OVERVIEW OF SRF-RELATED ACTIVITIES AT JEFFERSON LAB *

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Abstract

SRF-related activities at JLab are varied and increasing. Operation of CEBAF at 5.7 GeV for nuclear physics is now routine. There has been significant progress in the development and testing of components and subsystems for a new cryomodule design for coming upgrades of the JLab CEBAF and FEL. Construction of the first such module has begun, and further optimization studies continue. Jefferson Lab joined the collaboration to build the Spallation Neutron Source (SNS). JLab will contribute 81 cavities in 23 SNS cryomodules. Prototyping of the beta 0.61 and 0.81 cavities is nearing completion. Development and testing of the high-power coaxial input coupler for SNS is underway. Fresh efforts have been initiated to pursue improved understanding and control of SRF surfaces. JLab has led discussions and development of modern low-level rf controls tailored for power-efficient operation of high-gradient SRF cavities in lightly beamloaded, cw applications. To support these efforts, major upgrades and renovations to the JLab SRF facilities and information infrastructures are underway. The lab has recognized the importance of SRF to future developments in the accelerator community by the creation of the new Institute for SRF Science and Technology.

1 INTRODUCTION

Jefferson Lab continues to operate the CEBAF accelerator with its 338 SRF cavities toward an aggressive nuclear physics program. Operation at 5.7 GeV with polarized electrons is routine. The JLab energy recovering linac IR FEL has passed the 2 kW cw mark and is gaining usage as a tool for basic and applied research. The upgrade of the FEL to produce 10 kW IR is to begin in 2002. JLab is a major partner in the construction of SNS and is developing controls and fabricating and testing cavities for the planned RIA facility. The priority given by the nuclear physics community to the upgrade of CEBAF to 12 GeV has provided a clear challenge to those involved with SRF work. In addition, the success of the energy-recovering linac (ERL) concept in the JLab FEL has stimulated exploration of designs for new light sources, electron cooling of protons, and high current electron-ion colliders. JLab has recently joined the TESLA collaboration and looks forward to being a partner in future developments. To provide a solid technical basis to support all of this work, JLab is expanding its activities in basic SRF-related R&D and has formed the new Institute for SRF Science and Technology with the mission of expanding the knowledge base in SRF and applying that knowledge to future accelerators of all types.

2 RECENT OPERATION OF CEBAF

2.1 Optimization for physics

Construction of CEBAF was completed in 1993. Most of the 42 cryomodules (each containing eight 0.5 m 1497 MHz SRF cavities) have been kept permanently cold since before then. Originally designed as a 4 GeV machine, the normal pressure to exploit whatever is available has pushed the machine energy above 5.7 GeV for routine physics operation. Since many of the experiments use polarized targets, actual operation has infrequently utilized the available beam power. For October 2000 through June of 2001, CEBAF delivered 4573 beam hours for physics with an average experimental hall multiplicity of 2.78. [1]

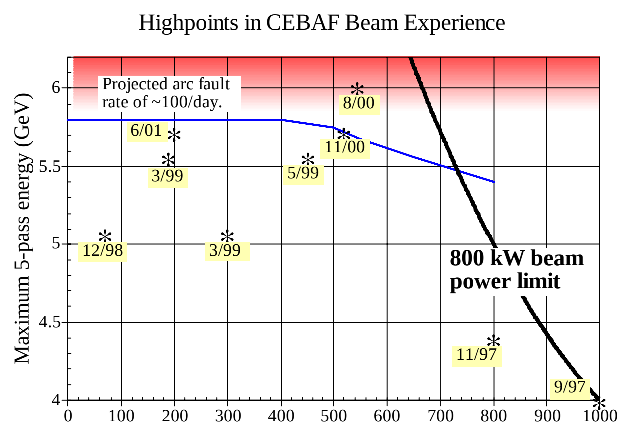

Figure 1. Progression of experience with CEBAF beam.

Post tuners have been installed in the feed waveguides to 111 cavities to better match the cw rf power to the higher gradients and lower currents. The typical loaded Q of 5×10^6 is transformed up to 8×10^6. Further increases in Q_L (lower bandwidth) cannot be handled by the present rf control system above about 10 MV/m because the Lorentz detuning exceeds the resonance bandwidth. Use of the waveguide tuners has allowed improved power optimization.

