JLAB CW CRYOMODULES FOR 4TH GENERATION LIGHT SOURCES*

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Abstract

Fourth generation light sources hold the prospect of unprecedented brightness and optical beam quality for a wide range of scientific applications. Many of the proposed new facilities will rely on large superconducting radio frequency (SRF) based linacs to provide high energy, low emittance CW electron beams. For high average power applications there is a growing acceptance of energy recovery linac (ERL) technology as the way to support large recirculating currents with modest RF power requirements. CW SRF and high current ERLs are two core competencies at Jefferson Lab. JLab has designed and built a number of CW cryomodules of several different types starting with the original CEBAF design, with variations for higher current in the two generations of JLab's free-electron laser (FEL), through two intermediate prototypes to the final high-performance module for the 12 GeV upgrade. Each of these represent fully engineered and tested configurations with a variety of specifications that could be considered for possible use in fourth generation light sources. Furthermore JLab has been actively pursuing advanced concepts for high-current high-efficiency cryomodules for next generation ERL based FEL's. These existing and proposed designs span the range from about 1mA single-pass to over 100 mA energy recovered current capability. Specialized configurations also exist for high-current non-energy recovered sections such as the injector region where very high RF power is required. We discuss the performance parameters of these existing and proposed designs and their suitability to different classes of fourth generation light sources.

INTRODUCTION

JLab has been a pioneer of large scale CW SRF and ERL technology for many years starting with the CEBAF 5-pass recirculated linac [1], the 1-cryomodule energy recovered FEL demonstrator [2], the 1 GeV energy recovery experiment in CEBAF [3] and most recently the 3-cryomodule energy recovered 10 kW FEL facility [2]. These machines have been enabled by JLab's core competency in CW SRF cavity and cryomodule design, construction and operation. CEBAF contains 42 in-house build 8-cavity cryomodules that have been operating since 1995. This installed base represents 35% of the world's accumulated experience with CW SRF. This technology was subsequently adapted for use in the energy-recovered FELs at ten times higher current.

*Work supported by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177.
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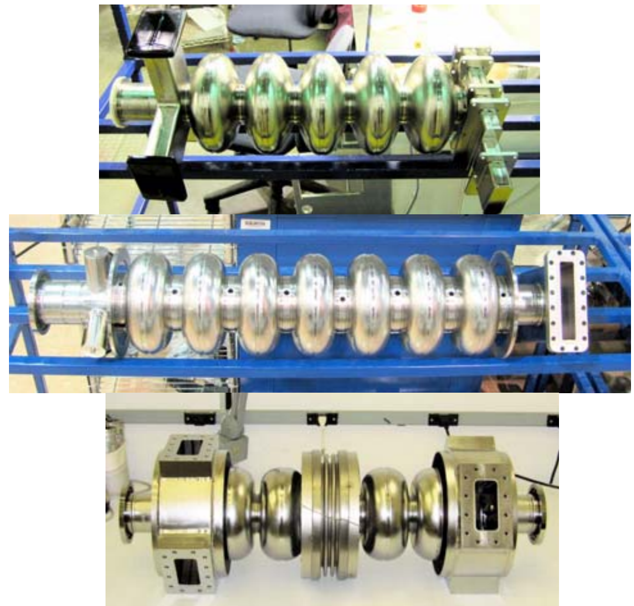


Figure 1: (Top) CEBAF 5-cell cavity, (middle) upgrade 7-cell cavity and (bottom) high current 5-cell cavity.

More recently a new cryomodule has been developed for the CEBAF 12 GeV upgrade [4] that has a higher packing factor, more active length, reduced coupler kicks and a higher operating gradient. Based on the success of the first two ERL machines JLab has also begun development of a next generation cavity and cryomodule design aimed at another factor of 10 increase in current to 100 mA [5]. This requires a quite different optimization than either the lower current 12 GeV module or the high-gradient pulsed ILC requirements.

LIGHT SOURCE REQUIREMENTS

Fourth generation light sources will deliver orders of magnitude higher brightness through multi-particle coherence, smaller source beam emittance, shorter bunch lengths and high average currents. All of these demands can be met using CW SRF-based linear accelerators. For modest average current but high bunch charge and extremely low emittance beams a single pass linac configuration can be used. For high currents, especially at high energy, an energy recovery configuration may be preferable. In the first case typical parameters are a few GeV, ~1 nC per bunch and repetition bunch rates in the 100 kHz to 1 MHz range. In the latter case average currents of up to 100 mA are proposed at lower charge per bunch. Both cases require CW RF and benefit from the efficient operation and large beam apertures afforded by SRF cavities.

