

## SRF CHALLENGES FOR IMPROVING OPERATIONAL ELECTRON LINACS\*

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### Abstract

The performance of the operational SRF-based electron linacs CEBAF, ELBE, and S-DALINAC continues to evolve positively. These facilities are exploiting opportunities to improve operational capability by both remediation of past limitations and also construction of new capacity using state-of-the-art designs and processes. A project to rework the weakest ten cryomodules in CEBAF was completed and enabled robust operation for physics at 6 GeV. The 12 GeV Upgrade of CEBAF is now underway and involves construction of ten new CW >100 MV cryomodules with 80 new 7-cell low-loss cell shaped fine-grained niobium cavities, all electropolished. The technical challenges associated with the preparation of these cavities will be reviewed and their performance in both individual acceptance testing and cryomodule testing to date will be summarized. The ELBE facility at Helmholtz Zentrum Dresden Rossendorf continues to develop its source with an SRF gun system. The long-running S-DALINAC at Technische Universität Darmstadt is operating reliably and is evolving in the direction of reduced energy spread and use of polarized electrons for nuclear physics and astrophysics research.

### CEBAF

#### Historical Context

The construction requirements for a 4 GeV CEBAF in 1987-1993 required 42 cryomodules each providing 20 MV net from eight 0.5 m 5-cell 1.497 GHz niobium cavities. While initial performance requirements were met from the start, the interests of the physics community have maintained pressure to provide the highest 5-pass energy possible for nuclear physics research, well beyond initial specifications. By 2002 CEBAF was operating reliably at up to 5.75 GeV. In 2003 CEBAF performance suffered following an uncontrolled warm-up caused by loss of site power due to Hurricane Isabel.[1] At this time planning was already underway for a project to upgrade CEBAF to 12 GeV. The project, described more below, was to involve population of ten empty zones with a new, higher-capacity cryomodule design. A need existed to strengthen the energy base provided by the original set of cryomodules.

While two cryomodules had small helium leak issues, the principal performance limiting phenomenon was derived from internal field emission from particulate

contamination un-removed by the cavity processing methods available circa 1991. Extended operation under field emission conditions produced electrostatic charging of the 2K ceramic rf window on each cavity, which in turn produced an operationally-limiting phenomenon of periodic arcing and the attendant beam delivery interruption.[2] In 2006, a cryomodule refurbishment project was launched to rework the ten weakest cryomodules in order to provide a reliable 6 GeV base for the then-future 12 GeV Upgrade Project. Since the operational target for each cavity in the reworked modules was 12.5 MV/m, the objective for each module was 50 MV, thus the label C50. [3]

#### Scope of the C50 Project

During the refurbishment process, each cryomodule was disassembled and its cavities removed and subjected to improved processing techniques. The input rf waveguide assembly was redesigned to include a “dogleg” in the waveguide section internal to the helium vessel. The original polyethylene warm RF window outside the cryomodules was replaced with an improved ceramic model. Improvements were made to the mechanical tuners to reduce backlash. Components that were subject to mechanical wear or radiation damage over the years were replaced as well.

In order to eliminate potential vulnerability to hydrogen-induced  $Q$  disease, the cavities were vacuum heat treated at 600°C for 10 hours. After a fresh tuning, the cavities were subjected to a 30  $\mu\text{m}$  acid etch followed by high pressure rinsing with ultra pure water, both within a class 100 cleanroom. These processes were designed to greatly reduce particulate contamination on the surface of the cavities and as a result effectively eliminate field emission. As a further safeguard against operational interruptions from arcing, a replacement dogleg waveguide section was designed to reduce or eliminate this type of arcing behavior by eliminating the line of sight from the cavity interior, and generated electrons, to the cold window. (See Figure 1.)

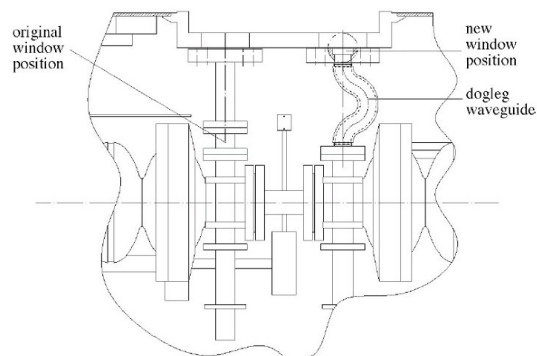


Figure 1: Coupler modifications.