*Work supported by the U.S. Department of Energy, contract DE-AC05-84ER40150.
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Increasing the prompt waveguide vacuum interlock from 1×10^{-7} to 5×10^{-7} eliminated a source of common trips triggered by rf transients associated with nearby thunderstorms.

The arcing at the cold ceramic windows persists as the primary operational limitation on the gradients of the SRF cavities. The detailed behavior of this field-emission-induced phenomenon is particular to each cavity. The methods for operational characterization and optimization have been previously reported.[2] A particular challenge has been to identify the non-local effects of window arcs being induced by high-gradient operation of a nearby cavity.

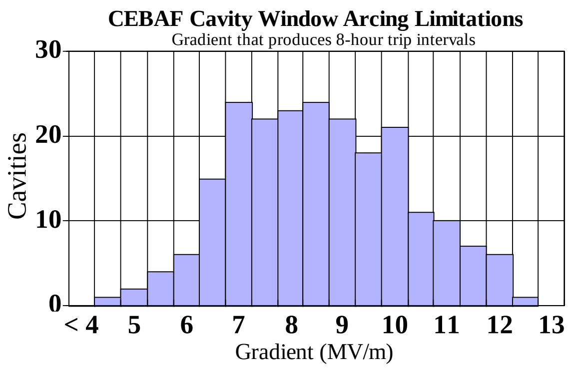

Figure 2. Distribution of cavity gradients that induce three arcs/day.

The result is a fairly well established dependence of unavoidable arc trip beam interruptions as a function of CEBAF's five-pass operating energy. (See Figure 3.) No more than about 100 trips/day are considered acceptable. The beam current dependence is present only because JLab chooses to not run its klystrons at their full power rating to keep the power bill down and extend the klystron lifetimes. Efforts are underway to minimize the lost beam time for each trip (presently 45 s).

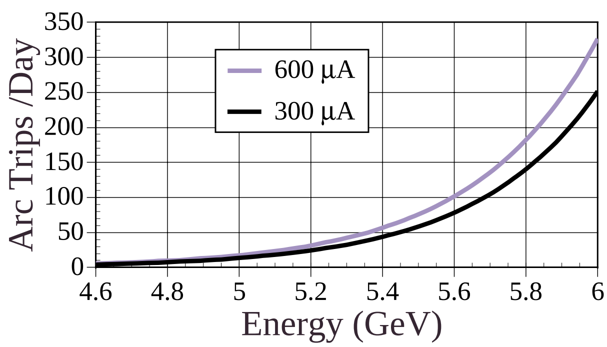

Figure 3. Arc trip frequency with CEBAF five-pass energy.

2.2 Cold helium leak

CEBAF recently encountered its first helium leak to the beamline inside a production cryomodule. During the August 2000 maintenance down, the room temperature waveguide windows on cryomodule NL11 were replaced. This window maintains the vacuum in the thermal transition region of the input waveguide. The module was warmed to room temperature and the windows exchanged. After cooldown, some minor problems were encountered with rf controls on two of the eight cavities, but otherwise the module appeared to function normally.

Over the subsequent several weeks, however, the cavities became progressively unusable. The rf controls behaved erratically. A systematic verification of control hardware and rf waveguide components found no problems.

The poor performance was eventually diagnosed as the result of a cold helium leak into the beamline, somewhere in the region of the first cavity pair. Presumably the leak was opened by the thermal cycle to room temperature. Since several weeks of useful operation had been obtained before the onset of problems, we warmed the module to ~30 K and pumped out the beamline in the same manner as done following helium processing. This "burping" of the module entails minimal additional risk and has been effective at restoring NL11 to service for periods of several weeks. Since attempting to locate and fix this leak would require removal and disassembly of the cryomodules, this procedure is now considered routine maintenance and is accomplished during regular accelerator maintenance periods. Approximately 18 hours are required from rf off to module full and rf back on. The cold superfluid leak rate is estimated to be of order 2×10^{-5} std cc/s, compared with a mean superfluid helium leak rate of 4×10^{-11} std cc/s per cavity pair measured in vertical test during CEBAF construction.[3] This "burping" has been applied eight times to date. No increase in leak rate has been observed.

2.3 Warm window changes

To improve durability, we have designed a replacement for the warm rf window on the first-generation CEBAF cryomodule. These windows are presently either Teflon or polyethylene. The new system is a modification of an existing window design developed for the CEBAF upgrade and FEL applications.

