ACHIEVING 800 KW CW BEAM POWER AND CONTINUING ENERGY IMPROVEMENTS IN CEBAF*

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Abstract

During the past year, CEBAF at Jefferson Lab has demonstrated its full capacity of sustained 800 kW beam power. All systems performed as intended. The energy stability at the design parameters of 4.0 GeV, 200 μA CW beam was measured to be better than 3×10^{-5} rms. During the fall of 1997, physics experiments were conducted using 4.4 GeV beam. Having demonstrated the benefits of *in situ* helium/rf processing of SRF cavities for increasing the energy reach of CEBAF, we began a program of processing all installed cryomodules. This processing has proven effective against the principal gradient limitation of the SRF cavities in CEBAF: discharges at the cold rf waveguide window, induced by electron field emission in the cavities. Such effects limit approximately half of the cavities. Regular operation at 5.0 GeV is just beginning, and preparations are underway to support 5.5 GeV in early 1999.

1 CEBAF DESIGN

CEBAF was designed and constructed as a 4.0 GeV, 200 μA CW recirculating electron linac. [1] The acceleration system employs 330 superconducting radiofrequency (SRF) cavities operating at 1497 MHz and 2.0 K. Each cavity is individually regulated and powered by a 5 kW klystron. Beam may be recirculated through the split linac up to five passes before delivery to the three experimental halls.

2 OPERATING EXPERIENCE

The accelerator has been supporting physics experiments since October 1995. Routine multi-hall operation has proceeded for the past two years. Tolerable CW beam currents are typically either limited to very low currents (100 pA–100 nA) by event discrimination constraints—for example, in the Hall B Large Acceptance Spectrometer—or to ~130 μA by heating of cryogenic targets in Halls A and C.

The first physics run above 4 GeV took place during November 1997. One experiment took 4.4 GeV beam while another received four-pass 3.5 GeV beam.

The SRF cavities in CEBAF as well as the rest of the acceleration system have been quite stable and reliable. By August 1998, over 4,000,000 cavity-beam hours had been accumulated.

3 FULL POWER TEST

On September 16, 1997, a test was performed on the CEBAF accelerator to demonstrate its full design capability of 200 μA CW beam at 4.0 GeV. This beam was delivered to the Hall C dump with minimal difficulties and with stability characteristics consistent with normal operations. Since no physics target was available that could handle 200 μA, the test was performed without a target in place. Rastered beam went directly to the dump. One clear indicator of the robustness of the integrated accelerator system was the ability to place 200 μA on the injector Faraday cup, retract that cup, and immediately transport lossless, full-power beam to the Hall C dump and maintain this current for at least tens of minutes with all orbit locks off. The duration of the full test was 10 h.

As illustrated in Figure 1, the test demonstrated the economy of exploiting SRF technology. A typical cavity operating at 6.5 MV/m fully matches the input 3.8 kW rf to the beam.

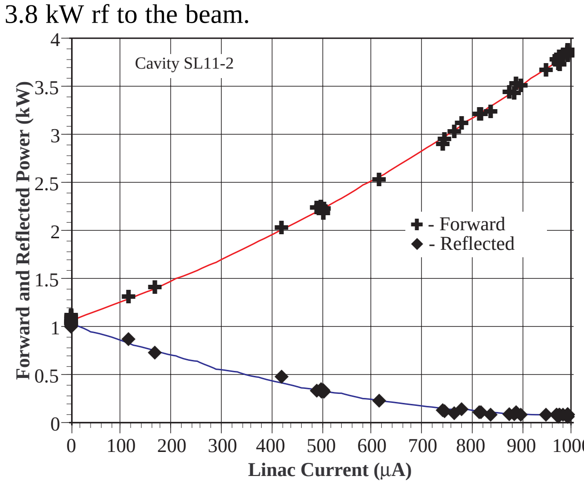

Figure 1. Matched rf load at full current.

During delivery of 200 μA to Hall C, measurements were made of the stability of beam position and energy. The dominant features observed were at 60 Hz. Beam motion in high dispersion and zero dispersion regions was comparable with comparable beta functions, so it's unlikely to be due to energy variation which, based on

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a set of BPM measurements, had a fractional peak-to-peak amplitude of 4×10^{-5}.

