An Automated RF Control and Data Acquisition System for Testing Superconducting RF Cavities

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Abstract

An integrated RF control and data acquisition system has been developed to perform acceptance testing of superconducting RF cavities for CEBAF. The system provides options for automated resonance locking, VCO frequency and PLL phase optimizations, CW cavity coupling measurements, pulsed RF coupling and Q measurements, and cavity field regulation as well as data logging and retrieval. The system has dynamic range sufficient to stably operate CEBAF SRF cavities at accelerating gradients in the range 0.05 - 20.0 MV/m and is switchable between six cavity testing positions.

I. INTRODUCTION

As superconducting RF cavities are used in increasing numbers in particle accelerators, an increased degree of automation is called for in the instrumentation used to test cavity performance. Construction of CEBAF requires the installation of 338 SRF cavities.[1] Because of the large investment in assembly effort, provision is made to performance test all cavities prior to insertion into the horizontal cryostats used in the accelerator. A testing system for SRF cavities has been designed and constructed at CEBAF to accommodate the systematic testing of a large number of cavities and to provide a durable facility available indefinitely for possible rework of cavities. By providing automated control of all RF parameters, enhanced testing efficiency is obtained relative to the hardware and instrumentation styles commonly used in R&D applications.

II. RF HARDWARE CONFIGURATION

The SRF cavities to be tested have a fundamental accelerating mode frequency of 1497.0 MHz, are equipped with variable input coupling, and have a fixed transmission port coupling Q_{ext} nominally equal to 2E11. Unloaded Q-factors of the cavities are typically >3E9.[2] The cavities are tested with the input RF port near critical coupling so the resonance bandwidths are < 1 Hz.

The major features of the RF control and measurement system are represented in Figure 1.

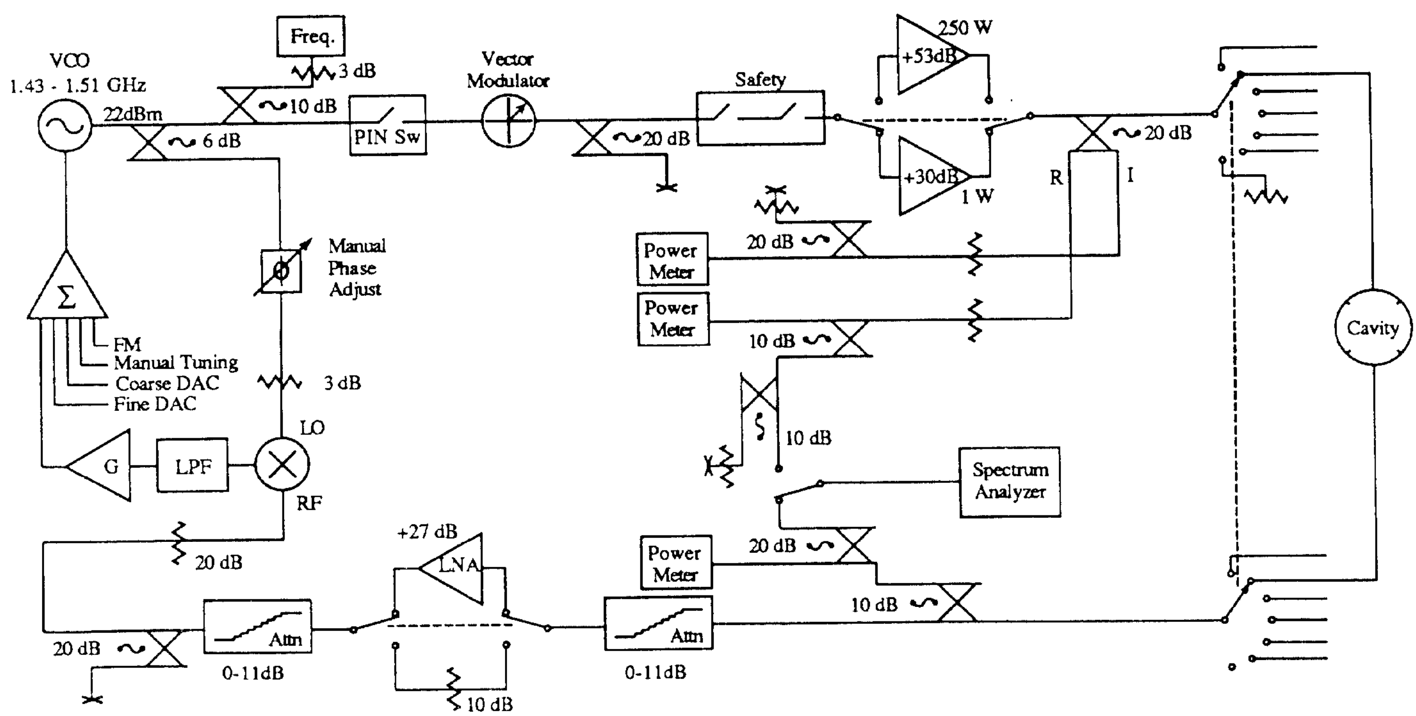

Figure 1. RF Network for Performance Testing CEBAF Cavities.