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Secondary electrons induced by field emission would not be able to directly impact on the cold ceramic window thus significantly reducing vulnerability to any charging.

### C50 Performance

Following the rework, cavity performance increased markedly. Prior to rework, the operational performance of over 90% of the cavities was limited by the periodic arcing phenomenon. After rework and reinstallation in CEBAF, none of the cavities have evidenced such arcing. All of the reworked cavities are limited either by quench limits derived from original fabrication defects or available rf power. While most of the cavities were capable of supporting higher fields, a few even to 20 MV/m, the CEBAF rf systems support only up to 13.5 MV/m. During the rework process cryomodules were cycled out and back into CEBAF such that two cryomodule zones at a time were empty, temporarily further reducing the energy capability of the machine. A further operational constraint was keeping the total voltage of the north and south linacs roughly balanced during the intervening physics runs. Figure 2 shows the demonstrated operational beam voltage capacity of the ten C50 cryomodules before and after rework.

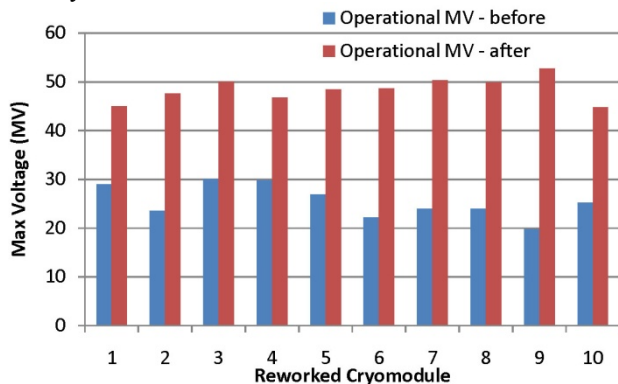


Figure 2: Maximum voltage from C50 cryomodules before and after rework.

Figure 3 illustrates the recovery and stabilization of the CEBAF maximum energy between 2007 and 2009. At the end of this period, CEBAF was running reliably at 6 GeV, limited there, not by SRF systems but by beam transport capacity.

While the gradient performance of the cavities was excellent, the  $Q_0$  and thus the 2K dynamic heat load was not. Although individual cavity tests in vertical cryostats demonstrated BCS-limited  $Q$ 's, all cavities showed significantly lower  $Q$ 's after assembly into cryomodules, very similar to their low-field performance in original construction. Such low  $Q$ 's had historically been attributed to  $Q$ -disease and contamination. Now, unfortunately belatedly, it was demonstrated to be something that was environmentally induced, presumably by inadvertent magnetic fields. During the rework of the last few of the C50 cryomodules attempts were made to add or reconfigure magnetic shielding in ways that protected the cavities, but ultimately these changes

resulted in no improvement of  $Q$ 's in the completed cryomodules.

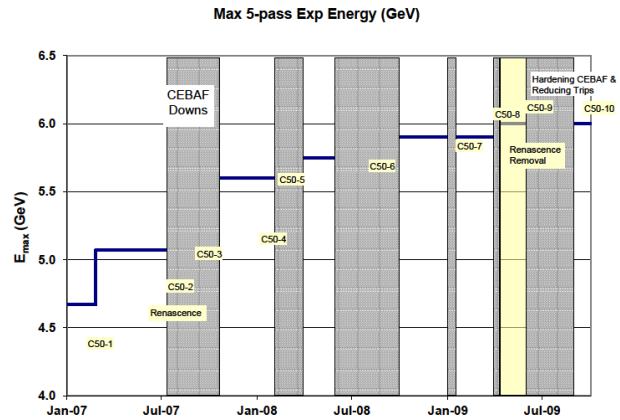


Figure 3: Evolution of CEBAF maximum energy during the C50 rework project.