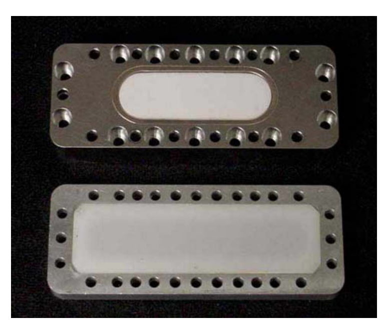

Figure 4. New ceramic and old polyethylene style warm rf windows for CEBAF Mk I cryomodules.

The window assembly uses a ceramic window brazed into a Kovar cup that is in turn brazed into a stainless steel flange. See Figure 4. This assembly is bolted onto the existing cryomodule warm window assembly using an indium wire seal. Two cryomodules, one in the FEL and one in CEBAF slot SL21, have been operating reliably with similar windows at power levels up to 30 kW.

To reduce the risk of opening another cold helium leak as in NL11, we are developing a new technique for changing the warm windows on installed cryomodules that does not include a full warm-up. To change the warm window, the waveguide vacuum space must be vented. The current plan is to vent and purge the waveguide vacuum space with only helium while maintaining the cryomodule at ~40 K. At this temperature helium will not condense and can be pumped out after window exchange. A test of our ability to maintain a cryomodule in this temperature range was performed during the May 2001 CEBAF maintenance period. The module was maintained at an intermediate temperature for several days, but was accidentally allowed to warm to ~70 K, well above the target temperature. Additional testing will be required to qualify the change-out technique. Installation of the first replacement windows is scheduled for late September 2001.

2.4 Helium processing

Helium processing of the installed cryomodules in CEBAF has proven quite fruitful, adding ~430 MeV to the five-pass maximum energy. [4] A perhaps final reapplication of the developed procedure is being made during 2001 to the cryomodules processed first. Up to six cryomodules will receive helium processing during the September-October maintenance down. An additional 10–20 MV gain is anticipated for the North linac. Higher power pulsed helium processing is being considered as a technique for seeking further additional voltage from the existing cryomodules.

3 FEL STATUS AND PLANS

The JLab FEL first produced 1.7 kW cw 3 μm light in June 1999.[5] Since that time the FEL has been serving a number of applied and basic research users. The injector “quarter-cryomodule” and the full cryomodule used for recirculation continue to operate reliably. The high-frequency HOMs produced by the intense short bunches have required the routine masking of the IR window heating interlock to avoid false trips.[6]

The maximum output power has recently exceeded 2.1 kW, and record-breaking powers at harmonic frequencies have also been exploited for micromachining and ablation. An initial test exploring pulsed laser deposition of niobium films might eventually prove relevant to SRF applications.[7] The energy-recovering-linac (ERL) concept demonstrated by the FEL has attracted significant attention, and is serving to stimulate exploration of new accelerator applications.

An upgrade of the FEL to 10 kW in the IR is underway, with an expected completion in 2002.[8] The IR Upgrade design calls for adding two cryomodules. One of these cryomodules is presently installed in CEBAF, and the second is to be a Mk II version of the CEBAF upgrade design. The three cryomodules are expected to provide 40/40/70 MV, respectively. It is likely that this implementation will also enable > 1 kW operation of the FEL in the V-UV to 240 nm. Details are provided by Merminga’s contribution to this workshop.[9]

JLab intends to pursue previously inaccessible studies of ultrafast phenomena in condensed matter physics, atomic physics, chemistry and life sciences. Combining the recently acquired superconducting synchrotron Helios with the FEL, JLab will develop a unique capability for pump/probe experiments.[10]

4 SNS ROLE, PROGRESS, AND PLANS

Since the Santa Fe workshop in 1999, JLab has joined as a partner lab in the construction of SNS. As part of the R&D program, we are responsible for developing the beta 0.61 and 0.81 SRF cavity designs, including their coaxial fundamental and HOM couplers, and designing, building and testing a prototype cryomodule.[11] For the SNS construction project, we are to provide 23 cryomodules, 11 containing three β=0.61 cavities and 12 containing four β=0.81 cavities. The accelerating gradients of the 0.61 cavities must exceed 10.1 MV/m; high β cavities must exceed 12.5 MV/m. These specifications correspond to peak surface electric fields of 27.5 MV/m. As an SNS R&D program, JLab will, building from the work of KEK, develop an electropolishing system and enhanced contamination control procedures during the construction of the 0.61 modules in hopes of subsequently increasing the gradient of the high-β cavities to 15.9 MV/m. JLab is also providing the cryogenic refrigeration and distribution system for SNS.