Cavity design

CEBAF was built using five cell cavities of a classical elliptical design, with waveguide fundamental power couplers (FPCs) and HOM dampers (figure 2). This design was very successful, having no significant multipacting barriers below 20 MV/m, and has allowed CEBAF to meet or exceed all of the original design goals. Currents up to 0.5 mA CW and energies as high as 6 GeV have been demonstrated. This same cavity was adapted for use in the JLab FEL at currents up to ~10 mA using energy recovery in the linac. Principal modifications included stationing the waveguide HOM loads at higher temperature and fitting higher power windows in the injector module.

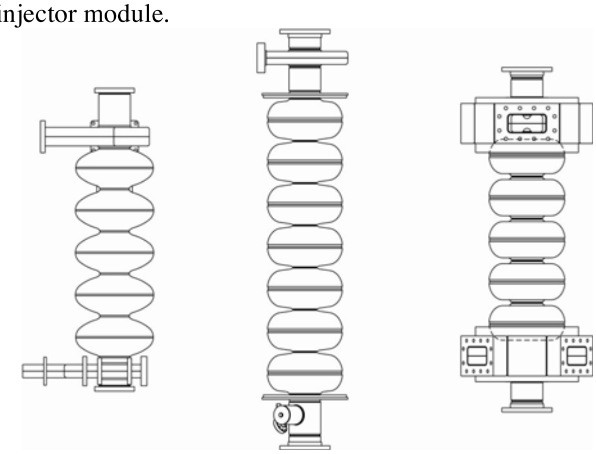


Figure 2: JLab CW cavities for (left) CEBAF, (center) 12 GeV upgrade and (right) high-current.

For the 12 GeV energy-doubling upgrade of CEBAF a new cryomodule has been designed. Cavities for this module have 7 cells and by eliminating bellows, valves and other beam-line components the overall packing factor has been improved significantly. This together with advances in SRF cavity preparation allowed the design goal to be increased to 100 MV/module, an average of 17.8 MV/m in the cavities. These cavities retain a waveguide FPC for up to 13 kW CW operation but adopted TESLA style HOM dampers, see figure 2. Three generations of upgrade style cavities have been developed during prototyping [6]. The first two used the original CEBAF (OC) profile but with 7-cells in the new configuration. These modules delivered 70 MV and 80 MV with beam respectively [7]. The third prototype "Renascence" tested two different cell shapes, a high-gradient shape (HG), with low Epk/Eacc and a low loss shape (LL), with high R/Q*G. In practice the low-loss shape worked as well as the high gradient one but with lower cryogenic losses so was adopted for the final upgrade design. With the aim of dual use in the FEL and CEBAF an attempt was made to increase the HOM damping in Renascence by adding additional HOM cans on the FPC end of the cavity. Unfortunately these changes led to increased end group heating which required modifications to the feedthrough, HOM probes and additional heat strapping to be implemented. Once these changes were implemented Renascence tested successfully [8] and has been installed in CEBAF. To avoid these issues in the 12 GeV project final design the FPC end HOM cans were deleted and the field-probe end HOM cans were redesigned for lower heating. Testing of a 2-cavity module in this configuration, code named C100, met all the 12 GeV design goals [9].

For future light source applications requiring higher current a different optimization is required. For such facilities beam stability is paramount so a high beam break up (BBU) threshold is desirable. Moreover with high beam currents the amount of HOM power extracted by the cavities can be substantial so HOM damping schemes suitable for high-power are needed. Broadband waveguide HOM dampers such as those used in CEBAF can easily propagate this power while acting as natural high-pass filters to reject the fundamental mode. Simple waveguide loads can readily handle the power from a 100 mA beam in a well-damped cavity. For the high-current case a new cell shape was developed, optimized for strong HOM damping, good operating efficiency and with strong HOMs placed at relatively safe frequencies to minimize power extraction from the beam [10].

Table 1: JLab 1497 MHz CW cryomodule parameters.

