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OPERATING EXPERIENCE IN SRF ELECTRON LINACS*

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The operating experience of SRF linacs is reported. Accelerators included are HEPL, MACSE, S-DALINAC, and CEBAF.

Keyword: Superconducting

1 INTRODUCTION

During the last two years there has been considerable operating experience with electron linacs utilizing SRF technology. This represents a significant increase in the total experience to date. A review of this operating experience will be presented. This review covers laboratory overviews, cavity performance, cavity support systems, and accelerator support systems. Experience from HEPL, DARMSTADT, MACSE, and CEBAF are included.

These laboratories demonstrate the status and progress of SRF technology in electron linac application. HEPL establishes the long term reliability and functionality of SRF applications with over two decades of operations utilizing the same technology. HEPL continues to provide a large number of beam hours for users each year. S-DALINAC is also a well established installation delivering beam to users. At the same time new SRF designs are being incorporated into the accelerator extending capabilities. At MACSE the developmental accelerator has identified and characterized technical parameters important to current designs and applications. This has been

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accomplished with a limited number of operational hours. CEBAF has completed the installation and commissioning of the largest number of SRF cavities in an accelerator. This represents a significant increase in the total number of SRF cavities in operation in the accelerator community.

2 OVERVIEW OF ACCELERATORS

2.1 HEPL

The first SRF electron linac in operation was commissioned at HEPL more than 20 years ago and continues to provide 2500–3000 hours of operation per year. The machine uses one, three, and six meter multi-cell cavities. The six meter cavity has fifty five cells, operating at a frequency of 1.3 GHz and a temperature of 4.2 K and is the design base for the 1 and 3 meter cavities. The cavities are powered by 10 kWatt klystrons utilizing the original rf couplers. The accelerator has had as many as eight cavities in use and presently has six. The performance of these cavities has been extremely reliable. These cavities were last touched twenty years ago and continue to perform consistently. The focus of HEPL operations at this time is providing high peak current for Free Electron Laser applications.

2.2 MACSE

This accelerator is an experimental machine used for the development of superconducting cavities and related accelerator systems.[1,2] The configuration of the machine during it's last running period included five multi-cell cavities. An injector cavity was housed singularly in one cryostat and the four remaining cavities were installed in a large cryostat. All cavities are a 5 cell design operating at 1.5 GHz. The five cell cavities have been removed and replaced with 3 cell cavities that have not yet been operated.

2.3 S-DALINAC

The linac at Darmstadt is used for a variety of nuclear physics and radiation physics experiments. The machine includes a superconducting injector linac and a superconducting main linac.[3] The injector linac uses 2, 5, and 20 cell cavities. The main linac is made up entirely of 20 cell cavities with a total of

8 installed. All cavities operate at a frequency of 3 GHz and a temperature of 2 K. The main linac is capable of delivering beam to user facilities after one, two, or three passes for energies up to 130 MeV.

2.4 CEBAF

The accelerator is designed for use in the study of nuclear physics. It has a superconducting injector linac and two parallel superconducting main linacs containing 338 SRF cavities. All cavities are a 5 cell design with waveguide couplers. The cavities operate at a frequency of 1.5 GHz and a temperature of 2 K. The accelerator is designed to simultaneously deliver beam to three experimental halls after 1–5 passes through the main linacs for energies up to 4 GeV. The machine has delivered electrons for the first physics experiment during November of 1995.

Table I summarizes operating performance of these accelerators to date.

TABLE I Summary of operational performance

	HEPL		*MACSE*	*S-DALINAC*		*CEBAF*
	Present	*Historical*		*Present*	*Historical*	
Cavities	1, 3, 6 m	1, 3, 6 m	5 cell	2, 5, 20 cell	5, 20 cell	5 cell
# installed	1, 1, 4	1, 1, 6	5	1, 1, 10	1, 10	330
f_o	1.3 GHz	1.3 GHz	1.5 GHz	3 GHz	3 GHz	1.5 GHz
E_{acc}	2–3 MV/m	2–3 MV/M	7–18	5+ MV/M	5+ MV/M	4–14 MV/m
Q_o	10^8	10^8	10^{10}	1×10^9	1×10^9	$3-8\times10^9$
Operating hrs.	2,500	20,000	200	500–2,000	2000	14,000
Cavity hrs.	15,000	120,000	800	6,000–24,000	105,000	4,000,000
Beam current	200 μA		100 μA	3×20 μA	50 μA	3×20 μA
Beam energy			16 MeV	90 MeV	104 MeV	4 GeV

