

PREPARATION AND TESTING OF THE SRF CAVITIES FOR THE CEBAF 12 GeV UPGRADE*

#A. Reilly, T. Bass, A. Burrill, K. Davis, F. Marhauser, C.E. Reece and M. Stirbet
Jefferson Laboratory, Newport News, VA 23606, U.S.A.

Abstract

Eighty new 7-cell, low-loss cell shaped cavities are required for the CEBAF 12 GeV Upgrade project. In addition to ten pre-production units fabricated at JLab, the full set of commercially produced cavities have been delivered. An efficient processing routine, which includes a controlled 30 micron electropolish, has been established to transform these cavities into qualified 8-cavity strings. This work began in 2010 and will run through the end of 2011. The realized cavity performance consistently exceeds project requirements and also the maximum useful gradient in CEBAF: 25 MV/m. We will describe the cavity processing and preparation protocols and summarize test results obtained to date.

INTRODUCTION

At Thomas Jefferson National Accelerator Facility (JLab), the accelerator portion of the Continuous Electron Beam Accelerator Facility (CEBAF) upgrade will be constructed within the framework of the existing CEBAF accelerator. Ten new higher-voltage cryomodules, five per Linac, will be added. Each cryomodule will consist of eight higher performing 7-cell cavities. The 12 GeV cavities have been supplied by Research Instruments (RI). In addition to fabrication, RI completes the bulk chemistry, removing 160 microns, and tunes the cavities to 1497 MHz with greater than 90% field flatness. A 12 GeV C100 cavity is depicted in Figure 1.



Figure 1: A 12 GeV C100 low-loss shape 7-cell cavity.

GROUNDWORK

Several months prior to receiving the first shipment of 12 GeV C100 cavities, a program was established to

define and practice the C100 cavity production process and RF test protocols on 7-cell low-loss shaped cavities. Pansophy based data travelers were used to capture all important process data and information [1]. Some production process steps were well established, others, such as electropolishing were not well defined. Over the course, close to 70 process and test procedures and data travelers were created and put into practice. All the documents were uploaded and made accessible through Pansophy. The proposed 12 GeV C100 cavity production process and qualification procedures were exercised full loop on 7-cell cavities for several process cycles.

Pre-Production Cavities

The process and test protocols were further validated and refined using the 7-cell pre-production cavities fabricated at JLab. The pre-production cavities, known as R100, were used to further refine the EP process, characterize the frequency shifts caused by handling and helium vessel welding, and to reduce the number of cold RF test required to qualify the cavities. The R100 and the 12 GeV C100 cavities do not have stiffening rings, which makes the cavities more vulnerable to incidental RF detuning. RF data was collected before and after each process step to characterize the amount of frequency shift due to deformation resulting from processing and handling. Fixtures and tooling were fabricated and procedures modified to minimize the handling and processing induced deformation. Additionally, a detailed characterization was conducted on the effects helium vessel welding had on cavity frequency. A robust welding procedure was developed and changes were made to the warm frequency target to offset the changes induced by helium vessel welding.

The R100 cavities were also used to understand how the presence of a helium vessel would affect qualification data collected during the vertical RF test. The eight R100 cavities were first RF tested without a helium vessel, then again with the helium vessel. The results of the comparison varied cavity to cavity. On average, the maximum gradient achieved and the Q_0 at maximum gradient showed no change within the error bars of the measurements. The same process of RF testing before and after the helium vessels were added was repeated on the first eight C100 cavities. The results were similar with the exception of cavity C100-6 which had a maximum gradient of 41.6 MV/m without the helium vessel and 30.4 MV/m with the vessel. The lower gradient is due to the 3-inch diameter helium vessel outlet port reducing the maximum heat that could be rejected from the cavity due to its inherent critical heat flux

*Work supported by DOE. Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.

#areilly@jlab.org

limitation (about 70W at 2.07K). The drop in gradient was not as evident in other cavities because their initial maximum gradient was close to the heat flux limitation. The data facilitated the decision to only conduct the vertical RF qualification test after helium vessels are welded on.