This behavior is well illustrated by the data for cavity IA-085 in Figure 4. While the field capability of the cavity was significantly increased by reprocessing, after assembly into a cryomodule, the  $Q$  of this cavity returned to its prior value.

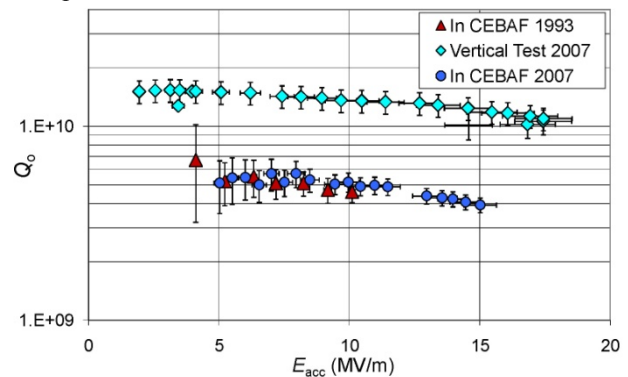


Figure 4: Vertical test vs. cryomodule test of IA-085.

The net result of these persistently low  $Q$ 's is to roughly double the 2K dynamic load for a 50 MV cryomodule from 100 W to ~190W. Further investigation and remediation is anticipated when, after the 12 GeV Project is completed, attention returns to maintenance rework of the original set of cryomodules.

### Renascence Cryomodule

As preparation for the 12 GeV upgrade, a series of prototypes were developed and operated.[4] The final one of these prototypes was called *Renascence*. [5] This module contained two styles of cavities designed and fabricated at JLab. It also included some alternate design elements in its cavity tuning system. This cryomodule provided a series of unique learning opportunities which have been documented elsewhere, from helium vacuum leaks via instrumentation feedthroughs, to thermal stabilization of HOM pickup probes, to multi-pass beam breakup (BBU) created by weak damping of a couple of dipole modes in one cavity [6,7], to evaluation of an alternate cavity tuning system.

Detailed investigation of the cause of the BBU in CEBAF enabled us to develop a thorough QA test for each cavity during its individual vertical cryostat performance test. A mode survey is employed for each cavity to screen for fabrication anomalies which result in tilted field profiles which in turn leave transverse modes with significant shunt impedance with too-high loaded- $Q$  and inadequate damping.

### Improved Cavity Design and Process

For the 12 GeV project, refinements were made to the cavity design, while keeping the low-loss cell shape. [8] To ease fabrication and tuning, the stiffening rings between cells were eliminated from the design.

Independent of the 12 GeV Project, a set of eight cavities was fabricated in-house to the upgrade design. Sensitized to the possibility of weakly coupled HOMs due to fabrication tolerances, dimensional and tuning effects were tracked in detail through the fabrication of these cavities and coordinated with 3D rf modelling. An excellent detailed review and refinement of fabrication control techniques for multicell cavities was completed by F. Marhauser. [9]

We refer to these cavities as R100-1 through R100-8. These cavities were then used to exercise preparation procedures to be used by the 12 GeV Upgrade Project. Learning from both research on the electropolishing of niobium [10,11] and the on-going practical experience from the ILC cavity high-gradient program, [12] we selected a candidate efficient compromise protocol. Previous experience showed that whatever benefit that EP provides over BCP accrues in less than 30 micron incremental removal. For both the R100 cavities and the subsequent C100 cavities for the 12 GeV project, the following preparation protocol was used:  $\sim 160$   $\mu\text{m}$  etch by BCP @  $10^\circ\text{C}$ , 600C vacuum heat treat for 10 hours for hydrogen degas, 30  $\mu\text{m}$  electropolish with cavity temperature regulated to  $20^\circ\text{C}$ , two cycle high pressure rinse with ultra-pure water, and 24 hour bake at  $120^\circ\text{C}$  under vacuum after assembly. Because the stiffening rings used on the initial LL-type cavities were dropped from the design, the upgrade style cavities have significantly greater vulnerability to mistuning by simple handling procedures, in addition to susceptibility to microphonics. To deal with the former, cavity cradling fixtures are now used during all transport.