Prototype cavities of both types have been fabricated and tested at JLab. (See Figure 5.) The prototype coaxial input coupler design is complete, and two have been tested to 500 kW.[12] Designs are complete for several cryomodule subsystems and most major procurements have been placed, including the cavity production contract. Testing of the prototype β=0.61 cryomodule is planned for spring 2002. Production assembly and testing of the SNS cryomodules is to begin in Summer 2002.

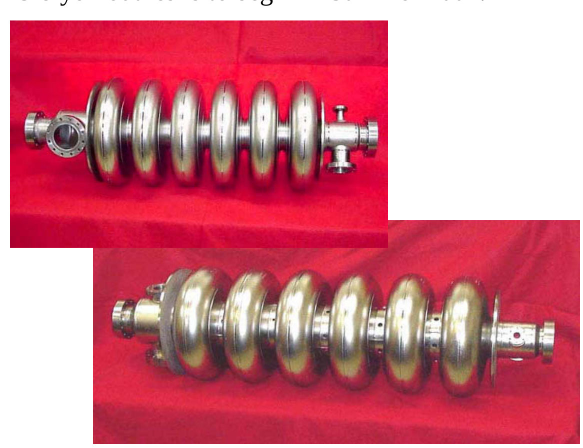

Figure 5. SNS prototype β=0.61 and 0.81 cavities.

5 FUTURE DIRECTIONS

Under the leadership of the new head of the JLab Accelerator Division, Swapan Chattopadhyay, two new organizations have been created. The Center for Advanced Studies of Accelerators, CASA, will pursue concepts and designs for new accelerator applications. The Institute for SRF Science and Technology, which has significant overlap with CASA, will develop and provide SRF-based solutions for accelerator needs at JLab and elsewhere. In addition to design and production responsibilities for cryomodules, a significant part of the institute's mission is SRF materials R&D.

Satisfying JLab's commitment to the SNS construction, building the IR FEL upgrade, and preparing for the upgrade of CEBAF to 12 GeV are the principal production activities for the next few years. The institute expects to extend and enhance existing collaborative relationships with other laboratories worldwide. We anticipate full participation in the design, development, and production needs for RIA, TESLA, EIC, and next-generation light sources.

6 HIGHLIGHTS

6.1 Upgrade activities to date

During the past several years, cavity and cryomodule designs have been developed for use in upgrades to CEBAF and the JLab FEL.[13] Two of these cryomodules (Mk II) are to be completed in 2002, one for CEBAF and one for the FEL IR upgrade. Key subsystems are presently in fabrication and testing.

The cavities for these two cryomodules are of a hybrid design. They use the same cell shapes as the initial CEBAF cavities (Mk I), but adding two additional cells per cavity. The $\lambda/2$ stub input coupler is replaced by a $\lambda/4$ stub to eliminate the field asymmetry that gives rise to a transverse "coupler kick" and to reduce the tight mechanical tolerances required to establish the desired external Q of the coupler to the cavity. The waveguide HOM couplers of the Mk I cavity have been replaced with an adaptation of the DESY couplers developed for TESLA use. Sixteen of these cavities are presently in fabrication at JLab. The performance specification for the cavities in the Mk II cryomodules is average E_{acc}=12.2 MV/m, with a Q_0 of $> 6\times10^9$.

The first space frame in which the eight seven-cell cavities are to be mounted is presently being evaluated. (See Figure 8.)