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A pair of cavities sharing a common internal vacuum are individually RF tested at 2.0 K in one of two vertical cryostats. In addition, there is the ability to test individual cavities in a third cryostat. Because the cryogenic cycle time for a dewar and cavity pair is long compared with the time required for RF testing, a common RF system is shared between the three cryostats.

A linearized voltage controlled oscillator provides a 22dBm RF signal electrically tunable over the range 1430 to 1510 MHz, which spans the fundamental pass band of CEBAF cavities. A PIN switch with TTL driver and 10 nsec switching time permits pulsed RF testing of the SRF cavities. The output of the PIN switch is conditioned by a vector modulator manufactured by Vectronics Microwave Corp. This vector modulator is implemented with 9-bit TTL selected PROM programmed linearized attenuation having 0.125 dB steps in both the I and Q hybrid legs. With a bi-phase switch in each leg, the 20 TTL lines enable selection of an arbitrary phase shift across the vector modulator with $< 0.5°$ resolution and simultaneous amplitude control over a 40 dB range with 0.125 dB resolution.

Safety interlock RF switches (operation discussed below) allow for interruption of the drive signal prior to routing to one of two solid state amplifiers. A 1 watt amplifier is used for low power testing, and an amplifier, manufactured by Power Systems Technology, Inc. capable of 250 watts output with 53 dB gain, is used for high power operations. The output of the selected amplifier is routed to the cavity under test with a SP7T coaxial switch which is electrically ganged with a similar switch that selects the transmitted signal from the cavity. These switches, manufactured by Loral Microwave-Wavecom, are rated for reliable operation to over one million actuations per position.

The amplitude of the transmitted RF signal is trimmed or boosted with a combination of programmable switch selected step attenuators and a low noise amplifier. This conditioning of the transmitted signal is done to maintain a -20 dBm level at the RF port of the phase detecting mixer while the power transmitted out of the cavity ranges from -25 to +35 dBm. This regulated power level, together with the phase lock loop electronics described below, maintains a consistent locking range of 50 kHz and a capture range of about 5 kHz over a potential testing range of accelerating gradients of CEBAF SRF cavities of approximately 0.03 to 25 MV/m.

For power measurements, portions of the incident, reflected, and transmitted RF signals are coupled into calibrated HP437 power meters and Schottky diode detectors. In addition, samples of the reflected and transmitted signals may be manually switched into a spectrum analyzer.

III. CONTROL ELECTRONICS

a) RF Controls

The VCO control electronics consist of a phase lock loop amplifier, a two channel D/A converter module and a function generator module. These modules along with one 4 channel low noise amplifier module and a computer-to-vector modulator interface module were fabricated using a 3U 220 mm eurocard standard and low noise techniques. These modules are interconnected and interfaced with one another, Nubus I/O boards in a Macintosh II computer, and the vector modulator using a small back-plane printed circuit board. Ground-plane printed circuit boards and 0.141 hard line are used throughout this section. All sensitive analog circuitry are housed in shielded enclosures.

The phase error signal is applied to the input of the PLL amplifier where it passes through a 100 kHz, LRC, low pass filter which presents a constant 50 Ω impedance to the mixer to 50 MHz. The phase signal is then amplified using a variable gain amplifier. It is also summed with the output of the function generator (FM drive) and either the manual tuning input or the outputs of the D/A converter module which have been heavily filtered. The composite signal is buffered and then connected to the VCO after passing through a 25 kHz single pole low pass filter. The output noise of the amplifier with the input shorted is 30 μVp-p which equates to 240 Hz of residual FM noise at the VCO output.

Manual tuning of the frequency is accomplished by adjusting two front panel potentiometers, one of which passes through a 150:1 resistive divider network. The function generator provides a triangle waveform of varying amplitude which is used to sweep the frequency.

Computerized tuning is accomplished using a dual D/A converter module. This module consists of a dual 12-bit DAC, associated amplifiers, and drive logic. The two 0-10 V signals are applied to the input of the VCO loop amplifier module where both DAC channels pass through 3 Hz low pass filters, are scaled, and applied to the summing amplifier. The frequency step for the coarse DAC is 16.5 kHz, and for the fine it is 30 Hz. The low frequency filters force the RF frequency slewing to be slow enough to permit PLL acquisition as the incremented frequency steps across the narrow cavity resonance.

