RF CONDITIONING OF THE SPIRAL2 CW RFQ

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Abstract

The SPIRAL2 RFQ is designed to accelerate light and heavy ions with A/Q from 1 to 3 at 0.73 MeV/A. The nominal beam intensities are up to 5 mA CW for both proton and deuteron beams and up to 1 mA CW for heavier ions. The four-vane cavity is made with 5 1-meter long sections mechanically assembled, it works at 88 MHz and is powered up to 180 kW CW to achieve the nominal vane voltage of 113.7 kV for A/Q = 3 ions. This paper describes the RF conditioning of the RFQ at GANIL with the setting of its RF systems and cooling system used to tune the cavity resonance frequency.

INTRODUCTION

Integration at GANIL started in September 2014 with assembly of the five modules on their support. RF tuning (beadpull) has been then performed with the adjustment of the 40 slugs in order to achieve specified voltage profile by the beam dynamic requirements. Final measured voltage errors in March 2015 are smaller than 2.1% for the quadrupole component, 0.5% for the dipole S-component and 1.1% for the dipole T-component. Then, installation of cooling system, RF lines, vacuum system and cabling (see Fig. 1) has been performed during the main part of 2015 [1].

Figure 1: SPIRAL2 RFQ installed at GANIL.

INSTALLATION AT GANIL

RF Power Systems

The RFQ is powered by 4 loop couplers and 4*60 kW RF amplifiers (tubes with 3 kW solid state preamplifiers) purchased to DB Elettronica (Italy). Each amplifier is protected by AFT circulator able to accept 60kW reflected power. 4 directional couplers measure forward and reverse power between each circulator and cavity.

Low Level RF Systems

CEA/Saclay developed the LLRF system to control the accelerator cavities of Spiral2. Its architecture, based on in-house VME64x boards equipped with a Virtex-5 FPGA, uses a modular approach (RCAV module) to build a generic design applicable to all the cavity types of the SPIRAL2 accelerator (RFQ, normal conducting rebunchers and superconducting cavities).

The RFQ has the most complex control [2]: it is fed with four power amplifiers and the frequency of the cavity changes quickly during start-up process.

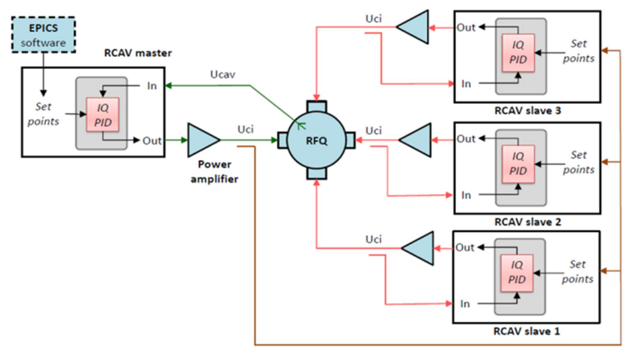

Figure 2: LLRF systems.

As the RFQ is driven with 4 power amplifiers, the 4 incident voltages from the amplifiers must be kept in constant phase and amplitude relations. To do so, one master module regulates the cavity field and 3 slave modules regulate the incident wave Uci of their own amplifiers. The master incident wave is used as a set point for the 3 slave feedback loops (Fig. 2).

During start-up, the RFQ is rapidly detuned because of the increasing dissipated power, while the tuning system, controlling the temperature of five tons of copper, is very slow. To allow RF tuning of the cavity in a reasonable amount of time, a frequency generator implemented on the FPGA controlling the IQ modulator of the master module is used to follow the resonance frequency during start-up with a range of ±100kHz.

Cooling System

The RFQ cooling system built is able to dissipate 240kW of power (Fig. 3). It is based on a water skid with 2 independent cooling circuits (one for the vane circuit and one for the body circuit) controlled in temperature by the means of 3-way valves. These valves are used to mix hot water from the RFQ with cold water from tank, in order to achieve the desired temperature. One of these circuits is used for frequency regulation with the detuning information provided by the LLRF systems.

Figure 3: RFQ cooling system.

Local Control System

Control system is based on EPICS environment. All the subsystems (RF amplifiers, LLRF systems, cooling systems, vacuum system…) are connected together in order to monitor all the characteristic parameters.

Instrumentation and Diagnostics

Fast interlock of reflected power, arc detection performed by the LLRF, vacuum interlock, water control (flow and temperature control of the 2 RFQ cooling circuits), temperature monitoring of the RF power loop with interlock are integrated into the RFQ control.

In order to measure the voltage law during operation, the cavity is equipped with 16 RF pick-ups equally distributed in the four quadrants along the cavity length. By means of a digital acquisition system, voltage signals proportional to the field level along each RFQ quadrant are continuously recorded during operation. Calibration is performed by assuming that the field behaviour at low power level is equivalent to the one measured during the bead-pull [3].

