OVERVIEW OF THE SPALLATION NEUTRON SOURCE LINAC LOW-LEVEL RF CONTROL SYSTEM*

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Abstract

The design and production of the Spallation Neutron Source Linac Low-Level RF control system is complete, and installation will be finished in Spring 2005. The warm linac beam commissioning run in Fall 2004 was the most extensive test to date of the LLRF control system, with fourteen (of an eventual 96) systems operating simultaneously. In this paper we present an overview of the LLRF control system, the experience in designing, building and installing the system, and operational results.

INTRODUCTION

The installation of the Spallation Neutron Source (SNS) Linac Low-Level RF (LLRF) control system is complete, and beam commissioning of the entire Linac is planned for summer 2005. All 96 Linac LLRF stations utilize the same hardware, software and firmware platform to achieve the required cavity field amplitude and phase regulation of ±1% and ±1deg, respectively. This platform was developed under collaboration between Los Alamos, Lawrence Berkeley and Oak Ridge national laboratories and is described more fully in previous papers [1,2].

DESIGN

The SNS Linac LLRF control system (Figure 1) is a digital control system that fundamentally realizes a Proportial-Integral (PI) feedback controller. The heart of the system is the Field Control Module (FCM), which digitizes four channels of 50 MHz analog inputs, digitally processes the data stream, and produces a RF output signal at either 402.5 or 805 MHz, depending on the location in the Linac. The FCM is a VXIbus module and is comprised of a mother-board and three daughter-boards: Analog Front End (AFE), Digital Front End (DFE) and RF Output (RFO). The DFE consists primarily of four A/D converters and a single Virtex II Field Programmable Gate Array (FPGA). Communication with the outside world is via the slot-zero controller (IOC) running the VxWorks operating system. The LLRF Finite State Machine is implemented as an EPICS sequencer running on the IOC. The LLRF control system also provides high-power RF protection via the High-Power Protection Module (HPM), which provides for fast shutdown of the RF drive in case of RF overpower, arcs in the RF distribution system, poor vacuum, and "soft" interlocks such as cryo, coupler cooling, and HPRF permit [3]. Down conversion of reference and cavity signals is performed in a temperature-regulated chassis. The master oscillator (MO) provides low-noise phase-coherent reference signals that are distributed throughout the klystron gallery and tunnel [4].

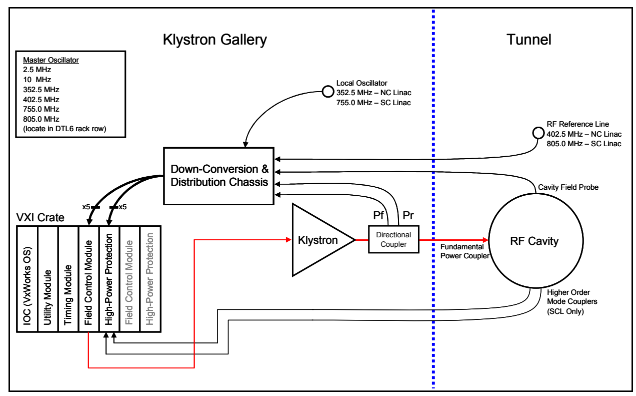

Figure 1: Block diagram of the SNS Linac LLRF control system.

PRODUCTION

The prototype design and production was very successful. The FCM mother-board and RFO daughter-board needed only one revision; the DFE daughter-board needed two revisions. The production vendor was given a contract to provide four distinct printed circuit board assemblies (HPM, FCM mother-board, DFE and RFO daughter-boards) in quantities of 125 each in two phases. Phase I called for the production of 20 units of each printed circuit board assembly. The intent was to catch any outstanding design problems prior to letting the full production. In the case of the DFE, this proved to be beneficial in that we achieved higher performance on the Phase II production by specifying a few different components without changing the board layout. Two follow-on orders for additional DFE and RFO daughter-boards gave a final production count of 560 fully assembled printed circuit boards.

Due to schedule constraints, all electrical components required for production were procured by SNS and provided to the vendor. The vendor was responsible for procurement of the printed circuit boards and assembly of the components to the boards. The boards were assembled through a combination of SMT process and hand installation. The completed boards were subjected to visual inspection and flying probe measurements for

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quality assurance. A sampling of the BGA devices was inspected via x-ray techniques. The HPMs were fully assembled with VXI module front and side panels, whereas the other boards were assembled into VXI modules at SNS.