The new tuner for the upgrade exceeded the specification for resolution during its initial evaluation using the Horizontal Test Bed (HTB).[14] The tuner, which uses a concentric linear motion scissor-jack mechanism to place all bearing parts external to the cryomodule, met the necessary resolution of < 2 Hz using only the mechanical tuner.[15]

Figure 6. CEBAF Mk II upgrade cavity

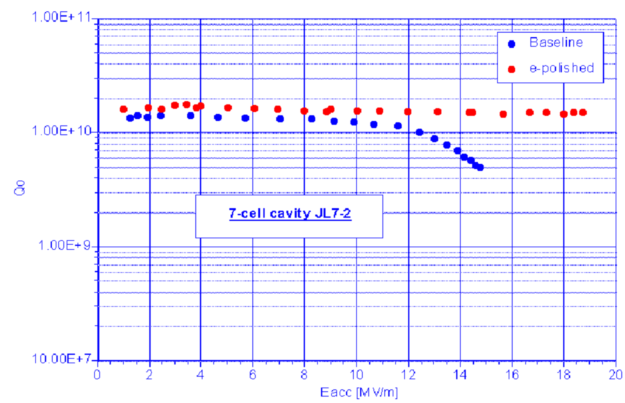

Figure 7. Early test of seven-cell upgrade cavity without couplers, before and after electropolishing.

Figure 8. Upgrade cryomodule space frame and vacuum vessel.

Since control of microphonics is crucial in this application, the cavity microphonic response to tuner actuation was monitored and found to be less than 0.3 Hz peak. The piezoelectric fine tuner also met or exceeded all specifications. The frequency response of the whole system, including the tuner, was also evaluated for possible dynamic applications such as active vibration cancellation.

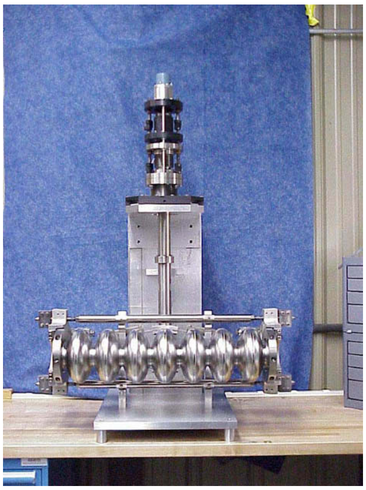

Figure 9. Prototype tuner for CEBAF upgrade.

Initial tests of microphonic sensitivities of the upgrade cavities were also carried out on the HTB. Although the mechanical suspension was different than that of upgrade cryomodules, opportunity was taken to characterize the rf resonance response of the cavity/cryostat system to background vibration, swept frequency, pulsed rf, and external mechanical impulse.[16] The dominant excitation from background was an ambient vibration at 54.7 Hz. The most significant mechanical vibration mode of the structure was observed at 33.7 Hz. The net microphonic detuning in the HTB was 2.5 Hz rms, which is below the design limit of 3.5 Hz rms. Similar tests will be made on the SNS and upgrade cryomodules during the next year.

6.2 New options for CEBAF upgrade

It would take 16 new cryomodules with the performance specification of the Mk II style to obtain 12 GeV with 5.5 passes through CEBAF.[13] Ten of these cryomodules would fill presently empty slots, while six would replace the weakest of the Mk I cryomodules. The maximum beam current of the 12 GeV design is 465 μA. A presumption in past plans was that the present CEBAF klystron design could be pushed to 8 kW by raising the gun voltage. Events of the past year demonstrated that this is not an option, and the development of a new gun is being pursued.

Removal of this constraint on the 12 GeV design and the stretch-out of the schedule allow further optimization of the cavities to reduce overall project costs. Exploiting current design and fabrication methods, we intend to develop a Mk III cavity for CEBAF that will increase the shunt impedance and geometry factor while obtaining state-of-the-art SRF performance.

One potential improved cavity design has been proposed by Barni et al.[17] With it one can construct a 12 GeV CEBAF design that might be realized with only ten new cryomodules, using 13 kW klystrons.[18] This design assumes an average cavity gradient of 19.2 MV/m. An even more ambitious design goal is to realize 25 MV/m in the 0.7 m cavities, while dissipating only 33 W at 2.1 K, using the same klystron. Such a goal could only be realized by reliably eliminating field emission sources from the cavity, maintaining surface resistances of ~25 nΩ, and implementing an agile rf system capable of handling the Lorentz-force detuning and microphonics.

6.3 SNS cavity prototyping

Under the leadership of P. Kneisel, the design, fabrication, and testing of the SNS prototype cavities has proceeded quickly and successfully.[19] With minimal time available for development, an international collaborative effort quickly produced initial electromagnetic and mechanical designs. Design codes were used to evaluate potential multipacting behavior, Lorentz-force sensitivities, and microphonic vibrational modes. The coaxial fundamental coupler was scaled from the KEK design, and the HOM couplers were scaled from the DESY design for TESLA.

