DESIGN OF A DIGITAL LOW-LEVEL RF SYSTEM FOR BEST MEDICAL CYCLOTRONS

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Abstract

A versatile digital Low-Level Radio Frequency (LLRF) system has been designed for the various energy cyclotrons being developed by Best Cyclotron Systems Inc. (BCSI). Primary design considerations are given to robustness, low cost and the flexibility to be used on all BCSI resonator designs. As such, the system allows for operating frequency selection from 49 to 80 MHz and is compatible with single or double resonator configurations through the use of local oscillator synchronization and high-speed command exchange. An I/Q demodulation/modulation scheme is employed allowing for frequency and amplitude control. High-speed phase control of separated resonators allows for beam intensity modulation techniques to be applied. This paper discusses the overall system design as well as integration results for a single resonator cyclotron.

INTRODUCTION

To accommodate with the variety of BCSI cyclotrons being established, a frequency selectable digital LLRF controller was designed [1] [2]. The controller fits into a standard 19 inch rack-mounted module and contains all of the necessary electronics, inputs, outputs and power supplies to be a fully self-contained unit.

Figure 1: The front panel of the LLRF module showing status lights, local control potentiometers and RF I/O.

A discussion of the internal components will follow, along with a description of the control procedures and their testing.

ARCHITECTURE

Hardware

The major hardware subsystems of the LLRF are the analog RF front- and back-end, Digital Control Card (DCC), motor drivers and power supplies. Each of these components were designed to be modular and easily replaceable. A block diagram of the subsystems and their interconnections is seen in Fig. 2.

Incoming RF signals are routed through filtering, mixed to an intermediate frequency and I/Q modulated before being converted to digital signals. Similarly, outgoing RF signals are converted to analog, filtered, I/Q demodulated and frequency mixed up to the cyclotron frequency.

Digital signals are routed directly between the analog board and the Altera Cyclone III FPGA on the DCC via two 80 pin connectors. This allows for fast signal processing to occur with minimal latency. The Analog Devices Blackfin microcontroller handles the higher level interface with the motor drivers and Host PC. The motor driver boards are based off the MicroSystems A4988 chip and are socket mounted for quick replacement.

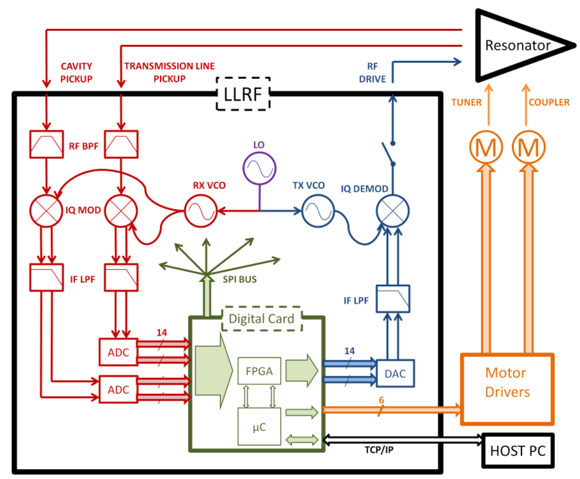

Figure 2: Hardware architecture of the LLRF board showing the major logical sections.

Software

The FPGA and microcontroller are tightly bound in function by using Direct Memory Access over Serial Peripheral Interface (SPI) and Parallel Peripheral Interface (PPI). They share a bank of 60 read-only and 60 read-write registers to communicate. This same set of registers, albeit with different read-write privileges, is shared between the microcontroller and the host PC over TCP/IP.

The FPGA is responsible for the high-speed signal processing such as the amplitude control loop, spark recovery, interlocks and safety. Additionally, all of the IC programming is handled at this level including the data converters and operating frequency selection using a dedicated SPI bus.

Higher level procedures are contained within the microcontroller. These include the RF drive state machine, motor control, host PC communication and automated frequency control loop.

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Integration

This LLRF can be used on both single and double resonator cyclotrons. On a single resonator the layout will appear exactly as in Fig. 2.

For a double resonator configuration there is defined a master and slave LLRF, selected using on-board jumpers. The master generates all of the clocks and phase references which are inputs to the slave board. Commands from the host PC to the master are shared with the slave using a SPORT connection. Data can be transfered between the boards to allow the master to handle automatic phase locking of the two resonators.

The operational frequency of the boards can be selected for a cyclotron between 49-80MHz by setting a few switches and restarting the LLRF. As this change does not require any hardware or software modifications it greatly increases the utility and modularity of the LLRF controllers.

