Commissioning of the CEBAF Cryomodules*

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Abstract

When complete, the Continuous Electron Beam Accelerator Facility will house a 4 GeV recirculating linear accelerator containing 42 1/4 cryomodules arrayed in two antiparallel linacs and an injector. Currently, over half of the cryomodules have been installed. Each cryomodule contains eight superconducting niobium 5-cell rf cavities that operate at 1.497 GHz [1]. A cryomodule must provide an energy gain of 20 MeV to the 200 μA beam [2]. The resultant dynamic heat load must be less than 45 W. The cavity parameters that are measured during the commissioning process include the external Q's of the cavity ports, the unloaded Q (Q_0) of the cavity as a function of accelerating gradient, and the maximum operating gradient of the cavity. The sensitivity of the resonant frequency to changes in pressure and gradient is also measured. Finally, the mechanical tuners are cycled and characterized. In all cases, the performance of CEBAF cryomodules has exceeded the design requirements. A portable test stand allows local control of the rf system and provides automated data acquisition. This paper describes the cryomodule commissioning hardware, software, and measurements.

I. INTRODUCTION

Each installed cryomodule must undergo a series of tests to determine whether it meets the requirements for proper operation of the accelerator. The results of these tests provide a set of numbers that describe the rf characteristics of the individual cavities in a cryomodule. These characteristics are important for several reasons. They will become part of the calibration set that will be used by the rf phase and amplitude control system. These results also describe limits for safe operation of the cavities. Furthermore, these results provide useful feedback to the production group. Table 1 lists these parameters with the design requirements.

Table 1.
Cavity parameters

Q_{ext} (fundamental power coupler)	$6.6\times10^6 \pm 20\%$
Q_{fp} (field probe)	$1.3\times10^{11}\ ^{+62\%}_{-37\%}$
Q_0	$\geq 2.4\times10^9$
f_0 (π mode, T=2 K)	1.497 GHz
E_{max}	≥ 5.0 MV/m
Pressure Sensitivity	< 60 Hz/torr

These parameters are all measured during the commissioning process. A Q_0 vs. E_{acc} curve is generated, and the effect of the ponderomotive force on the resonant frequency of the cavity is also measured. Finally the mechanical tuners are cycled several times to insure proper operation.

The cryomodule production group has put together a portable test stand that is controlled by a Macintosh computer. This system is capable of fully interlocked local control of the rf system. With this system, the commissioning of a cryomodule can be completed in about three eight-hour shifts.

II. DESCRIPTION OF THE TEST SYSTEM

A block diagram of the test system is shown in Figure 1. A voltage controlled oscillator (VCO) is used to control the klystron amplifier. The VCO can operate in either a continuous wave (CW) mode or a gated pulsed mode. The pulsed mode is used to measure the emitted power (P_e) from the cavity and to measure the loaded Q (Q_L). A PIN diode is used as a gating device. The VCO uses a phase-lock loop to track the cavity field probe signal. The VCO is connected to a fast shutdown (FSD) node so that rf will be turned off by any fault signal in the interlock chain. These faults include waveguide window arc and temperature faults. The rf will also be turned off by waveguide and beamline vacuum faults, liquid level, and helium pressure faults through the fast shutdown node. Once the klystron drive signal has been tuned and the amplitude has been set, the computer can control the pulsed/CW mode of the VCO.

The VCO routes the gated signal, P_e, to an analog power meter, and to the spectrum analyzer. The analog meter integrates the measurement of the pulsed P_e signal over time. The spectrum analyzer is used in the time domain mode to measure the decay time of the emitted power signal.

Three digital power meter channels are available to measure the incident power (P_i) from the klystron, the transmitted power (P_t) from the cavity field probe, and the reflected power level behind the circulator (P_{rtrip}). This last signal is part of the interlock chain and is necessary to protect the klystron. A 18 GHz frequency counter is available for fast frequency measurement. All the instruments other than the analog power meter have GPIB capability.

A heater controller is used to power one of the four heaters that are located in the helium vessels. Heater control is required in order to make a calorimetric Q_0 measurement. The heater power level can either be set manually or controlled by the computer.

A self-excited loop is provided that allows the klystron drive to track the resonant frequency of the cavity during tuner cycling operations. The SEL is also connected to the FSD node for interlocked rf operation.

Geiger-Mueller tubes are positioned near each waveguide assembly of each cryomodule and on the beam tube at each end of the cryomodule.

