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Design and Results of the Radio Frequency Quadrupole RF System at the Superconducting Super Collider Laboratory

J. Grippe, E. Marsden, and O. Marrufo
Superconducting Super Collider Laboratory*
2550 Beckleymeade Ave., Dallas, TX 75237 USA

A. Regan, D. Rees, and C. Ziomek
Los Alamos National Laboratory

Abstract

The Superconducting Super Collider Laboratory (SSCL) and the Los Alamos National Laboratory (LANL) entered into a joint venture to design and develop a 600 kW amplifier and its low-level controls for use in the Radio-Frequency Quadrupole (RFQ) accelerating cavity of the SSC. The design and development work has been completed. After being tested separately, the high power amplifier and low level RF control system were integrated and tested on a test cavity. Results of that tests are given. Tests were then carried out on the actual RFQ with and without the presence of the accelerated beam. Results of these tests are also given, along with the phase and amplitude information.

I. INTRODUCTION

The RFQ cavity requires 225 kW of power at each of two RF input ports at a frequency of 427.617 MHz. To provide this power with an adequate amount of safety margin and enough drive to ensure a fast cavity fill time, a 600-kW amplifier was designed and built. The requirements [1] placed upon the amplifier are as shown in Table 1.

Table 1
RFQ Amplifier Requirements

Operating Frequency	427.617 MHz
Bandwidth	300 KHz Minimum
Power Output	600 kW peak
Gain	77 dB nominal
Pulse Length	100 microseconds
Pulse Repetition Rate	0–10 Hz
Pulse Droop	1% maximum
Linear Range	<0.5 db within any one hour period
Phase Stability	<10 deg. within any one hour period

The purpose of the low level RF, along with providing the drive power to the amplifier, is controlling the phase and amplitude of the cavity RF. The RF field in the RFQ cavity is to be maintained within 0.5 degrees of the desired phase and 0.5% of the desired amplitude.

A block diagram of the RFQ RF System [2–4] is shown in Figure 1.

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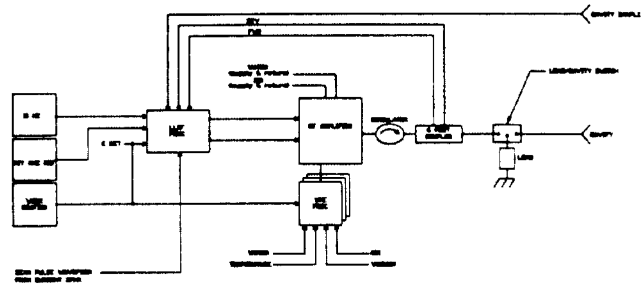

Figure 1. RFQ RF System.

II. TOPOLOGY

The amplifier consists of three stages of RF amplification. The first stage is a solid-state amplifier which takes the input RF and amplifies it by approximately 48 dB. The intermediate amplifier consists of a cathode-modulated Eimac 8938 Triode, cavity, and a high voltage power supply. The tube is air cooled and has a gain of approximately 15 dB. The final power stage consists of a Burle 4616 tetrode and its associated cavity, a 25 kV anode power supply rated at 2 kW average power output, and the necessary grid supplies. The tetrode operates in Class AB with approximately 5 mA of bias current from the high voltage power supply. At the 600 kW output level the efficiency is approximately 60%.

The low level RF circuitry is VXI based and uses the in-phase (I) and quadrature signal components (Q) or more commonly called an I&Q detection system. The cavity field sample is downconverted to 20 MHz, where a vector detector performs I&Q detection. The resulting I&Q baseband signals are fed to a pair of Proportional Integral Differential (PID) controllers, one for the I signal and another for the Q signal. The setpoints for the I&Q channels are also fed to the PID controllers where the cavity field error signals are generated and processed. The outputs of the I&Q PID controllers are fed to a 20 MHz vector modulator, the output of which is upconverted to the 427.617 MHz operating frequency. The output of the upconverter passes through a fast RF switch and additional amplification before driving the high power amplifier.

Many signals in the low level RF crate are available as analog signals on the module front panels and, once per beam pulse, are monitored through sample and hold circuits which are then sent to slow speed, on board A/D's. Additionally, certain critical analog signals can be remotely selected and fed across the VXI backplane to a twisted pair line driver for remote viewing or fast digitizing. All timing pulses for low level RF

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circuitry and the high power amplifier gate are derived on board each VXI module through the use of a programmable timing generator triggered by a single 10 Hz pulse from the Linac timing system.

