

Performance Experience with the CEBAF SRF Cavities*

C. Reece, J. Benesch, M. Drury, C. Hovater, J. Mammosser, T. Powers, and J. Preble
CEBAF, Newport News, VA 23606 USA

Abstract

The full complement of 169 pairs of niobium superconducting cavities has been installed in the CEBAF accelerator. This paper surveys the performance characteristics of these cavities in vertical tests, commissioning in the tunnel, and operational experience to date. Although installed performance exceeds specifications, and 3.2 GeV beam has been delivered on target, present systems do not consistently preserve the high performance obtained in vertical dewar tests as operational capability. The principal sources of these limitations are discussed.

I. INTRODUCTION

The CEBAF recirculating linac uses 338 superconducting rf cavities to accelerate the beam. With four passes through the linacs, 3.2 GeV beam has been delivered onto a target. Operation to date has been limited to low current, pulsed beam. As commissioning continues, the delivery of 200 μ A CW beam at > 4 GeV is anticipated. Installed capacity may support operation above 5 GeV.

This paper reviews the characteristics and performance of the CEBAF SRF cavities. The cavities are but a part of the integrated system which delivers beam for nuclear physics research. At the start of the construction project these cavities together with the attendant 2 K liquid helium system were considered to present considerable technical risk. High-quality performance by our vendor [1] and careful attention to QA procedures, though, have resulted in the cavities performing reliably well above their design specifications of $E_{acc} = 5$ MV/m in qualifying tests.

Performance summaries have been presented previously for subsets of the cavities.[2–6] Process details described there will not be repeated here.

II. CAVITY PERFORMANCE AND LIMITATIONS

A. Cavity Performance Parameters

CEBAF was able to exploit a tested SRF cavity design developed at Cornell University for storage ring applications.[7] With only minor modifications, the cavity design was directly applicable to CEBAF. The nominal values of various parameters of the cavity are collected in Table 1. The principal figures of merit, of course, are the accelerating gradient and the unloaded quality factor (Q_0).

The CEBAF five-cell cavities were assembled and tested as pair units prior to assembly of four pairs into the horizontal cryomodules. In this cryomodule configuration, the cavities were commissioned for operation in the accelerator tunnel. Systematic performance tests in this configuration are difficult, principally because Q_0 must be measured calorimetrically.

SRF cavity performance is the combination of:

(1) physical design factors—these determine the beam-cavity interaction characteristics,

Table 1: CEBAF SRF Cavity Design Parameters

fundamental frequency	1497.0 MHz
accelerating gradient, E_{acc}	> 5 MV/m
active length	0.5 m
cell-to-cell coupling	(3.09 \pm .02)%
geometry factor	275
R/Q	960 Ω /m
E_{pk}/E_{acc}	2.56
Q_{ext} input coupler	$6.6 \times 10^6 \pm 20\%$
tuner phase error budget	10°
microphonic phase error budget	30°
Lorentz force frequency sensitivity	$-2.2 \text{ Hz}/(E_{acc}[\text{MV/m}])^2$
pressure frequency sensitivity	80–137 Hz/torr
niobium RRR	250
HOM Q_1 - 1976 MHz mode	4000
HOM Q_1 - 1980 MHz mode	1800
beampipe ID	70.4 mm
At $E_{acc} = 5$ MV/m:	
Q_0	2.4×10^9
2 K dynamic heat load	< 2 W
x-plane effective dipole steering	7.5×10^3 MeV/c
y-plane effective dipole steering	-1.7×10^3 MeV/c
effective normal quadrupole	1.2×10^{-3} MeV/c/cm
effective skew quadrupole	-1×10^3 MeV/c/cm

(2) material and surface dependent factors—these determine the maximum sustainable stored energy and the 2 K heat load,

(3) extrinsic operability factors—these include availability of rf drive, total 2 K cooling capacity, and reliability concerns such as frequency of interruptions to operations due to interlock trips.

The design factors have been well characterized elsewhere,[4,7,8] and the principal parameters are included in Table 1. The particular limitations of each cavity were established during the vertical cryostat tests, and the integrated system limitations have been determined from cryomodule commissioning and accumulating operating experience.

