THE SPALLATION NEUTRON SOURCE ACCELERATOR LOW LEVEL RF CONTROL SYSTEM*

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Abstract

The Spallation Neutron Source Low Level RF Team includes members from Lawrence Berkeley, Los Alamos, and Oak Ridge national laboratories. The Team is responsible for the development, fabrication and commissioning of 98 Low Level RF (LLRF) control systems for maintaining RF amplitude and phase control in the Front End (FE), Linac and High Energy Beam Transport (HEBT) sections of the SNS accelerator, a 1 GeV, 1.4 MW proton source. The RF structures include a radio frequency quadrupole (RFQ), rebuncher cavities, and a drift tube linac (DTL), all operating at 402.5 MHz, and a coupled-cavity linac (CCL), superconducting linac (SCL), energy spreader, and energy corrector, all operating at 805 MHz. The RF power sources vary from 20 kW tetrode amplifiers to 5 MW klystrons. A single control system design that can be used throughout the accelerator is under development and will begin deployment in February 2004. This design expands on the initial control systems that are currently deployed on the RFQ, rebuncher and DTL cavities. An overview of the SNS LLRF Control System is presented along with recent test results and new developments.

INTRODUCTION

The SNS LLRF Control System is comprised of three main components: the RF control chassis, the High Power Protection Module (HPM), and the reference system. The RF control chassis is a digital feedback controller that uses a Field Programmable Gate Array (FPGA) for fast data processing. Three generations of control chassis are planned for supporting the near- and long-term goals of the SNS project: the 1st generation control chassis (Fig. 1) was designed at LBNL for use with the 402.5 MHz rebuncher cavities in the Medium Energy Beam Transport (MEBT) beamline downstream of the RFQ [1]. The 2nd generation control chassis (Fig. 2) is a refinement of the MEBT control chassis and will serve the RFQ and DTL sections of the linac through DTL commissioning [2]. The 3rd generation control chassis is under development and will begin deployment in the CCL, SCL and HEBT in early 2004. It is planned to eventually retrofit the RFQ and DTL with the 3rd generation control chassis. The HPM provides for fast shutoff of the RF drive to the klystron in case of RF over power, arc detection, and vacuum system interlocks [3]. The reference system provides for distribution of the phase-synchronous RF signals necessary to operate the linac and includes cavity and reference signal transport and downconversion (Fig. 3).

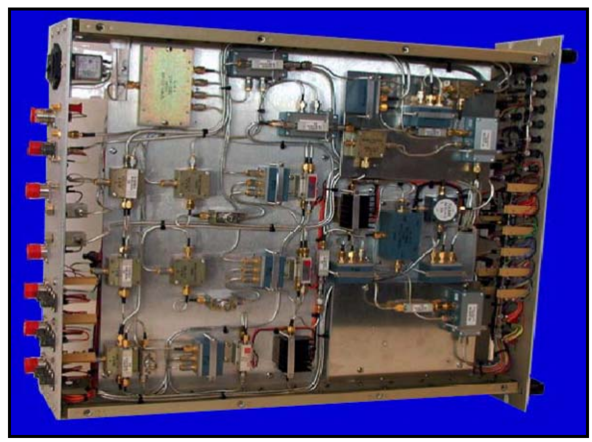

Figure 1. The 1st generation RF control chassis that is used for the MEBT rebuncher cavities.

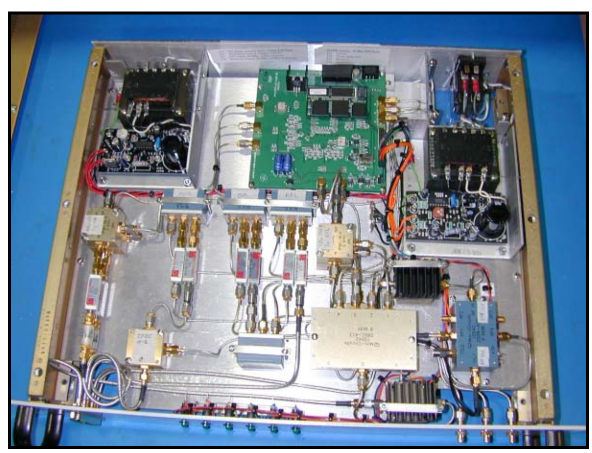

Figure 2. The 2nd generation RF control chassis that is used for the RFQ and DTL.

The 1st and 2nd generation RF control chassis have been used already in Dec.-Jan. for beam commissioning of the RFQ and MEBT rebunchers. Installation of RF control systems for DTL tanks 1 and 3 is complete; tank 3 was tested without beam in early May. Tank 1 will be tested and commissioned with beam during Summer

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2003. The HPM has been used successfully for high power protection during operation of the RFQ and DTL.

