RF Control System Upgrade at TRIUMF

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Abstract

The low level rf control system for the 23 MHz, 1MW rf drive of the TRIUMF cyclotron is being completely redesigned using state-of-art hardware and software. Frequency control using direct digital synthesis provides good frequency resolution, as well as allowing rapid changes in frequency. Digital signal processors (DSPs) are used in the amplitude and phase regulators. This permits adaptive control of feedback parameters, and eliminates drift due to component aging. The entire system is housed in a single VXI mainframe, which provides a low noise environment for the feedback control circuitry. Functional modularity is provided by different plug-in modules. Local intelligence in the VXI controller automates the logically intensive routines such as power-up sequencing. It also provides supervisory controls to the rest of the modules and communicates with the site-wide control system.

1. INTRODUCTION

The TRIUMF cyclotron main rf system [1] has been in operation for a number of years. The control system described here represents a major upgrade using state-of-art hardware and software. To minimize disruption to current operations and possible loss of beam time, initial trials have been conducted using a resonator test facility [2]. This facility simulates the TRIUMF cyclotron's resonator by using a single pair of the resonator segments inside a vacuum chamber. The resonator is powered by a 50kW rf amplifier to generate 100kV peak tip voltage. The test results presented here were obtained with the system operated in conjunction with this facility.

This system evolved from earlier work on controls for a fourth harmonic booster cavity [3] and beamline rf separator [4]. Unlike its predecessors, this system is VXI-based and employs a hybrid analog/digital approach. This has the advantage of permitting the incorporation of low-level analog and rf components, together with their associated digital controls, in the same modular rack. The VXI system enables easy field repair and upgrades, while object oriented programming provides similar benefits to the software.

2. SYSTEM ARCHITECTURE

A simplified block diagram of the system is shown in Figure 1.

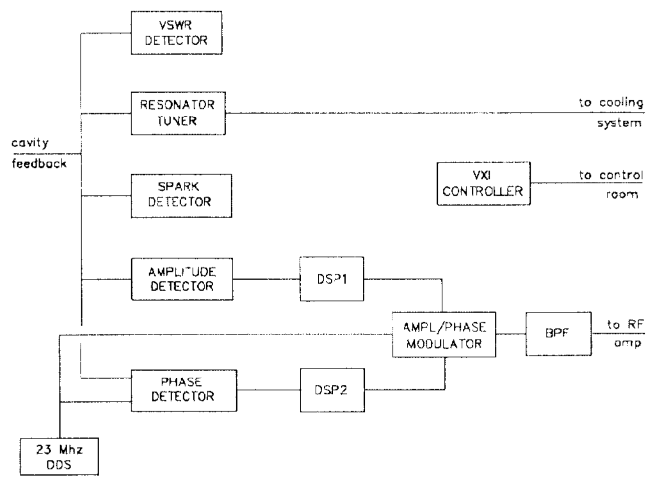

Figure 1. Cyclotron Control System Block Diagram

Local intelligence is provided by a VXI-based 80386 microprocessor, which is programmed in object oriented C++. It provides high level supervision of the hardware modules, automatic powering up of the rf system, local operator interface, and remote control interface.

The 23 MHz frequency source is a direct digital synthesizer, able to change frequency instantaneously without any glitches in the output amplitude. For this application, the frequency is set by a 15 bit word, providing a range of 320 kHz with a resolution of 10 Hz. Synchronous detection is used by the amplitude detector. This type of detector has very good linearity over the entire signal range. It is also insensitive to temperature variation, frequency or phase variations in the input signal.

The phase detector is a type 3, edge-triggered JK flip-flop device. Constructed of 100K ECL NAND gates, the usable detection range is 270° at 23 MHz. It provides a bipolar output that equals zero when the rf input and the reference are in phase. A type 1 detector, whose output is maximum at 0° phase difference and minimum at 180° phase difference, is used to supplement the main detector. It serves to identify the usable detection range as well as the presence of rf.

Amplitude dependence of the phase detectors is eliminated by a pair of low phase shift amplitude limiters at both the input and the reference. A ten percent modulation in amplitude results in a phase error of 0.1°. The input limiter also provides the rf source for the self-excited mode of operation. In this mode, the resonator is used as the frequency determining element, with the path length of the feedback loop adjusted such that the self-excited rf frequency is always equal to the resonant frequency of the resonator, regardless of the tune of the resonator.

Voltage amplitude and phase regulation is achieved by fixed point Motorola DSPs. These run at a clock frequency of 48 MHz, which gives an effective sampling rate of 2.4 MHz. Fast analog-to-digital converters (ADC's) in front of the DSPs and digital-to-analog converters (DAC's) after the DSPs, as well as optimized code result in a transport delay of 0.83 microseconds.