A Macintosh computer is used for control of the test system, data acquisition, and measurement algorithms. The "Labview" software is an object-oriented, icon-based programming language that allows the computer to control ana-

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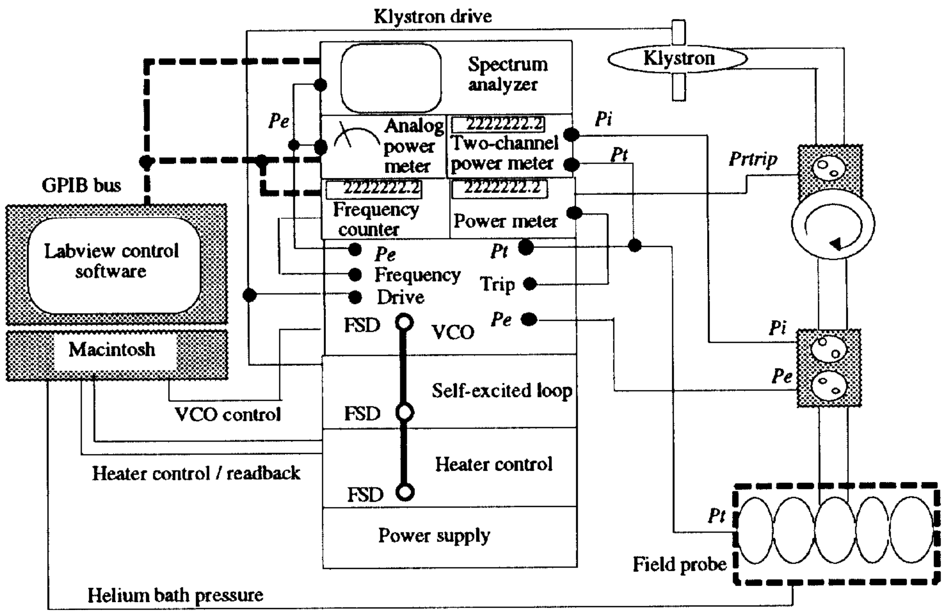

Figure 1. Test stand block diagram

log and digital I/O. This software also allows the computer to function as a GPIB controller. The computer, in its current configuration, can handle 14 analog output channels, 8 differential analog input channels, and 16 digital I/O lines.

III. MEASUREMENT SEQUENCE

Before any high-power operations begin, a series of measurements is made using a network analyzer. These measurements include a bandwidth measurement of Q_L for each cavity:

$$Q_L = \frac{f_o}{\Delta f} \tag{1}$$

The frequency and amplitude of each of the fundamental passband modes are measured for each cavity. Finally, a reflection measurement is made to determine attenuation from the field probe to the external port of the cryomodule for each cavity. This last measurement is combined with other attenuation measurements for cables and couplers to create a matrix of attenuation values. These are entered into the computer, allowing automatic calculation of the absolute power levels at the cavity plane. These measurements may be performed while the cavity temperature is at 4.2 K.

A complete interlock checkout is performed prior to any klystron operations. Simulated fault signals are applied to the various detector circuits while the operator observes the FSD.

When the interlock checkout and low-power measurements have been completed, and the cavity temperature has been lowered to 2.15 K or less, high-power commissioning can begin. The rf phase and amplitude control modules are disconnected from the rf system and replaced by the VCO and power meters.

The VCO drive signal is first tuned until the resonant frequency of the cavity is located. Then, the klystron power level is raised until the accelerating gradient is at about 4 MV/m. At this time, a measurement of Q_{ext} is made. This is accomplished by using the fact that for a strongly overcoupled cavity (β>>1):

$$Q_L \equiv Q_{ext} << Q_o,\ Q_{fp} \tag{2}$$

Q_L can then be measured by the time decay method. While the klystron is in the pulsed mode, the spectrum analyzer is used to examine the emitted power waveform. A measurement is made of the time required for a 20 dB decay in this signal. The following equation is used to calculate Q_L and from that Q_{ext}:

$$Q_L = 4.34\omega \frac{\Delta t}{20\,\mathrm{dB}} \tag{3}$$

The VCO is switched to the CW mode. The incident and transmitted power levels are then acquired, allowing calculation of the accelerating gradient.