The SNS cavities are fabricated from niobium with RRR > 250. The prototype cavities are being built at JLab. A new 500-ton press was procured to deep-draw the half cells. The JLab electron beam welder (EBW) is used for all niobium welding. A new TIG-welding station has been set up to weld the titanium helium vessel to the NbTi end dishes.

For details of the SNS cavity designs and test results see Ciovati’s contribution to this workshop.[20] Figures 10–12 show fabrication, processing, and testing of SNS cavities.

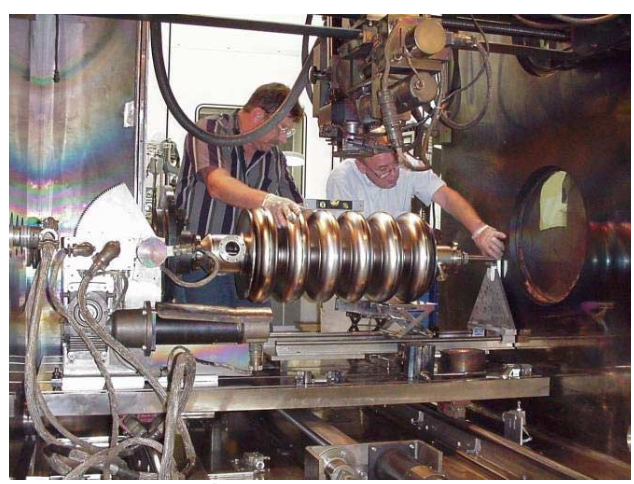

Figure 10. E-beam an SNS prototype cavity.

Figure 11. Preparation of an SNS cavity for test in the vertical test area (VTA).

Figure 12. TIG welding of an SNS prototype cavity helium vessel.

Figure 13. Setting up an SNS medium-beta cavity for internal chemistry.

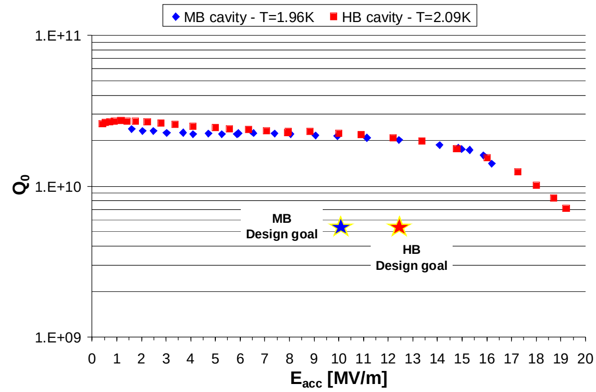

Figure 14. Test of first beta 0.81 prototype cavity.

6.4 SNS coupler prototyping

The fundamental power couplers for the SNS SRF cavities must support a peak power of 550 kW for a 1.3 ms pulse length at 60 pulses per second. The general design of the high power coaxial input coupler for the SNS SRF cavities is a geometrical scaling with frequency from the geometry used for Tristan and KEK-B.[21] Detailed rf, mechanical, and thermal designs have been completed satisfactorily. The prototypes were fabricated at JLab and then conditioned and tested using a high power klystron at LANL. The first pair of couplers (see Figure 15) have been operated successfully at 500 kW after ~32 hours of conditioning. See K. Wilson et al. contribution to this workshop. [12]

Figure 15. First SNS prototype input couplers.

6.5 SNS cryomodule design

The designs of the two SNS cryomodules [22,23] borrow from several existing cryomodules already in use or in planning. Alignment and support of the cavity string is supported via nitronic rods, as was done in the original CEBAF Mk I cryomodules. The alignment rods are attached to a rigid space frame, as is planned for the CEBAF upgraded cryomodule. The space frame allows assembly of the cavity string before insertion into the vacuum vessel.

The end cans, which provide the interface for the cryogens, are similar to the L shaped ones used in CEBAF. A 2 K heat exchanger was added to the return end can as was done in the LHC cryomodules. This allows the refrigerator to supply 3 bar, 4.5 K gas to the cryomodules that is split into two streams. One stream goes through the 2 K heat exchanger before going through the JT valve and producing the superfluid helium used to cool the cavities. The other stream is controlled by a second JT valve and used to cool the outer conductor of the coaxial fundamental power coupler.