These acquisition system and processing algorithm have allowed studying the field behaviour in the RFQ dynamically at different power levels and with different temperature conditions of the RFQ cooling circuit.

CONDITIONING

First Campaign in November 2015 During 3 Weeks

The RF conditioning started on November 15th, 2015 with only 3 amplifiers because one had a failure. The process was mainly done in CW mode and progressed quite fast up to the maximal possible accelerating field level (85kV for 110kW within the cavity). The body circuit has been used for frequency regulation while the vane circuit has been used in temperature control.

The measurements from the 16 RF pick-ups have then been compared to the final beadpull measurement (Fig.4). The variations of voltage errors are bounded by ±0.2% of nominal voltage, as accelerating voltage is varied from 20kV to 80kV. Moreover, the behaviour of the accelerating voltage is repeatable along the time.

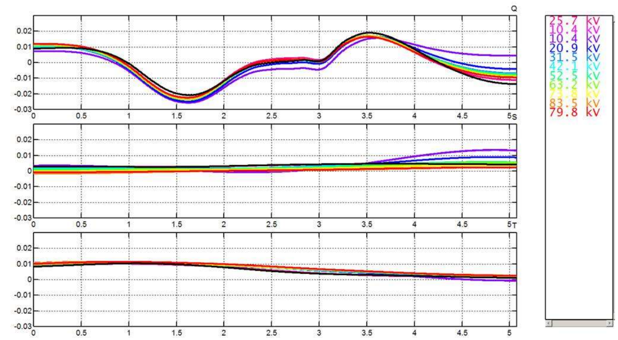

Figure 4: Voltage error according accelerating voltage.

The main difficulty met during this first campaign is the limitation of the functionality of the frequency generator implemented on the LLRF. RF power amplifiers have several limitations (differences between the 4 amplifiers, delayed response, nonlinearities of the gain). Moreover, they are breakable when they're working close to their maximum power. In order to protect them, the bandwidth of the feedback systems has been strongly reduced, restricting the possible frequency shift to ±4kHz (instead of ±100kHz for the LLRF alone).

With this solution, the cavity is operational at 85kV for beam application in about 20 minutes with stable long term behaviour.

Last Campaign in January 2017 During 3 Weeks

The 4 amplifiers are operational and their reliability has been improved with many modifications. But no solution has been found to improve the range of the frequency generator of the LLRF. This restricts strongly the efficiency of the conditioning of the RFQ. In case of arc into the RFQ at high voltage (more than 100kV), RF must stop quickly. In some cases, automatic restart provided by the LLRF (in less than 1s) doesn't recover the power into the RFQ. More than 60min is then required to get back to the maximum voltage.

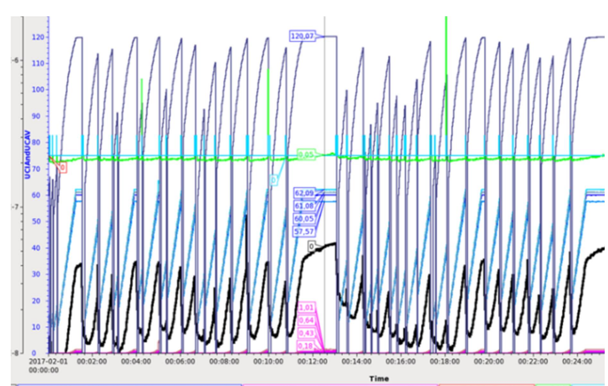

Figure 5: RF conditioning with frequency follow system.

In order to have a more efficient conditioning, an additional RF system has been added outside of the LLRF. It is able to measure the detuning of the cavity and to drive the frequency modulation input from a frequency generator different of the master generator. In this case, the 2

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cooling circuits are operated in temperature regulation. So the cavity frequency is let free to drift.

This improvement allows getting back to the maximum power in less than some tens of second as shown in Fig. 5. With this system, in less than 2 weeks of conditioning, the RFQ has achieved its nominal voltage of 113.7kV with peaks at 120kV during several minutes.

The measurements done by the 16 RF pick-ups have been again compared to the last beadpull measurement. The magnitude of the voltage peak relative errors (with respect to the specifications) are now about 3.4% for Q, 0.7% for S and 1.3% for T components (Fig. 6). A fine analysis of measurements shows that this perturbation has been clearly induced by only one pickup located in quadrant 4 of the RFQ.

Tentative interpretation may be a problem with this pickup (mechanical default, ionization...) and/or the associated cables and connectors (the jump in pickup voltage is something about 3.5% or 0.3 dB). The cable was found loosen and might be the explanation. Next run should confirm this assumption.

