RF DISTRIBUTION SYSTEM FOR HIGH POWER TEST OF THE SNS CRYOMODULE

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Abstract

A four-way waveguide RF power distribution system for testing the Spallation Neutron Source (SNS) multi-cavity cryomodule to investigate the collective behavior has been developed. A single klystron operating at 805MHz for 1.3 msec at 60Hz powers the 4-way waveguide splitter to deliver up to 400 kW to individual cavities. Each cavity is fed through a combination of waveguide splitters and vector modulators (VM) to provide independent magnitude and phase controls. The waveguide vector modulator consists of two quadrature hybrids and two motorized waveguide phase shifters. The phase shifters and the assembled waveguide vector modulators were individually tested and characterized for low power and high RF power in the SNS RF test facility. Precise calibrations of magnitude and phase were performed to generate the look up tables (LUTs) to provide operational references during the cryomodule test. An I-Q demodulator module was developed and utilized to measure relative phases in pulsed high RF power operation. PLC units were developed for mechanical control of the phase shifters. Initial low/high power measurements were made using LabVIEW. An operation algorithm has been implemented into EPICS control for the cryomodule test stand.

INTRODUCTION

The superconducting linac section of the SNS has two types of cryomodules: one with three medium β (β=0.61) cavities and the other with four high β (β=0.81) cavities. One of the issues with the SNS superconducting cavities has been field emission (FE). It has been shown to be one of the major limiting factors of accelerating gradients in the superconducting linac. In addition, the gradients depend on the relative amplitude and phases between neighboring cavities due FE-driven collective effects [1].

The SNS RF Test Facility (RFTF) has been upgraded to support commissioning of SRF cavities and to provide diagnosis, trouble shooting, and conditioning of various RF/SRF systems for the SNS linac. The RF test stand can operate with either 402.5MHz (2.5MW) or 805MHz (5MW) klystron amplifiers [2] but cannot currently support four 805 MHz klystrons operating simultaneously. In order to test the cavities in a SNS cryomodule simultaneously, a four-way RF distribution system has been developed. It consists of waveguide splitters that drive vector modulators (VMs) that can do independent magnitude and phase controls. The waveguide vector modulators were developed using motorized waveguide phase shifters [3].

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A new spare high - β cryomodule has been built and powered successfully at SNS in March 2012. The successful cooldown and testing demonstrated the capability of SNS personnel to fabricate cryomodules in-house. The 4-way system is to be used with the spare cryomodule for the first time in early June, 2012 to demonstrate collective limits of the cryomodule.

4-WAY RF DISTRIBUTION SYSTEM

A photo of the four-way RF control system is shown in Figure 1. The system consists of three magic-Ts, four vector modulators (VM_1-VM_4), and high power water loads. Look up tables (LUTs) are generated through measurements with initial phase offsets. Control resolutions, and error compensations were considered.

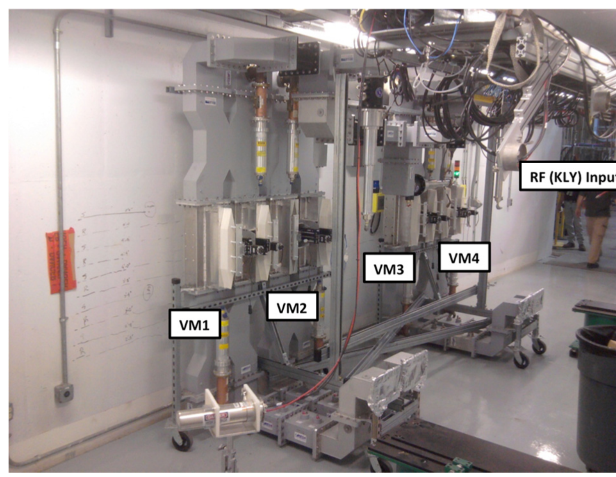

Figure 1: 4-way power splitting system.

