main accelerator facility at LNL is constituted by a complex of two machines: the Tandem XTU, installed in 1982 and operating at a maximum terminal voltage of 16MV, and the superconducting linac ALPI, in operation since 1995, capable of accelerating ions up to 700 MeV, at a maximum specific energy of 20 Mev/amu. The PIAVE (Positive Ion Accelerator for Very low Energy) project aims to replace the Tandem as injector and extend the mass of accelerated ions up to ^{238}U with a maximum current of 5 µA. The ion beams are generated by an ECR source placed on a 350 KV platform; then an innovative structure based on a couple of superconducting RFQs provide a velocity increase to $\beta = 0.035$. The further energy gain required to reach $\beta = 0.055$, that is the optimal velocity for the injection into the linac, is provided by a set of eight QWR resonators operating at 80 MHz. The most challenging aspect of the PIAVE project has been the construction and the control of the two RFQ resonators: in fact, the lack of stiffness of niobium makes them very sensitive to the radiation pressure, as well as to the pressure of refrigerating gas.

PIAVE CONTROL SYSTEM OVERVIEW

Since the PIAVE injector is, de facto, an extension of the existing linac and will be maintained by the technical personnel that operates the linac today, we managed to reuse the existing hardware and software as much as possible, making changes only where required by the introduction of new devices or by the evolution of technology. The PIAVE control system architecture is based on a classic three tiers scheme where the highest level has the workstations running the operator interface, at the middle level there are VME systems to dispatch data and commands to the low level devices and to perform control tasks where required, at the lowest level there are embedded controllers, mostly connected through serial line interfaces.

Not all the accelerator subsystems comply with the architecture described above: i.e., in the magnet control system, the data coming from the power supplies are routed to the control network through terminal servers instead of VME crates. As for the linac ALPI, the control of vacuum and cryogenic systems was turned over to external companies and developed using PLCs and commercial SCADA software. In the following paragraphs we shall describe only the control of the new devices that have been added for PIAVE or the significant changes that have been made with respect to the ALPI control system.

THE CONTROL OF THE ECR SOURCE

The control of the ECR ion source is mostly based on intelligent instruments (about 24 devices of 12 different types) equipped with an RS232 interface; only a few passive devices are controlled through analog and digital I/O cards. Among the ECR instrumentation, it is worthy to mention a TWT amplifier for plasma heating, an HP34970 microwave generator, four FUG power supplies, 4 turbo pump controllers, 2 Balzer TPG pressure controllers, an HP437 microwave meter and a Group3 teslameter; a number of general purpose instruments are also connected to the control system. All these devices are installed on the HV platform (350KV): at the ground voltage there are the power supplies (Glassman mod. PS/PG400) that provide the high voltage to the platform itself and to an electrostatic lens. These are controlled through an HP3497, a multi-purpose instrument with a serial interface that includes four high resolution ADC and DAC channels.

The ECR source was the first component of the PIAVE project to be designed and put under test, in late 1999. At that time, its control configuration was a mere copy of ALPI: that is, all the instrumentation requiring analog and digital I/O was interfaced to a VME crate (with VxWorks) while the serial links were managed by a DEC terminal server; a small ALPHA workstation was also installed on the platform to provide a local display for diagnostic purposes. Today, the control is greatly simplified: an industrial PC running under Linux provides the same functionality at a much lower cost. The serial lines are connected to the PC through a couple of 16 port controllers (Equinox SST-16) while analog and digital PCI cards by National Instruments replaced the old XYCOM VME boards. Linux drivers and libraries were available from the manufacturers or from the open source community, so most of the existing control software was plainly ported to the new configuration; only few VxWorks dependent tasks (i.e. the recovery of the communication over a serial line after an error or link failure) needed to be rewritten from scratch.

THE MAGNETS CONTROL

In the ALPI-PIAVE complex more than 80 magnet power supplies (DANFYSIK MPS858) are connected to the control network: of these, 15 belong to the new injector. The standard interface is RS422 (RS232 for the steerers); a number of teslameters, all equipped with a RS232 interface, are also included in the magnet control system. The link to the network is realized through terminal servers (originally DEC700, based on LAT protocol). When the graphic interface was ported from the DEC ALPHA workstations to Linux PCs, we tried, to limit the cost of migration, to continue using the DEC terminal servers and installed LAT on Linux PCs. Although the applications continued to run, we found they suffered from a low performance in terms of response speed. After some investigations, it resulted that the bottleneck resided in the poor implementation of LAT under Linux. So, beginning from the PIAVE control system, we decided to replace the terminal servers with new ones working under TCP/IP. Comparative tests were made on some devices available on the market and the 16 port serial hub Device Master 98985 (from Comtrol) was chosen. We can estimate that the cost of the magnet control system based on such devices and Linux PCs has been reduced by a factor of four at least; the ratio seems even better if we consider that the parts are easily replaceable and no maintenance contracts are required.

