Production Vertical Cavity Pair Testing at CEBAF

C. Reece, T. Powers, J. Mammosser, and P. Kushnick
Continuous Electron Beam Accelerator Facility
12000 Jefferson Avenue, Newport News, VA 23606-1909 USA

Abstract

The construction of the 42 cryomodules for the CEBAF recirculating linac has required the testing of a large number of SRF cavities during the assembly process. The CEBAF cavities are assembled and tested as hermetic pairs prior to insertion into horizontal helium cryostats. Between May 1990 and September 1993, over 275 rf tests were made on cavity pairs at 2.0 K. This paper outlines the approach taken to accomplish the testing, the results obtained, and comments on particular details which may be of interest to the community.

Introduction

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} typically 1.3×10^{11}. Unloaded Q-factors of the cavities are typically $>8 \times 10^9$. The cavities are tested with the input rf port near critical coupling so the resonance bandwidths are of course < 1 Hz.

Production testing of CEBAF SRF cavity pairs was performed in the Vertical Test Area located in the CEBAF Test Lab. This facility was constructed in a manner that supports cavity testing with a relatively fast cycle-time and efficient use of labor. Integrated control and data acquisition systems were used extensively. Both the cryogenic system and the production rf system are built from a hybrid of commercial instruments, custom interface hardware, and LabVIEW® control software. Over 275 production rf tests were performed. From these tests, 15 pairs were rejected due to poor rf performance and were subsequently reworked. All of the 338 SRF 1497 MHz cavities have been assembled into hermetic pairs and have completed rf testing at 2.0 K. Among these, 55% demonstrated usable gradients greater than 10 MV/m.

Although the rf performance characteristics exceed the CEBAF baseline requirements of $Q_0 = 2.4 \times 10^9$ at 5 MV/m, the cavities were routinely tested to their performance limits. The usual limiting phenomena were encountered: field emission loading and quenches. It may be of some interest to note that the frequency with which performance is limited by quenching suggests that additional material advances may be required for applications requiring the reliable achievement of accelerating gradients of more than 15 MV/m.

Cryogenic Configuration

The CEBAF Vertical Test Area cryogenic facility contains eight liquid helium cryostats, two of which are dimensioned specifically for testing of assembled cavity pairs. All of the dewars are cooled by a closed-cycle helium system supplied by a remote refrigerator system.[1]

After the cavity pair has been placed in the dewar, 8–9 hours are required to purge and leak

---

This work is supported by US DOE Contract DE-AC05-84ER401540.

check the dewar, and fill it and reach 2.0 K with 800 l of helium covering the cavities. Typically, more time than this was available, and part of this process was performed unattended overnight. A fully automated system was successfully implemented that dynamically allocates the mass-flow capacity of the shared pumping system among the subatmospheric dewars. This permitted both graceful cooldown, excellent bath temperature regulation, and stable interaction with the cryogenic plant. The cryogenic system readily accommodated as may as four pair tests per week.

Figure 1 illustrates a cryogenic cycle of a vertical pair test.

