TRIUMF ISAC II RF CONTROL SYSTEM DEVELOPMENT

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Abstract

The rf control system for the ISAC II superconducting cavities is a hybrid analogue/digital design which has been through several iterations in the course of its development. In the current design, 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 current design also allows for the rapid implementation of operating firmware and software changes, and can be done remotely, if required. This paper outlines the development of this system, some of the challenges met towards achieving successful and reliable operation with a superconducting system, and those yet to be met before this system is completely commissioned.

INTRODUCTION

This paper reviews the development of the current TRIUMF superconducting rf control system. The design history is traced from its roots as an adaptation of earlier approaches implemented in the normal conducting ISAC-1 cavity systems. The changes made necessary by a superconducting cavity are outlined. Finally, the modifications to the initial concept, which were developed over the course of a number of test runs with a prototype cavity, are detailed. The paper concludes with a few notes on the status of the current design.

RF CONTROL SYSTEM

A block diagram of the normal conducting rf control system which provided the basis for the superconducting controls is shown in figure 1. This is a more or less standard I/Q system using a single DSP to implement both the I and Q PID loops. A separate DSP provides proportional control for the tuning system. The phase lock loop which provides the frequency reference for the system features the ability to be driven either from the system reference frequency source or a feedback signal from the cavity. This makes it possible to run in self-excited mode during cavity conditioning and/or warmup. A manual phase shifter is used to zero the initial loop phase for this mode of operation. The DSP design approach gives the flexibility to implement features such as digital limiting, to prevent overdriving the cavities, and low pass filtering, to remove the effects of power supply ripple.

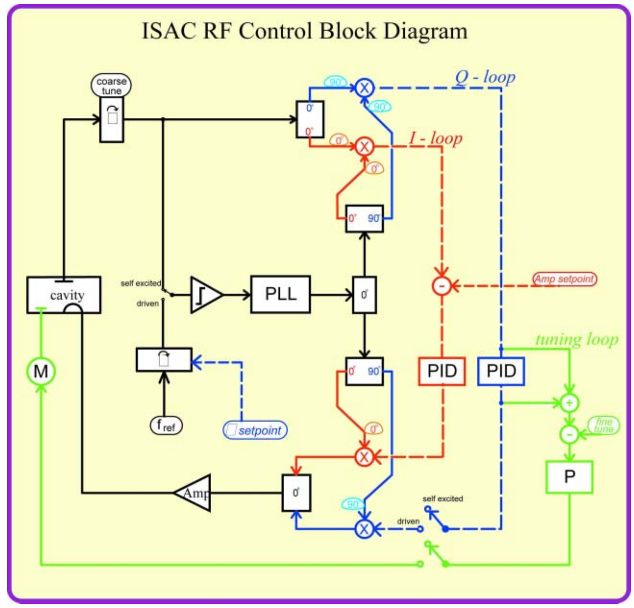

Figure 1 – Normal Conducting System

Superconducting Control System

The major difficulty anticipated in moving to a superconducting system is that the much higher Q (10^9 vs. 10^3 for a normal conducting system) leads to a much greater degree of difficulty in achieving amplitude, frequency and phase lock to a fixed reference frequency. At a cavity frequency of 106 MHz this results in a bandwidth of only about 0.1 Hz. Figure 2 shows the first implementation of a control system for the prototype superconducting cavity. The most obvious difference in this new design is that the self-excited mode is now the normal mode of operation. The loop phase in the previous design was normally adjusted so that the quadrature I and Q signals corresponded to amplitude and phase feedback, respectively. This approach is also used in the superconducting design, but the phase loop is now both a frequency and phase loop. In practice, the tuning loop is be used to bring the cavity frequency within range of the frequency/phase control. Another difference is the provision of a signal injection path via a directional coupler. This is used to kick start the self excited loop since there is insufficient noise in the supercooled cavity to initiate oscillation.

