

# OPERATING EXPERIENCE WITH SUPERCONDUCTING CAVITIES AT JEFFERSON LAB

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The CEBAF recirculating superconducting electron linac at Jefferson Lab is now in full operation supporting nuclear physics experiments in three target halls at up to 4.4 GeV. The 330 SRF cavities, operating at 2.0 K, continue to perform well above design specifications, and have accumulated over 8,000,000 operating cavity-hours. We have to date no evidence of degradation of cavity performance. The SRF cavities have demonstrated excellent reliability. The one-klystron-per-cavity design provides CEBAF with flexibility and redundancy for normal operations. Several techniques have been developed for establishing optimum operating conditions for the 330 independent systems. Operation of the cavities and control systems at the full design current of 1 mA has recently been achieved. The principal constraints on usable gradient for low-current operations are (1) discharge at the cold ceramic rf window induced by electron field emission in cavities, (2) tuner controls, and (3) stability of the waveguide vacuum in the region between the warm and cold windows. Several cryomodules have been improved by application of rf-helium processing while installed on the beamline.<sup>1</sup>

*Keywords:* Superconductivity; Radiofrequency; Cavities

## INTRODUCTION

This paper presents the operating experience with SRF cavities employed in the CEBAF recirculating linac at the Thomas Jefferson National Accelerator Facility (Jefferson Lab). The full design operating envelope for CEBAF called for a 200  $\mu$ A CW electron beam at

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4.0 GeV with low emittance and energy spread ( $\varepsilon \cong 2 \times 10^{-9}$  mr,  $\sigma_E/E \cong 2.5 \times 10^{-5}$ ). This envelope has been demonstrated and exceeded. Productive exploitation for nuclear physics research is now underway.<sup>2</sup>

The CEBAF beamline's 330 solid niobium SRF cavities operate at 1497 MHz and 2.0 K.<sup>3</sup> Each one has an active length of 0.5 m and is separately powered by a 5 kW klystron. Eight such cavities are contained in each cryomodule. The design accelerating gradient is 5 MV/m, so that by up to five passes through the two linacs, electrons can attain 4 GeV. Beams can also be extracted at less than five passes, enabling multiple simultaneous experiments in three experimental halls at differing, but correlated, energies.

## OPERATIONAL ACHIEVEMENTS

In September 1997, a demonstration test was mounted to confirm the full beamloading design envelope of CEBAF. With the north and south linacs trimmed to 400 MV each, five-pass CW beam was placed on the Hall C dump and the current was increased to 200  $\mu$ A. The increased beamloading exercised the rf control systems in new regimes, and driveline limits were encountered for 12 cavities. Slight redistribution of the gradients removed the obstacles.

Stable 200  $\mu$ A, 4.0 GeV beam was maintained on the dump for over an hour. There were no unexpected difficulties. No target was in place for this run, and no single-user program presently requires this full current.

At the opposite end of CEBAF's dynamic range was the stable delivery of a 100 pA CW beam for commissioning tests with the Large Acceptance Spectrometer in Hall B. The first physics runs above 4 GeV took place during November 1997. One hall received up to 115  $\mu$ A at 4.4 GeV, while another hall simultaneously received four-pass beam at 3.5 GeV. The maximum beamloading current in the linacs was 805  $\mu$ A, constrained by the present administrative limit of 180  $\mu$ A on the net output current. This running mode presented no challenges to the SRF systems.

In April 1997, another demonstration test was mounted to begin the process of extending the energy reach of CEBAF. While the linac

voltages have significant headroom, the power supplies for the arc dipoles were not capable of supporting greater than about 4.4 GeV. As a test of the SRF systems, a short high-gradient single-pass run took place. The linacs were each trimmed to 560 MV, 40% above nominal design. With the injector providing its nominal 45 MV, a 90  $\mu$ A, 1.165 GeV CW test beam was placed on the beam switchyard tune-up dump.