12 GeV CAVITY PRODUCTION AND QUALIFICATION

12 GeV C100 Cavity Process Steps

The experience gained as part of the program to define and practice the proposed C100 cavity process and test protocols resulted in the 12 GeV C100 cavity production and qualification process shown below. Details, including key process parameters, are given in subsequent sections.

- Receipt inspections – Dimensional and RF
- Ultrasonic clean
- Hydrogen degasification
- Electropolish
- Ultrasonic clean
- Tune
- Dimensional check
- Helium vessel welding
- RF check
- Final dimensional check and surface prep
- Ultrasonic clean
- High pressure rinse
- Partial assembly
- High pressure rinse
- Final assembly and leak check
- Low temperature bake
- Vertical RF test at 2.07 K
- High pressure rinse
- String assembly

Receipt Inspections

As part of quality assurance (QA) the cavities receive visual, dimensional and RF property inspections. Upon receipt, the C100 cavities are visually and dimensionally inspected in an as-received condition. The exterior of the cavity is inspected for scratches, pits, stains, dents, or any other forms of damage. Pictures of all the vacuum sealing surfaces and flanges are taken and uploaded to Pansophy. Following the visual inspection, the cavity is placed onto the Coordinate Measuring Machine (CMM) for dimensional inspection. Measurements are taken to verify the cell shapes, interface locations and straightness of the cavities are within tolerance. As an additional straightness check, a plastic coated plug gage is carefully lowered into the cavity. If this plug gage clears all of the cavity irises, the straightness is deemed acceptable. The cavity is then passed on for the receipt RF inspection.

The second part of the receipt QA is a verification of the RF properties. All seven passband frequencies are recorded and a bead-pull is performed at the resonant

frequency. The external Q of the fundamental power coupler is measured and verified to be within specification. The HOM filters are physically measured to ensure the feed-through probe tip will have the proper gap between tip and filter. If the filter is out of tolerance it is physically manipulated to meet specification. The data is recorded in a Pansophy traveler. If all acceptance criteria are met, the cavity is denoted as “accepted” and is then approved to proceed through the production process. Cavities that do not pass all the acceptance criteria are quarantined and marked as non-conforming. A non-conforming report (NCR) is written and routed to the respective owners for corrective actions. In some cases, the cavity is returned to the vendor for repairs. Once the NCR is cleared and the data demonstrates the quarantined cavity has met the acceptance criteria, the cavity is approved for production.

Hydrogen Degasification

In preparation for the hydrogen degasification, the cavities are ultrasonically cleaned in a heated solution of 60C ultrapure water (UPW) and surfactant. The standard hydrogen degasification process for C100 cavities was developed for use on the CEBAF C50 cavities. The cavities are heat treated in a vacuum furnace at 600C for 10 hours. The ramp rate for the vacuum furnace is 5C per minute. The total cycle time for the hydrogen degasification process is approximately 52 hours. In evaluating the cavity production throughput, the vacuum furnace was identified as a bottleneck. To alleviate the bottleneck, a cavity rack, made from molybdenum, was fabricated to hold up to three C100 cavities, which was calculated to be the maximum number of C100 cavities that could be effectively heat treated in the vacuum furnace simultaneously. Although the furnace has the capability to simultaneously treat three cavities, the current schedule requires two cavities be treated concurrently. The vacuum furnace hot zone and rack holding two C100 cavities is illustrated in Figure 2.