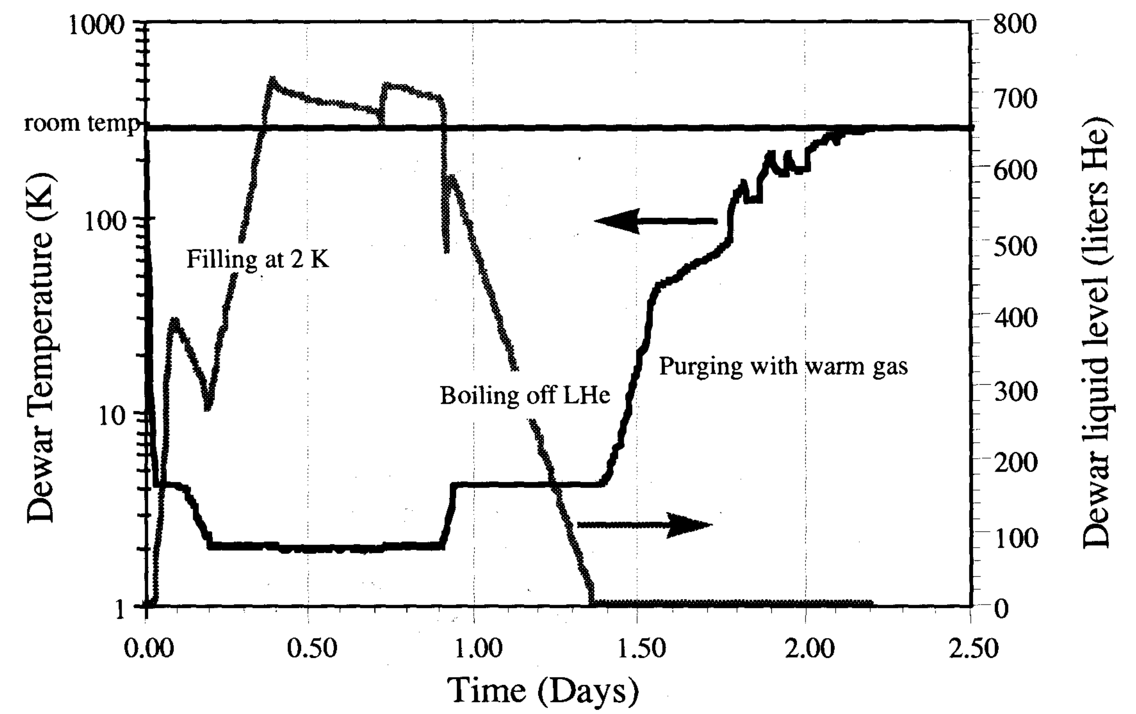

Figure 1. Typical temperature and liquid helium level cycle for pair test

RF Hardware Configuration

Pairs of cavities sharing a common internal vacuum were individually rf tested at 2.0 K. In addition, there was the ability to test individual cavities in two other cryostats. 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 was shared between the four cryostats.

An integrated rf control and data acquisition system was developed to perform the acceptance testing of the CEBAF cavities.[2] The system enabled convenient VCO frequency and phase-locked-loop phase optimizations, cw cavity coupling measurements, pulsed Q measurements, as well as data logging and retrieval. The system has a dynamic range sufficient to stably operate CEBAF SRF cavities at accelerating gradients in the range 0.05 - 25 MV/m without manual hardware changes and is switchable between the six cavity testing positions.

By providing automated control of all RF parameters, enhanced testing efficiency was obtained relative to the hardware and instrumentation styles commonly used in R&D applications.The major features of the RF control and measurement system are represented in Figure 2.

The rf drive line includes a linearized voltage controlled oscillator, a PIN switch for pulsed testing the SRF cavities, a vector modulator, a choice of low and high power amplifiers, and routing switches. The vector modulator was manufactured by Vectronics Microwave Corporation. It is