Had the magnetic element systems been available, the rf could have supported 5.6 GeV, five-pass beam delivery. With only an hour or so for trimming gradients, cold window discharge arc trips occurred approximately every 5 min, unacceptably high for most experiments. The test provided opportunity to exercise the cavities at higher than normal operating gradients and to assess their stability at these levels. Knowledge from this experience is being used to increase stability and reliability for normal operations.

## OPERATIONAL LIMITATIONS

### Cavity Gradients

The energy reach of CEBAF is fundamentally tied to the sustainable gradients of the linac cavities. Each cavity has its performance characteristics, the most important of which are the  $Q$  vs. gradient and susceptibility to arcing at the cold ceramic window. Figure 1 shows the distribution of maximum sustainable gradients in CEBAF by type of limitation. The assortment by limitation is also displayed in Figure 2. The principal limitation of the installed cavities – affecting 80% of them – is electron field emission and associated phenomena, such as X-ray production, charging and arcing at the cold ceramic rf window,<sup>4,5</sup> and anomalous 2K heat load. In addition, 12% of the cavities are limited by quench and about 4% are constrained by the stability of the vacuum in the region between the 2 K and 300 K rf windows.

Starting in the fall of 1996, we began developing methods for applying rf-helium processing to the cavities while still on the beam-line. Initial results were very encouraging, so a total of 12 cryo-modules have thus far received this processing, yielding an additional

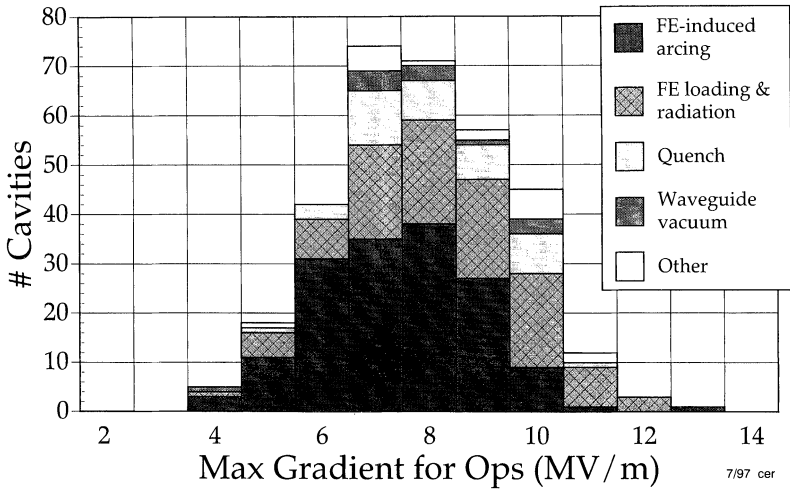


FIGURE 1 Distribution of maximum gradient by type of limitation.

## SRF Cavity Gradient Limitations in CEBAF

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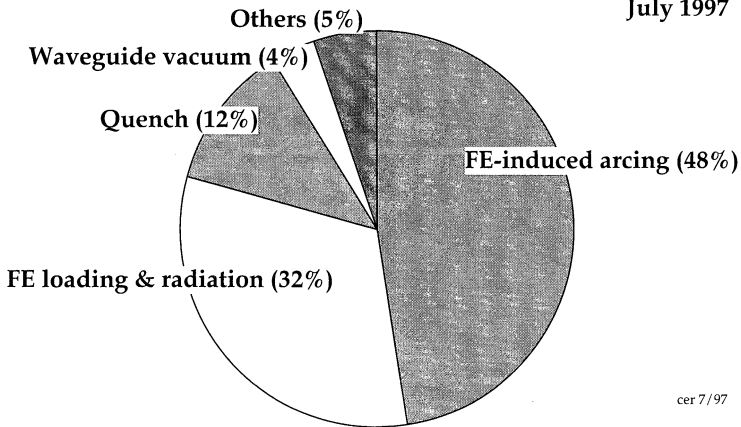


FIGURE 2 Type of limitation on gradient in CEBAF SRF cavities.

41 MeV/pass capability.<sup>6</sup> The indicators of improvement via this processing technique are the raising of onset levels for X-ray production by field emission, and the reduction of arcing at the cold rf window. When adequate time was available to make calorimetric  $Q$

measurements on the first module processed, corresponding reduction of losses was observed. See Table I.