After assembly of the complete R100 cryomodule, it was given its acceptance testing in the JLab Cryomodule Test Facility (CMTF) April-May 2011. The static cryogenic load to the 2 K circuit was 22 W and 240 W to the 40 K intermediate circuit. Figure 5 shows the performance of the cavities during this test. Note that this calorimetric  $Q$  measurement includes the dynamic losses associated with the copper-plated waveguide transition between room temperature and the 2K cavity, so is necessarily less than the cavity would be alone. This module is the best performing CW cryomodule yet produced by Jefferson Lab.

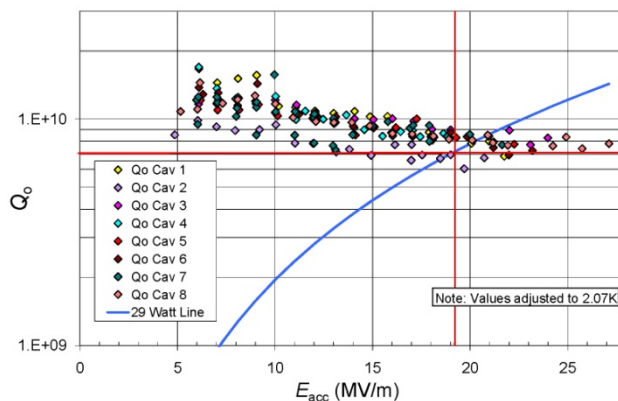


Figure 5: Initial performance test of the cavities in cryomodule R100.

### 12 GeV Upgrade Cryomodules

The current top priority for the nuclear physics research program in the U.S. is the completion of the CEBAF 12 GeV Upgrade Project. This project is well underway, and in addition to a new experimental hall, upgrade of many magnets, and installation of an additional recirculation arc, includes construction and commissioning of ten new cryomodules. The design of these modules has been previously described. The batch of 80 required 7-cell 1.497 GHz cavities plus 6 spares have been procured from Research Instruments. Processing and assembly of the cavities began at JLab in August 2010.

To provide additional performance margin, the project accepted the adoption of light electropolish as applied to the R100 cavities as the final surface treatment of the fine-grain niobium cavities. A structured production process was put in place, and the construction of cavity strings, followed by completed cryomodules was begun. At the time of this conference, cryomodule C100-1 is nearing completion of its acceptance testing, C100-2 is about to begin its acceptance testing, and assembly of the following two cryomodules is in progress. 60 of the cavities have received their final electropolish treatment and 33 have been welded into their helium vessels and received individual performance testing in the Vertical Test Area (VTA). See the contribution to this conference by Reilly et al. that describes the cavity preparation and testing process. [13] No significant issues have been encountered with either field or  $Q$  performance of the SRF cavities. Three cavities did require additional HPR to remove contamination that produced field emission-induced limitations. As a CW accelerator, the integrated cryogenic load is a primary constraint. The 2K dynamic heat budget for each cavity is 29 W. In the most optimistic situation, the highest usable gradient for the upgrade cavities in CEBAF will be 25 MV/m. The project requirement is 19.2 MV/m average. All cavities have met the performance requirements individually.