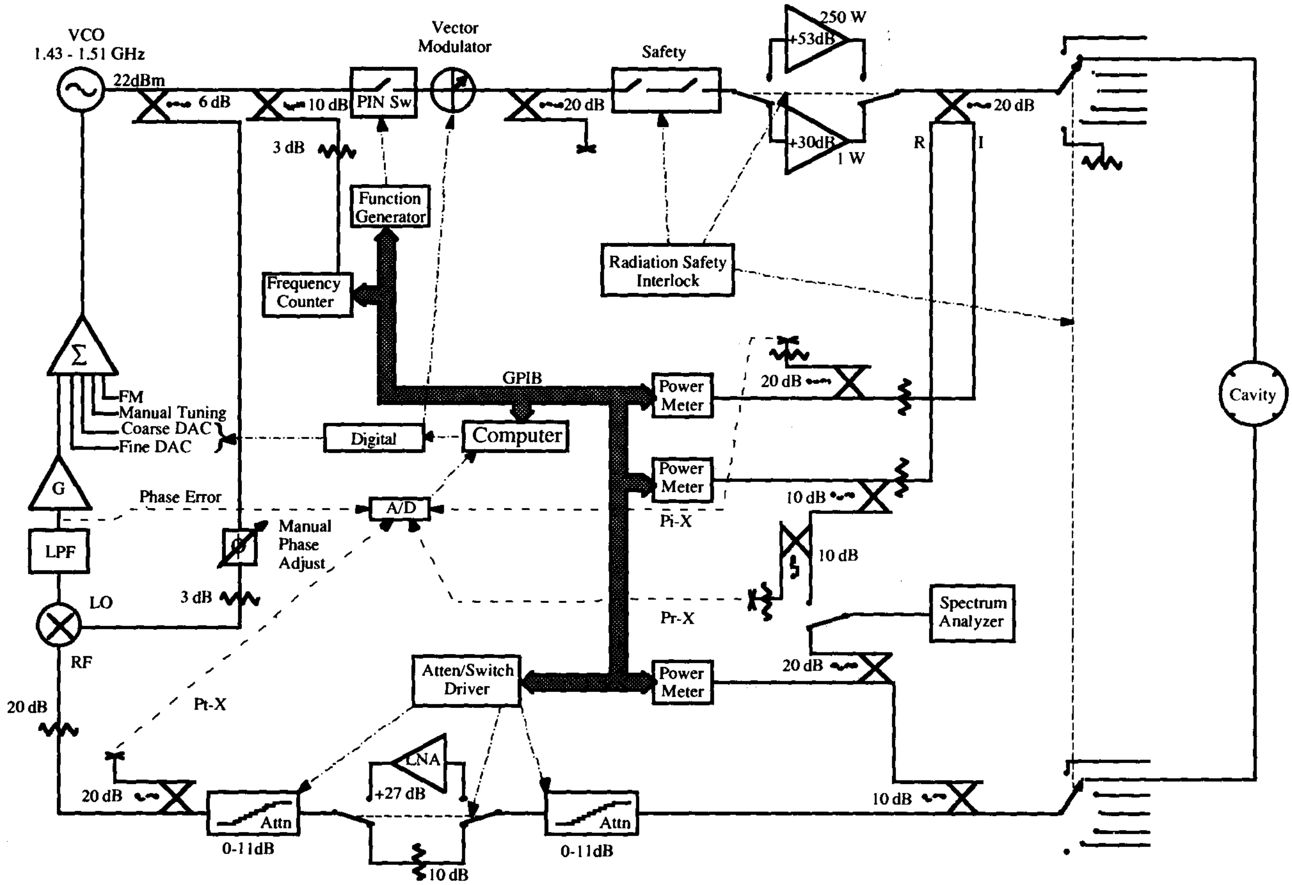

Figure 2. Rf control system for production cavity pair testing

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. The inclusion of this devise, together with the software interface, proved extremely valuable in operation of the system.

A 1 watt amplifier was used for low power testing, and an amplifier manufactured by Power Systems Technology Inc., capable of 250 watts output with 53 dB gain, was used for high power operations. The output of the selected amplifier was routed to the cavity under test with a SP7T coaxial switch that was electrically ganged with a similar switch that selects the transmitted signal from the cavity. These switches are rated for reliable operation to over one million actuations per position.

The amplitude of the transmitted rf signal was trimmed or boosted with a combination of programmable, switch-selected step attenuators and a low noise amplifier. This conditioning of the transmitted signal was performed to maintain a -20 dBm level at the rf port of the phase detecting mixer while the power transmitted out of the cavity ranged from -25 dBm to +35 dBm. This regulated power level, together with the phase-locked-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 0.03–25 MV/m.

The VCO control electronics were implemented with low noise circuit techniques so that the PLL amplifier produced 30 μVp-p noise, which corresponded to only 240 Hz of residual FM noise at the VCO output.

Safety interlock rf switches in the amplifier drive line served three major functions: they inhibited introduction of high power rf to a cavity unless radiation shielding was in place, they ensured that rf routing switches were not switched live, and they disable all rf whenever significant radiation levels are detected outside shielding. Movable massive shielding lids surrounding the tops of the recessed cryostats provided attenuation adequate to reduce the possible 2000 R/hr inside to < 0.1 mR/hr outside.

SOFTWARE

All aspects of the software-controlled data acquisition, rf control, and analysis were performed on a Macintosh II computer in the environment provided by LabVIEW 2®, published by National Instruments. LabVIEW® programming provides a convenient, integrated graphical user interface both for program development and user interaction.

By way of GPIB communications and ADC channels, the computer monitored all relevant rf parameters. An additional ADC was used to log the intensity of any x-radiation detected above the dewar.

As mentioned above, the rf phase and amplitude were controlled via a 20-bit signal applied to the vector modulator. A program module provided the operator with the ability to control independently phase and attenuation of the vector modulator with two on-screen dial controls. Another module trimmed the mixer rf input to the optimum level and, by adjusting the vector modulator phase setting, automatically compensated path length differences as attenuators were switched in or out. This maintained a nulled phase error signal in the PLL as the operating power level was changed.

