TRIUMF ISAC II RF CONTROL SYSTEM DESIGN AND TESTING

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Abstract

The rf control system for the ISAC II superconducting cavities is a hybrid analogue/digital design which has undergone several iterations in the course of its development. In the current design, the cavity operates in a self-excited feedback loop, while phase locked loops are used to achieve frequency and phase stability. Digital signal processors are used to provide amplitude and phase regulation, as well as mechanical cavity tuning control. The most recent version also allows for the rapid implementation of operating firmware and software changes, which can be done remotely, if the need arises. This paper describes the RF control system and the experience gained in operating this system with a four-cavity test facility.

INTRODUCTION

This paper outlines the development of the current TRIUMF superconducting rf control system. This design began as an adaptation of an existing design which has been used successfully for a number of years to control the normal conducting cavities of the ISAC-1 linac. It evolved over the course of a number of cycles of testing and development. Test time was limited by the realities of working with limited quantities of liquid helium, so that activities had to be carefully scheduled to make optimum use of the available time. Some of the more recent test results are presented.

RF CONTROL SYSTEM

Figure 1 shows an example of the normal conducting control system which served as a foundation for the superconducting controls. As shown, it is a conventional I/Q PID system. A single DSP multipexes both the I and Q controls, while a second DSP provides the cavity tuning function. The system is capable of operating in either self-excited or driven mode. The former mode is primarily used during cavity conditioning or warmup. In this mode a manual phase shifter is adjusted until positive feedback is achieved and VSWR minimized. In driven mode the system is locked to a distributed frequency reference (from a crystal-referenced synthesizer). A phase locked loop is used to smooth the transitions between modes and prevent abrupt changes in phase. The DSPs are equipped with flash memory which allows the firmware to be readily changed when required, even remotely, if necessary.
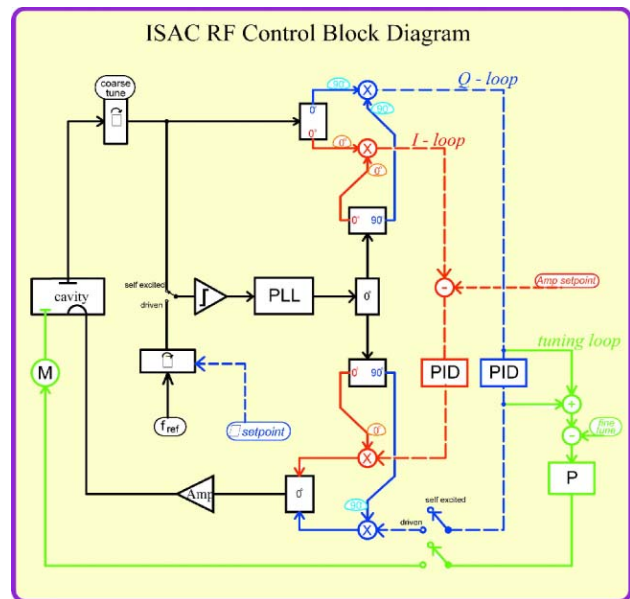

Figure 1: Normal Conducting System

The Superconducting Control System

A typical Q for a normal conducting ISAC cavity would be on the order of 5×10^3. For a superconducting ISAC II cavity the corresponding figure is approximately 2×10^9. For the cavity frequency of 106 MHz, this results in a bandwidth of less than 0.1 Hz. This results in a much greater degree of difficulty in achieving amplitude control and phase lock to a fixed reference frequency. To circumvent this problem, several approaches have been used. The first and simplest is to overcouple the cavity. This has the effect of considerably increasing the effective cavity bandwidth, reducing the difficulty of obtaining frequency and phase lock, at the expense of increased rf power. The second design change was to make the self-excited mode the normal mode of operation. Figure 2 shows a block diagram of the most recent superconducting controls design implementation. Without going into detail, it is evident that the design has changed significantly. The tuning loop has been redesigned for higher bandwidth, and uses a servomotor rather than a stepper. This has raised the tuning loop bandwidth to about 40 Hz – possibly enough to damp some of the lower frequency microphonics, but not enough to control a tuning system mechanical resonance at about 70 Hz. The tuning loop is used to minimize the drive power required by the frequency/phase loop.
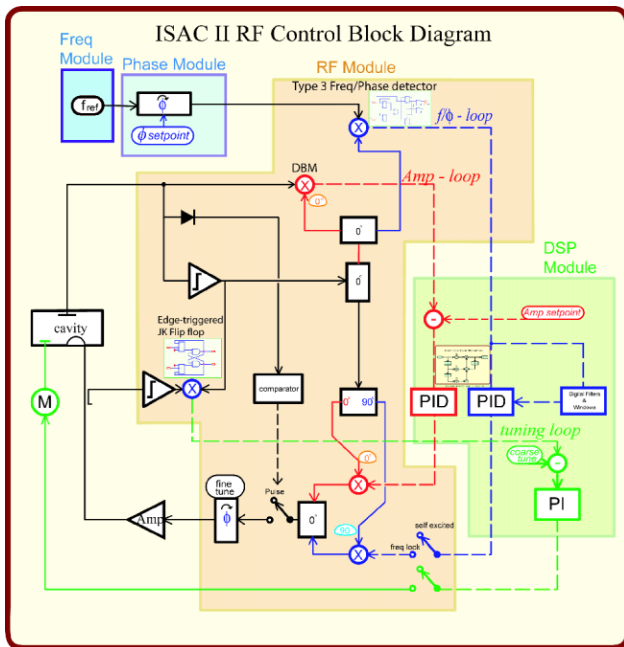
Figure 2: Superconducting System

