DESIGN AND TESTING OF THE TRIUMF ISACII HIGH-β RF CONTROL SYSTEM*

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Abstract

The rf control system for the twenty 141 MHz TRIUMF quarter wave superconducting cavities is a hybrid analogue/digital design. It is based in part on an earlier design developed for the 106 MHz 1/4 wave superconducting cavities of the ISACII linac. This design has undergone several iterations in the course of its development. In the current version, a value-engineering approach was used to reduce the cost and simplify the hardware. The result is a single C-size VXI module that incorporates all the required low-level rf functions - amplitude/phase control, tuning control, and control of the rf coupler. It accomplishes these functions at a substantially lower cost than the previous two-module solution. It also includes support for field upgrade of the DSP/PLD hardware and firmware. Some early test results of the system operating in the linac are outlined, and conclusions are summarized.

INTRODUCTION

This paper briefly reviews the development and outlines the design of the TRIUMF high-β 141 MHz superconducting rf control system. This design draws heavily on work done for the existing ISACII linac and some of this design history is outlined. Some test results obtained with the commissioned system are presented. Finally, a few conclusions are offered.

ORIGINAL ISACII DESIGN

This was the first superconducting linac application at TRIUMF. It consists of five four cavity cryomodules operating at 4K. The cavities are quarter wave resonators mechanically tuned via a servomotor system. The control system for these cavities has been documented elsewhere [1], but is reviewed briefly here. A block diagram of this system is shown in Fig. 1. A commercial low phase noise crystal-based synthesizer provides the reference frequency for the system via phase-stable coaxial cable.

The rf module includes two phase detectors implemented in a single FPGA. One is used to control the rf phase while the second controls the tuner. The FPGA also includes two counters – one for the reference and the second for the cavity frequency. These are used for initial tuning of the self-excited cavity prior to closing the phase loop. A single DSP provides amplitude and phase control while a second DSP is used to regulate the tuner. Considerable design effort went into optimizing the system for low noise, as the noise floor of the controls has a direct impact on the phase and amplitude noise of the cavities. This control system is divided into two VXI C-size modules, one for the rf, a second for the A/D and DSP functions, plus a third plug-in module for the FPGA phase detectors and frequency counters.

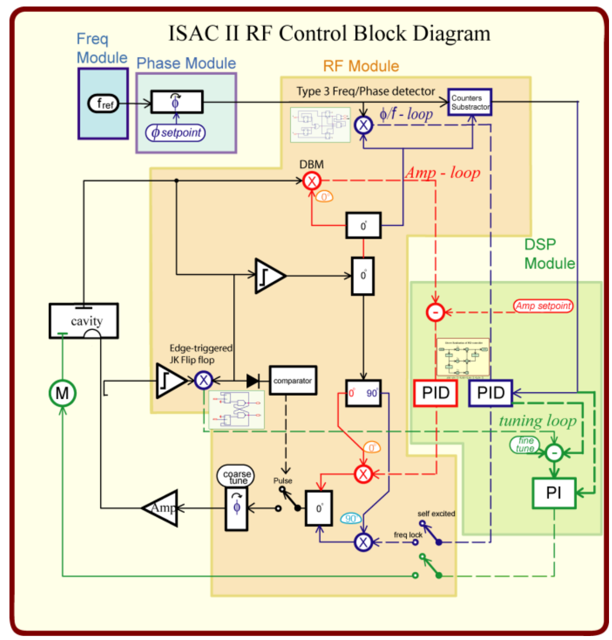

Figure 1: Superconducting control.

HIGH-β ISACII DESIGN

Design Goals

There were several reasons for exploring a new design for the high-β expansion of the accelerator. Component obsolescence, in particular for the FPGAs, meant that some of the original parts were no longer available. A look at the two original PCBs reveals that both are relatively low density and have a number of components in common, in particular those used for the VXI bus interface. This led to the obvious question of whether the two main PCBs could potentially be combined into one. When a test PCB layout showed that the combination was physically possible, a more detailed design study was begun.