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

Data Analysis

Several software modules were developed that integrated the control of rf parameters and data acquisition with real time data analysis, logging, and display. Analysis of cavity performance parameters, including unloaded Q-factor, accelerating gradient, and transmission probe external Q-factor, and error analysis were performed automatically with each measurement. The time dependence of the logarithmic slope of the transmitted decay signal was used to measure the loaded Q-factor directly as a function of stored energy. This feature increases the reliability of pulsed high field Q measurements when non-linear loss mechanisms become significant.

PERFORMANCE IN PAIR TESTS

Each cavity pair assembly was evacuated in the cleanroom and was normally maintained under vacuum thereafter.[3] The pair was then mounted on a vertical test stand and placed in a cryostat for testing. The ambient magnetic field at the cavity was reduced to ≤ 10 mG by an active coil and layers of magnetic shielding. The cavity vacuum was $\leq 10^{-6}$ torr prior to cooldown. The new He desorption leak detection technique with a sensitivity of 10^{-15} std cm^3 sec was routinely used to verify indium seal integrity in HeII.[4] This proved to be very convenient and powerful for our circumstance.

Typically, 45 minutes per cavity was required to characterize the Q_0 and E_{acc} performance and to calibrate the transmission pickup probe. In addition, measurements were made of Qs of higher-order modes (HOMs) and a resonance in the fundamental power coupler. The latter was done to assess rf dissipation in the cold ceramic window. Test results for three sample cavities are presented in Figure 3.

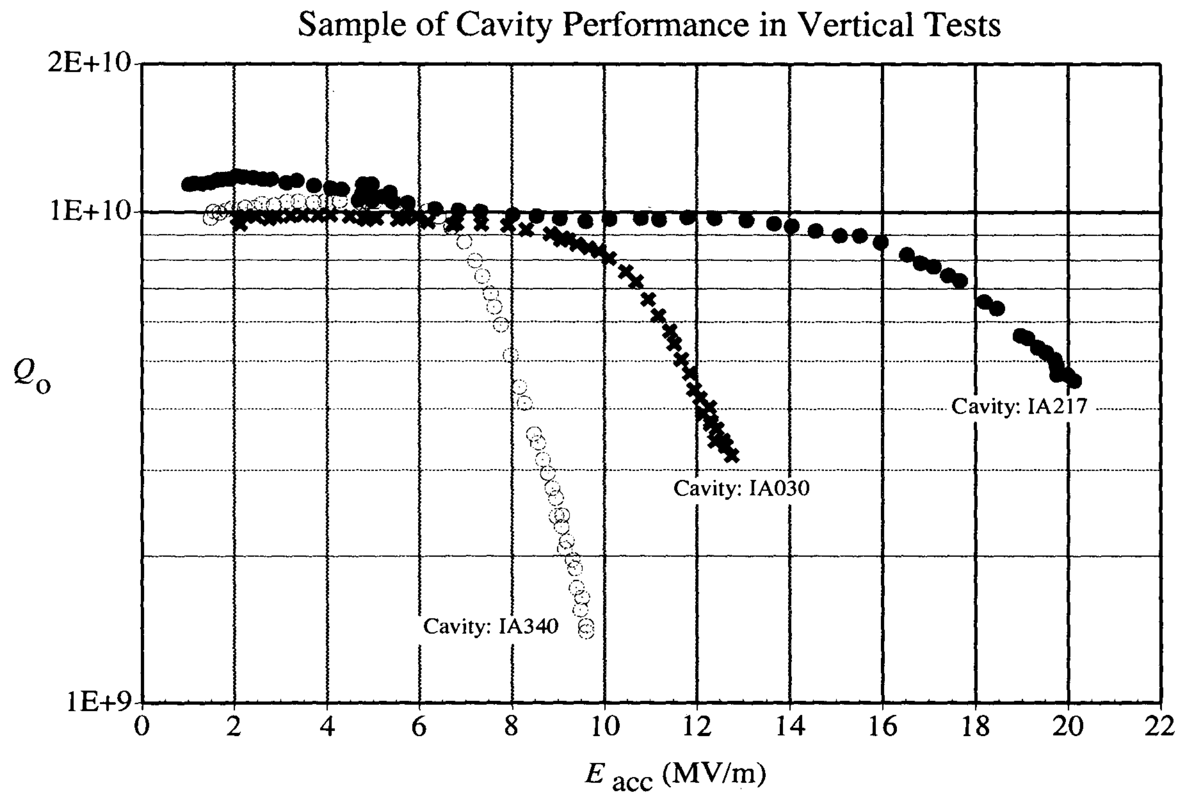

Figure 3. A sample of production cavity performance in vertical testing

In the majority of cases, the Q value at 2.0 K was near 10^{10}, corresponding to a residual resistance of approximately 15 nΩ. Lower Q values were observed when the ambient magnetic field at the cavity during cooldown had increased due to current fluctuations in the coil or when insufficient amounts of material had been removed during chemical processing.

