PERFORMANCE OF THE FEL CRYOMODULES*

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The Thomas Jefferson National Accelerator Facility (Jefferson Lab, formerly known **as** CEBAF) is building a highly efficient, kilowatt-level infrared free-electron laser, the IR Demo FEL. The IR FEL uses superconducting radiofrequency (SRF) cavities to accelerate the electron beam that provides energy for the laser. These cavities provide the high-gradient acceleration for the high average currents necessary for a compact FEL design. Currently, a quarter cryomodule injector and a full eight-cavity cryomodule have been installed in the FEL linac. These units were tested as part of the IR FEL commissioning process. The main focus of these tests was to determine the maximum stable operating gradient. The average maximum gradient reached by these ten cavities was 11 MV/m. Other tests included measurement of cavity parameters such as the unloaded Q (Qo) vs. gradient, the input coupling, calibration of field probes and behavior of the tuner mechanisms. This paper presents the results of those tests.

I. INTRODUCTION

Each cryomodule is tested after installation and a set of cavity performance characteristics is measured. These characteristics will become part of the database used by the **RF** phase and amplitude control system. These parameters also describe limits for safe operation of each cavity in the cryomodule. Of course, any operational problems that are uncovered will then be addressed as necessary. Table 1 lists the characteristics that are measured during this commissioning process. During this process, the cavity tuning elements are also tested. These elements include the mechanical tuner and the magnetostrictive tuner.

Table 1 Cavity Performance Specifications

Q_{ext}(fundamental power coupler)	2×10^6(1/4module) 4×10^6(full module)
Q_{ext}(field probe)	5.2×10^{11}(1/4module) 3.3×10^{11}(full module)
Q_0	$\geqslant5\times10^9$@8MV/m
E_{max}	$\geqslant$10MV/m(1/4 module) $\geqslant$8MV/m(full module)

Wherever necessary, an attempt is also made to “process” the vacuum space between the warm and cold waveguide windows. This will, in most cases, improve the cavity operating gradient. A portable test stand is used to perform the tests. A laptop computer is used to control the test sequences and to collect data.

Ⅱ. TEST SETUP

The portable test stand contains a voltage-controlled oscillator (VCO), power meters and a frequency counter. **A** spectrum analyzer is used both as a visual tuning aid and to measure the decay time of the power emitted from the cavity. A power supply is used to drive one of the four heaters located in the helium vessel. The helium bath pressure is monitored with a digital voltmeter (DVM). The test stand also includes the electronics necessary to allow the VCO to use the cryomodule interlocks. Geiger-Mueller tubes along with signal processing electronics are used to monitor radiation generated by field emission process. A laptop PC is used to control the test sequence and to collect data. It is connected to the test stand mainly through a GPIB cable.

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Ⅲ. MEASUREMENTS

The VCO has two modes of operation, pulsed and continuous. The pulsed mode is used to measure the power emitted from the cavity when the power is turned off. This offers one method of calculating the accelerating gradient. This also allows the measurement of the decay time of the emitted power using the spectrum analyzer. Since the cavity is highly over-coupled, the loaded Q (Q_L) is approximately equal to the external Q (Q_{ext}) of the fundamental power coupler (FPC). Knowing the operating frequency (1.497GHz) and the time required for a 20 dB decay in emitted power, Q_L can be calculated with the following formula:

$$Q_L = 4.34\,\omega\,\frac{\Delta t}{20dB} \tag{1}$$

The pulsed power mode is also useful for processing techniques.

The incident power and the transmitted power are measured while the VCO is in the continuous power mode. The incident power measurement allows a second independent gradient calculation. The Q_{ext} of the field probe can be calculated from the ratio of emitted power to transmitted power:

$$Q_{ext} = \frac{k^2}{1920} \tag{2}$$

Where,

$$k = 8.5 \times 10^4 \sqrt{\frac{P_0}{P_t}} \tag{3}$$

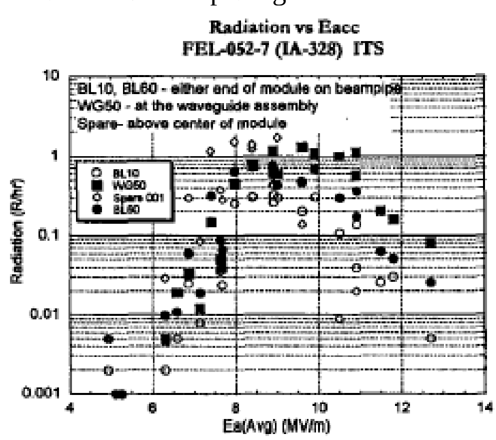
The unloaded Q (Q_o) of the cavity is measured calorimetrically. The inlet and outlet valves on the 2K helium circuit are closed and the pressure change due to the static heat-load and due to a known heat-load from one of the cryomodule heaters are measured. This allows calculation of the dynamic heat load from rf (P_d). Once the dynamic heat load is known, Q_o can be calculated:

$$Q_0 = \frac{E_{acc}^2}{1920 P_d} \tag{4}$$

The usual test procedure is to first increase the gradient in steps of about 0.5 MV/m starting at 4MV/m. Data from measurement of radiation generated by field emission is taken at this time. Figure 1 shows a typical radiation plot for an FEL cavity.

The waveguide vacuum is monitored as well at this time. If the vacuum degrades enough to cause an interlock fault, then an attempt is made to clean up the vacuum space. The method used is to pulse the rf at a low **(1%)** duty cycle. The power level is gradually raised, giving the vacuum time to recover. At the maximum power level, the duty cycle is gradually raised. The result is a cavity that will run at higher gradients with significantly fewer waveguide vacuum problems. The maximum operating gradient (E_{max}), is determined at this time.

Once this is accomplished, Q_0 can then be measured. Q_0 is measured between 4 MV/m and the maximum gradient in 0.5-1 MV/m steps. Figure 2 shows the results of a typical test in the FEL.



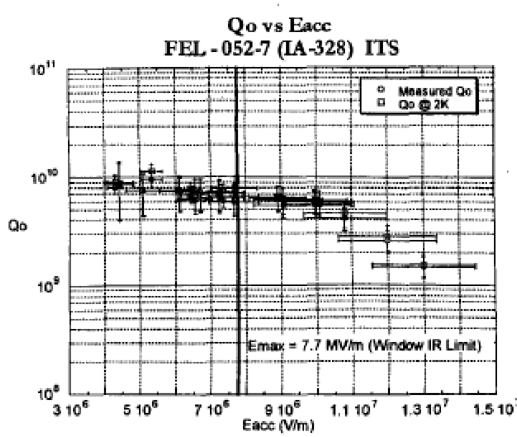


Figure 1 **Figure 2**

As a final step, the cavity is operated at E_{max} for an extended period. This is done to determine whether E_{max} is a stable operating point.

The possible limits on E_{max} include arc detector faults, waveguide vacuum and beam-line vacuum faults, window temperature faults, radiation levels greater than 2 R/hr and a heat-load contribution from field emission that is greater than 1 Watt.

IV. RESULTS

The specification for the Q_{ext} of the field probe (Qfp) is based on the requirement for 100 mW of power from the field probe at a given accelerating gradient. That gradient is 10 MV/m for the quarter cryomodule and 8 WV/ m for the full cryomodule. Figure 3 shows the distribution of values for the two cryomodules. A dark line shows the specification on the graph.

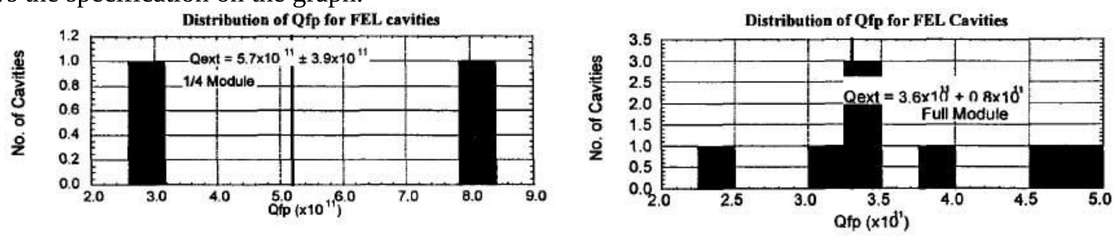


Figure 3

The Q_{ext} of the fundamental power coupler changes by a factor of two from the quarter cryomodule to the full cryomodule.Figure 4 shows the distribution of values.