CONTROL PROCEDURES

Start Procedure

An automated start procedure is implemented to minimize the time between RF off and RF full-power. The single button start requires sophisticated control logic to be contained in the LLRF. An outline of the procedure is as follows:

1. Pulse the RF power at 20% of full power until the cavity readback is above 15% of full power while tuning
2. Transition from pulsed RF to CW and enable the spark recovery and frequency tuning loop
3. Close the amplitude control loop
4. Ramp up the RF drive to full power

All of the timing and threshold parameters are digitally adjustable which allows for rapid tuning of the procedure to ensure reliable start-up and operation.

Amplitude Control

The cavity voltage amplitude is stabilized using a proportional-integral control loop. The loop is implemented in the FPGA using a hardware description language, and also includes overshoot protection and integral anti-windup. An initial cutoff frequency of 20kHz is selected and can be fine tuned during the particular cyclotron commissioning.

Frequency Control

Automatic frequency control logic is contained in the microcontroller and has a response time of approximately 100Hz. The loop acts to maintain a constant phase offset between the forward drive and cavity voltage. Motor position feedback is given by a linear resistor and optical encoder. Frequency control is available in pulsed and CW mode.

Phase Control

For cyclotron systems that have two independently driven resonators it is necessary to employ automatic control of their RF phases to achieve proper beam acceleration. By transmitting phase information between the master and slave LLRF boards, the slave can adjust its phase to match the master's.

It is possible to use phase control of independent resonators to provide a modulation to the beam [3]. This can produce either very short pulses for specific applications, or relatively long pulses with an adjustable duty factor to decrease the overall beam intensity during commissioning.

Spark Detection and Recovery

A crucial part of proper resonator operation is the detection of and recovery from high-voltage discharges (or sparks) within the cavity. Sparks are detected by monitoring for a rapid decline in the cavity voltage which happens on the order of 1μs. After detection the recovery procedure pauses the PI amplitude loop, turns off the RF drive for 2μs, applies an open loop drive to regain cavity voltage and then resumes the amplitude control. Properly regulated cavity voltage is restored within approximately 100μs for a typical case.

During the cavity voltage recovery, the spark detection is again enabled to protect against the case where an additional spark occurs during the ramp. The cavity voltage envelope during a single and triple spark event is shown in Fig. 3.

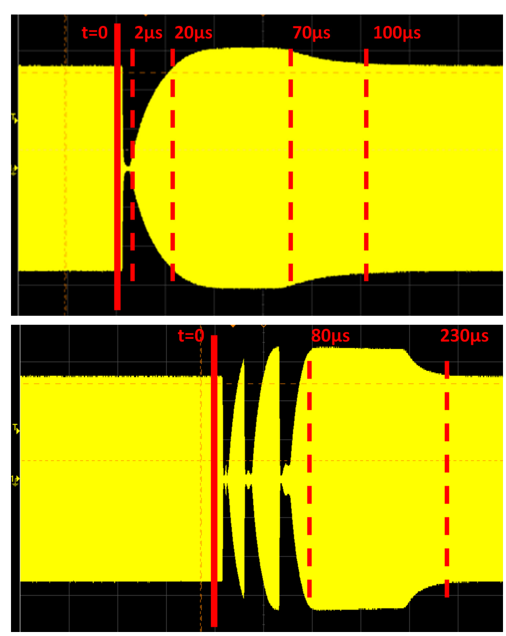

Figure 3: Cavity voltage during the detection and recovery from a single spark (top) and triple spark (bottom).

PERFORMANCE

The LLRF has been successfully commissioned on a single-resonator cyclotron. Cavity amplitude and frequency stability have been confirmed over an eight-hour test while monitoring and recovering from sparking events. The data from a shorter one-hour test are shown in Fig. 4 illustrating the system stability while reaching thermal equilibrium. Fine tuning of the amplitude control loop is continuing to reach a stability target of $5 \cdot 10^{-4}$ or better.

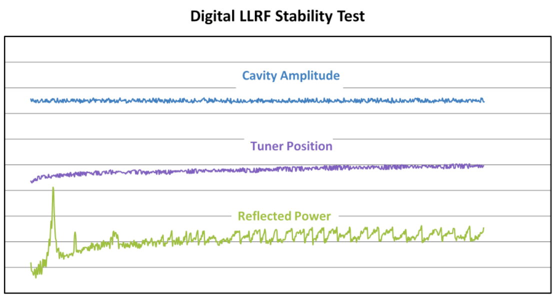

Figure 4: Initial one-hour stability test on a single resonator cyclotron (vertical axes are unscaled).

CONCLUSION

The design of the BCSI digital LLRF controller has been presented. The overall architecture of the hardware, software and system integration has been described.

Many control procedures have been implemented and tested on a single resonator system including amplitude and frequency control, automated startup and spark detection and recovery. Stability tests have also been run, showing good performance over an eight hour period of fully automated control. Application of this controller will continue with a double resonator system requiring phase control and board synchronization [4].

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