We intend to exhaust the opportunities for such gains as a first step toward significant upgrades of the machine into the 6–8 GeV region.

Figure 3 presents the maximum voltage from each CEBAF cryomodule in November 1997, including the gains from rf-helium processing.

TABLE I Relief from arcing and FE loading after rf-helium processing of NL03

<i>Cavity</i>	<i>Max G before processing (MV/m)</i>	<i>Initial limitation</i>	<i>G (MV/m)</i>	<i>Q<sub>0</sub> (×10<sup>9</sup>) Before</i>	<i>Q<sub>0</sub> (×10<sup>9</sup>) After</i>	<i>Max G after processing (MV/m)</i>	<i>Final limitation</i>
2	4.2	arcs	7.7	1.5	3.3	8.7	arcs
4	5.5	FE loading	8.7	2.5	4.1	9.0	FE loading
6	4.9	arcs	6.8	2.1	> 5.3	7.7	FE loading
8	5.5	arcs	8.8	2.85	4.7	6.9	arcs

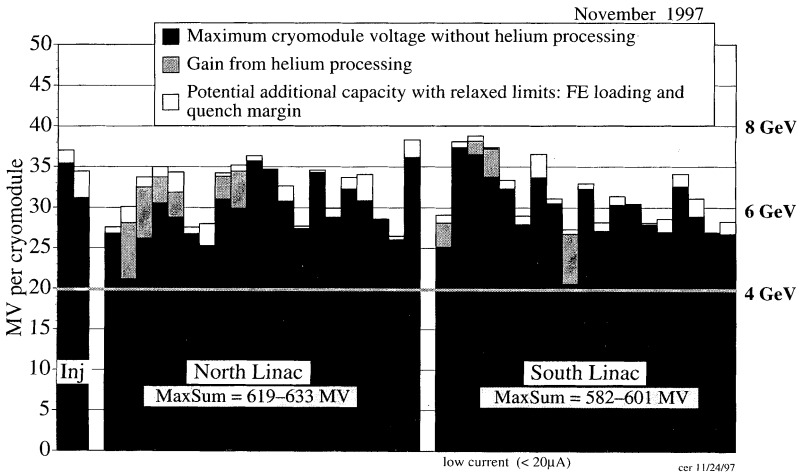


FIGURE 3 Maximum voltages obtainable from the CEBAF cryomodules.

## **Operational Stability**

The SRF cavities in CEBAF have been quite stable and reliable. By October 1997 over 8,000,000 cavity-hours and 3,000,000 cavity-beam hours had been accumulated. To date, there is no evidence for degradation of cavity performance.

The occurrence of periodic arcing at the cold windows has proven to be a manageable phenomenon, as it is a quite reproducible function of gradient for each cavity with the charging field emission behavior. Operationally, the maximum useable gradient for a cavity is bounded by that field at which it predictably arcs more than three times per day.

The vacuum between the cold and warm waveguide windows is subject to transients which require the rf to be shut off and beam delivery to be briefly interrupted. This occurs for a subset of cavities and only when there are significant changes in the standing wave pattern, as when higher powers are applied to allow a detuned cavity to still achieve its nominal gradient setpoint. Such instabilities have, however, not been observed as the cavities are beamloaded and the increasing forward power is more closely matched into the beam. The pressure excursions are interpreted, based on partial pressure analysis, as the redistribution of adsorbed hydrogen and helium in the thermal transition region of the waveguide. This type of problem has become much less significant as we have gained greater control over maintaining the proper tune of the cavities.

Of the 330 installed SRF cavities, two are not operational. One of these is disabled by a mechanical tuner problem; the other suffers from a helium leak into the intermediate waveguide vacuum space. Neither of these is repairable without removing and disassembling its cryomodule.

About 25% of the cryomodules have active turbo-pumps on the insulating vacuum. In one case the leak rate is such that occasionally the turbo-pump has insufficient capacity to handle the gas desorbed when the cryomodule warms above 4 K.