Other motivating factors were that the two modules and one plug-in were the work of three designers using different CAD systems, components, power supply conventions, etc.. These badly needed some common standards to simplify fabrication and support, especially as a couple of dozen units were required. A further potential benefit is that the controls for an entire

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cryomodule (6-8 cavities) could be incorporated in a single 13-slot VXI mainframe. Another objective was to provide an easy method of updating FPGA and DSP firmware, without the need for removing modules from the VXI mainframe.

Design Issues

A decision was made to adopt Orcad for the schematic capture portion of the design, and Protel for the PCB layout, with a netlist providing the interface between the two. Where four layer PCBs had been adequate for the previous designs, six layers were required for the higher density of the combined module. Fortunately, advances in PCB fabrication meant that little, if any, cost penalty was incurred for the extra layers.

To isolate the rf and analogue/DSP portions of the PCB a split ground plane with rf chokes to isolate the power supplies was employed. Other isolated ground planes were used to shield the critical A/D convertors.

The original two module design had used more than twelve separate power supply voltages and a number of on-board regulators. Wherever practical, these were consolidated into minimum set of supply voltages – preferably those available from the VXI mainframe supply. The three discrete regulators required for the FPGA supplies were consolidated on the main PCB. The one other remaining regulator is used to isolate the 5V analogue supply.

To reduce rf radiation and/or EMI susceptibility, virtually all of the passive and a large number of the active components were changed to surface mount types. Some buffers required for inter-module analogue signals were removed as they were no longer required. Much care was taken to isolate rf, analogue, and digital signal lines from each other.

To meet the requirement for in-system firmware reprogram-ability, a standard module-edge JTAG interface was chosen. This can be jumper-configured for stand-alone operation, or to allow access to all of the modules in a given VXI mainframe.

Production Issues

The goal was to produce 35 modules – enough to meet the requirements of ISACII high-β, VECC commitments [2], as well as the electron linac project [3]. While this number was deemed too large to produce with in-house resources, it was too small to interest the automated fabrication shops. The solution arrived at was to contract the assembly to a local shop which specialized in hand assembly of small production runs. This meant that more time was required for testing and debugging, in particular for the prototype units.

Testing

To meet the requirements for Canadian nuclear safety, TRIUMF has recently adopted a number of documented procedures in support of its QA program. To comply with this program, and in view of the large number of modules to be tested, a formal test procedure was developed. Blank PCBs are given visual as well as bed of nails (shorts/opens) tests by the board manufacturer. Assembled PCBs are given a serial number, and a test document is completed and filed for each unit. This test procedure begins with visual inspection, and includes checks of supply rails for opens/shorts and correct supply voltages. Subsequent steps include programming and verification of all programmable logic, and testing of the JTAG interface. VXI communication with the two DSPs and microcontroller is tested next, followed by a software integration test. Further tests verify and optimize the performance of the rf systems, including the two phase detectors and the frequency comparator. All of these tests helped ensure a relatively low incidence of problems during the commissioning phase of the project.

Commissioning

System integration and final testing brought the usual share of problems, not the least of which was the bankruptcy of the solid-state amplifier supplier during the production run. Other problems experienced included shorts on the rf power coupler cables within the cryomodule. The latter appeared to be due to the method used for venting the coaxial cables in the vacuum chamber. The amplifiers proved to be overly prone to tripping on small transients and not correctly calibrated to trip with excessive drive levels. These challenges were eventually met, and the linac was successfully tested with beam. Due to time constraints, additional testing had to be postponed until a block of unused accelerator time was available. For more information on commissioning refer to [4].

Final Testing

In this test, four cavities from one of the cryomodules were tested under varying conditions to establish the RMS residual phase noise. A prototype control sytem using two modules was also tested on one of the cavities for comparison.

An Agilent Dynamic Signal Analyzer was used for the phase noise measurements. To calibrate the phase detector, the phase loop is unlocked, the reference and cavity frequencies shifted by about 20 Hz, and the resulting 360 degree phase signal captured and quantized. Figure 2 shows a sample reference spectrum which was used in calibrating cavity 1.