The AFE daughter-board procurement was handled separately due to the nature of its development. The design and production was performed by a vendor that had previously designed and produced a very similar board for SNS Diagnostics. Phased production was specified - 20 units for Phase I and 105 units for Phase II - for a total of 125 printed circuit boards.

The production quality was generally very good and there have been very few board failures. The RFO daughter-board has been the most problematic. Some of the first failures were due to filters that were not hermetically sealed and did not survive the wet wash process at the end of assembly. The solution to this problem was to change the process so that the filters were installed after the wet wash. There were also a few problems with transformer failures and misplaced or wrong components.

ASSEMBLY AND TESTING

Dedicated test stands were established in the SNS LLRF laboratory for testing and calibrating the HPM and FCM VXI modules. The following steps were taken upon receipt of all printed circuit boards:

- Perform a visual inspection aided by a microscope
- Install PROMs, set configuration switches, install jumpers
- FCM only: Install daughter-boards, cables, and front panel (Figure 2)
- Power up modules and execute test procedures
- Record performance in database

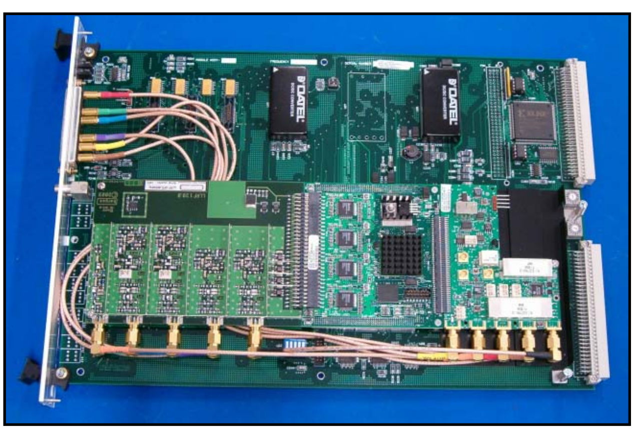

Figure 2: The Field Control Module is assembled and tested at SNS prior to installation in the Linac. The AFE, DFE and RFO daughter-boards are clearly visible from left to right.

The HPM test procedures were well developed when the boards were received, and all boards were tested and calibrated in a relatively short time. In contrast, the FCM test procedures evolved as we gained experience. Initially we planned to test the FCM mother-board and DFE daughter-board together and separately test the AFE and RFO daughter-boards. Later we decided it was more efficient to test fully assembled FCMs and perform separate board tests only in the case of substandard performance. The FCM assembly and testing was performed over several months and followed a "just in time" schedule for supporting accelerator installation. All boards are serialized by the vendor and are tracked according to their serial numbers. In addition, modules are bar coded and entered in the Operations equipment tracking system.

INSTALLATION

The installation of the Linac LLRF control system is complete and 81 of 96 systems are presently turned over to Operations. The remaining 15 systems will be turned over after the final four cryomodules undergo cool down and checkout. Racks, power distribution and cables were installed by craft labor. Rack components and cabling were installed by RF technicians. Termination of Heliax cables was a joint effort. An example of the rack layout in the superconducting Linac is shown in Figure 3.

Figure 3: Each rack In the Superconducting Linac contains LLRF control hardware for two RF systems. The VXI crate contains (from left) an IOC running the VxWorks OS, a utility module, a timing module and two HPM/FCM pairs.

PERFORMANCE

The primary performance measure of the LLRF control system is the achieved amplitude and phase regulation of the RF cavity accelerating field. Short term observations indicate that the requirement of ±1% and ±1deg on the amplitude and phase, respectively, is readily achieved on normal conducting and superconducting cavities. This is

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supported by beam commissioning results. For example, a beam energy spread of 0.08% RMS was measured (Figure 4) during commissioning of the Drift Tube Linac (DTL).