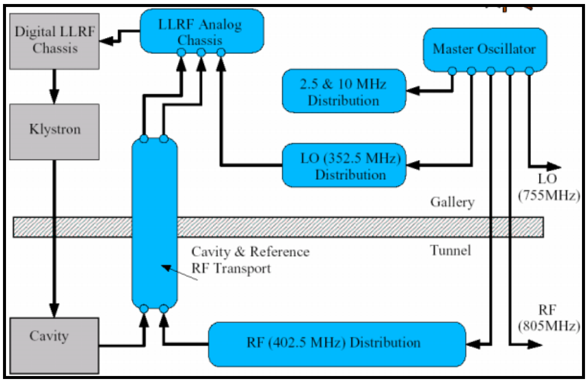

Figure 3. The reference system for the SNS linac.

NEW HARDWARE DEVELOPMENT

The 1st and 2nd generation RF control chassis have been and will continue to be essential to meeting the near-term testing and commissioning schedule. However, these systems are based on relatively small FPGAs (150k gates) and feature rather limited memories. Therefore it was decided last October to design a new RF control chassis that would overcome these limitations and provide a suitable platform for long-term SNS linac operations. The schedule for developing and producing this chassis is very tight; prototypes were due (and received) in March, and first high power tests are planned for Summer 2003. Production is scheduled to commence in September, and installation should begin in February 2004. This aggressive schedule forced a conservative design approach that called for conciseness and an evolution of existing hardware rather than a green field design. This 3rd generation RF control chassis is implemented as a VXI motherboard with three daughtercards: Analog Front End (AFE), Digital Front End (DFE) and RF Output (RFO). The AFE is nearly identical to the SNS Diagnostics Beam Position Monitor (BPM) AFE and was procured from the same vendor. The DFE is an evolution of the digital boards used in the 2nd generation RF control chassis and the BPM hardware; it consists mainly of four A/D converters and a 1.5M gate FPGA. The FPGA can be loaded with a soft core processor that may be useful in the future if more local processing is needed (as compared to the slot-0 controller). The RFO circuitry is a copy of that already proven in the 2nd generation chassis. This package, being a VXI module, has been dubbed the Field Control Module (FCM) and is further documented in a companion paper [4].

The software and firmware is key to the success of this development effort. Following the hardware design philosophy, we chose to re-use the existing code base to the extent possible. Hence the FPGA code implemented on the 2nd generation RF control chassis has been ported to the FCM. Similarly, the slot-0 controller code and EPICS interface have been retained. The VXI motherboard uses a proven VXI-bus interface. The code development is backed up by system simulations and FPGA code simulations. The standard SNS code repository is used for revision control.

The FCM is presently undergoing bench testing. The FPGA code has been downloaded via the JTAG interface, and basic read/write capability to FPGA registers and block RAM has been demonstrated via the VXI backplane. The AFE has been characterized separately and meets performance requirements. A few RFO parameters have been measured already. The RFO will be more fully characterized in integrated testing of the FCM. The VXI motherboard was tested prior to installing the daughterboards.

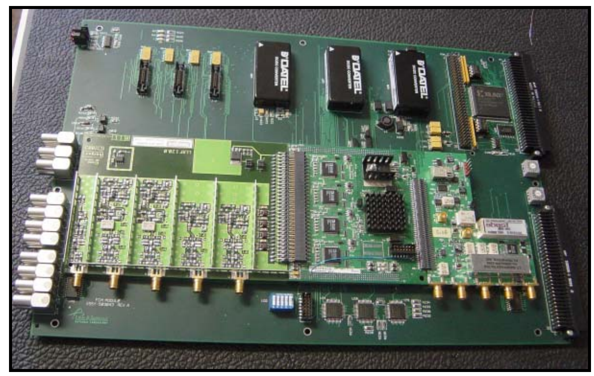

Figure 4. The prototype Field Control Module. The Analog Front End, Digital Front End, and RF Output daughtercards (left to right) are mounted on the VXI motherboard .

PERFORMANCE MEASUREMENTS

The superconducting cavities of the SNS linac are subject to Lorentz force and microphonics detuning. Regulation of the cavity fields therefore requires RF power above and beyond the beam power. Fast acting piezoelectric tuners are being installed on all of the superconducting cavities to mitigate Lorentz force detuning effects if necessary and to allow for future operation of the SCL at increased accelerating gradients. Because of concern about these detuning effects, a long-planned test of the LLRF control system with the first production medium-beta cryomodule was carried out at Jefferson Lab in early March with very encouraging results. The 2nd generation RF control chassis was used for this test. The primary goal was to demonstrate field regulation within the specification of ±1% and ±1deg at the design parameters of 10 MV/m accelerating gradient, 60 Hz repetition rate, and 1.3 ms pulse length. First feedback control was demonstrated on March 1; follow-on testing showed that we can indeed meet the field regulation requirements (Fig. 5). Typical amplitude and phase waveforms are shown in Figure 6 for open and closed loop control of the cavity fields. Feedforward control is necessary to minimize ringing due to the turn-on transient and was used to obtain the results shown in Figure 5. Our long term plans call for automatic adaptive feedforward in addition to feedback control.