Test Results

To startup the cavity, the coupling loop is initially moved into the cavity to the mechanical limit. This provides a coupling factor roughly 500 times higher than that required for critical coupling. As mentioned previously, this has the advantage of significantly increasing the effective bandwidth of the cavity, as well as decreasing the risetime for pulse mode operation.

Cavity conditioning was carried out over a period of about two days, and was normally begun before the cavity reached superconducting temperature. Initial conditioning involved the application of CW power until the multipactoring threshold was reached. The power was then held at that level until punch-through could be achieved. At high power levels where field emission became a factor, pulse mode conditioning was used. This reduced the risk of quenching and the resulting loss of helium. Tests of the first cavity initially failed to reach the design target field strength of 6 MV/m. Several measures were taken to improve this figure. A high pressure water rinse was added to the final stages of cavity cleaning before evacuating the cavity. A final helium conditioning step was added. Together with the water rinse, this produced a 9.5 MV/m field before the beginning of field emmission. The final step was the installation of a mumetal shield to block the background magnetic field, and raise the measured cavity Q to the design goal of $2x10^9$. Since the first cavity tests, five more cavities have been tested, the latest of which achieved a field of over 11 MV/m before quenching.

The amplitude and phase control system frequency response curves from the most recent test run are shown in figures 3 and 4, respectively. As shown in these figures, control bandwidths of 130 Hz for amplitude and 100 Hz for phase were achieved.
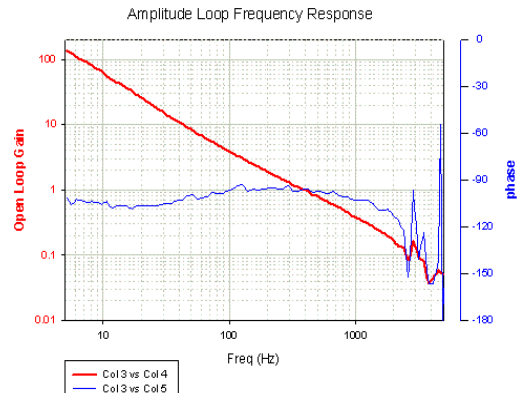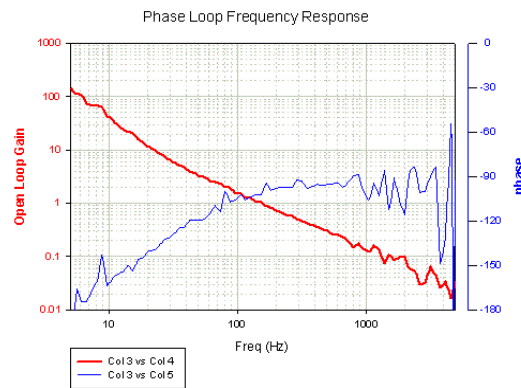

Figure 3: Amplitude Loop Response

Figure 4: Phase Loop Response

Normal vs. Superconducting Design

One issue that arose in the course of prototype testing is the very wide dynamic range required of a superconducting control system vs normal conducting. The system must also function with the cavity at normal temperatures, where much higher power and drive levels are needed. This means that factors such as analog offset voltages become significant at the low drive levels required when superconducting temperature is reached. This led to some redesign of the analog part of the controls to reduce offset errors.