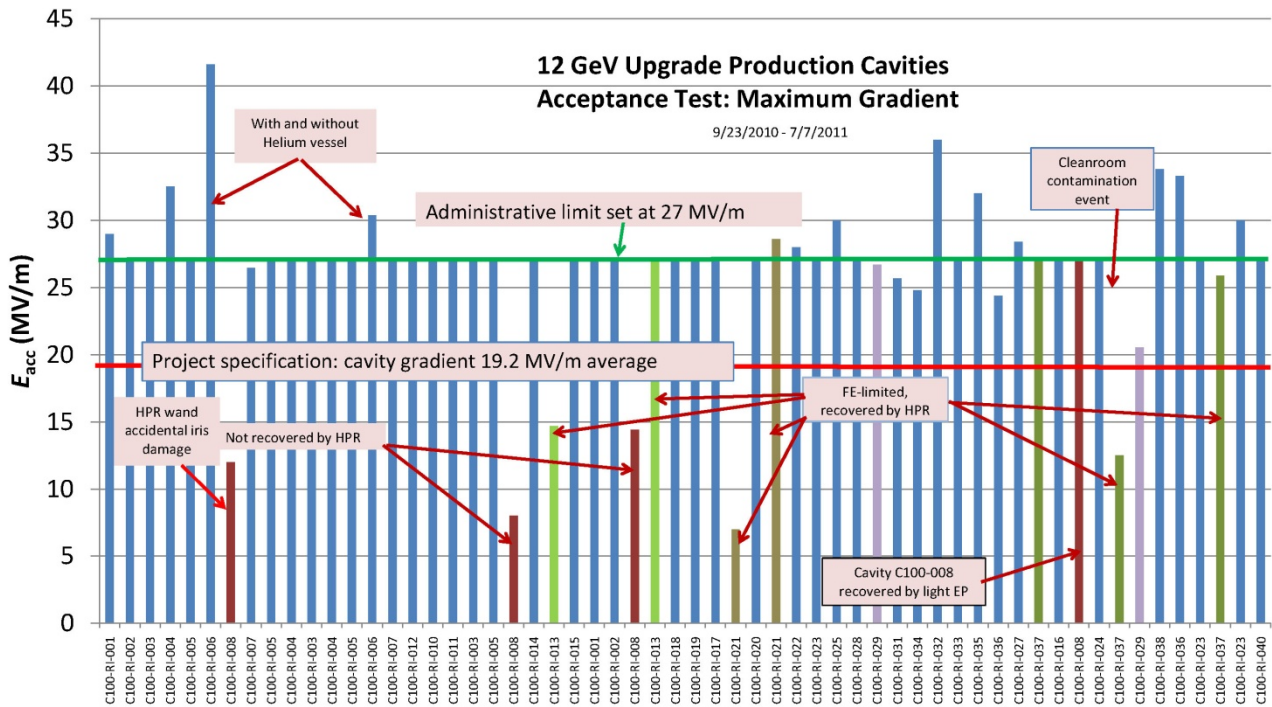


Figure 6: Performance of C100 cavities to date in individual acceptance testing.

In order to avoid taking on non-beneficial risk, performance testing of the cavities is often stopped at 27 MV/m even though the cavity limitation has not been encountered. Technological methods now predictably exceed gradient requirements. This circumstance appears to be new to the SRF community. This long-sought goal has largely been achieved for cw applications. The streamlined process is now demonstrated to provide more than adequate performance, as illustrated by cavity C100-6 in Figure 7. (The technological goals of pushing implementation costs and cryogenic loads down yet remain for the foreseeable future.)

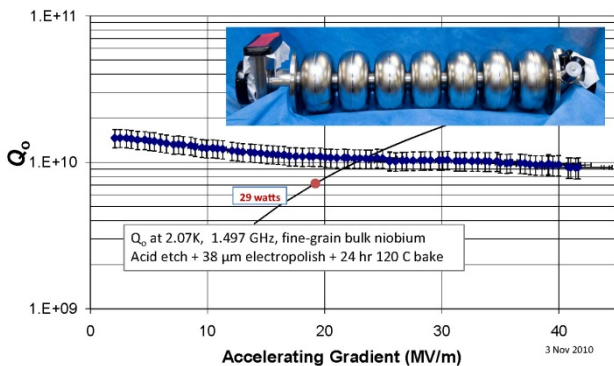


Figure 7: Production test of cavity C100-06 following standard preparation.

One cavity, C100-08, was accidentally scratched on multiple irises by misalignment with the high pressure rinse wand. Performance was fully recovered, however, after a 30 μm EP. Facility service interruptions due to the construction of the adjoining Technical and Engineering Development Facility (TEDF) [14] have added challenges

to maintaining a construction schedule and strong quality assurance. We look forward, though, to occupying new facilities in 2012.

Figure 8 shows the performance in helium vessels of the set of cavities that were subsequently assembled into C100 string number 3. All cavities performed well above requirements.