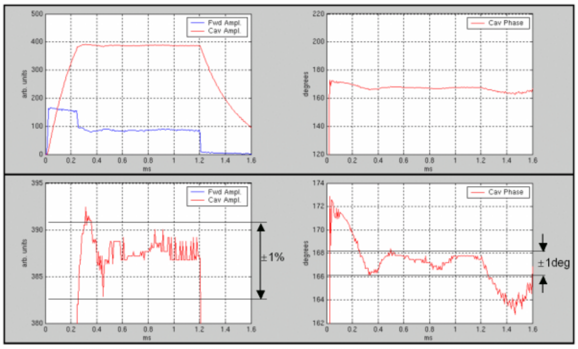

Figure 5. First demonstration of required amplitude and phase regulation on a production medium-beta cryomodule.

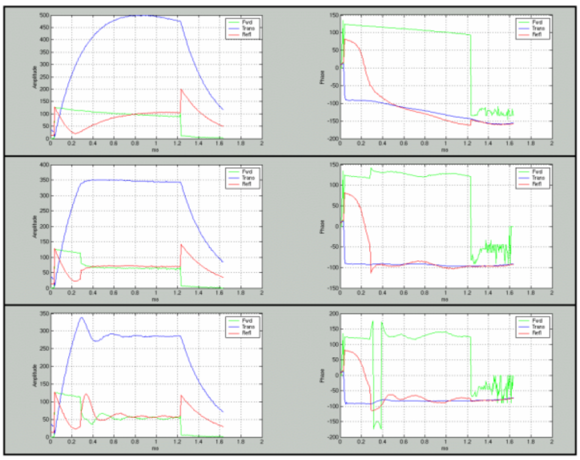

Figure 6. Amplitude and phase responses for three cases: open loop, closed loop with proportional gain only, closed loop with proportional and integral gain. Cavity field, forward power, and reflected power are shown in blue, green, and red, respectively.

Several other features of the LLRF control system were tested in March and April with the first production cryomodule. Two resonance detection algorithms were tested: 1) in the case where the detuning is only a few bandwidths, the frequency error is determined from the decay of the cavity field after the end of the RF pulse; 2) in the case of larger detuning, a single-pulse burst-mode technique has been demonstrated up to a detuning error of about 15 bandwidths. More recently, the decay technique has been applied in testing of DTL tank 3 at Oak Ridge. The detuning information was used to control the stepper motor tuner in the cryomodule tests, and it is presently being implemented for control of the water temperature on the DTL.

The performance of the superconducting cavities must be confirmed following the installation and cooldown of the cryomodules at Oak Ridge. This will be done by calorimetric measurements of Q_o as a function of accelerating gradient under pulsed conditions. The LLRF control system was used to perform this test at Jefferson Lab with good results.

The piezo tuner was operated in conjunction with the LLRF control system. The piezo power supply was driven with a pulse generator. One example (Fig. 7) is given where the piezo drive pulse was manually adjusted to flatten the phase response of the cavity field. Optimization of the piezo drive parameters and the interplay between the piezo tuners and the LLRF control system will be an interesting task.

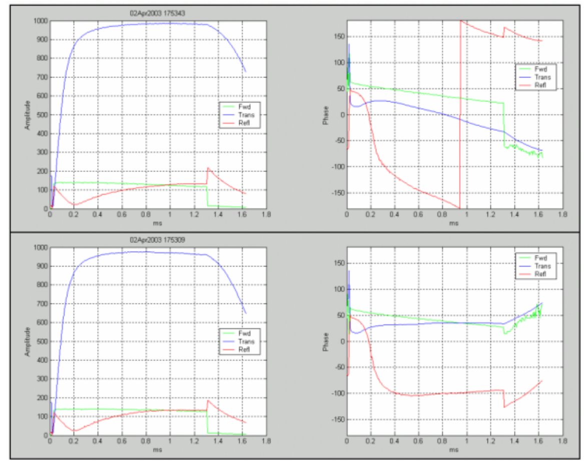

Figure 7. Demonstration of effect of piezoelectric tuner on dynamic cavity performance. Open loop operation at 12.5 MV/m for two cases: piezo tuner inactive, and piezo tuner driven with rectangular pulse having width=860 µs, amplitude=220 V, and lead=580 µs.

SUMMARY

The testing and commissioning of the FE and DTL is being supported by the 1st and 2nd generation SNS LLRF control systems. The 3rd generation system, that will ultimately serve the FE, Linac and HEBT, is under development and will begin deployment on the CCL and SCL beginning in early 2004. A successful proof-of-principle test has recently been completed with the first production cryomodule; the performance requirement of ±1% and ±1deg amplitude and phase regulation has been demonstrated. The LLRF Team, which is distributed across three laboratories, is well on its way to providing a flexible control system that will meet the performance requirements of the SNS accelerator.

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