Prototype Test Results

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

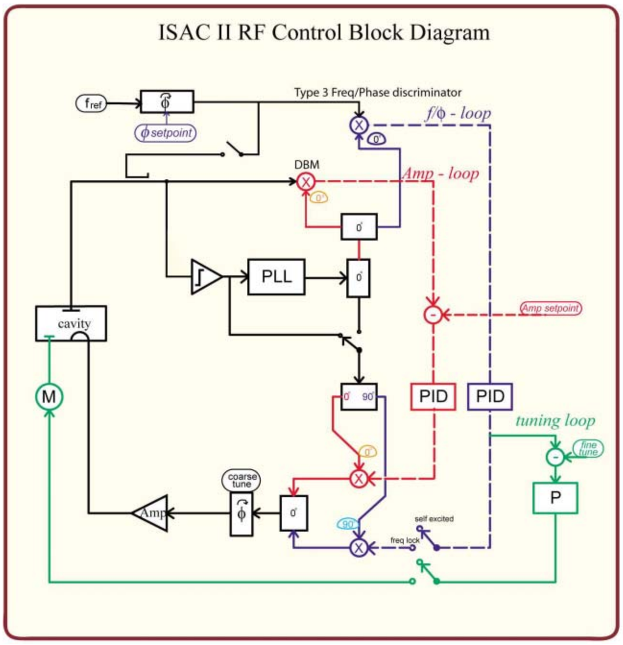

Figure 2- Superconducting System

The initial conditioning of the cavity was carried out over a period of about 48 hours and was initiated before the cavity reached superconducting temperature. CW power was applied until the multipactoring threshold was reached and kept at that level until punch through could be achieved. Pulse mode operation was required for conditioning at the higher power levels where field emission became the limiting factor. This was necessary to prevent cavity quenching and rapid loss of helium. Subsequent conditioning involved the use of helium conditioning as documented in earlier papers [1],[2] and brought the cavity close to its design field strength (5 vs. 6 MV/m). Subsequent tests were preceded by high pressure water rinsing of the cavity. Together with further helium conditioning, these steps raised the onset of field emission to 9.5MV/m, well above the operating field. The maximum Q was still below the design goal, however, at about $4x10^8$. A mumetal magnetic shield was installed around the cavity, and this brought the Q to the design level of $2x10^9$.

In normal operation, the cavity is operated at a coupling factor of about 100 to achieve a more manageable bandwidth of about 10 Hz [3].

Control System Design Issues

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. Since the system must also function with the cavity at normal temperatures, where much higher power and drive levels are needed, factors such as analog offset voltages become significant when superconducting temperature is reached. This meant some redesign of the analog part of the controls for lower 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 sampling 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.

Phase Detectors

Various types of phase detectors are used in the control system. Phase detectors are required in the PLL, 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 2 PD with acquisition-aiding capabilities.