THE CONTROL OF RFQ RESONATORS

The design key of the new injector is based on the two superconducting RFQs [Fig. 1]. These multi-gap structures are built in bulk niobium and have a length of 138 and 75 cm. respectively, with a tank diameter of 65 cm.

The intervane maximum voltages are 148 and 250 KV respectively, that correspond to a field gradient of 22 and 25 MV/m. At the maximum field, the energy stored is about 4J; the measured Q_0 is better than $5*10^8$, so the nominal field can be reached with less than 10W of power dissipated at helium temperature.

Due to their relatively long mechanical structure, the RFQs suffer from a strong dependency of their resonant frequency over various environmental and intrinsic factors: those that appeared most difficult to be controlled were the radiation pressure, measured to be about 0.9 $Hz(MV/m)^2$, and the fluctuations of the helium gas pressure, measured to be about 40 Hz/mBar [2],[3].

Fig.1 The RFQ2 cavity

Bandwidth and energy considerations

With a $Q_0 = 5*10^8$ and an operating frequency of 80 MHz, the unloaded bandwidth results to be about 1 Hz, that is clearly too narrow for phase locking in a real accelerator plant. It is a common practice, when operating with superconducting resonators, to broaden the loaded bandwidth by overcoupling the cavity. This results in a significant waste of RF power that is reflected back to the amplifier or power circulator. Following our experience with niobium sputtered QWRs we originally estimated the bandwidth had to be broaden to +/- 10Hz to cover the fast disturbances induced on the eigenfrequency by the environmental noise. To have such a bandwidth about 250W of RF power are required; moreover another 250W are necessary to lock the resonator phase, as will be explained in the next paragraph.

The "standard" phase lock method

The most common method to operate superconducting resonators in continous wave mode (c.w.) is to get them self oscillating in a loop that includes, other than the resonator itself, the power amplifier and the controller. The principle of operation is simple: the system oscillates at a frequency for which the sum of phases along the loop is a multiple of 360 deg. By changing the phase between the input and the output of the controller we force the cavity to move along its resonant curve and thus we can control the loop frequency. Phase control is obtained by means of a complex phasor modulator (CPM) that, while rotating the phase, adds an in-quadrature power proportional to the phase error. Since the resonator impedance changes too, the additional power is reflected back to the amplifier. The reactive power necessary to keep the resonator locked if its eigenfrequency changes by Δf is given by $2\pi*E*\Delta f$, where E is the energy stored in Joule.

The main advantage of this method resides in the ideal decoupling, provided the amplifier and the CPM have a linear response, between the phase and amplitude control loops: conversely, the CPM adds exactly the amount of reactive power needed to lock the phase without affecting the resonator field. The same device can be used to compensate real disturbances on the field amplitude be feeding its I (zero degree) modulation port with the amplitude error signal obtained by comparison of the resonator pick-up signal with a level reference. Another advantage is the modulation bandwidth that, in commercial devices, can be as high as tens of MHz: this means that the cutoff frequency of the phase error amplifier (typically a few hundreds of KHz) is not reduced by the presence of the modulator and, as a consequence, it is possible to operate with a high gain in the feedback loop. The main drawback of the CPM-based control is its inherently narrow bandwidth determined by resonator loaded Q. In fact, overcoupling the resonator is limited by practical considerations like the power dissipated by the coupler and by the RF lines inside the cryostat.