RF transmission components at the output of the power amplifier consist of a high power circulator to isolate the amplifier from the high reflected power during the cavity fill time, a six-port coupler to provide amplifier reverse and forward power to the low level RF, and a manual high power waveguide switch that can be used to direct the RF energy to a dummy load for test purposes.

III. TEST RESULTS

Table 2 lists the results obtained when testing the amplifier into a high power water load.

Table 2
Amplifier Test Results

Gain	77.4 dB
Linear Range	200 to 500 kW
3 dB Bandwidth	900 kHz
1 dB Bandwidth	550 kHz
Maximum Power Output	625 kW
Efficiency	63%

The frequency response data for the amplifier is listed in Table 3. The data is plotted in Figure 2.

Table 3
Frequency Response

FREQ (MHz)	Po (kW)	Pin (kW)	GAIN (dB)
427.1	228	12.5	71.1
427.2	323	12.5	72.6
427.3	443.2	12.5	74
427.4	546	12.5	74.9
427.5	611.8	12.5	75.4
427.6	620	12.5	75.4
427.7	615	12.5	75.4
427.8	566.5	12.5	75
427.9	498.6	12.5	74.5
428.0	432.2	12.5	73.8
428.1	343.6	12.5	72.9
428.2	261.4	12.5	71.7

Tests of the RF system, LLRF and amplifier are shown in the following figures. Figure 3 illustrates the field in a test cavity without a simulated beam. After initial cavity filling and settling time the phase is controlled to within 0.1 degree and the

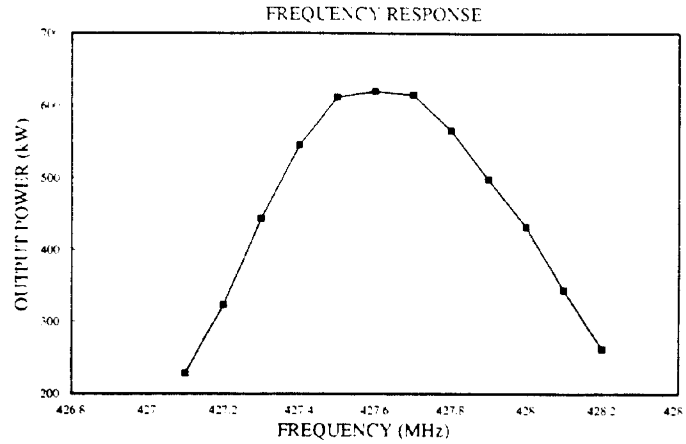

Figure 2. RFQ amplifier.

amplitude is controlled within 0.1%. Figure 4 illustrates the field in the test cavity with simulated beam loading, with both LLRF feedback control and feedforward consisting of a square input pulse to the PID controllers 0.2 microseconds before the beam pulse. The maximum phase variation in this case is 0.2 degrees and the maximum amplitude variation is 0.4%. These tests prove that the SSC RFQ RF system can meet its phase and amplitude performance requirements with a combination of feedback and feedforward in the control system.

The photograph of Figure 5 was taken, open loop, with the RF amplifier delivering 365 kW of power at 427.617 MHz into the RFQ cavity. A 20-milliampere, 2.5-MeV beam was present. The lower trace of the photo shows the high VSWR during the cavity fill time. Immediately after the fill and before the beam arrives, the mismatch of the cavity to the amplifier can be seen. During the beam the improved match is apparent followed by the high reflection at the end of the pulse. The upper trace shows the effect of beam loading on the cavity RF.