Four channel low noise preamplifiers were constructed to provide user and computer interface to various crystal detectors and other signals throughout the system. Each channel consists of a three op-amp instrumentation amplifier circuit using low noise amplifiers, metal film resistors and ground plane circuit techniques. Channels used for crystal detector signals typically operate with 50 dB of gain (Av=316), which scales the top of the detector square-law range to a convenient 8 volts, while miscellaneous signals are buffered by unity gain channels. Signal outputs are buffered and routed to the front panel and to the A/D converter on the computer I/O card.

b) Safety Systems

Safety interlock RF switches in the amplifier drive line serve three major functions: they inhibit introduction of high power RF to a cavity unless radiation shielding is in place, they ensure that RF routing switches are not switched live, and they disable all RF whenever significant radiation levels are detected outside shielding. Radiation interlocks were implemented using simple relay logic, while the dewar selection and high power amplifier selection logic was implemented using programmable logic devices.

Movable massive shielding lids surrounding the tops of the recessed cryostats provide attenuation adequate to reduce the possible 2000 R/hr inside to < 0.1 mR/hr outside. Closure of a lid, which is detected using a pair of microswitches, is fed into the radiation interlock system.

In addition to the provision of interlocks on the primary drive circuit, there is logic which drives the switching of the input/output of the power amplifier which inhibits high power operation unless the lid of the selected dewar is closed. Appropriate delays are imbedded into the dewar selection and high power amplifier selection logic to ensure that no RF signal is applied unless the selected RF switches are closed and that no switch changes are made until the RF energy stored in the cavity has had time to decay.

IV. SOFTWARE

a) Programming Environment

All aspects of the software controlled data acquisition, RF control, and analysis are performed on a Macintosh II computer in the environment provided by LabVIEW 2®, published by National Instruments. LabVIEW 2® programming provides a convenient, integrated graphical user interface both for program development and user interaction. The programmer graphically constructs custom virtual instruments which interact with I/O hardware in the desired manner. Since the execution sequence is driven by data flow, these virtual instruments can subsequently be arranged in logically straight forward hierarchical combinations. Modular data acquisition, control, and analysis routines are thus easily integrated for various applications and may be dressed for efficient user interaction.

b) Data Acquisition

The following parameters may be read by the RF system computer via GPIB control of commercial instruments: RF frequency, incident, reflected, and transmission CW power levels, and field emission current. A buffered 12 bit A/D converter channel is provided for each crystal diode detector in the system and also the phase error signal from the mixer. Time dependent RF levels may thus be monitored at sample rates to 100 kHz. The A/D channels may be auto-scaled, making the detector output directly readable over the full square-law range from -53 to -20 dBm. An additional A/D channel is used to log the intensity of any x-radiation that may be induced by field emission in a cavity. Communication over an RS-422 line with the cryogenics control computer permits logging of dewar pressure, He bath temperature, and liquid level.

c) Control

As mentioned above, the VCO frequency may be controlled by two 12-bit DAC's, and RF phase and amplitude are controlled via a 20-bit signal applied to the vector modulator. One program module can set the uncorrected VCO frequency with 1 kHz resolution. Another provides the operator or another module with the ability to independently control phase and attenuation of the vector modulator. These are integrated with monitoring of the transmitted power crystal detector in a resonance search routine which systematically searches the frequency-phase plane near a desired mode, locates the transmitted power maximum, and nulls the phase error signal in 15 - 30 seconds.

Another module trims the mixer RF input to the optimum level and automatically compensates path length differences as attenuators are switched in or out by adjusting the vector modulator phase setting. This maintains a nulled phase error signal in the PLL as the operating power level is changed.

Programmatic control of the PIN switch is provided via GPIB communication with a pulse generator. One shot operation is available as well as user specified repetition rate and duty cycle pulsed mode.

d) Data Analysis

Several software modules have been developed which integrate the control of RF parameters and data acquisition with real time data analysis, logging, and display. Analysis of coupling parameters, calculation of the required cavity performance parameters, (unloaded Q-factor, accelerating gradient, and transmission probe external Q-factor), and error analysis is performed automatically with each measurement. The time dependence of the logarithmic slope of the transmitted decay signal is used to measure the loaded Q-factor directly as a function of stored energy. This feature increases the reliability of high field Q measurements when non-linear loss mechanisms become significant.

Another module enables pulsed RF testing and analysis, employing the computer directly as a four-channel digital storage scope which automatically scales to the selected RF pulse repetition rate and performs coupling and decay analysis.

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VI. REFERENCES

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