	CEBAF module	**C100 module**	**ERL† module**
Voltage	50 MV*	100 MV	80 MV
Length	8.5 m	8.7 m	8.5 m
#cells/ cav	5	7	5
Aperture	70 mm	53 mm	70 mm
Est. BBU	~25mA	1mA	100 mA
HOM Q's	10^3-10^5	10^5-10^7	10^2-10^4
RF Power	6.5 kW	13 kW	10-100 kW‡

* With original cavities [11]. †Using CEBAF type cryostat. ‡Depending on degree of energy recovery.

Cryomodule configurations

The original CEBAF cryomodule is a modular design in which pairs of cavities are assembled into separate cryounits that can then be combined with bridging rings to make larger modules. This method allows common parts and components to be used in short injector cryounits or full-length 8-cavity cryomodules. One advantage of this approach is that cavity pairs can be qualified in vertical test in their final configuration and then remain under vacuum during module assembly. In this case demonstrated performance has been shown to be maintained through module assembly to the final commissioning. One disadvantage is that some beam line length is consumed by valves and interconnects resulting in a lower overall packing factor. For the upgrade design the 7-cell cavities are assembled in a hermetically sealed string in the clean room without valves between them, allowing eight 7-cell cavities to occupy almost the same length as the original 5-cell ones, table 1. The cavities are supported by a space frame around the cold mass that is in turn suspended inside the cryomodule. The upgrade cryomodule uses a one-piece cylindrical vacuum vessel with penetrations for tuner, FPCs and instrumentation.

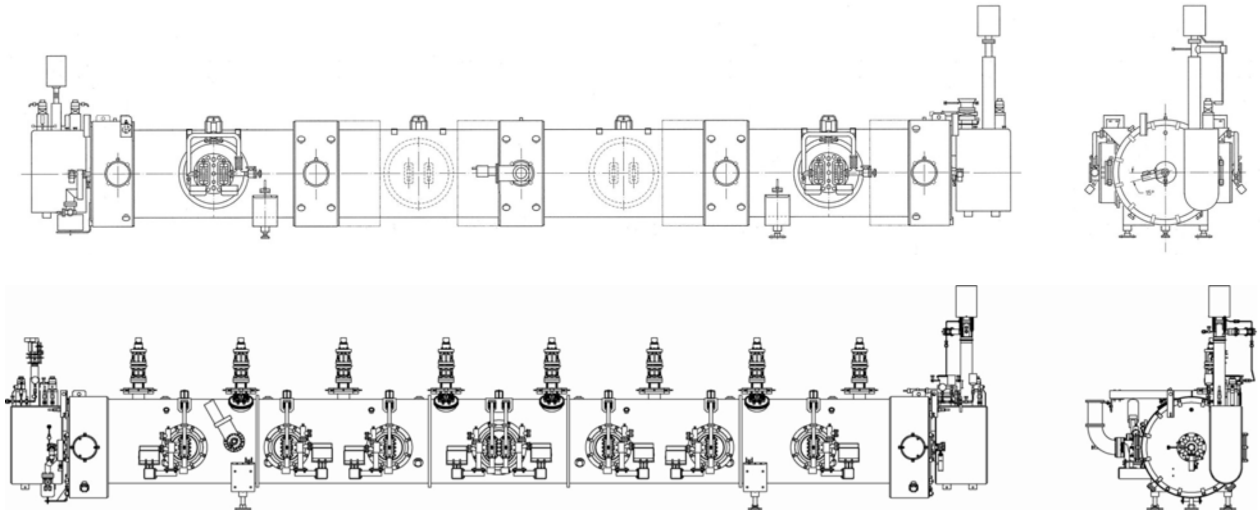


Figure 3: Original modular CEBAF cryomodule (top) and new 12 GeV upgrade design (bottom).

Helium vessels

In the CEBAF cryounits two cavities share a large common helium vessel. HOM loads, tuners and cold FPC waveguides are all contained in this volume and are immersed in superfliuid helium. This has the advantage of having a large helium inventory and good active cooling of all components but requires rigorous quality control on the many indium joints inside the vessel.

The upgrade cavities have individual helium vessels on each cavity and no helium to beam line vacuum flanged joints. However in this configuration the end group components are outside the helium vessel and are cooled only by conduction. Some problems with end group heating have been observed requiring additional thermal strapping to stabilize. For the new high-current module the cavities also have individual helium vessels but they wrap around the waveguide end groups providing active cooling but still with no internal flanged joints, figure 7.