From the perspective of cavity performance alone, the "usable" accelerating gradient of a cavity has been defined as that field which is the minimum of:

$E_{acc}[Q_0 = 2.4\text{x}10^9]$,

$E_{acc}[Q_{FE}=10^{10}]$, and

E_{acc}[quench] - 1 MV/m.

Using this definition, Figure 4 presents the distribution of usable gradients of cavities which completed testing in the VTA through September 1993.

Several minutes of cw rf processing with up to 100 W critically coupled to the cavity produced 10–30% gain in performance in approximately 50% of the cavities. This rf processing normally took place as a continuous process, until "jumps" in field level occurred. "Electronic" quenches with $\tau \leq 150$ ns have been observed in some of such instances.[5]

There were many cases where rather strong barriers were encountered below 1 MV/m. Such barriers are very unlikely to be multipacting barriers in the cavity because they would represent a very high order of multipacting. Possibly these low-field barriers were caused by some electronic processes in the variable coupler or the rf window, but this has not been confirmed. Frequently it was beneficial to apply high rf power to the other members of the fundamental passband in order to process a barrier. The barriers processed more readily with 10–50 W applied to the $\pi/5$- or $2\pi/5$-modes than with the same power applied to the π-mode.

Early tests were plagued by failures of the input rf feedthrough used in the dewar top-plate. This was identified as the result of a low-pressure gas discharge within the Type-N connector inside

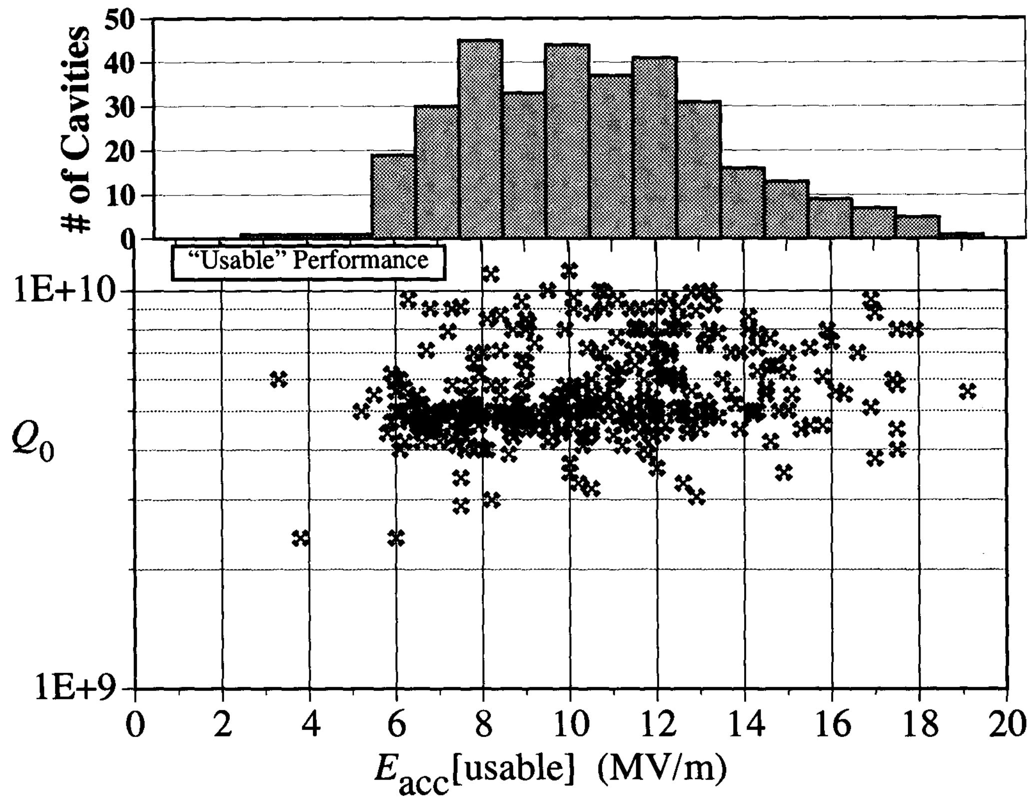

Figure 4. Cavity Q factor at maximum usable gradient

the dewar. Conditions are very favorable for an rf discharge to occur with about 25 torr of helium and greater than about 30 W of travelling wave rf power. After hermetically sealed rf cable assemblies with welded dewar feedthroughs[6] were incorporated into the test stands, the problem was eliminated.