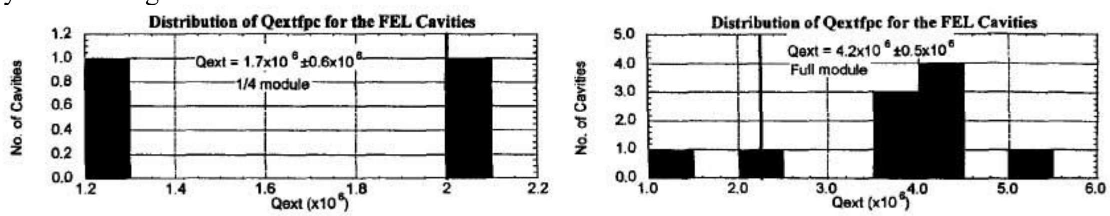


Figure 4

In order to minimize the dynamic heat load, Q_0 should be as high as possible(See Table 1).The value selected reflects the current capabilities of the five-cell cavities in use at Jefferson Lab.Only two of the 10 cavities in question failed to meet the requirement of 5×10^9.The design value results in a dynamic heat load of about 6.7W per cavity at 8MV/m. Figure 5 shows the distribution of Q_0 at the design operating gradient and at the maximum operating gradient.

The final parameter to be considered is the maximum safe accelerating gradient. All but one of the cavities meet or exceed that requirement. Figure 5 shows the distribution of E_{max} in the FEL.

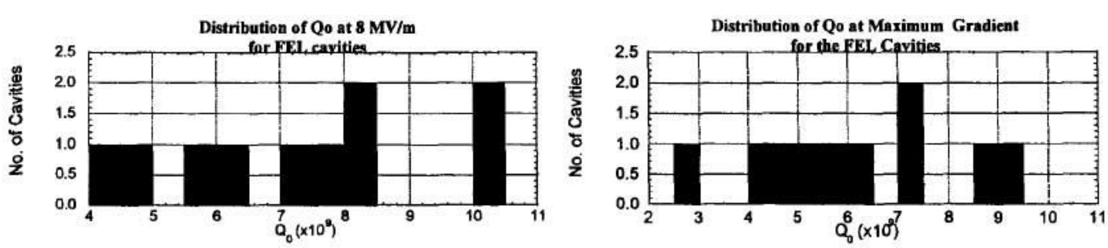


Figure 5

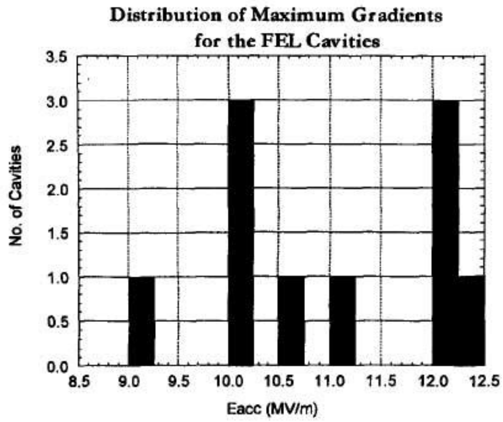


Figure 6

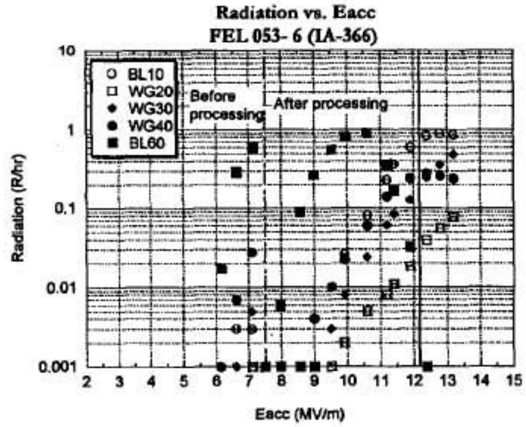


Figure 7

The total energy gain available from the FEL linac is approximately 54.6 MV/m.

An unexpected result of the attempts to process the waveguide vacumm space appears to be a reduction in radiation from field emission.This appears to have occurred in at least one case. Figure 7 shows the radiation vs. gradient plot for one cavity in the full cryomodule.The maximum power available for processing was about 5kW.

V. CONCLUSION

The FEL cavities meet or exceed the performance requirements in nearly all cases. The FEL linac can provide up to 54.6MeV with a dynamic heat load of approximately 120W. The design requirement for energy gain was 42MeV. This is a significant improvement in performance. The full cryomodule in the FEL linac provides nearly 44MeV of energy gain and is the best performing cryomodule built to date.