With the DSP running a Proportional-Integral-Differential (PID) controller program, a regulator bandwidth of 50 kHz. was achieved. Control programs in the processors are able to switch between open and close loop. A numerical limiter prevents integrator wind up and clamps the maximum rf drive power to a presettable limit to prevent damage to the power amplifier and the resonator. This limit, the regulator setpoint, the PID parameters, and the control algorithm can be varied dynamically while the feedback is in operation.

Amplitude and phase are modulated by splitting the rf signal into I and Q components. The two components are modulated using wide band analog multipliers and recombined. Its performance has been described in a previous paper [2]. The tuner control module is currently under development. It will detect the phase between the drive line and the cavity and use a DSP-based proportional-integral controller (possibly with deadband) to control the mechanical cavity tuning system. The spark detector detects a decay in the cavity rf voltage at a rate greater than that expected from the resonator time constant. The VSWR detector provides a signal to lower the drive level when the reflected power exceeds the threshold that the power amplifiers can safely tolerate.

3. System Operation

The control system was tested in the rf test stand facility, and proved to be very simple to operate. Initial setup required adjustment of the length of the feedback path for self-excited mode operation, and rough selection of PID coefficients to ensure stable closed loop operation. At the operator's request to power up, the system automatically selects pulse mode at the synthesizer frequency, and begins ramping up the output power. When the pulsed resonator voltage exceeds a threshold indicating that multipactoring has been overcome, the frequency source switches to CW mode. It then reverts to self-excited mode operation, while ramping is continued. When the resonator voltage rises to the desired voltage, the amplitude regulation is enabled by closing the amplitude feedback loop. The spark detector is also enabled, if so desired. If the spark detector is enabled and a spark occurs, the rf drive is removed within 1 microsecond. Depending on the severity of the spark, the rf drive may be turned back on automatically, or remain off until an operator intervenes.

Once the regulating loops are closed, the PID coefficients can be optimized by monitoring the residual amplitude and phase noise on a frequency analyzer. The onset of loop instability can be observed as high noise power at the phase cross-over frequencies from 10 kHz to 50 kHz, depending on the PID coefficients. Because the PID controllers are constructed using DSPs, the PID coefficients have wide dynamic ranges and can be easily varied while the feedback loops are operating. By stopping the update of the DSP output, closed loop operation can be switched to open loop without generating any transients in the system output level.

Under self-excited mode, the rf is able to track the resonant frequency of the cavity as the system warms up under power. If at anytime the resonator voltage falls below the multipactoring threshold, the system shuts down, and the above process is repeated.

4. Closed Loop Measurements

Figure 2 shows the amplitude loop gain of the whole system, including the PID controller, the rf amplifiers and the resonant cavity. The PID controller has a pole at 0 Hz for high dc gain. Its zero is set at 5 kHz, which is canceled by the resonator pole for closed loop stability. There is a spurious response at 10 kHz whose source has not yet been determined. The phase lag starts to increase exponentially above 10 kHz, with zero phase crossing at 40 kHz. The PID controller and the resonant cavity account for 90° phase shift at this frequency. The transport delays due to the ADC, the DSP, the DAC account for 15° at this frequency, while the pre- and post- anti-aliasing filters account for another 30°. Operational amplifiers in the low level control account for 20°, and the remaining 25° is due to the rf power amplifiers in the loop.

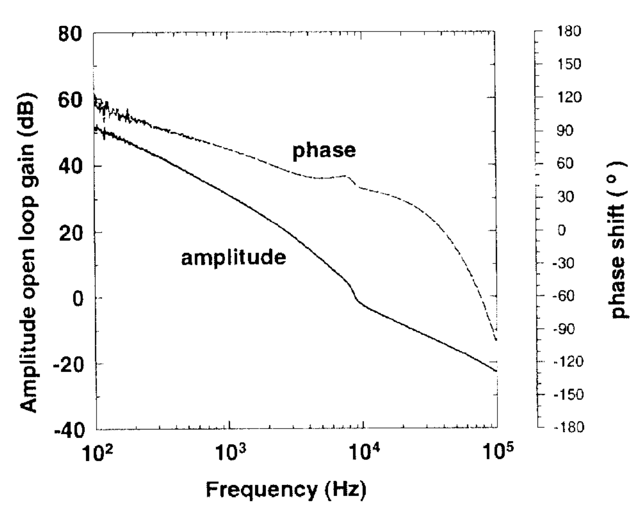

Figure 2. Amplitude Loop Frequency Response

After setting the PID coefficients for optimum gain and stability, the loop gain at 100 Hz was measured to be 50 dB. At lower frequencies the measurement was masked by noise. The phase margin is 50° and the gain margin is 12 dB.

Figure 3 shows the residual amplitude modulation (noise) of the resonator voltage under open and closed loop conditions at a fixed driven frequency. The noise floor of the measurement system is -100 dBV/Hz$^{1/2}$.