The tuner is a scaled version of one designed for use on the TESLA cryomodules and uses a cold stepper motor with harmonic drive. A copper thermal shield operating at 40 K is incorporated in the cryomodule, as are two mu-metal shields, one at 2 Kelvin and the other at room temperature.

6.6 Controls development

Every accelerator application of SRF requires a set of rf controls that meet particular needs. It is clear that a new control system will be required for the upgrade cryomodules in CEBAF. The controls needed eventually for RIA are rather similar. Both applications will employ high-gradient cavities that are lightly loaded with cw beam. Interests in rf power economy favor higher external Q's, but tuning control assurance and microphonics add practical constraints. Modern digital technology has some distinct advantages over analog systems. To help foster a convergence of the best ideas on this subject, JLab hosted the Workshop on Low Level RF Controls for Superconducting Linacs in April 2001. [24] The workshop was organized by C. Hovater and L. Merminga. The use of a hybrid system combining an analog self-excited loop and implementing digital feedback for phase and gradient control appears to be very attractive for low-current cw applications. JLab is developing such a control system that may serve the needs of both the CEBAF upgrade and RIA.

6.7 SRF R&D

Collaborative R&D work done with DESY and INFN for TESLA and with MSU for RIA is presented by others at this workshop.

The DC field emission scanning microscope integrated with SEM and EDS analysis has been commissioned by Tong Wang. The system identifies all sites on 2.5 cm diameter samples that field emit below 100 MV/m. Systematic comparison of surface preparation techniques has begun. See reference [25], this workshop.

A vacuum deposition system has been built to test the idea of energetic condensation of Nb on a copper substrate. The system directly uses microwave power to create the pure Nb plasma. A description of the system and the first Nb films produced are contributed to this workshop by Genfa Wu.[26]

An exploration of the effectiveness of alternative electropolishing solutions has recently begun at JLab. Initial results are presented by A. Wu.[27]

6.8 Facility upgrades

The automated closed chemistry system and high pressure rinsing station just installed at the time of the last SRF workshop have been fully commissioned and are in active use. These stations are located within the Class 100 cleanroom. A new electropolishing station is being prepared in the chemistry area of the cleanroom.

The balance of the cleanroom suite has been reconfigured to accommodate the clean assembly of cavity strings. This is in contrast to the assembly of cavity pairs used for CEBAF Mk I cryomodules. A portion of the cleanroom has been allocated for cleaning and assembling the SNS input couplers.

The rf processing and testing of the SNS fundamental power couplers requires a high power rf source. Preparations are underway to accommodate a 1 MW pulsed 805 MHz system to be provided by LANL in February 2002. This single klystron source will be shared between the coupler test stand and the cryomodule test facility (CMTF).

The CMTF in the JLab Test Lab building is being renovated in preparation for testing SNS and upgrade cryomodules. The temporary control room and test cave that were setup in 1989 are being reconfigured into an arrangement that supports production testing of SNS (and potentially RIA) cryomodules at 805 MHz using 20 kW cw and 1 MW sources, as well as upgrade cryomodules for CEBAF and the FEL with multiple 8 kW klystrons at 1497 MHz. Use of the cryomodule test cave, which previously housed a synchro-cyclotron, has suffered from remanent magnetic fields locally as high as 6 G. These fields saturated the magnetic shielding in cryomodules and reduced the accessible Q_0 values to $< 5\times10^9$. This cave has now been outfitted with a large magnetic shield to reduce the ambient fields to ~0.1 G within the room-size volume where cryomodules are tested. (See Figure 16.)

Figure 16. Magnetic shielding being installed in the CMTF cave.

The cryogenic capacity of the Test Lab facilities is also being increased from about 4 g/s to 7 g/s liquid helium. The efficiency of the local plant is being improved and an additional cold box is being brought online. A new cold transfer line from the accelerator site will be available as a backup cryogen source. Controls enhancements will be made in the distribution of cryogens between the CMTF and the vertical test area (VTA) with its eight semi-independent dewars.[28]

Additional facility upgrades that are complete or in progress include a major controls upgrade for the EBW, a new furnace for hydrogen degassing of large (SNS) cavities (Figure 17), an extension and enhancement to the production ultrapure water system setup of new assembly lines for SNS and upgrade modules, and automation of an existing brazing furnace.