Flanges and seals

The CEBAF cavities use indium seals on all cold flanges inside the helium vessel. These have proven to be very reliable providing that flanges are mechanically prepared and chemically cleaned according to a detailed set of procedures. Flanges between cryounits and other beam line components are CONFLAT™ type knife-edge seals. No RF impedance liners or gaskets are required at these low currents. The upgrade cavities use TESLA type AlMg crush seals on all round flanges within the cavity string and rectangular crush seals on the cold waveguide flanges. Inter-cavity connections use compact "radial-wedge" type flanges. Warm waveguide window seals are rectangular knife-edge types with copper gaskets. For the high-current cavities the final sealing technology has not been decided. The prototype cavities have been made with flat rectangular flanges that can use either indium seals or AlMg crush seals.

Tuners

The CEBAF tuners attach to the end cells of the cavities inside the helium vessels and are actuated by external motors via reduction gears and rotary feedthroughs, figure 4. This design does not consume beam line space however the rotary feedthroughs do have a finite service life. The original installations had significant hysteresis due to backlash in couplings but this has been effectively eliminated on refurbished modules. The upgrade prototype cryomodules have tested two new tuner types, a "scissor-jack" type, figure 5, that is very rigid, has practically no hysterisis and has a warm external motor, and a 'zero-length" rocker type, figure 6, that attaches to the helium vessels and has a cold motor and drive similar to the SNS type. Both mechanisms incorporate Piezo elements for fast tuning. Presently the scissor type tuner is the preferred choice for the upgrade cryomodules because of its ruggedness and serviceability. For the high-current cryomodules it is proposed to use a modified version of the rocker tuner actuating on the helium vessel to avoid interference with the waveguide end groups, figure 7.

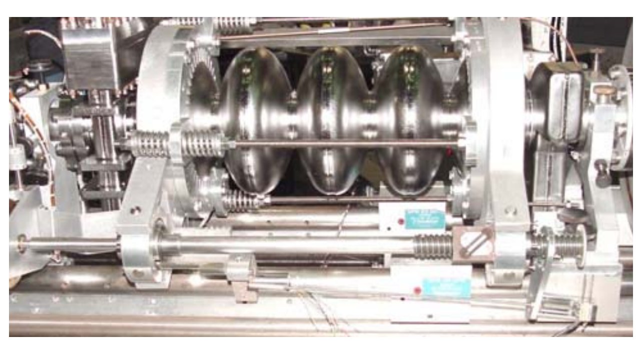


Figure 4: CEBAF in-helium cavity tuner mechanism.

Figure 5: Upgrade style "scissor-jack" tuner.

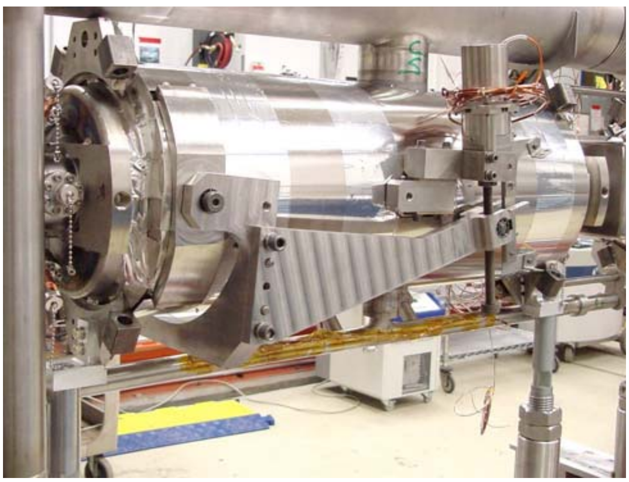


Figure 6: Upgrade style "zero length" tuner.