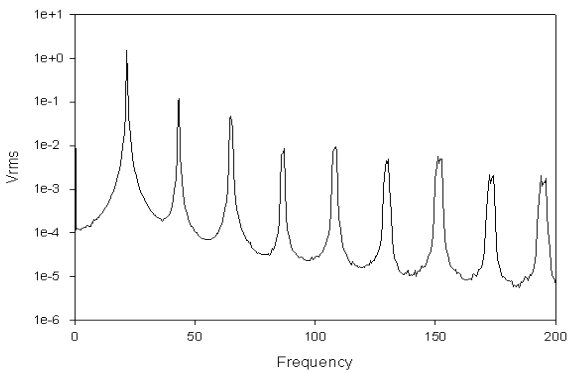

Figure 2: Cavity 1 calibration.

The spectrum is a series of harmonics of the difference frequency. When integrated and divided by 360, they provide a reference level for 1 degree of phase noise. Figure 3 shows two phase noise plots of the same cavity under phase-locked conditions. The first plot shows the system operating with the minimum gain required to maintain phase lock. Integrating this plot yields an RMS phase noise of about 6 degrees. The second plot shows the same cavity with the system operating at maximum gain. In this case, the RMS phase noise averages out to about 0.01 degree.

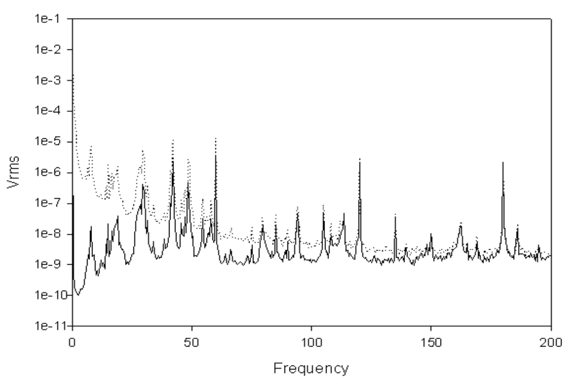

Figure 3: Cavity 1 phase noise.

Figure 4 shows two plots obtained with another cavity. Here the objective was to compare the prototype two module control to the production single module solution. Unfortunately, the PID's integral gain was inadvertently set too high (bordering on instability) on the two module system, making a direct comparison difficult. At mid-band and above this effect is minimal, and the single-module system appears to have slightly lower noise. The single module control for this system had an RMS phase noise figure of 0.014 degrees, while the corresponding number for the two module system was 0.0012 degrees.

CONCLUSIONS

As mentioned, operating with gain bordering on instability is not practical. In practice, optimum system stability is usually obtained at gain settings less than those used for the above tests. Nevertheless, sufficient margin is available to make phase noise figures on the order of 0.1 degree or less attainable under operating conditions.

The single VXI module system developed for the high-β rf controls has met all of the performance requirements for the accelerator, while achieving significant cost and space savings. Unfortunately, the full potential savings could not be realized, as the rf amplifiers could only be mounted in groups of four, owing to rack space limitations. Otherwise, a complete cryomodule control system for up to eight cavities could have been contained in a single VXI mainframe.

Another unexpected benefit is simplification of support requirements in the event of a system failure. There is no longer an issue of diagnosing which module is at fault and in need of replacement or who to call for help, as only a single module need be replaced.

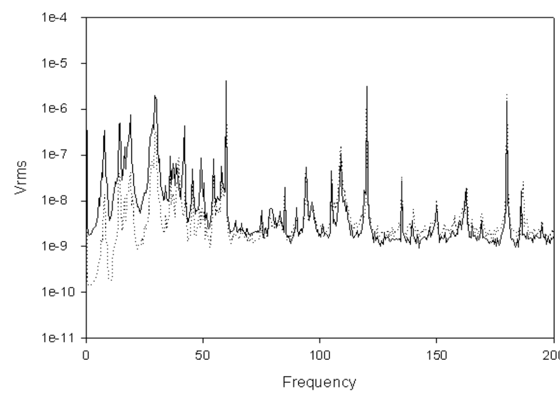

Figure 4: Cavity 4 phase noise.

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