Field emission (FE) loading was the most common performance limiting mechanism; although, 148 cavities have exceeded gradients of 9 MV/m without significant FE loading. See Figure 5.

During the first half of production, a strong propensity for the lower of the cavities in a vertical pair test to have greater FE loading than the upper drew attention to the initial cooldown conditions. After the incoming helium flow was redirected to cool the assembly as uniformly and as quickly as possible, the asymmetry of the FE onset was not observed.[7] It has been suggested that enhanced field emission is attributed to locally concentrated adsorbed gas from the residual components of the cavity vacuum.

Minor Q-switches have been observed in about 2% of the cavities. Typically, a hysteretic step in Q from $9x10^9$ to $6x10^9$ was seen at a gradient of 3 to 7 MV/m. The Q-switches usually persist after cavity reprocessing.

Thermal-magnetic quench has been exhibited by about half of the cavities in the last 100 qualified pairs. Among these, the average E_{acc}[quench] is 13.0 MV/m. The Q value and gradient just below quench are presented in Figure 6.

On several occasions, cavity pairs were removed from horizontal cryostats and retested vertically to assess the durability of the cavity rf performance through these handling procedures. The rf performance did not degrade in those cases where the cavities received exposure only to filtered N_2 or cleanroom air.

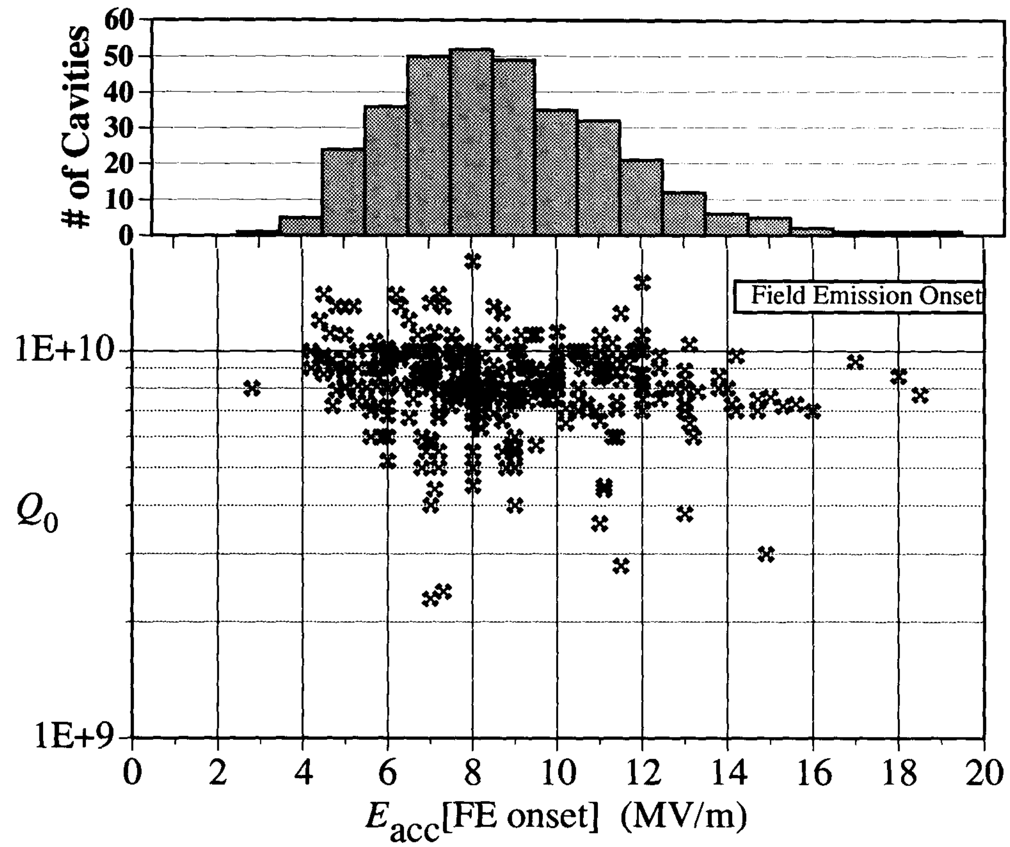

Figure 5. Q and gradient at onset of field emission loading

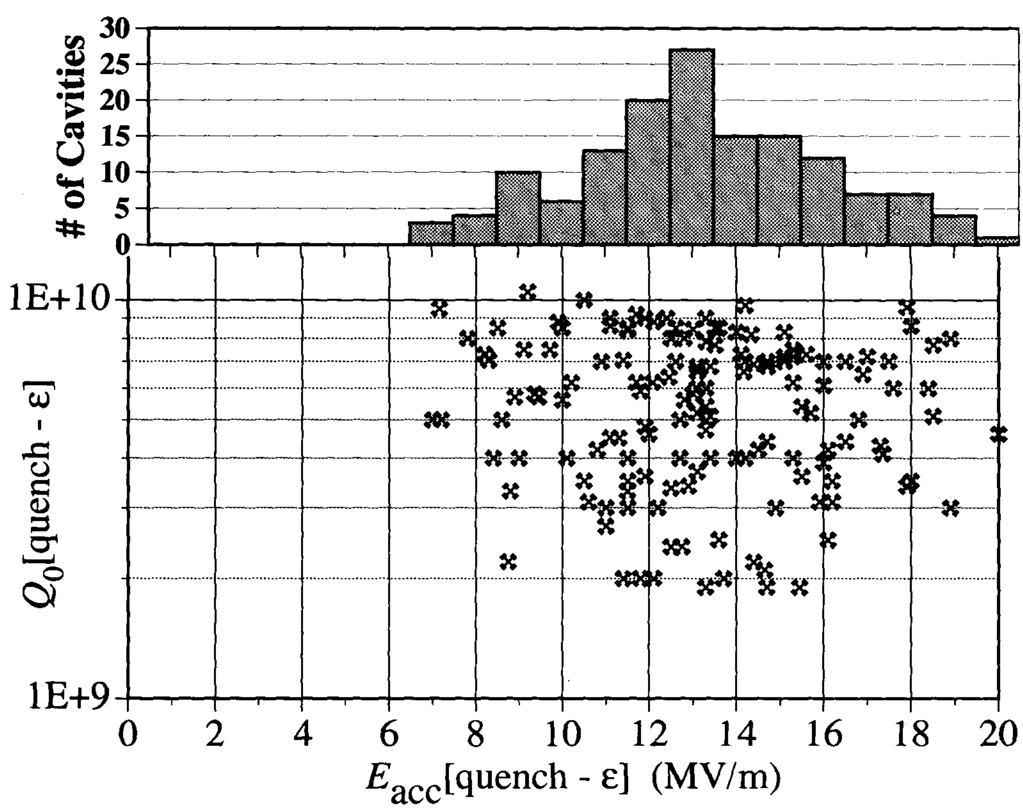

Figure 6. Q and gradient just below quenching field

During each production pair test, the frequencies and Q's for two higher-order modes were also measured. Figures 7 and 8 show the distribution of results.