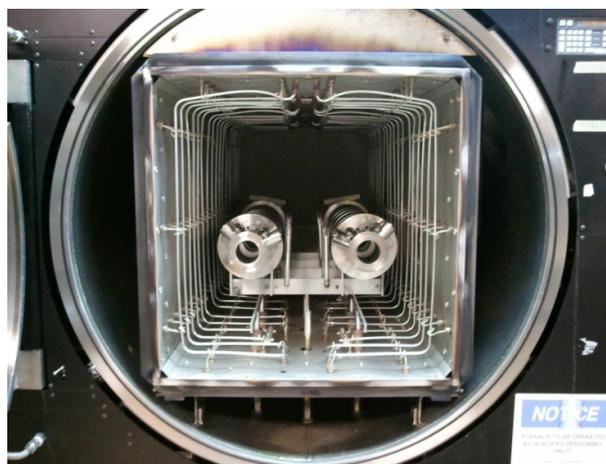


Figure 2: Two C100 cavities loaded into the hot zone of the vacuum furnace.

During the heat treatment cycle, the hot zone temperature, the vacuum pressure, and the partial pressure

of ten gases are continuously recorded. The data is electronically archived for each cavity heat treatment in the traveler. After the cavities have completed the hydrogen degasification process, they are progressed and prepared for electropolishing.

Electropolish

The standard electropolish process for C100 cavities was derived from processing experience gained and lessons learned from electropolishing 9-cell cavities as part of JLab's ILC program under the direction of R.L. Geng [1] and from research and development work done on small samples by H. Tian and C.E. Reece [2][3][4]. A depth of approximately 30 microns is removed by the EP process.

The cavities are electropolished in a horizontal orientation. The composition of the electrolyte is a 1:9 mixture of 49% hydrofluoric acid and 96% sulphuric acid. The electrolyte is introduced through an aluminium cathode. The cathode has distribution ports that coincide with the cavity cell equators, one port per equator, oriented upwards. The electrolyte level is maintained at slightly above the elevation of the cathode. The flow rate of the electrolyte is varied to maintain the level of the electrolyte. The inlet acid temperature ranges from about 14C to 20C and is controlled by a glycol chilled water circuit located in the acid sump. The voltage at the power supply is 13V to 15V. The cavity rotates at 1 rpm. Typical values for the average current density range from about 12 mA/cm² to 21 mA/cm². To maintain a uniform cell wall temperature, a spray cooling system was added. The cooling system maintains the exterior cell wall temperature at 20 C measured at the equators. The EP spray cooling system is shown in Figure 3.

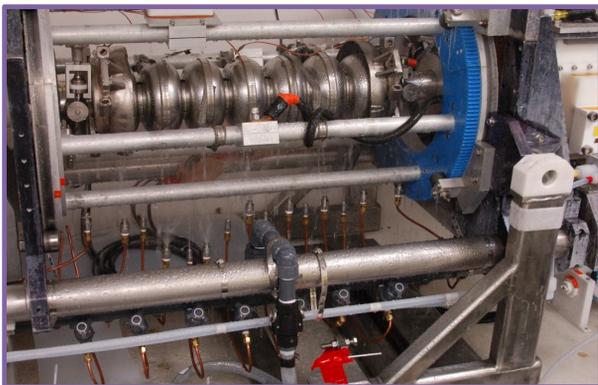


Figure 3: A 7-cell cavity being electropolished in JLab's horizontal electropolish tool. The spray cooling system maintains cell wall temperatures at approximately 20C.

Presently, there have been 77 EP cycles completed on 74 distinct 7-cell cavities at JLab. The EP process is stable and repeatable. A typical process parameter chart is illustrated in Figure 4. The chart shows the stability of the parameters over the duration of the active electropolishing. After electropolishing, the cavity is

rinsed with UPW for 1 hour and ultrasonically cleaned in a heated solution of 60C UPW and surfactant to remove precipitated sulphur. The cavity is then prepared for tuning.