The slow tuners

In our control system, large (but slow) frequency drifts are compensated through mechanical tuners; these devices are driven by stepping motors and allow a tuning range in excess of 100KHz with a typical response of 0.5Hz/step. The stepping motor controllers are VME boards; the maximum speed is 800 steps/sec. The slow tuning feedback is accomplished by a soft task that samples the residual phase error at a rate of 5 Hz (settable up to 20 Hz) and implements a PI algorithm by modulating the number of steps applied after each sample. Because of our previous experience with ALPI niobium cavities, we put a particular care in designing the slow tuning system, nevertheless we underestimated the amplitude and the speed of the perturbations to keep under control. In fact, the stability of the gas pressure in the cryogenic plant resulted to be around +/-10mBar with a typical changing rate of +/-2.5mBar/min that, in itself, is quite acceptable: however if we consider that the dependency of the cavity frequency over the pressure is about 40Hz/mBar it results that the frequency fluctuates at a rate of +/-100Hz/min. The real problem, however, resides in the fact that the rate of these changes is not constant and, in relation to some events in the cryogenic plant, pressure peaks as much as 5 times the average fluctuations can happen: in these circumstances we were not able to keep the RFQs locked in phase.

The VCX alternative

While the design of a new and more precise mechanical tuner was started, we also considered the possibility of making the slow tuner requirements less critical by broadening the range of the electronic tuners. A further overcoupling was ruled out to avoid problems with the power dissipated by the main coupler lines. So, we decided to exploit an alternative method that consists in coupling the resonator, through RF switches, to an external reactance (VCX) and controlling the cavity frequency by modulating the duty cycle of switches status.

Since the project schedule didn't leave enough time to develop a new design from scratch, we made an agreement with Argonne National Laboratory (Chicago, U.S.A.) to reuse, after the necessary adaptation, part of the VCX hardware they developed for the ATLAS accelerator; in turn, we modified our control system to drive the new device. The most critical part of the VCX is the power unit, that houses the reactance and the RF switches (Unitrode UM4010 pin diodes). The tuning window depends on the coupling factor [1] between the resonator and the VCX, that is limited by the power that can be dissipated by the switches and by the VCX coupler. Our VCX was designed to provide a tuning window of +/- 100Hz; at the maximum field this means that a reactive power of about 10KW ($500V_{off}$ * $20A\ I_{on}$) must be managed by the RF switches. Under these conditions the VCX coupler dissipates around 110W: for this reason the power unit operates submersed in liquid nitrogen. It should be noted that the VCX method, while providing a wider tuning range for a given amplifier power, intrinsically generates a wobble on the phase due to fact that the cavity is continuously switched between two frequency boundaries (corresponding to the ON and OFF status of pin diodes). The amplitude of this perturbation depends on the ratio of the tuning window over the resonant frequency: in our case it is about +/-1 degree, that is compatible with the beam dynamics specifications.

Practical realization

The integration of VCX was done without affecting the basic functions of our standard resonator controller. In particular, the old board is used to setup the self-excited loop operation and the CPM is used to stabilize the field amplitude. A PWM (Pulse Width Modulator) was designed to drive the VCX. The new module is based on a programmable device (Altera FPGA). The phase error signal is filtered and sampled at 25 KHz; then a simple logic generates, at the same frequency, a TTL signal whose duty cycle is a linear function of the phase error. The gain on the feedback loop is set through a DAC in a VME board. An external pulser, based on power mosfets, is used to translate the signal to a level suitable to drive the RF switches.