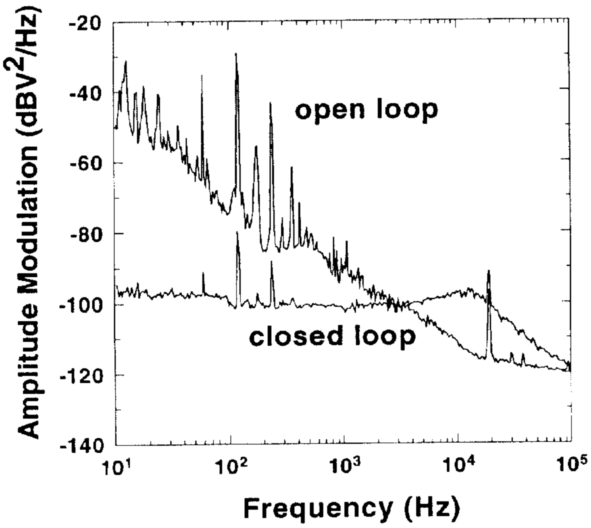

Figure 3. Residual Amplitude Noise

Due to the presence of vibration in the resonator (induced by the pumping system) the open loop voltage showed high noise power at low frequencies. Other noises, related to the power line harmonics, are also present. Under closed loop operation, these noise inputs are reduced by amounts equal to the open loop gain, or to the noise floor of the system. In particular, the 120 Hz line harmonic, which is -30 dB in the open loop configuration, is reduced by the measured open loop gain of 50 dB to -80 dB under closed loop operation.

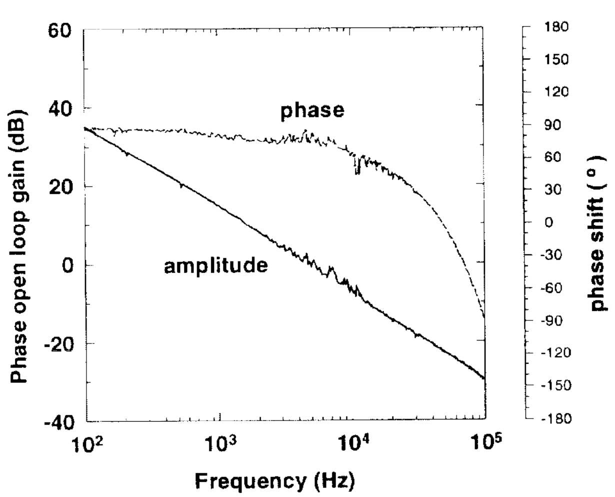

Figure 4. Phase Loop Frequency Response

Figure 4 similarly shows the phase loop gain of the whole system. After setting the phase PID coefficients for optimum gain and stability, the loop gain at 100 Hz is 35 dB, the phase margin is 70° and the gain margin is 22 dB.

Figure 5 shows the residual phase modulation of the resonator under open and closed phase loop conditions.

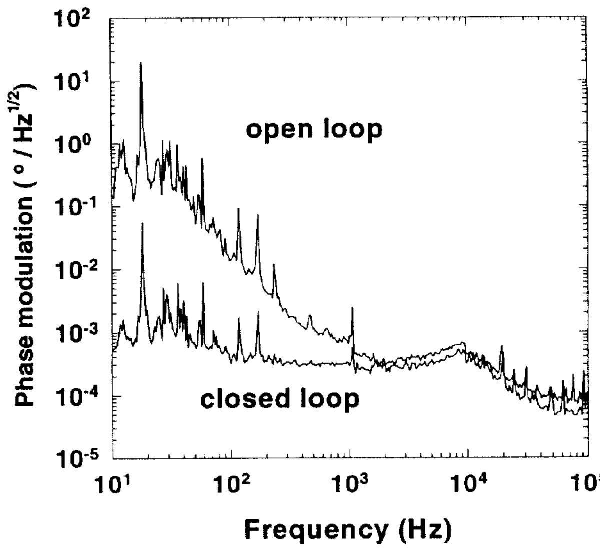

Figure 5. Residual Phase Noise

The amplitude regulation is enabled in both cases. Resonator detuning due to mechanical vibration gives rises to the large amount of phase noise at low frequencies. Phase variation as large as 20° exists in the open loop condition, as shown in the figure. Under closed loop conditions, this variation is reduced by the open loop gain to less than 0.1°.

5. Conclusion

From the test results recorded to date, it appears that this system can more than meet the requirements for most rf control systems. The amount of useful gain obtained is approximately equal to the maximum possible with the 12-bit digitizing system used. The use of a digital system makes for smooth transitions between open and close loop operation, provides an accurate limiting function, and allows for the use of adaptive control.

6. References

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