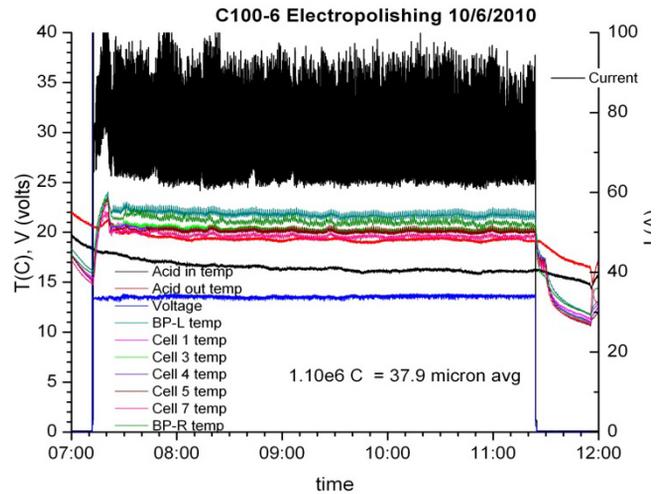


Figure 4: The process parameter chart for C100-6 showing the current, the power supply voltage, the temperature of the electrolyte at the inlet and outlet of the cavity and the temperature of 5 cell equators and each beam tube during processing. C100-6 had a pre-helium vessel maximum E_{acc} of approximately 42 MV/m.

Tuning and Dimensional Check

The cavities are tuned by mechanically deforming each cell to reach the desired overall frequency and field flatness. Tuning plates with a contour that matches the shape of a C100 cell wall are used with mechanical force to adjust the cell spacing to an overall target frequency of 1494.150 MHz \pm 50 kHz with a field flatness of greater than 90% field flat (normalized field \pm 5%). Additionally, field profiles for ten critical HOM frequencies are measured and recorded. Figure 5 shows a C100 cavity in the tuning bench.



Figure 5: A 7-cell C100 cavity in the tuning bench being tuned.

Once tuning is complete, the cavity is again checked for dimensional tolerance and straightness. On occasion, a

cavity will need to be manually straightened, and then re-tuned. In some instances it takes more than one cycle to bring a cavity to within both the tuning and straightness specifications.

Helium Vessels

The procedure for welding on the helium vessel was developed through a systematic process of measuring the changes in RF properties as components were added, tack welds made, and seam welds completed. The procedure was optimized to minimize the changes in RF properties. Once defined, the warm frequency target was adjusted to offset the expected changes due to welding. Prior to welding, the permeability of the stainless steel bellows, shell, heads, and tuner tabs are verified to be below the limit. The Kapton encapsulated resistance heaters are then installed and the components are assembled onto the cavity in the welding tack fixture (Figure 6). Tack welds are made as prescribed in the detailed procedure. The cavity is then removed from the fixture, placed horizontally, and pressurized to 1 atm with argon. The welds are systematically completed and the permeability of the completed vessel assembly is again verified. The helium vessel is leak checked under vacuum and passed on for a final dimensional and RF check prior to high pressure rinsing and assembly.



Figure 6: A C100 cavity in the helium vessel tack welding fixture.

High Pressure Rinsing and Assembly for RF Tests

High pressure rinsing (HPR) and assembly of the vacuum and RF test hardware is done in a clean room. Prior to entering the clean room, the jacketed cavity is ultrasonically cleaned. The high pressure rinsing and assembly is segregated into two phases of rinsing and assembly. The interior of the cavities are first high pressure rinsed by a set of spray nozzles attached to a wand which starts at the highest location in the cavity, and then traverses downwards along the centerline of the

cavity at a rate of 0.2 inches per minute. As the wand traverses, the cavity rotates at a rate of 2 revolutions per minute. Ultrapure water at approximately 1250 psig, measured at the HPR tool, is used at a total flow of about 2.3 gpm. After the first stage of HPR, the cavity is dried in a class 10 clean area over night. When dry, the HOM and field probe antennas, the fundamental power coupler top hat, and top beam pipe flange are assembled onto the cavity, leaving only the bottom beam pipe open. The partially assembled cavity then receives the second stage of HPR with the same set of rinse parameters. The cavity is again dried overnight, the bottom flange is attached, and the cavity is assembled into an RF test stand. In the stand, the cavity is slowly pumped down to a baseline vacuum pressure and then leak checked. If leak tight, the cavity is removed from the clean room and placed vertically into a dewar for cold RF testing.