Beam commissioning of the Normal Conducting Linac (NCL) was performed with short beam pulses of 40-50 us. This short pulse length is a beam transient from the point of view of LLRF control, and feedback PI control alone is not sufficient to maintain regulation within specifications during this transient. The LLRF team deployed Adaptive FeedForward (AFF) beam loading compensation [5] during the NCL beam commissioning and achieved very good results. The beam phase versus time is shown in Figures 5 and 6 with AFF disabled and enabled, respectively. These data were measured with Beam Position Monitor 101 (BPM101), which is located at the entrance to the Coupled-Cavity Linac (CCL). AFF reduced the beam phase variation by a factor of ~20 with a 40 mA beam current.

Long term stability of the LLRF control system is required but has not yet been systematically measured. We plan to perform this measurement during upcoming beam commissioning runs and to correlate the results with data from beam diagnostics measurements.

We are also pursuing a better understanding of optimal configuration of the LLRF control system to achieve robust and high performance. Some initial results of these efforts are presented by Ma in a companion paper [6].

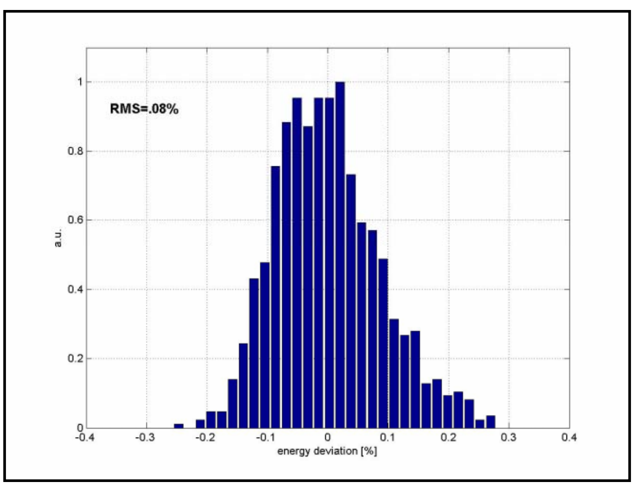

Figure 4: Beam energy spread measured downstream of DTL2 during April 2004 DTL beam commissioning. (courtesy of A. Aleksandrov).

CONCLUSION

The installation of the SNS Linac LLRF control system is complete. The performance of the control system meets requirements and has enabled successful beam commissioning of the normal conducting linac. Preparations for beam commissioning of the entire linac are underway, and we anticipate reporting comprehensive performance measurements in future publications.

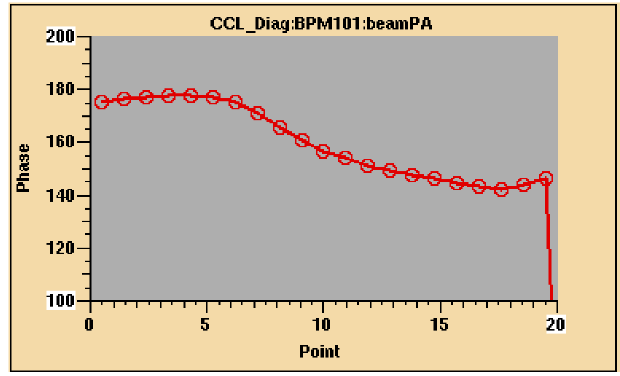

Figure 5: Beam phase vs. time at the entrance to CCL1 with Adaptive FeedForward disabled. Beam current is 40 mA. Beam pulse length is 40 us.

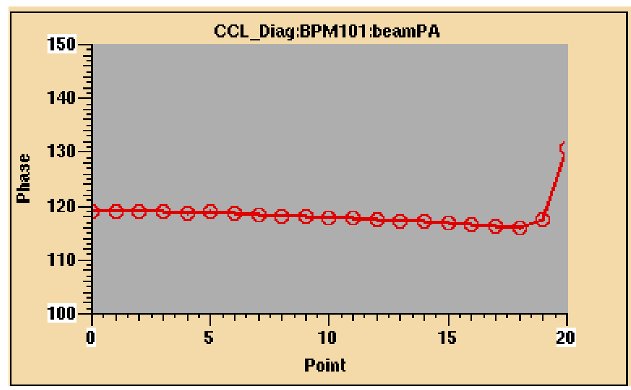

Figure 6: Beam phase vs. time with Adaptive FeedForward enabled. The variation in beam phase is reduced by a factor of ~20 compared to Figure 5. Beam parameters are unchanged.

ACKNOWLEDGEMENTS

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