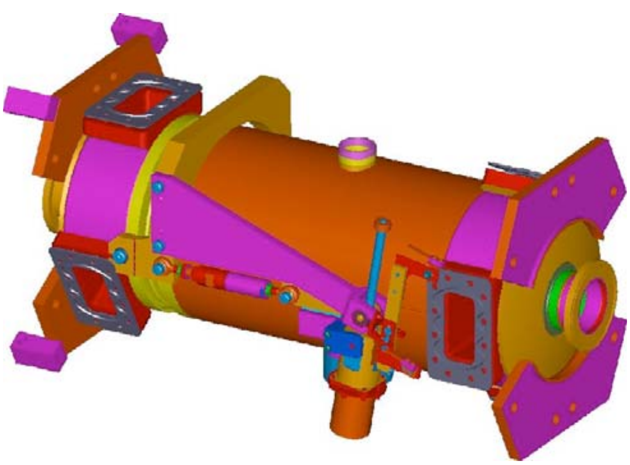
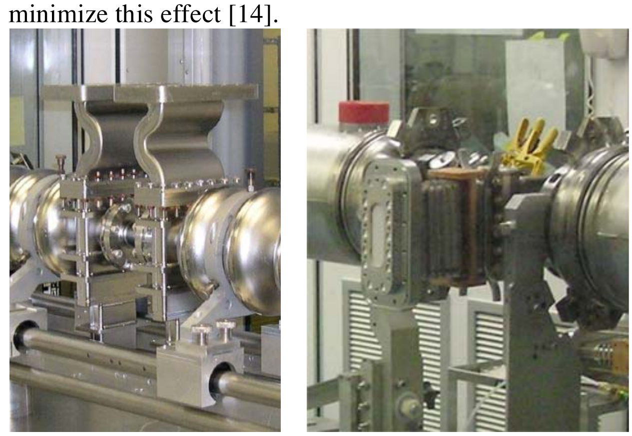


Figure 7: High-current cavity with helium vessel and "zero length" tuner.

Fundamental Power Couplers

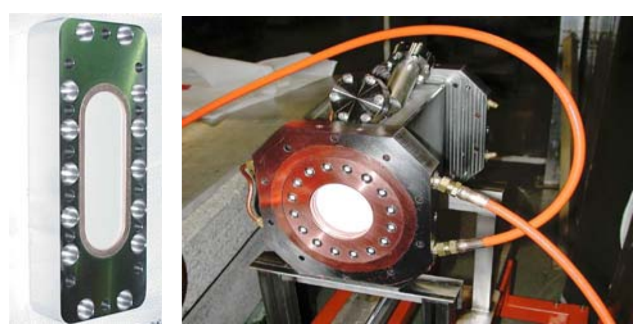
All JLab built CW cryomodules so far have used waveguide fundamental power couplers and windows. These are simple, compact, and offer high power-handling capability. The CEBAF modules used a cold waveguide window to enable pair testing without the need to break vacuum afterwards, and a warm window with an actively pumped connecting section. These are designed for up 6.5 kW CW forward power, although 50 kW versions were built for the FEL injector module. In the original configuration the cold windows suffered from charging and arcing due to interception of field-emitted electrons. This was subsequently eliminated on refurbished modules by installing "dog-leg" cold waveguides that eliminate line of sight between the ceramic and the beam pipe, figure 8a. In the upgrade modules the cold window is eliminated but the warm window is further from the beam line, figures 8b and 9a, and rated at 13 kW. A double warm window option has been developed after a window failure on the FEL prototype module caused a significant loss of performance in that module. No charging related window trips have been observed so far in the three upgrade prototype cryomodules. The high-current cryomodule is designed to use full height high-power warm waveguide windows of up to 100 kW capability, figure 9b, [12] with either tapered or dog-leg warm to cold waveguide transitions.

The CEBAF FPC's and waveguide HOMs introduced transverse deflecting kicks into the cavity fields [13]. This effect was mitigated by alternating the orientation in the cryomodule to cancel the effect to first-order. The upgrade and high-current cavities have been designed to minimize this effect [14].



a) b)

Figure 8: a) CEBAF dogleg FPC with cold window (left) and b) upgrade coupler with warm window (right).



a) b)

Figure 9: a) Improved upgrade warm window and b) high-power waveguide window for high-current module.