VTA CAVITY QUALIFICATION

A significant component of JLab's SRF R&D activities is cavity testing and characterization. This is performed in the Vertical Test Area (VTA), a unique facility designed for testing and measurement of SRF cavities in superfluid helium. The VTA consists of eight dewars, six of which are fitted with movable radiation shields, which permit high power testing of cavities without personnel exposure to ionizing radiation. Cavities can be tested in the VTA at frequencies from 650 MHz to over 3 GHz at input power levels up to 500W. The VTA is shown in Figure 7.



Figure 7: VTA showing six dewars and radiation shields.

In addition to cavity testing, the VTA also supports other cryogenic tests of SRF-related components such as vacuum feed-throughs, mechanical and piezo-electronic tuner mechanisms, and material electrical and thermal characterization (e.g., thermal conductivity, RRR, and T_c measurements).

The VTA dewars are supplied with liquid Helium (LHe) from the Cryogenic Test Facility (CTF), which can supply the VTA with 4K LHe at the rate of about 250-300L/hr. Dewars are pumped to sub-atmospheric

pressures in order to achieve temperatures as low as 1.9K, using a vacuum pump with a capacity of about 7 g/sec. Multiple dewars can be pumped down simultaneously, in accordance with system capabilities (defined by vacuum pump mass flow limits). All helium used in the VTA is returned to the CTF where it is purified of any contaminants (most notably nitrogen) and re-liquefied.

The VTA dewars are instrumented with thermometers, LHe level sensors, and pressure transducers, and are controlled via interlocked electro-mechanical valves, which prevent damage to or contamination of the CTF helium supply. Some functions, such as dewar LHe filling, pumpdown, and warmup, are computer controlled, while others are performed manually. A complete test cycle for the larger (850 liter capacity) dewars can be accomplished (warm-to-warm) in 36 hours or less. Smaller dewars (100-200 liter capacity) can be cycled in about 18 hours. The combination of automated and interlocked control, along with efficient cryogen and thermal management, yields a facility with an SRF cavity test throughput unequalled anywhere in the world. Extensive descriptions for VTA facility can be found in several publications [7] [8] [9].

Upgrades were done in the VTA to better support the cavity qualification for CEBAF's 12 GeV upgrade project; a 500 W CW RF power amplifier replaced an existing 200 W amplifier, improvements were made to high-power and low power RF cabling, and the software for test control and data acquisition were updated to new requirements. Finally the cryogenic system was improved to increase efficiency and throughput to satisfy VTA production tests and R&D tests while simultaneously supporting cryomodule testing in the adjacent Cryomodule Test Facility (CMTF).

The qualification of C100 cavities for 12 GeV is done in the VTA as specified in the cavity process flow. Once the cavity is cooled down, low power RF tests (cable calibration and HOM survey) are done, followed by RF high power tests. These activities conform to well established procedures. The results are captured in travelers stored in the Pansophy system.

One of the prototype low-loss cavities tested in the VTA during the preparatory phase demonstrated that the cavity production process had the potential to produce cavities with maximum gradients well above the specifications. Repeated RF test on cavity LL02 showed cavity gradients in excess of 42MV/m. Similar results were achieved for a C100 production cavity, C100-6, pre-helium vessel (Figure 8).

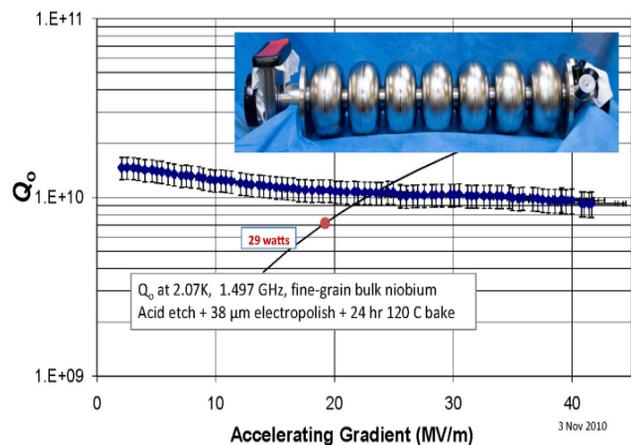


Figure 8: Q_0 versus E_{acc} (MV/m) curve for C100-6 pre-helium vessel.