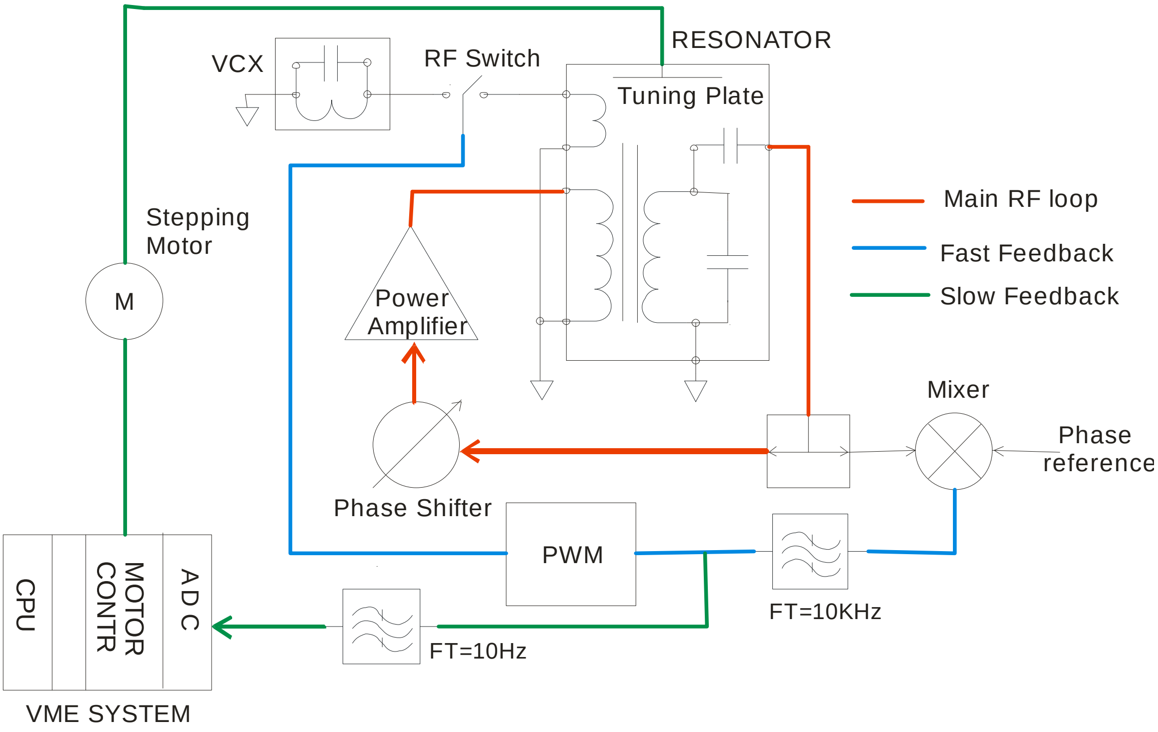

Fig. 2. Principle of a self excited loop system with VCX tuner

The RF system: hardware configuration

As illustrated, the fast feedback on phase and amplitude is realized through an embedded controller that is based on an analog circuit. An on board microprocessor allows to setup the working parameters and monitor the operation via a RS232 link. Moreover, each resonator has a power amplifier and a step motor controller associated with it: these devices, as well as the serial links, are managed by means of VME cards. The processor board is a Motorola MVME2100 while the digital and analog cards are XYCOM-240 and 560 respectively. A 16 port serial controller has been assembled by installing two IP modules (Tews TIP866) over a SBS VIPC616 carrier. The stepping motor controller has been designed at LNL: it is based on a VME logic board and an external power unit driving 8 motors. The operating system is Vxworks 5.4.

SOFTWARE

Most of the work for the PIAVE injector has been carried out on VME/VxWorks side.
New tasks have been added for the VCX control and alarm management, that is of crucial importance to protect the pin diode switches against improper operations. Special care has been dedicated to the slow tuning problem: the working parameters (i.e. the phase error threshold at which start moving the tuner, the motor speed, the number of steps) are remotely settable to

optimize the tuner response. The automatic recovery from unlock situations is another critical task that required a substantial rework.

The graphic interface has been upgraded to include the new devices without removing any of the previous functions: the operator can choose if using the CPM or the VCX just by clicking on one button. All the MMI applications have been ported from DEC ALPHA and SUN workstations to Linux (Fedora distribution) PCs. The applications are based on Xt toolkit (Athena Widget libraries); the migration to the new environment required only minor modifications.

The general software architecture remained the same of ALPI: the graphic clients communicate with the application servers on VxWorks side through network channels based on BSD sockets.

The system is scalable and reconfigurable with no need for recompiling the source code; the association between the hardware components, the type of interface and the number of I/O channel is described through ASCII configuration files.

CONCLUSIONS

The RFQ resonators of the PIAVE injector are now in operation: the first beam on target is scheduled for november 2005. The addition of the VCX to the phase control loop permitted to compensate the pressure transients in the cryogenic plant: the accuracy of mechanical tuners, as well as the control algorithm, has a crucial role in the system performance.

It is questionable if an analog controller still represents a valid solution in the field of RF controls today. We believe that, as long as the resonator operates in c.w. mode and the beam load effects are negligible, an analog controller can hold its own against a digital one.

A DSP based controller could be more effective in managing effects like the Lorentz detuning: in the case of our RFQs this effect was not negligible but could be safely controlled by the analog feedback. Another advantage of the analog controller is that vector modulators are available on the market for frequency up to few hundred of MHz: no up/down conversions are required and the resulting circuitry is very simple and fast. In case we redesign the controller for ALPI or PIAVE resonators we shall likely maintain the existing analog block but integrate the slow tuning control on the same board; all the required logic can be included in a unique FPGA. Ethernet connectivity is another important feature: it can be easily added by means of a PMC processor card.

REFERENCES

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