OPERATING EXPERIENCE

The CEBAF main linac has been operating for over a decade with very good reliability. The leading cause of downtime from the SRF part of the linac is due to field-emission induced cold window arc trips. This has been minimized by developing Fowler-Nordheim based trip rate models for each cavity and adjusting gradients for a minimum overall trip rate. However the phenomenon has been eliminated by the dogleg waveguides in refurbished modules and does not appear to be an issue in the upgrade style modules. The largest disturbance to operation of the linac was the power outage following hurricane Isabel in 2004 that caused the whole machine to be warmed up to ambient temperature [15]. This released a decade's worth of adsorbed gas and added an additional thermal cycle to all of the modules. One module was lost due to a leak from helium to the beam line as a result of thermal stresses on an indium seal and all the cavity trip rate models had to be rebuilt because of a strong randomization in field emission, but overall the loss in capability was surprisingly small. CEBAF running accounts for about 35% of the worlds accumulated SRF operating time (over 500 cryomodule-years of beam delivery). Jlab's FEL program has produced the world's highest power CW tunable laser, demonstrated stable energy recovery operation of a multi-cryomodule SRF linac and extracted the most usable charge from a DC/SRF photo-injector. The GeV-scale ERL experiment in CEBAF demonstrated the feasibility of a large scale energy recovered linac with a 50:1 energy ratio and plans are underway for a multi-pass energy recovery experiment.

CONCLUSIONS

JLab has a strong technology base in CW SRF and has designed and fabricated a large number of cryomodules of several different types. The original CEBAF modules have served as a 'workhorse" for physics for more than a decade with good reliability. The upgrade style modules offer a higher packing factor and higher cavity fields for more than four times the real-estate gradient of the original design. This module could be a building block for single-pass moderate current machines and will be in series production in a few years time. Based on this experience the proposed high-current design will offer good efficiency and stable high-current operation and would be a candidate for high-power ERL machines. A proof of principle design using 5-cell high-current cavities in an existing CEBAF cryostat has been proposed, that could be tested with beam in the JLab FEL. Subsequent to this an optimized cryomodule with improved packing factor and possibly more cells per cavity is planned. With these technologies in hand the future for fourth generation light sources has never looked brighter.

REFERENCES

[1] C.E. Reece, "Achieving 800 kW CW Beam Power and Continuing Energy Improvements in CEBAF, proc. LINAC 98.
[2] G. Neil, "High Power FEL Developments - A Review", invited Talk, proc. FEL 2007.
[3] A. Freyberger et. al., "The CEBAF Energy Recovery Experiment: Update and Future Plans", JLAB-ACP-04-283, DOE/ER/40150-2935, Proc. EPAC 2004.
[4] C. Reece, "A 100 MV cryomodule for CW operation", JLAB-ACC-05-03, Proc. SRF 2005, July 10–15, 2005, Ithaca, NY, USA.
[5] R. Rimmer et. al., "JLab High-Current CW Cryomodules for ERL and FEL Applications", JLAB-ACC-07-691, Proc PAC 2007.
[6] J. Sekutowicz et. al., "Cavities for JLab's 12 GeV Upgrade", Proc. PAC03.
[7] Anne-Marie Valente et. al., "Production And Performance of the CEBAF Upgrade Cryomodule Intermediate Prototypes", JLAB-ACC-04-19, Proc. EPAC 2004.
[8] C. Reece et. al., "Performance of the CEBAF Prototype Cryomodule Renascence", Proc. SRF07, Beijing, China.
[9] C. Reece et. al., "Optimization of the SRF Cavity Design for the CEBAF 12 GeV Upgrade", Proc. SRF07, Beijing, China.
[10] H. Wang, R. Rimmer, G. Wu, "Elliptical Cavity Shape Optimization for Acceleration and HOM Damping", JLAB-ACC-05-328, Proc. PAC 05.
[11] M. Drury et. al., "Performance of the First Refurbished CEBAF Cryomodule", Proc. PAC07.
[12] M. Stirbet et. al., "High power windows for WR650 waveguide couplers", JLAB-ACC-07-690, Proc. PAC2007.
[13] R.C. York, C. E. Reece, "RF steering in the CEBAF CW Superconducting Linac", Proc. PAC 87, p1307, Washington DC (1987).
[14] G. Wu, H. Wang, C. E. Reece, R. A. Rimmer, "Waveguide coupler kick to beam bunch and current dependency on SRF Cavities", Proc SRF workshop 2007, Beijing, China.
[15] R. Rimmer, J. Benesch, J. Preble, C. Reece, "SRF Performance of CEBAF After Thermal Cycle to Ambient Temperature", JLAB-ACC-05-347, Proc. PAC 05.