Accelerating gradient calculations begin with the following: [3]

$$\omega U \equiv P_d Q_o = P_e Q_{ext} = P_t Q_{fp} \tag{4}$$

The gradient is proportional to the square root of the stored energy in the cavity:

$$E_{acc} = \sqrt{\frac{R/Q}{L}\omega U} = \sqrt{\frac{R/Q}{L} P_d Q_o} = \sqrt{\frac{R/Q}{L} P_t Q_{fp}} = \sqrt{\frac{R/Q}{L}\omega \frac{\overline{P_e}}{PRF}} \tag{5}$$

where $\frac{R/Q}{L}$ is the shunt impedance per meter, 1920 Ω, and *PRF* is the pulse rate frequency, 50 Hz. In terms of the integrated emitted power P_e:

$$E_{acc} = 8.5\times10^4\sqrt{P_e}\;(f_o = 1.497\text{ GHz},\ PRF = 50\text{ Hz}) \tag{6}$$

In terms of the transmitted power:

$$E_{acc} = \kappa\sqrt{P_t} \tag{7}$$

From equation (5) it can be seen that:

$$\kappa = \sqrt{\frac{R/Q}{L}Q_{fp}} = \sqrt{\frac{R/Q}{L}\frac{\omega U}{P_t}} = \sqrt{\frac{R/Q}{L}\frac{P_e}{PRF\cdot P_t}} = 8.5\times10^4\sqrt{\frac{P_e}{P_t}} \tag{8}$$

Q_{fp} can be determined from κ:

$$Q_{fp} = \frac{\kappa^2}{1920} \tag{9}$$

In terms of the incident power, the following relation is needed

$$P_d Q_o = \frac{4\beta}{(1+\beta)}P_i Q_L \tag{10}$$

From equations (5) and (10), it can be seen that

$$E_{acc} = \sqrt{\frac{R/Q}{L}\frac{4\beta}{(1+\beta)}P_i Q_L} = \sqrt{\frac{R/Q}{L}4P_i Q_L}\,;\ (\beta >> 1) \tag{11}$$

Once the gradient level has been established, Q_0 can be measured. The cryomodule must be isolated from the cryogenic system by closing the supply and return valves. The change in pressure due to the static heat load (ΔP_S) over some constant time (usually one minute) is measured. Then, a known power level (H_P) is applied to one of the internal heaters. The pressure rise due to the heater power (ΔP_H) is measured. Finally, the rf is turned on at the desired field level.. While the klystron is in the CW mode, the pressure rise due to the rf (ΔP_{RF}) is measured. The rf heat load can then be calculated from the following equation:

$$P_d = H_P\frac{\Delta P_{RF} - \Delta P_S}{\Delta P_H - \Delta P_S} \tag{12}$$

From equations (4) and(5) it can be seen that:

$$Q_o = \frac{E_{acc}^2}{1920 P_d} \tag{13}$$

The level of the accelerating gradient is raised in 1 MV/m steps and the measurements cycle is repeated. The measurement sequence is complete when E_{max} is reached. Limiting factors for E_{max} include cavity quench, 1 W of field emission, R/hr of radiation measured at the beamline or waveguide assembly, excessive waveguide arc, window temperature, or vacuum faults that inhibit sustained operation of the cavity. A Q_0 vs. E_{acc} curve is shown in Figure 2.

Once the phase and amplitude have been adjusted, the entire measurement sequence described above can be performed by the computer with about four keystrokes at each gradient level. About an hour is required to generate a Q_0 vs. E_{acc} curve.

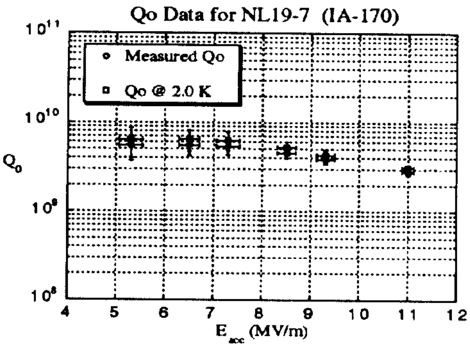

Figure 2. Q_0 vs. E_{acc} curve.

Frequency sensitivity to pressure is measured by setting a constant accelerating gradient. The resonant frequency is then monitored while the helium pressure in the cryomodule is cycled. The effects of the ponderomotive force on the resonant frequency are measured by monitoring changes in the frequency while varying the accelerating gradient. A constant pressure should be maintained during this measurement.

Finally, the tuners are cycled. The SEL is substituted for the VCO as klystron drive. The SEL will track the resonant frequency through the full range of tuner movement. Generally, the tuners are moved through a frequency range of ± 50 kHz around the design frequency, 1497 MHz.

IV. CONCLUSION

The commissioning test system allows fast and flexible testing of cryomodules. The use of a computer to control the test procedures minimizes the time required to test and allows most of the data reduction to be performed automatically. About half of the cryomodules have been installed and tested. Commissioning has shown that all of these cryomodules exceed the design performance requirements.

V. REFERENCES

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