There was no problem with input waveguide vacuum pressures as the input rf power increased and shifted to full travelling-wave conditions. An increase in the 2 K heat load was observed, increasing quadratically with total linac current, with an additional 200 W from the maximum 1 mA circulating current. The source of this heat has yet to be fully explored.

The beam dump cooling systems had no problem handling the 800 kW of beam power. The high-power beam dumps were designed to accept well over 1 MW. The test also challenged the beam current monitoring system used as part of the safety interlock system. We were able to approach the administrative limits with absolute beam accounting to better than 1%.

4 ENERGY IMPROVEMENTS

4.1 Limitations

The CEBAF cavities, though performing substantially better than initial specifications, are primarily limited in performance by internal electron field emission. Periodic arcs at the cold ceramic rf window are strongly correlated with field emission in the associated cavity.[2] Over a third of the 330 SRF cavities are now limited in usable gradient by this arcing phenomenon. Post-production tests have demonstrated that this arcing may be eliminated by moving the ceramic window away from the beamline and adding a dogleg in the cold waveguide section. All future rework will implement at least this change.

The other effects of field emission are x-ray production and spoilage of the cavity Q. Because it is more easily measured, we use the radiation as an indicator of decreasing Q and presently tolerate 2 R/h outside the cryostat from each cavity.

4.2 Helium Processing

The most economical route for incremental extension of the CEBAF energy reach has been through *in situ* conditioning of the SRF cavities, seeking to reduce the internal field emission and thus also the periodic arcing. Helium/rf processing, first attempted on an installed CEBAF cryomodule in September of 1996, has proven to be an effective method of improving cavity performance.[3]

Because of CEBAF's very full run schedule, we have continued to upgrade the processing methods in order to minimize any impact on run time. Beginning in 1998, the normal rf control system was used during processing rather than one of three stand-alone systems. A local ~70 MHz VCO was substituted for the fixed-frequency 70 MHz IF line. Including this VCO in a phase-locked loop then enabled dealing with the low-level multipacting barrier, as previously described.[4]

Also, to maximize the yield from helium processing, it is now preceded by a thermal cycle up to 40 K in order to desorb and remove any accumulated He and H. This is followed by several hours of detuned pulsed rf conditioning of the input cold waveguide region.

The actual processing is accomplished with 10^{-4} torr He on the beamline while driving the cavity at its highest sustainable field level for ~1 h. A subsequent thermal cycle to 40 K is used to remove the He. Following this procedure there have been no difficulties immediately resuming normal operation. The markers for effective processing are reduced arcing and reduced generation of x-rays by field-emitted electrons.

This upgraded processing scheme was commissioned on two cryomodules in February 1998. Using staggered crews, 16 additional cryomodules were processed during seven days allocated in July. The number of cryomodules processed was limited only by the capacity of the cryogenic system to handle the thermal cycles.

In addition to direct processing gains, other cavity gradient limitations are revisited during the processing work, and in many cases additional voltage has been found through reducing margin based on accumulated operating experience.

4.3 Results

To date, we have applied helium-rf processing at 2 K to 224 cavities in 29 of the 41 installed CEBAF cryomodules. Figure 2 shows the shift of limits after processing.

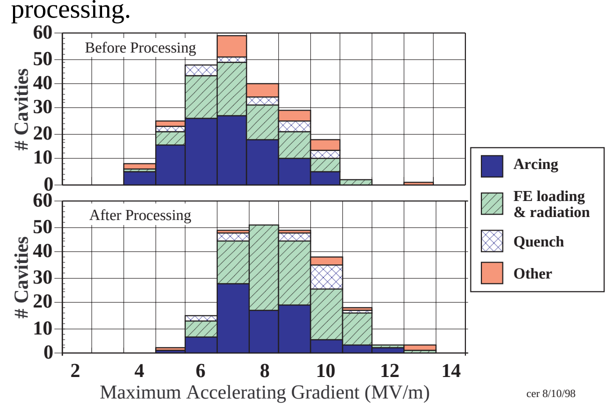

Figure 2. Change of limitations with processing.