B. Performance Limitations

Using the hermetic cavity pair configuration and coax-to-waveguide variable couplers,[9] CEBAF characterized the cavity-specific factors of all cavities in a vertical dewar testing arrangement. This test also provided a thorough leak-check of the assemblage. The ceramic rf windows are attached to the cavity prior to this test, and are thus part of the tested system, as are the higher-order-mode loads and beamline gate valves.

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Figure 1 illustrates the typical performance limitations encountered during vertical cavity pair testing. Either a thermal-magnetic quench provides a hard limit on the stored energy, or electron loading degrades the cavity Q_0 intolerably.

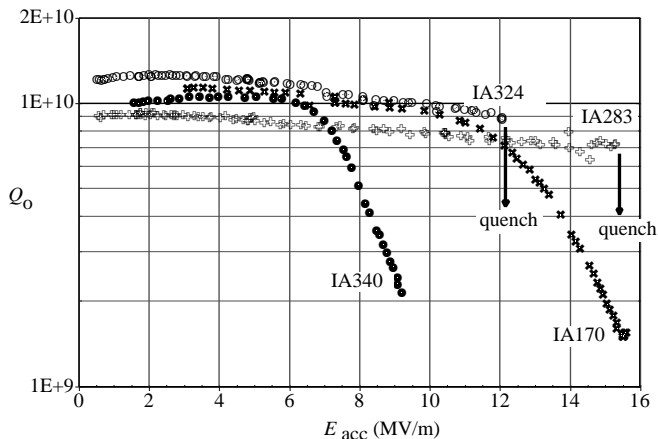


Figure 1. Typical quench and field emission loading seen in vertical tests.

Toward using the cryogenic capacity most efficiently and minimizing steady-state x-radiation fields, the *usable* gradients have been constrained to fields which induce less than 1 Watt of electron loading and, for commissioning tests, less than 1 rad/hr of generated x-rays external to the cryomodule. When cavity quench was encountered within these constraints, the usable gradient was derated 10% from the quench field.

Figure 2 presents the distribution of usable gradients and corresponding Q_0 of the CEBAF cavities as determined by the vertical pair testing. While some cavities performed well above 15 MV/m, there is a wide spread in fields attained even in these isolated tests.

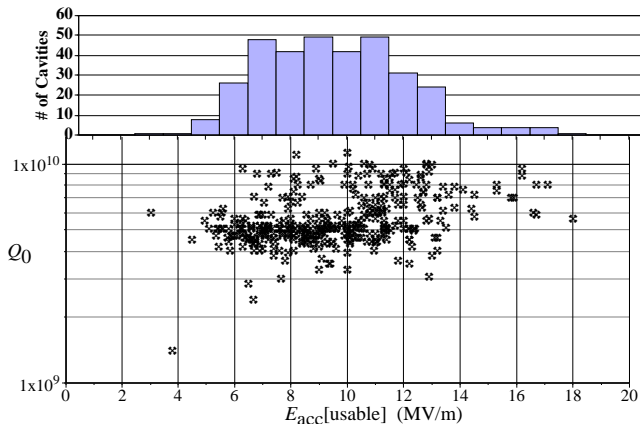


Figure 2. Distribution of usable SRF cavity gradients during vertical pair tests.

The distribution of peak fields reached in cavities which exhibited quenching is presented in Figure 3. In many cases heavy electron loading attended the quench. Again, there is a wide spread in the quench field, suggesting that significant improvements will be needed in the thermal stabilization of such cavities before one may reliably attain fields greater than about 12 MV/m.

The distribution of usable cavity capability observed during the commissioning tests is presented in Figure 4.

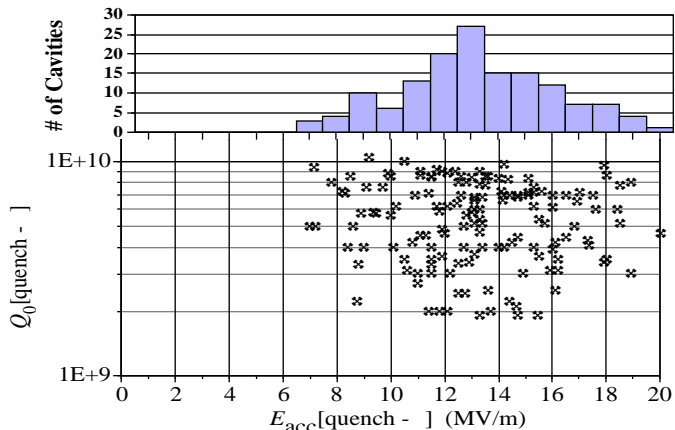


Figure 3. Distribution of quench fields in vertical tests.