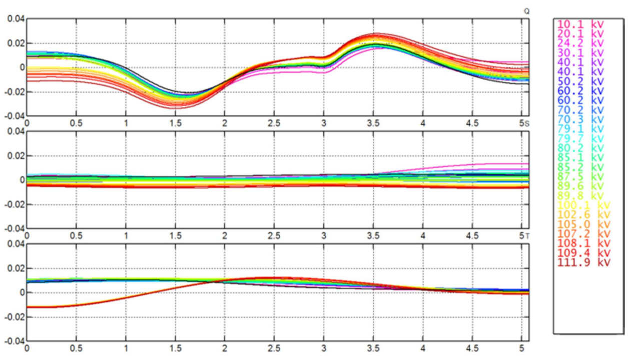

Figure 6: Voltage error according accelerating voltage.

OPERATION OF THE RFQ

The addition of the RF fast frequency following equipment to the LLRF has permitted to increase the efficiency of the conditioning mode. But this system does not allow beam acceleration at the nominal voltage and frequency. Indeed, the LLRF with its additional system is not synchronized with the timing system of the whole accelerator.

Other main difficulties met during this conditioning come from the cooling system of the RFQ.

First, the resonance frequency feedback presently done by the body circuit is very delicate. The control of this circuit is very difficult to set and becomes easily instable at high power. At the end of a power ramp, it is very difficult to obtain a stable operation mode for the RFQ before the beam injection. Figure 7 shows that the detuning value called DPCI has a fast variation leading to an instable response of the cooling system. This oscillation makes a fast increase of the reflected power which generates a RF stop.

Some studies are in progress to understand this issue. A solution to stabilise the system seems to use vane circuit to control the frequency of the RFQ while the body circuit will be regulated in temperature control. Other solution requires the 3 way valves displacement in the tunnel and/or a different control under evaluation.

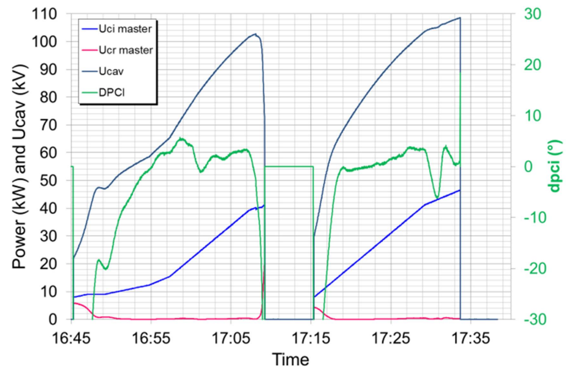

Figure 7: Example of RFQ instable control.

A Second problem is the discordance between injected power and cavity voltage. Figure 8 shows that at 113.7KV nominal voltage for ions, an extra power of 38kW is required. The copper surface temperature explains only up to 8kW out of the 38kW. Today 208kW are required to power up the cavity, while 170kW was estimated from calculation.

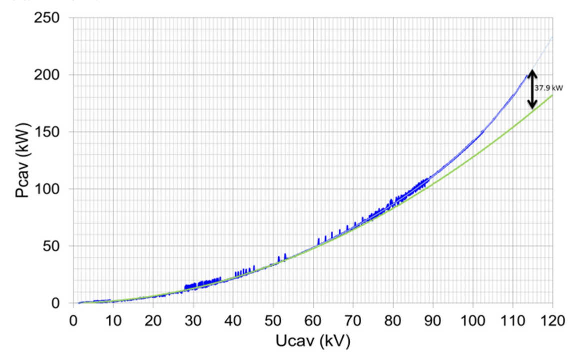

Figure 8: Cavity voltage according injected power.

Calorimetric measurement of the cavity power will be provided in order to understand the heat losses on each water channel.

CONCLUSION

The beam conditioning of the SPIRAL2 RFQ is in progress [4] for different kinds of beam. Several activities are in progress in Ganil in order to start the superconducting LINAC, limiting the availability of the RFQ for tests.

Some issues require tests in order to understand well the RFQ operating behaviour, especially at high voltage. All that work will improve the frequency control during the start-up time of the RFQ, will improve the cavity availability and will allow beam acceleration in the SC Linac.

REFERENCES

[1] O. Piquet, “RFQ developments at CEA-Irfu”, IPAC’16, Busan, Republic of Korea, May 2016, paper MOOCA02.

[2] S. Sube *et al.* “Spiral2 LLRF FPGA design applied to the control of the RFQ”, LLRF’13, Tahoe, USA, 2013.

[3] A. France, “Advanced RF Design and Tuning Methods of RFQ for High Intensity Proton Linacs”, IPAC’14, Dresden, Germany, June 2014.

[4] R. Ferdinand, “Commissioning of Spiral2 CW RFQ and LINAC”, presented at IPAC’17, Copenhagen, Denmark, May 2017, this conference.

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