Coaxial water loads are used as matched terminations with coaxial directional couplers. Waveguide directional couplers are installed to monitor the forward and reflected RF power to/from cavities at the VM outputs. EPICS control setup provides the controls of the RF power along with the phase shifter control.

A waveguide VM consists of two phase shifters installed between two hybrid junctions. The motorized phase shifters can be moved to have two independent phases that produce a specific magnitude and phase at the output. The phase shifter has shown phase shifting ranges of $\theta \geq 230$ degrees at 805 MHz and when fabricated into a vector modulator can control the amplitude < -20 dB and phases to 230 degrees. This is thought to be sufficient for initial tests.

A PLC based stepping motor control system has been implemented in EPICS control to operate the phase shifters. This allows for the operator to set the magnitude and phase. The original Low-level RF (LLRF) control system has been updated to support the additional cavities with power and phase monitoring capability.

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WAVEGUIDE PHASE SHIFTER

The waveguide phase shifter is designed and optimized in terms of phase shifting, insertion loss, and input return loss. Polyethylene (ε_r=2.25) dielectric slabs are used as phase shifting material placed in the broad wall center of the waveguide section that introduces relative phase delay up to 230 degrees. 3-D EM modeling was performed and all the parameters are optimized in CST MWS [4] (Figure 2). Optimized characteristics of designed phase shifter are depicted in Figure 3. The width of the waveguide opening was tapered to achieve acceptable return loss (S11 < -18dB) in the entire phase shifting range at 805MHz. The Polyethylene and the metallic housing were carefully aligned to suppress coupling to an orthogonally polarized field in the dielectric. Otherwise the localized electric fields may cause arcing or RF leakage during high power operation. The phase shifter was high power tested with matched load up to 650 kW at 6% duty cycle.

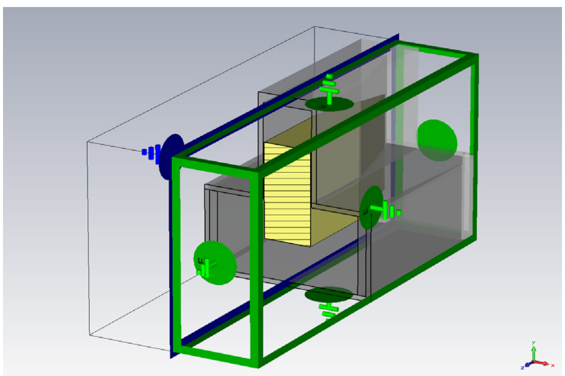
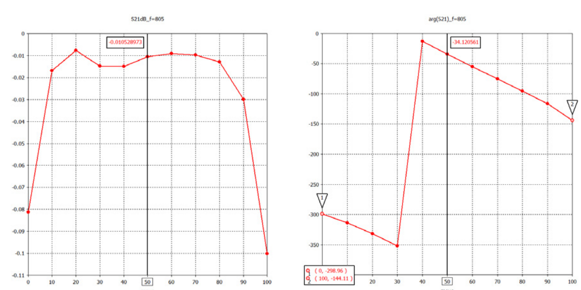


Figure 2: Waveguide phase shifter model.



(a) (b)

Figure 3: Optimized transfer characteristics, (a) insertion loss and (b) phase shift as a function of position.

SYSTEM INTEGRATION AND TEST

With the completed system, low power tests were successfully performed with a vector network analyzer (VNA). Amplitude and phases were adjustable at each cavity input as expected. All four ports were tested with short circuited ends simultaneously at independent and random output magnitudes and phases up to 400 kW.

The system has been installed in the test cave in preparation to test with the cryomodule (Figure 4). Each vector modulator has been tested and look-up tables were built for their control. EPICS screens have been designed for control of a set of specified amplitudes and phases for the required RF inputs at the cavities. During testing the four VM characteristics have been shown to be almost identical. Figures 5(a) and 5(b) show the amplitude and phase measurements at a 200 kW output power.