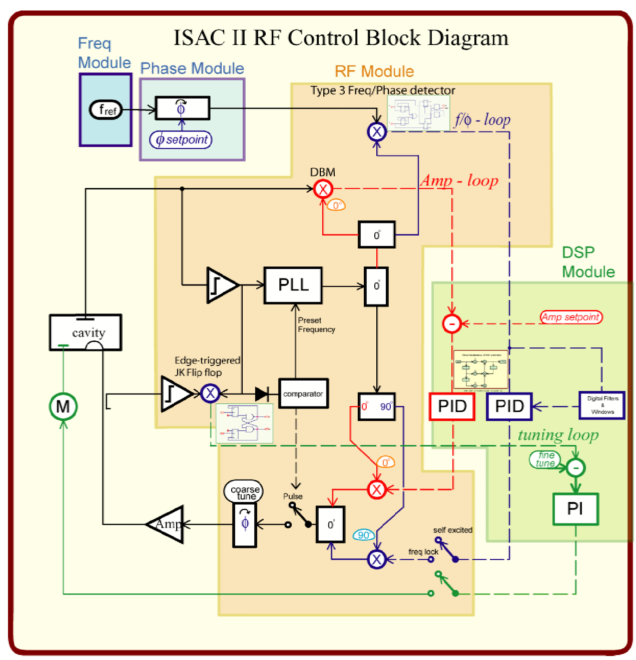

Figure 3 – Superconducting System

CAVITY Q MEASUREMENT

One of the important parameters of a super-conducting cavity is its Q/E_a response curve. The accelerating electric field E_a is measured directly using a voltage probe, and the cavity Q can either be measured from the decay time of the cavity or be calculated from E_a and the power dissipated in the cavity. The second method makes use of the fact that relationship between E_a and the stored energy U can be determined accurately using numerical methods, providing that E_a is below the threshold where U is dissipated in the form of field emission. This method is also used to calibrate the sensitivity of the voltage probe. The power dissipated in the cavity is calculated from the measured forward and reverse power, taking into account the cable attenuation between the point of measurement and the coupling loop. The attenuation measurement is non-trivial since the coupling loop end of the cable is inside a cryogenic environment and therefore is not accessible. Although these calibrations need to be done only once (unless the physical characteristics of the system are changed), they need to be done very accurately. To simplify the task of calculating Q and E_a, a semi-automatic method is used to measure and plot this curve. The voltage from the cavity probe is split into two paths. One is rectified by a zero-biased Schottky detector, connected to a Tektronix Digital Storage oscilloscope, and is used to calculate the decay time during pulse mode operation. The other is connected to a different input channel of the oscilloscope and is used to measure the voltage during cw mode operation. The forward and reverse power is measured by an Agilent power meter. These power levels are constantly monitored by the RF control system.

An Apache httpd web server invokes a back-end common-gateway-interface program which reads the oscilloscope values via a GPIB interface (figure 4). The program receives power measurements from the RF control system using a UDP/IP link. The decay time is calculated from the voltage vs. time trace of the oscilloscope data using least square curve fitting. These data are sent to a Web browser, where the calibration factors, E_a and Q are calculated on the client-side within a java-script web page. The raw data, the calculated values, as well as the calibration parameters can all be sent back to the Apache server and stored in an ODBC-compliance database. The same client-side web page can invoke another cgi program to retrieve and plot the stored data online.

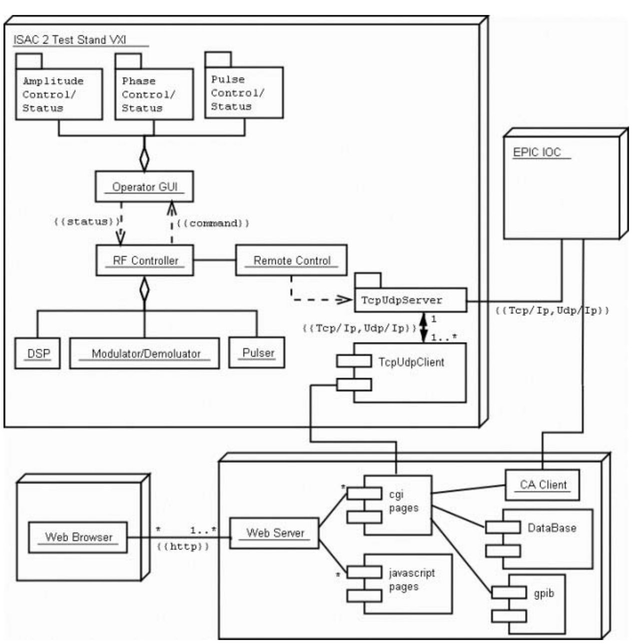

Figure 4 – Control System Deployment Diagram

One software component of the RF control system also acts as an EPICs IOC. Important RF status such as RF voltage, RF phase, tuner position, forward and reverse powers are updated every 200 ms. This IOC also scans for remote commands to turn on or off the RF, the regulations and changing of the voltage setpoint.

CONCLUSION

While this system was able to use some of the hardware from the normal conducting controls which preceded it, the performance required for a superconducting system proved much more demanding in terms of accuracy and dynamic range. Minor changes are still being made to optimize the sampling rate (currently about 67Khz) and resulting bandwidth, as well as the PID parameters. 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 and design Q. As has been mentioned, the Q is deliberately reduced by over-coupling during operation to keep the bandwidth to a practical level (about 10 Hz). The next phase of testing will involve four cavities sharing a common cryostat and is expected to take place in December.

REFERENCES

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[3] K. Fong, S. Fang, M. Laverty, “RF Control System for ISAC II Superconducting Cavities”, Proceedings of the 2003 Particle Accelerator Conference, Portland, USA, May 2003.