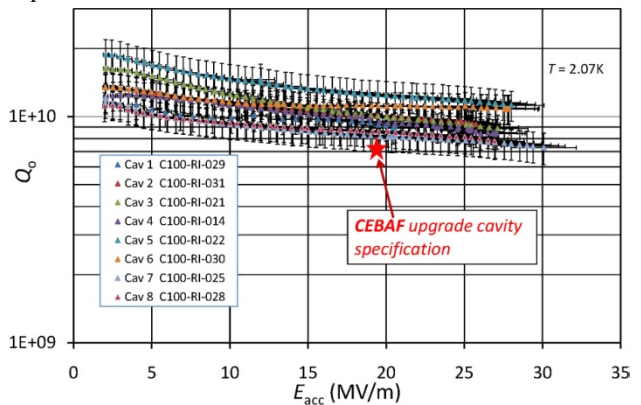


Figure 8: Vertical test performance of the C100 cavities for cryomodule number 3.

### C100-1 CM Performance

When the R100 and first C100 cryomodules were undergoing initial testing, a relatively high level of microphonic response was noted. For some of the center-most cavities, the 5 Hz rms detuning budget was fully consumed. Figure 9 illustrates the relationship between total allowed detuning, cavity loaded- $Q$ , and maximum operable CW gradient of the C100 cavities with the design beamloading of 460 μA and specified 12 kW rf available. The loaded- $Q$  of the cavities is  $3.2 \times 10^7$ . For the detuning budget, it has been assumed that the noise is

random and Gaussian, and that control to 6 sigma is required.

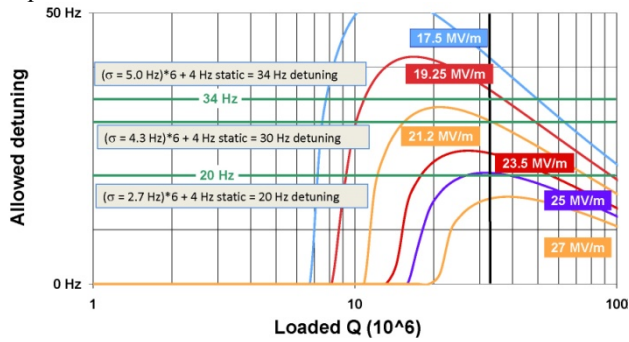


Figure 9: Contours of supportable detuning with 12 kW of available rf power and several different operating gradients.

While thorough characterization is ongoing, a distinct pattern in the harmonic content of the detuning spectrum of each cavity was observed, with dominant response in the 10-12 Hz, 20-24 Hz, and 43-45 Hz bands. See Figure 10. That the cavities on each half of the cryomodule appear to have independent microphonic coherence is taken as a clue that the vibrational modes involved are largely those of a half-cryomodule assembly. The cryomodule mid-point is by design fixed point, a node for longitudinal motion.

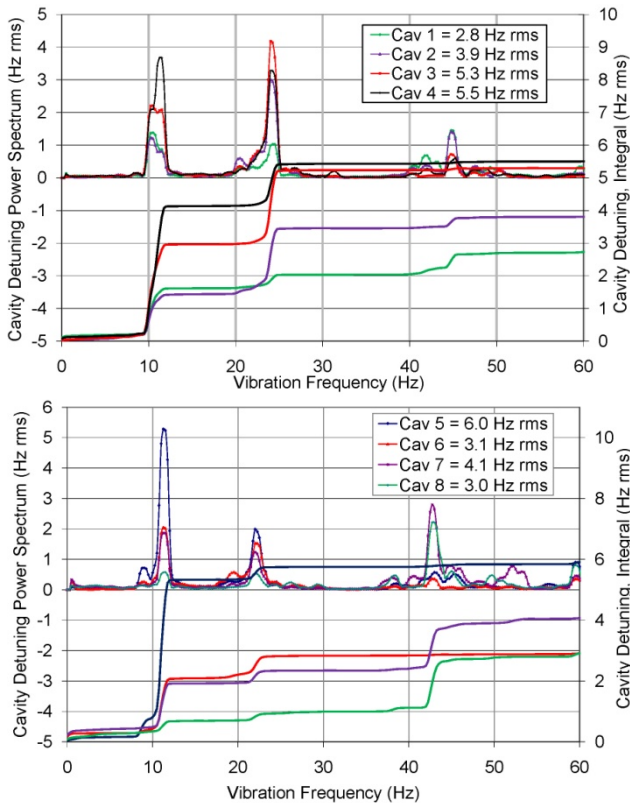


Figure 10: Harmonic content of microphonic detuning of the cavities in cryomodule C100-1 during initial testing June 2011.