For the 12 GeV upgrade, the project specification is 19.2 MV/m average, with 29 W average heat per cavity. The operational limit in CEBAF after upgrade to 12 GeV will be 25 MV/m, limited by klystron RF power. For qualification testing in the VTA, administrative limits were adopted for the first two cryomodules (to avoid any potential risk of cavity degradation from “pushing”):

- Limiting vertical cavity acceptance testing to 27 MV/m
- Vertical RF test only after HV is attached
- Helium vessel nozzle size limits heat load to ~70 watts @ 2.07 K

For the 12 GeV upgrade, about 20 VTA tests were done on R100 cavities, followed by more than 60 tests done on C100 production cavities. During tests, data are collected regarding HOM qualification at low temperature; cavity frequency, Q_0 , and radiation response as a function of cavity gradient; as well as Q_0 dependence of temperature. The measured Lorentz coefficient is used as a consistency check for gradient measurements.

Some unexpected issues that were dealt with successfully included: RF cables with unreliable connectors (break down after multiple cycle of cooling down, warming up), cryogenic RF cables with temperature (RF power) dependent electrical properties, several cavities plagued by superfluid helium leaks, and finally a few cavities were reprocessed to reduce field emission. (Figure 9). The consistently high RF performance produced by EP resulted in a much lower reprocessing rate than expected, making up for much of the time lost to unexpected issues.

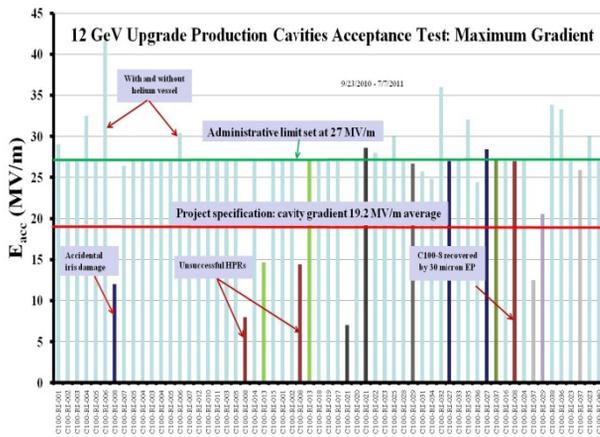


Figure 9: Maximum E_{acc} (MV/m) for C100 cavities. Cavity C100-RI-008 (red bars) had its irises damaged. The cavity was recovered after a second 30 micron EP.

Once the cavities are qualified in the VTA, they are staged for string assembly. Figure 10 summarises the values of Q_0 as a function of cavity gradient for the string of eight qualified cavities for cryomodule C100-3.

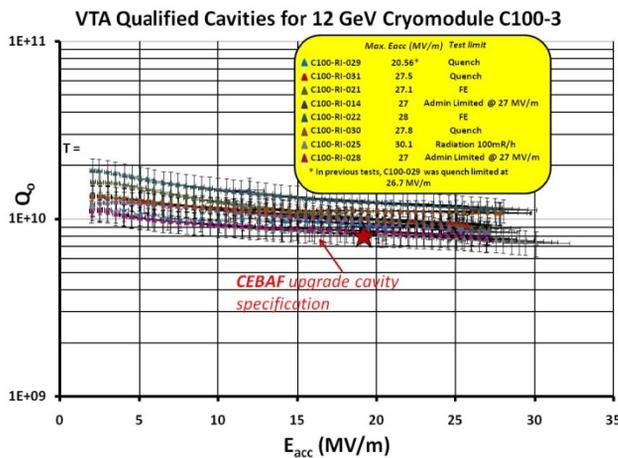


Figure 10: Q_0 versus E_{acc} (MV/m) for string C100-3.