Completion and commissioning of SIMS, scanning Auger, and TEM surface analysis systems are underway. These systems will play important roles in new SRF surface characterization studies.

Figure 17. New 1250°C furnace for hydrogen degassing of large cavities. (A 700 MHz test cavity is shown in the hot zone.)

6.9 Pansophy

The institute is implementing a new web-based information management system. We call it *Pansophy*. *Pansophy* will be our tool for developing, using, and retaining all procedures, design information, production travelers, test data, electronic log books, shared databases, online analysis modules, and scheduling information. [29] This system is a custom integration of several commercial software utilities, DocuShare™, ColdFusion™, Matlab™, Ingres™, and common desktop programs. Users of the system range from process managers, shop-floor technicians, and test engineers to after-the-fact data miners and operations staff. The system integrates important quality assurance elements of procedural control, automated data accumulation into a secured central database, prompt and reliable data query and retrieval, and online analysis tools, all accessed by users via their platform-independent web browsers.

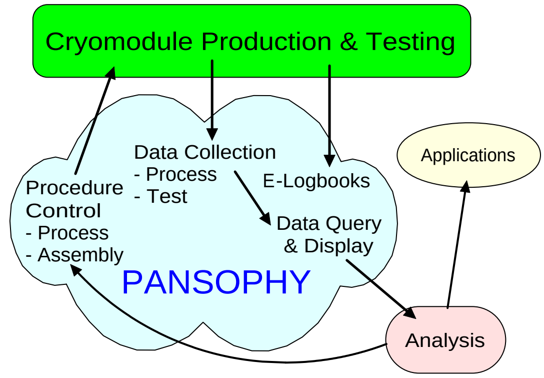

Figure 18. Conceptual schematic of the Pansophy system.

The cavity and cryomodule production travelers are the controlled procedures used to prepare, assemble, and test parts that become a commissioned cryomodule. These travelers specify actions to take and data to be acquired along the way. To efficiently capture the data into a database, the travelers themselves will be accessed and used via web browsers. The forms presented to the user are auto-generated from a custom MSWord template and directly create the database structure used to collect and store production data.

Figure 19. Pansophy home page.

One element in the Pansophy system is a web-based document sharing system, DocuShare™, which supports flexible access and revision control, as well as searchability and reliable backups.

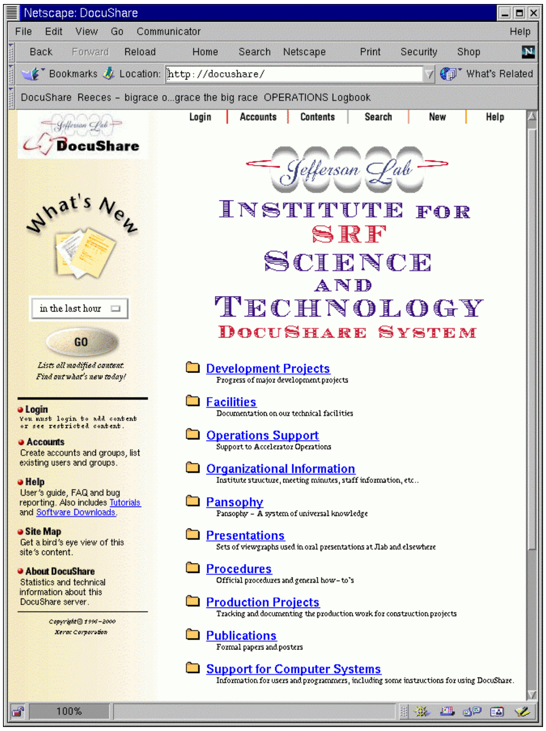

Figure 20. The institute's DocuShare home page on the JLab intranet.

7 SUMMARY

SRF activities at Jefferson Lab are now varied and busy. Around our core support of the existing and evolving CEBAF nuclear physics program and basic and applied FEL programs, the Institute has major commitments to external collaborations--SNS, and potentially RIA and TESLA--and is embarking on new missions for education and key SRF materials science research. Significant infrastructure investments are being made to support the growing level of activity and to meet the technical challenges that lie ahead.

8 ACKNOWLEDGMENTS

The vast majority of the work reported here is not the author's. It is to the good credit of all the members of the Institute for SRF Science and Technology at JLab, as well as many members of CASA and the Accelerator Engineering Department. The future, even more than the past, will be a highly collaborative one.

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