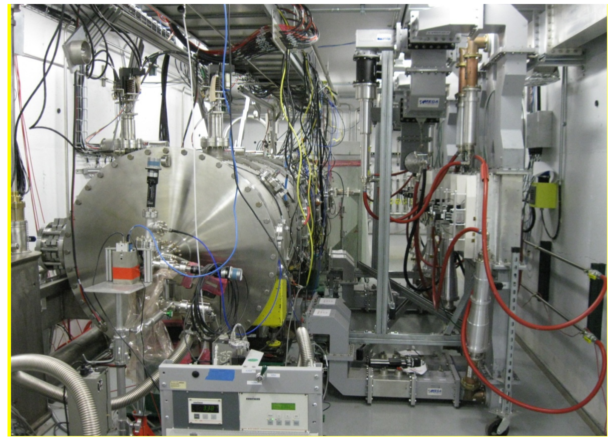


Figure 4: 4-way system placed with a cryomodule in test cave.

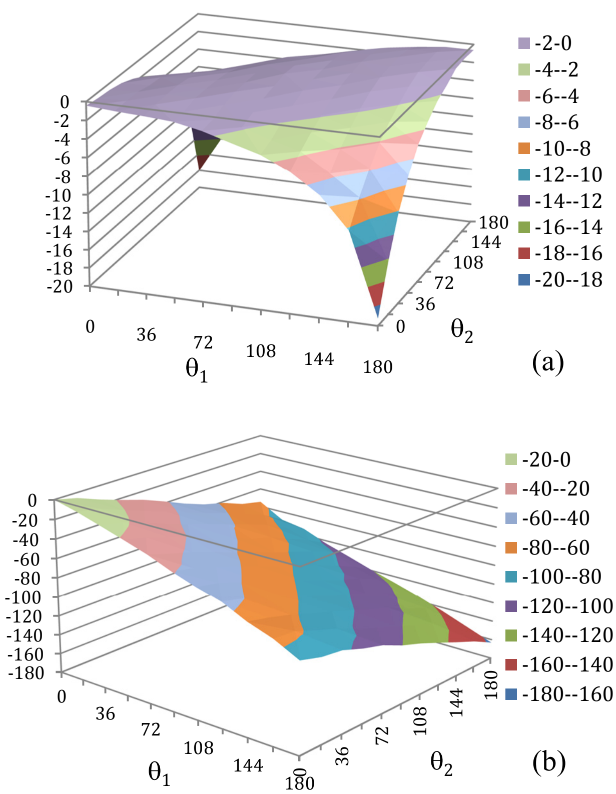


Figure 5: High power test result of vector modulator, (a) insertion loss and (b) phase shift (x, y axes phase shifters).

Phase Offsets Consideration

The relative phase delay differences between the ports were obtained using a VNA. The initial phase offsets are to be added in the phase operation ($\tilde{\theta}_{1N} = \theta_{1N} + \Phi_N^{offset}, \tilde{\theta}_{2N} = \theta_{2N} + \Phi_N^{offset}$). The overall phase operation range is limited by the unit phase shifter and maximum phase offset. It is 230 - 43.6 = 186.4 degrees in our case.