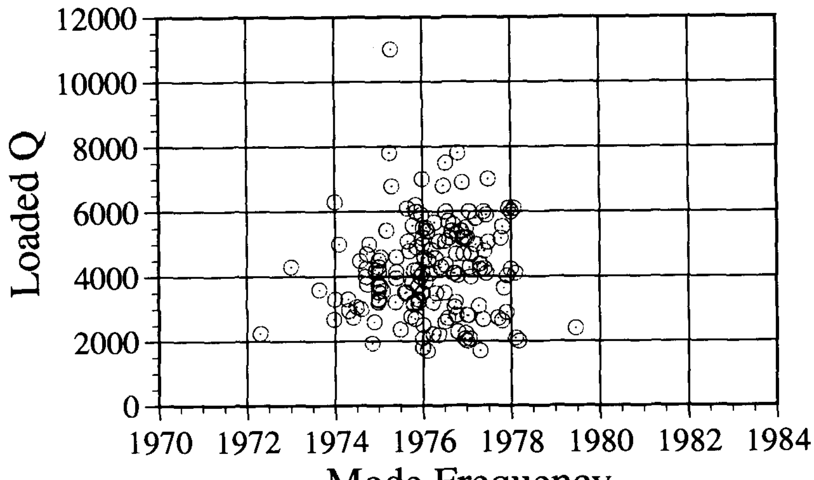

Figure 7. Q and frequency of the 1976 MHz mode

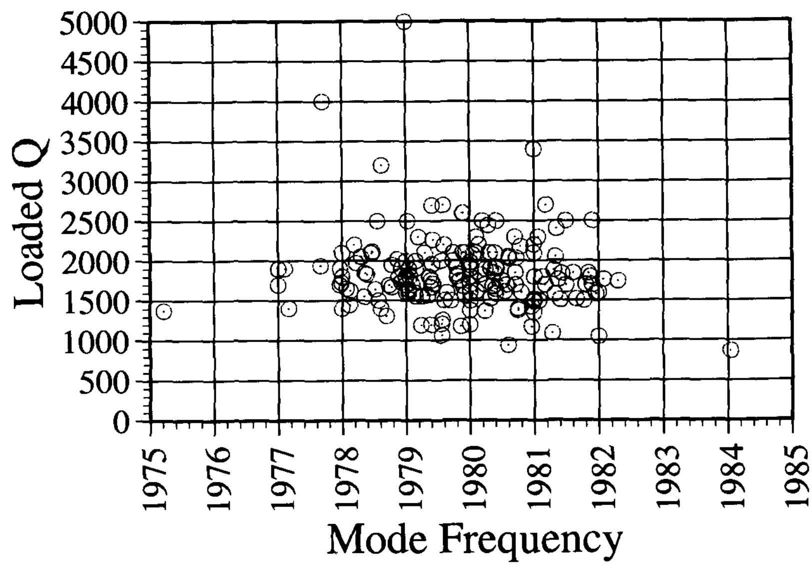

Figure 8. Q and frequency of the 1980 MHz mode

CONCLUSIONS

CEBAF has completed the production assembly and testing of 338 SRF cavities for the CEBAF linacs. The cryogenic and rf infrastructure implemented to support the testing was able to accommodate the needs in a convenient manner. Thanks to an excellent industrial partner and stringent QA procedures, the performance of the cavities consistently exceeded the CEBAF design specifications of $Q_0 = 2.4 \times 10^9$ and $E_{acc} = 5$ MV/m. In the cases where the achievable gradients were limited by thermal-magnetic breakdown, a rather large spread between 7 to 20 MV/m was observed. This suggests that the presently available high purity niobium of RRR ≥ 250 does not yet provide sufficient thermal stability to reliably support the gradients of $E_{acc} \geq 20$ MV/m needed for future linear collider applications.

ACKNOWLEDGEMENTS

The CEBAF cavity pairs were produced as a quality product due to a concerted effort of many people spread over a period of ten years. The principal architects were P. Kneisel and R. Sundelin. The cavity manufacturer, Siemens, delivered cavities on schedule and well within specifications. Dedicated processing and assembly staff refined the technique appropriately for production operations, and the auxiliary cavity pair components were developed, fabricated and integrated into the pair package by additional diverse CEBAF staff members. The results reported here, are thus the fruit of the labor and creativity of many people.

REFERENCES

[1]C. Reece *et al.*, "A Closed Cycle Cryogenic System for Testing Superconducting RF Cavities," *Conference Record of the 1991 IEEE Particle Accelerator Conference* (San Francisco, 1991), **Vol. 4**, pp. 2325–2327.

[2]C. Reece *et al.*, "An Automated RF Control and Data Acquisition System for Testing Superconducting RF Cavities," *Conference Record of the 1991 IEEE Particle Accelerator Conference* (San Francisco, 1991), **Vol. 3**, pp. 1508–1510.

[3]P. Kneisel, "Test of Superconducting Accelerator Structures in a Closed Vacuum System," *Proceedings of the 1987 IEEE Particle Accelerator Conference*, (Washington, D.C., 1987),**Vol. 3**, pp. 1893–1895.

[4]M. G. Rao, "He Desorption Leak Detection Method," *J. Vac. Sci. Technol.* A **11**(4), Jul/Aug 1993, pp.1598–1601.

[5]T. Powers *et al.*, "Investitgations of Arcing Phenomena In the Region Near CEBAF RF Windows at 2 K," contribution to this Workshop.

[6]Cable assemblies were custom fabricated by Kaman Instrumentation, Colorado Springs, CO.

[7]J. F. Benesch, "Preliminary Statistical Analysis of CEBAF's Cavity Pair Assembly Process Data," contribution to this Workshop.