Impulse response and FEA analyses appeared to associate these frequencies not with individual cavities, but with larger-scale vibrations of the cold mass. Further analysis and mitigation continues. When concern arose over microphonics, the assembly of cavities into helium vessels was temporarily suspended in order to retain opportunity to add transverse mechanical supports for the cavities should such be needed. Subsequent analysis indicated that the microphonic response was principally longitudinal and welding of helium vessels is expected to resume soon.

Acceptance testing of cryomodule C100-1 has just begun. Cavity performance testing is scheduled to begin during the conference. The 12 GeV Upgrade Project calls for the installation of the first two cryomodules into CEBAF by October 2011. The remaining cryomodules will be assembled and tested by middle of 2012, ready for installation into 2013.

## ELBE

The Electron Linac for beams with high Brilliance and low Emittance (ELBE) at Helmholtz-Zentrum Dresden-Rossendorf uses four TESLA-style 1.3 GHz cavities in two cryostats to provide multiple secondary beams, both electromagnetic radiation and particles. All four have been operating since 2005. Performance has been limited to 8-9 MV/m by field emission loading.

Recent efforts have concentrated on development and use of a superconducting rf gun. Progress with the Cs<sub>2</sub>Te photocathodes has yielded QE of 1-2% and long lifetime (>34.3 C extracted). The SRF gun cavity has had a maximum peak field of 16 MV/m, yielding a 3 MeV exit beam energy. Since the cavity gradient strongly influences the beam quality and supportable maximum bunch charge, there is great interest in developing a higher field cavity. A collaboration was established with Peter Kneisel at Jefferson Lab to fabricate two new SRF gun cavities, one made from high RRR fine grain Nb and the other from large grain Nb stock. The fabrication and testing of these cavities is reported at this conference. [15] See Figure 11.



Figure 11: SRF gun cavities for ELBE.

ELBE has also successfully deployed an array of solid state amplifiers to provide two 10 kW sources that have been in operation since 2010.

### S-DALINAC

The superconducting Darmstadt electron linear accelerator S-DALINAC was put into operation in 1987. It consists of ten superconducting 20 cell niobium cavities, operated at 2 K at a frequency of 2.9975 GHz. With a design accelerating gradient of 5 MV/m and a design quality factor of  $3 \times 10^9$  in cw operation, the final energy of the machine is 130 MeV. From the beginning, the cavity  $Q$ s have fallen short of the design expectations, with the result that the available cw beam energy, currently 85 MeV, is constrained by cryogenic capacity.

Extended 800°C baking of the cavities in the UHV furnace relocated from University of Wuppertal resulted in increased  $Q$ s for seven of the cavities from  $8 \times 10^8$  to  $1.5 \times 10^9$ , still less than what is desired, but adequate to increase the linac voltage. [16] Residual magnetic fields are a candidate cause for the observed high residual resistivity.

Cold leaks were encountered after cavity-to-coupler flanges had been disassembled many times and thermally cycled. The Helicoflex® gaskets were replaced with slightly larger thickness gaskets as a successful accommodation.

To reduce the heat load radiated via the input waveguides, new custom sections with radiation baffles are being developed. In other developments, component testing continues with cold piezo tuner work and OST instrumentation for quench location detection. [17]

Upgrades to S-DALINAC are underway 2011-2013. A third recirculation path will be added in order to reach the design energy, and other enhancements are aimed at improving beam energy definition and control.

### ACKNOWLEDGEMENTS

Mike Drury served as the project manager of the C50 project, and Kirk Davis is the source of all microphonic characterization measurements at JLab. Many other members of the Jefferson Lab staff also made numerous vital contributions to the JLab work summarized here. Jochen Teichert provided information regarding recent ELBE activities, and Ralf Eichhorn provided information on progress at S-DALINAC.

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