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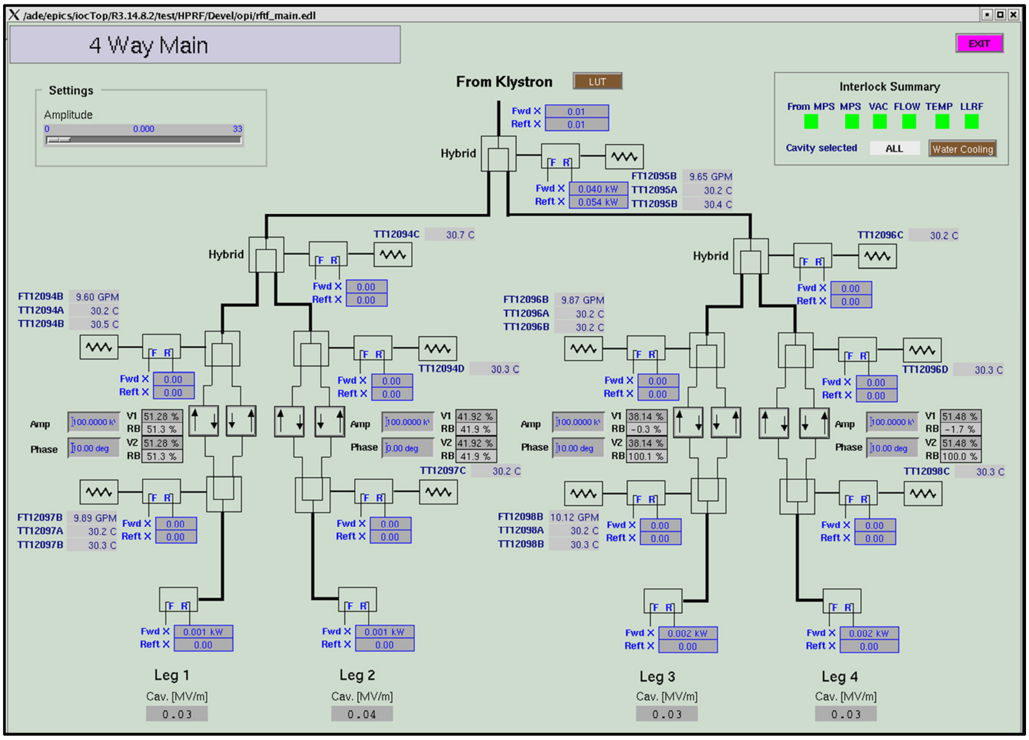

Figure 6: Main EPICS control screen of the 4-way system for command and readback display of RF at four ports.

CONTROL/EPICS/ LLRF

Vector modulator open-loop control is performed with DC voltage commands from EPICS. The PLC control on the stepper motors uses a 0-10V position signal from a potentiometer on each phase shifter. The accuracy of the 6” stroke feedback potentiometer is 0.1%. A LUT is provided to the system for feed-forward control in EPICS. The main control screen shown in Figure 6 is designed to provide command inputs for RF magnitudes and phases and corresponding readings from directional couplers, RF power coupler, and cavity field probes signals for all 4 ports.

The magnitude reading can be easily done with RF power meters. For phase measurements, a 4-channel quadrature (I/Q) demodulator is implemented to measure the relative phases between the outputs. The I/Q demodulator compares the LLRF reference signal to the cavity probes and outputs the dc I/Q values. Then the relative phase can be easily calculated using the quadratic equation.

The current LLRF control system installed in the RFTF is based on a standard SNS Linac system [5]. This system is designed for a single cavity control utilizing an individual klystron to provide the RF power required. The LLRF system was modified to utilize a second high-power protection module (HPM) along with three eight-channel power meters to allow for the required RF channels. A fault summing chassis was implemented to combine the protection signals from the four additional devices required to operate the full cryomodule. For the near term, only open loop operation will be utilized for simultaneous testing of multiple cavities in the cryomodules. The control algorithm is internally settable to use either the LUT based data or other equation based data.

CONCLUSION

A new spare high - β cryomodule has been built at SNS and its four cavities have been individually high power tested successfully. The collective behavior of the cavities in a cryomodule is to be investigated using the 4-way system for the first time in early June, 2012. Initial tests of the waveguide phase shifters and the integrated 4-way VM system shows good results up to 400 kW with all four ports connected into shorts.

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REFERENCES

[1] S. Kim, at al., “Status of the SNS Cryomodule Test,” Proceedings of PAC07, Albuquerque, NM, USA.
[2] Y. Kang at al., “High Power RF Test Facility at the SNS,” Proceedings of PAC05, Knoxville, TN, USA.
[3] Y. Kang, at al., “High Power RF Distribution and Control for Multi-Cavity Cryomodule Testing” Proceedings of PAC11, New York, NY, USA
[4] CST MICROWAVE STUDIO: http://www.cst.com
[5] M. Champion, at al., “Overview of the Spallation Neutron Source Linac Low-Level RF Control System” Proceedings of PAC05, Knoxville, TN, USA