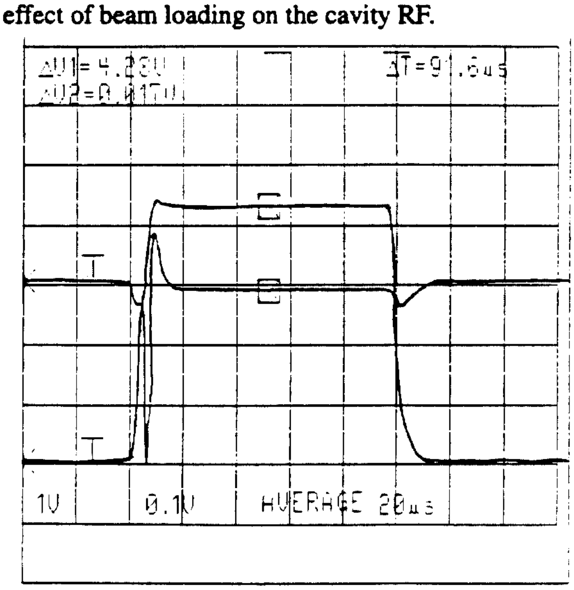

Figure 3. Amplitude (Upper Trace) and Phase (lower trace) of a test cavity without beam loading simulation. Phase 1 degree per division.

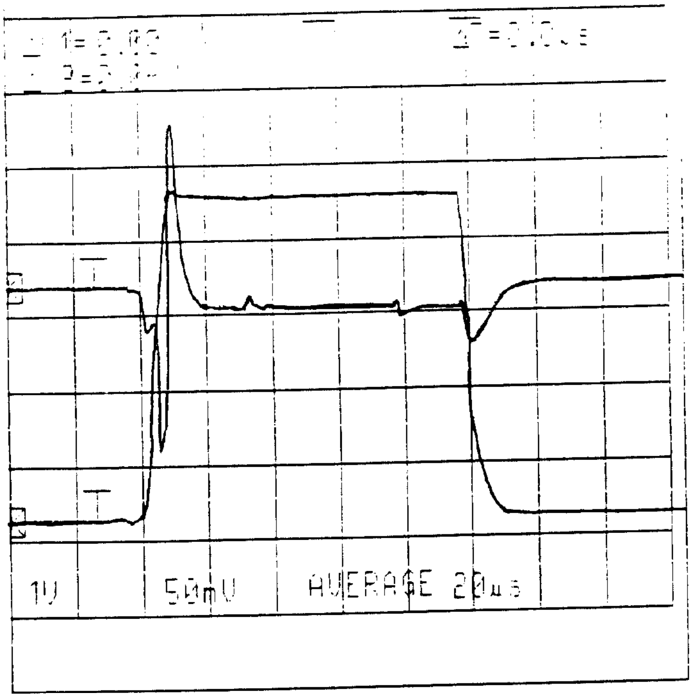

Figure 4. Cavity amplitude (upper trace) and phase (lower trace) of test cavity with beam loading simulation. Feed forward and feedback present. Phase 1 degree per division.

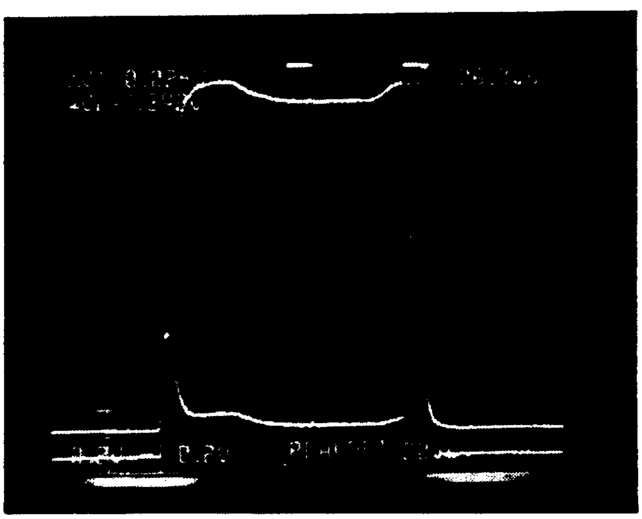

Figure 5. Photograph of amplitude (upper trace) and reflected power (lower trace) taken during 20 milliampere beam in RFQ cavity. System is running open loop.

IV. SUMMARY

From the data taken during the testing of the RFQ RF subsystem it has been shown that the system meets all the design requirements placed upon it. Testing into a test cavity was done by using a 60-dB coupler from the main RF power line since the test cavity was only capable of accepting 2 watts. Testing into the RFQ cavity is ongoing at the SSC central facility. As of this writing the 2.5 Mev, 20 milliampere design goal has been achieved.

V. REFERENCES

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