## **Tuning Control**

Looking to higher-energy operation, we anticipate a new problem with tuning control. The backlash in the mechanical tuners

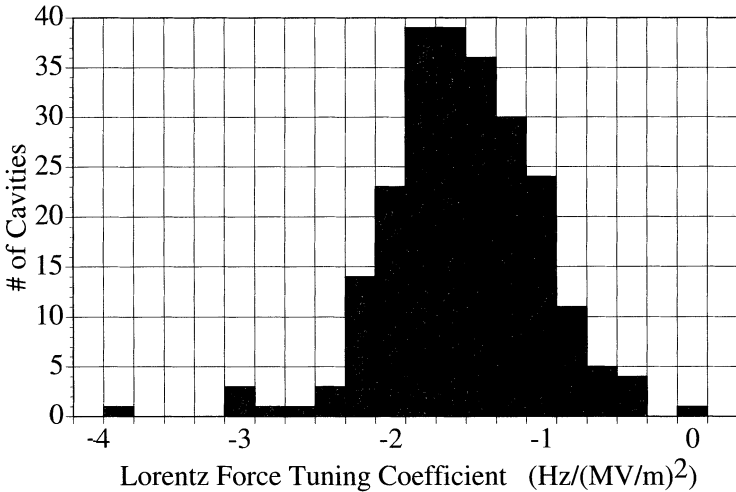


FIGURE 4 Distribution of Lorentz force tuning coefficients for the CEBAF cavities.

complicates the turn-on and tune-up of cavities with gradients greater than 9 MV/m, in which region the Lorentz force detuning approaches one bandwidth. The distribution of Lorentz force tuning coefficients for the CEBAF cavities is provided in Figure 4. The intention is to accommodate this backlash in the future via software.

The microphonic environment of the CEBAF cavities has proven to be quite good. The rms microphonic phase angle is typically less than  $2^\circ$ . Figure 5 presents the distribution for all CEBAF cavities after the addition of mechanical isolation reduced the rms phase angle for about 20 cavities from the  $5\text{--}12^\circ$  range.

### Flexibility

At 4 GeV the CEBAF SRF system has generous flexibility, with more than 25% voltage headroom at full current. If a problem develops with a klystron or other driveline component, that cavity can be detuned and shut down and beam operations restored in 10 min. It has also been demonstrated that 4 GeV beam can be provided with several whole cryomodules turned off.

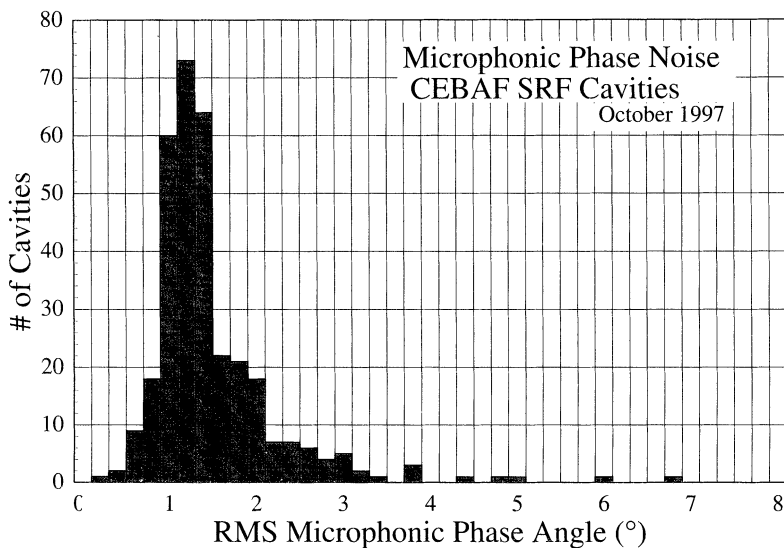


FIGURE 5 Microphonic phase noise of operating CEBAF SRF cavities.

Procedures have also been developed to economize the consumption of line power by the rf systems when less than full beamloading is required by the program. This permitted the trimming of 1 MW load between the 200  $\mu$ A run and the following 2 nA physics run without changing any fields seen by the beam.