Another issue that required design changes was the problem of crosstalk between the amplitude and phase control systems. These share a common DSP and multiplexed A/D convertor. Initially, the amplitude and phase signals were sampled sequentially, with a program controlled delay time to set the sampling rate. It was found that the resulting unequal sample and hold times for the two signals resulted in crosstalk between them. This had not been noticed on the normal conducting systems, but proved to be a significant problem, and made it very difficult to achieve phase lock reliably on the superconducting cavity.
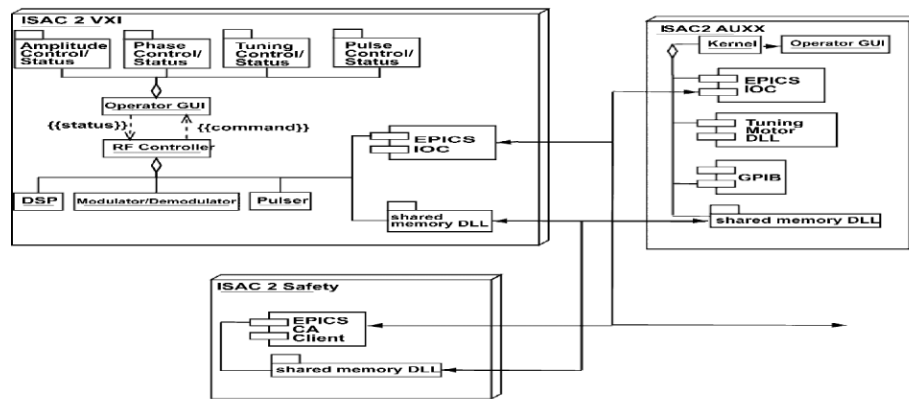
Figure 5: Control System Deployment Diagram

Phase Detectors

Two types of phase detector are used in the control system. Phase detectors are required for both the phase loop and the tuning loop. The inputs of the tuning loop PD always have the same frequency, but one or both of the inputs may not be present. In this case one cannot use a type 3 or 4 detector. To simplify adjustment, an edge-triggered J-K flip-flop is used. For the phase loop PD, we need both phase and frequency detection, but in this case the two inputs are extremely stable in phase. This tends to amplify the crossover-distortion problem in a charge-pump PD. To avoid the crossover-distortion an Analog-Devices AD9901 PD is used for the phase loop. It is a modified type 3 PD with acquisition-aiding capabilities.

Control Software

The rf control software has undergone a major revision to incorporate EPICS, various safety interlocks, and improved tuning control. This is indicated in Figure 5. Each PC can control up to 4 cavities, and each cavity is controlled independently by a separate task with its own virtual EPICS IOC. This is indicated as the upper left node in the figure.

All control parameters and status readback values can be access remotely by EPICS. Not shown in the figure is that up to 4 of these nodes can be running simultaneously.

The upper right node is used to control common shared resources such as the tuning motor controller and GPIB controller. This node communicates with the cavity controller tasks with shared memory inside a dynamic linking library, as indicated by the package labelled "shared memory DLL". Since the regulation bandwidth of the tuning loop depends on the communication throughput between the controller node and the common resource node, with this configuration an data update rate to the tuning controller is only limited by the maximum write speed of the hardware. Finally, external safety parameters are read via EPICS with another task, located in the bottom of the UML diagram. The safety parameters are distributed to all the controller tasks with the shared memory DLL. At the present time while we are still at the developmental stage, all the tasks have built-in graphical user interfaces. A replica of the graphic user interface with full control/status display can be employed remotely via EPICS. We are planning to remove the local graphical user interfaces when we have completed the commissioning stage.

CONCLUSION

This system has evolved considerably from the normal conducting controls which preceded it [1][2][3]. The performance required for a superconducting system proved much more demanding in terms of accuracy and dynamic range. Changes are currently being made to replace the DSP with a more current version as well as replacing the input A/D convertors with higher resolution, non-multiplexed versions. Amplitude control to within approximately 0.25% and phase control to within 1-2 degrees has been demonstrated. The cavity has more than met its requirements for field strength, design Q, and now tuneability. As has been mentioned, the Q is deliberately reduced by overcoupling during operation to keep the bandwidth to a practical level (about 10 Hz). The next phase of testing involves four cavities sharing a common cryostat and is in progress as this is being written. So far, all four cavities have operated simultaneously, and one has been operated with full control (amplitude, phase, and tuning loops closed).

REFERENCES

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