Helium processing and requalification of cavities have increased the available installed CEBAF voltage by 155 MV, corresponding to an added 775 MeV for five-pass beam. At this rate we project an additional 55 MV gain from processing the balance of the machine, which would be adequate for extending the energy reach of CEBAF above 6 GeV. Figure 3 presents the present voltage capacities of the 41 CEBAF cryomodules.

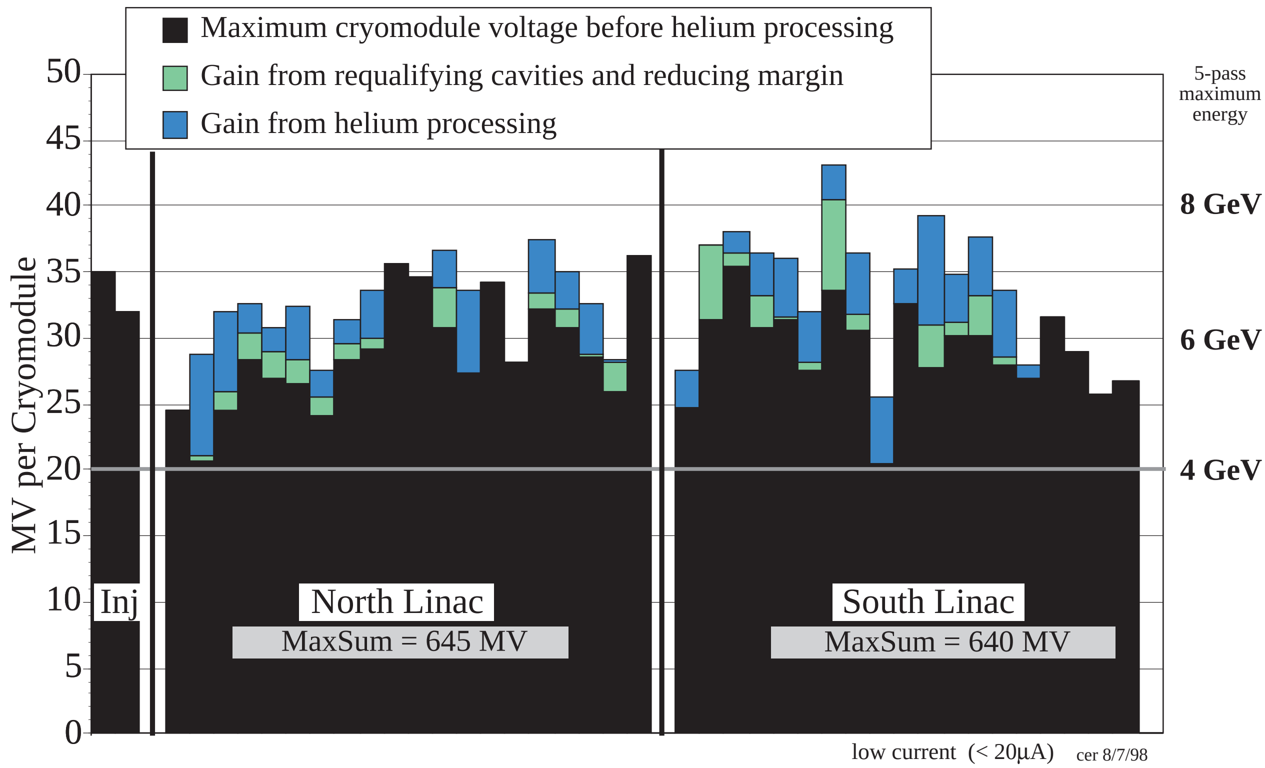

Figure 3. Maximum SRF Cavity Voltage per Cryomodule in CEBAF.

The distribution of present cavity performance limits is discussed in another contribution to this conference.[5]

5 UPGRADE PLANS

Beyond the virtually complete improvement to 5.5 GeV, upgrades to several arc dipole power supplies are being implemented in order to handle 6 GeV beam. Realization of this energy is planned for 1999.

Plans are presently being developed for a possible upgrade of CEBAF to 12 GeV. The most economical route includes the construction of new 80 MV cryomodules to populate the ten slots left empty by the early design switch for CEBAF from a four- to five-pass machine. Such new cryomodules will have improved filling factor by incorporating seven-cell rather than five-cell cavities, and take advantage of the process improvements in SRF technology of the last decade.[6]

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