The day-to-day operational setup of each of the rf systems is derived from the following: (1) the maximum power available from each klystron, (2) the maximum gradient of each cavity and (3) its loaded  $Q$ -factor, (4) the control headroom needed to counteract microphonics, (5) the maximum intended beamloading current, and (6) the total desired linac voltage. The maximum gradients consistent with the available power and beamloading for each cavity that is presently on are summed for each linac. The setpoint gradient of each cavity is reduced proportionally such that the desired sum is obtained. Four cavities in each linac are used to provide voltage stabilization against drifts in proper phasing and calibration of the cavities.



## DYNAMIC HEAT LOAD WITH BEAM CURRENT

One of the last performance parameters to be measured for the SRF cavity systems in CEBAF was the dynamic heat load with beam. During the high-current runs of fall 1997, the integrated 2K load for the whole accelerator was monitored as a function of beam current, (see Figure 6) with all gradients held constant. Potential contributions to such a dynamic load are additional dissipative losses in the cold rf windows, changing thermal profile in the waveguide transition region, and beam-induced losses via higher-order-mode (HOM) generation. (In CEBAF, the higher-order modes are dissipated at 2K.)

The observed dynamic load follows a quadratic dependence on linac beam current. Such a functional dependence is not expected from increased losses in the input rf system. The quadratic dependence is appropriate, however, for beam-induced HOM effects.

The observed amount of heating, while operationally of little consequence, is more than an order of magnitude larger than has yet

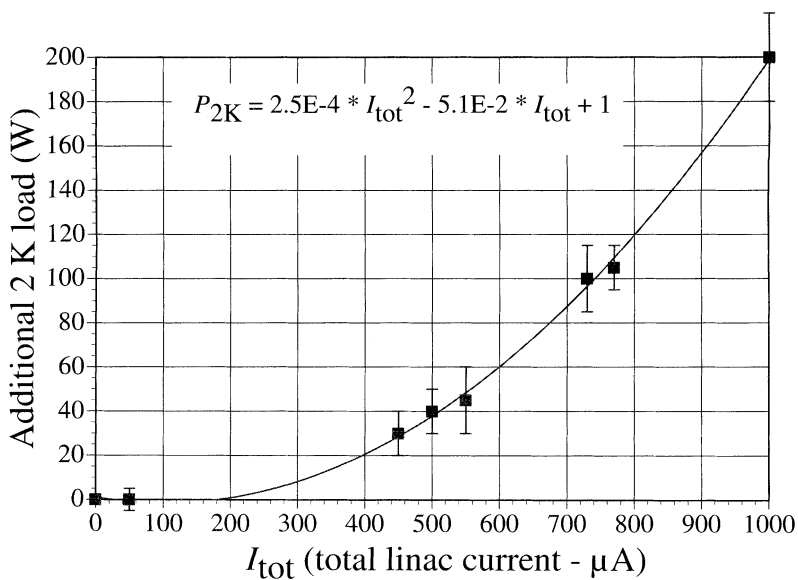


FIGURE 6 Dependence of 2 K load on total linac current.

been analytically attributed to HOM generation by the CEBAF 2 ps bunchlength in the CEBAF cavities.<sup>7</sup>

## SUMMARY AND PLANS

The SRF cavities in CEBAF continue to perform quite well within the present operational requirements. To extend the gradient capability of the cavities, we plan to apply helium processing to the balance of the machine as opportunity permits. It is expected that this will raise the energy bound of CEBAF to close to 6 GeV.

Subject to accumulating physics justification, the upgrade path for CEBAF beyond 6 GeV involves gradually replacing cryomodules and populating 10 empty slots in the linacs with new cryomodules which have improved filling factor and take advantage of improvements in SRF cavity preparation techniques of the past 7 years.

### *Acknowledgments*

The experience described here is the fruit of many persons' labor, including all of those involved in the construction of CEBAF. Current activities on this subject fall to members of either the Accelerator Development Department or the Operations Group in the Jefferson Lab Accelerator Division. Particular credit goes to L. Doolittle, who performed the measurement of the Lorentz force tuning coefficients.

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