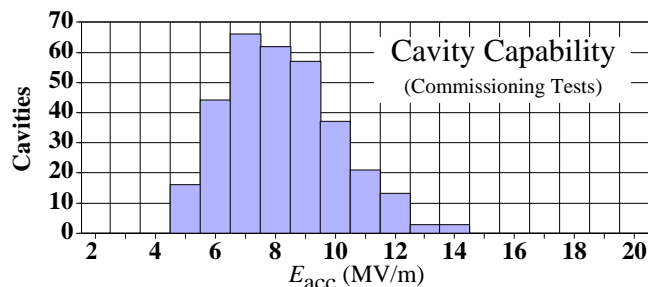


Figure 4. Distribution of usable SRF cavity gradients at commissioning.

C. Cold Ceramic Rf Windows and Arcing

The CEBAF ceramic rf window is mounted directly to the cavity waveguide fundamental power coupler. The alumina ceramic is located 100 mm off of the beamline. In this location, the window is subjected to the expected rf power, but also may be subject to charging via electron and x-ray flux.

Some of the electron loading observed in cavity tests has been attributed to cooperative and perhaps complex interactions between the cavity and windows.

On at least two occasions, particular cavities, with presumably specific field emission characteristics, repeatedly induced damage on windows mounted onto them, suggesting that secondary or photo electron flux on the window induced unsupportable charging. In other cases, it appeared that particular windows induce or significantly enhance electron loading in the cavities.

During sustained operation, quite a few cavities exhibit “arcing” in the region of the cold window at a rate which is otherwise unacceptable for operations—as high as 45 times per day. The additional constraint of < 2 arcs/day has thus been added to the criteria for usable maximum gradient for each cavity. This operational derating of maximum gradients has been necessary for 13% of the cavities.

Arcing in cavities appears to be correlated with the presence of nearby field emission—either in the arcing cavity or its neighbor. When arcing does occur, its frequency is strongly dependent on cavity gradient. Note that other cavities function stably, without arcing, above 9 MV/m. Several studies are exploring different aspects of this arcing phenomenon, including its dependence on the physical position of the window and spectral analysis of the light generated.[10,11]

III. CURRENT OPERATING CONDITIONS

During the installation and commissioning of individual cryomodules, cavity gradient and Q performance were tested, and stable operating bounds were established for short periods of time. The limiting constraint was noted for each cavity. To these limits the operational derating due to arcing has been added. The present distribution of types of cavity gradient limitations is provided in Figure 6. Clearly, the arcing and electron loading limitations, which as mentioned above we believe to be coupled, represent the most significant gradient performance constraints for CEBAF.

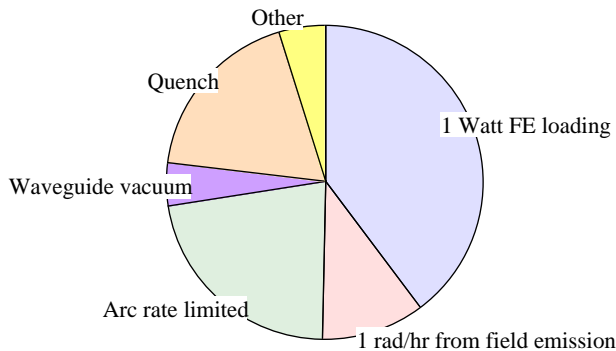


Figure 6. Distribution by type of cavity performance limitation—commissioning and operating experience

The installed cryomodules and rf drive systems are currently set up to support delivery of $15\ \mu\text{A}$, 4 GeV beam on Hall C targets. To reduce the consumption of ac line power during low current commissioning, the klystron supplies have been set to a lower tap setting. This has limited the available rf power per klystron to about 1.7 kW, down from their full 5 kW capability. This change has also had the benefit of extending the MTBF of the klystrons.

The present view of CEBAF SRF cavity operating performance is depicted in Figure 7 on a per-cryomodule basis. Five cavities are turned off, three with locked tuners, one with a broken interlock sensor, and one with a defective rf pickup probe. The operational derating of cavities has reduced the net usable voltage by 5% relative to commissioning test data.