String Assembly

The qualified cavities are staged in the clean room awaiting assembly into a string. String assembly is done in one continuous effort over one week. During the week, access to the clean room is restricted to string assembly and critical activities. For string assembly, the cavities are first high pressure rinsed and dried overnight in the class 10 area in the sequence they occur in the string. Prior to being placed on the rail system the beam lines are blanked off and the VAT valves, waveguides, and window subassemblies are assembled onto the cavities starting with the first cavity in the string sequence. As the cavities are assembled, they are placed onto the rail system. Once the eight cavities with subassemblies are placed onto the rail, all the beam line connections are

made to complete the string. Figure 11 shows a completed 12 GeV C100 cavity string.



Figure 11: A 12 GeV C100 cavity string.

SUMMARY

The production and qualification of the 12 GeV C100 cavities has been and continues to be successful. The process, procedures, and test protocols have proven to be efficient and robust, consistently yielding cavities that exceed the project requirements. To date, all cavities have been received and are progressing through QA. Approximately 60 of the 86 cavities have been electropolished. Thirty-two cavities have been qualified with a maximum accelerating gradient ranging from 24.8 MV/m to 42 MV/m with a mean of 27 MV/m, which is a consequence of the administrative RF test limits. The 32 cavities have been assembled into four strings and passed on for cryomodule assembly. There are 48 more cavities to qualify and six more strings to complete. The cavity production is scheduled to be completed in calendar year 2011.

ACKNOWLEDGEMENTS

The success of the 12 GeV C100 cavity production and qualification is credited to the JLab SRF expert team of technicians, scientist, and engineers who together have made many contributions through their dedicated efforts to achieve a robust repeatable production process resulting in high performing 7-cell SRF cavities.

REFERENCES

- [1] Valerie Bookwalter, Bonnie Madre, and Charles E. Reece: "Flexible Application of the JLab *Pansophy* Information System for Project Reports, Process Monitoring, and R&D Sample Tracking" in SRF 2007, Beijing, China, WEP49.
- [2] Valerie Bookwalter, Bonnie Madre, J. P. Ozelis, C.E. Reece: "The Use of Integrated Electronic Data Capture and Analysis for Accelerator Construction and Commissioning: *Pansophy* from SNS towards the

- ILC” in Proceedings of 2005 Particle Accelerator Conference, Knoxville, Tennessee, USA, RPPE062.PDF.
- [3] R.L. Geng. “Overviews of High Gradient SRF R&D for ILC Cavities at Jefferson Lab” Proceeding of SRF2009. Berlin, Germany, TUPPO015.
- [4] H. Tian, S. G. Corcoran, C. E. Reece and M. J. Kelley, J. Electrochem. Soc. 155(2008), p. D563.
- [5] H. Tian and C. E. Reece, PhysRev-STAB 13, 083502 (2010).
- [6] C. E. Reece and H. Tian, “Exploiting New Electrochemical Understanding of Niobium Electropolishing for Improved Performance of SRE Cavity for CEBAF” Proceeding of LINAC 2010, Tsukuba, Japan, 779-781 (2010).
- [7] T. Powers: “Theory and practice of cavity RF test systems” in: 12th International Workshop On RF Superconductivity, 10-15 Jul 2005, Ithaca, New York.
- [8] C. Reece, T. Powers and P. Kushnik: “An Automated RF Data Acquisition System for Testing RF Cavities” in: IEEE Particle Accelerator Conference, San Francisco 1991, Vol. 3 pp 1508 – 1510.
- [9] C.E. Reece, T. Powers, J. Susta and B. Almeida “A Closed Cycle Cryogenic System for Testing Superconducting RF Cavities” in: IEEE Particle Accelerator Conference, San Francisco 1991, Vol. 3 pp 2325–2327.