In the fall of 1995, we anticipate raising the tap settings to accommodate higher current operation. Under those conditions we expect significantly higher performance from the SRF cavities—supporting up to $200\ \mu\text{A}$ beam at energies greater than 5 GeV. At that time we plan to examine the arcing behavior of cavities that otherwise function well at high gradients. The CEBAF acceleration system now appears capable of supporting operation at least 25% above initial design requirements. We envision opportunities for further improvements toward yet higher energies.

IV. ACKNOWLEDGEMENTS

The staff of the SRF and RF groups are pleased to have provided and commissioned the acceleration system for CEBAF. Particular credit goes to R. Sundelin and P. Kneisel for their work designing and refining the core building blocks of the accelerator. Production assembly and commissioning of cryomodules were coordinated by H. F. Dylla and W. Schneider.

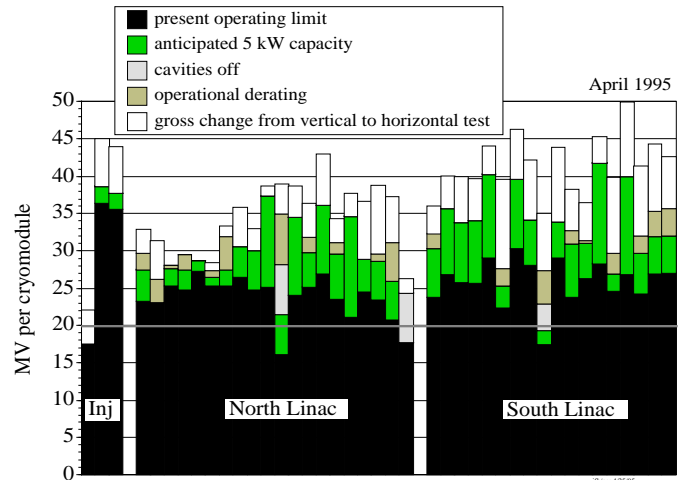


Figure 7. Capability of installed CEBAF cryomodules.

V. REFERENCES

- [1] M. Dzenus *et al.*, "Production of Superconducting Niobium Cavities for CEBAF," *Conference Record of the 1991 IEEE Particle Accelerator Conference*, **Vol. 4**, pp. 2390–92.
- [2] J. Mammosser, "Status Report: SRF Activities at CEBAF," *Proceedings of the 6th Workshop on RF Superconductivity*, October 4–8, 1993, Newport News, VA, **Vol. 1**, pp. 33–48.
- [3] M. Drury *et al.*, "CEBAF Cryomodule Commissioning in the South Linac," *ibid.*, pp. 610–616.
- [4] J. Mammosser, "Analysis of Mechanical Fabrication Experience with CEBAF's Production SRF Cavities," *Proceedings of the 1993 Particle Accelerator Conference*, Vol. 2, pp. 947–949.
- [5] H. F. Dylla *et al.*, "Operating Experience with High Beta Superconducting RF Cavities," *ibid.*, pp. 748–752.
- [6] C. Reece *et al.*, "Performance of Production SRF Cavities for CEBAF," *ibid.*, pp. 1016–1018.
- [7] R. M. Sundelin, "High Gradient Superconducting Cavities for Storage Rings," *IEEE Trans. Nucl. Sci.*, **NS-32**, 3570 (1985).
- [8] Z. Li, *Beam Dynamics in the CEBAF Superconducting Cavities*, Ph.D. dissertation, College of William and Mary (1995).
- [9] P. Kneisel, "Test of Superconducting Accelerator Structures in a Closed Vacuum System," *Proceedings of the 1987 IEEE Particle Accelerator Conference*, **Vol. 3**, pp. 1893–95.
- [10] T. Powers and P. Kneisel, "Arcing Phenomena at CEBAF RF-Windows at Cryogenic Temperatures," these proceedings.
- [11] V. Nguyen-Tuong *et al.*, "Electronic Activity at CEBAF Cold RF Window Induced by Cavity Operation," *Proceedings of the Fourth European Particle Accelerator Conference*, 27 June–1 July 1994, London, **Vol. 3**, pp. 2200–2202.