*$\beta = 0.85$

3 CAVITY PERFORMANCE

3.1 HEPL

These are the first SRF cavities operated in a electron linac. During the design and production of these cavities multipackting barriers and the limited thermal conductivity of the available niobium material determined performance limits. Operation of the cavities has been stable for the life time of the machine. Currently they are in operation after twenty years without being removed from their cryostats. Performance characteristics are only tracked by measurement of operating gradients. It is assumed the Q_o of the cavities is in the 10^8 range.

3.2 MACSE

The cavity performance has been impressive with operating gradients between 7–18 MV/m. Field limitations for all cavities are attributed to quench breakdown. It is assumed the quenches are a result of bad welds at the equator of the cells. During initial operations following a cooldown some field emission loading is evident. This is easily removed with a short period of rf pulse processing at full power from the 5 KWatt klystrons. After processing the electron loading does not return. Quality factors for the cavities are $\sim 10^{10}$. The highest gradient cavity, 18 MV/m, was made unusable when a rf input coupler failed. The remainder of the cavities continued to perform without degradation until removed from the linac.

3.3 S-DALINAC

During the last two years the cavities at Darmstadt experienced significantly degraded performance. The degradation was the result of rf input and output coupler failures. The failure of both couplers was coincidental resulting in an initial helium contamination followed by an air contamination of the cavity surfaces. All the cavities in the main linac were reprocessed at either Darmstadt or DESY. The performance of all cavities following the chemical polishing and reassemble has been similar to historical levels. The lack of improvement in cavity performance after chemical polishing may be an indication of a performance limitation inherent in the cavity design. Additional questions have been raised by unexplained changes in cavity Q_o. Performance degradation was noted with spontaneous recovery in several instances.[4]

3.4 CEBAF

Currently CEBAF has 320 cavities in operation. During the last two years 16 cavities have been commissioned and the main linacs have been optimized

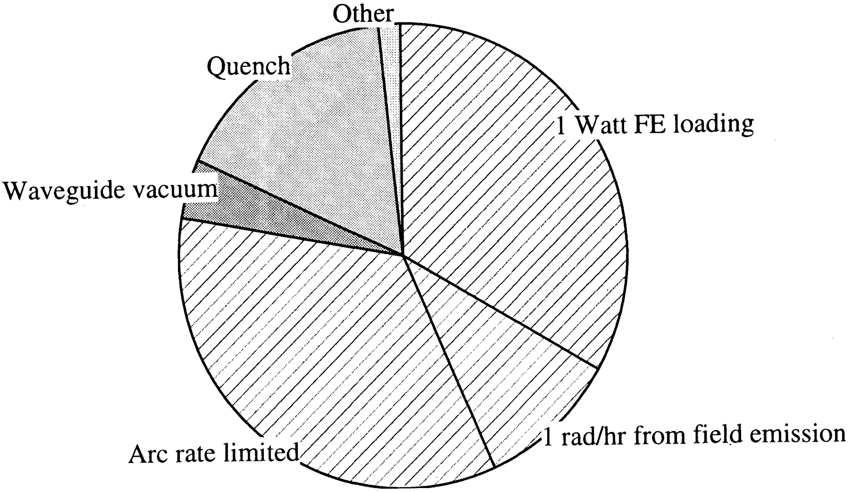

FIGURE 1 Distribution of CEBAF cavity limitations.

for support of 4 GeV beam operations and currents up to 20 μA. The cavity operating limitations were determined during commissioning[5] for each cavity in the accelerator. Since that time some cavities have had these limits lowered. The primary reason for these reductions in operating field level is excessive arcing in the waveguide coupler. At this time 10^8 cavities have had their operating field levels reduced to lower arc rates to an acceptable level ($<$ 0.25/day). Figure 1 shows the distribution of cavity limitations.

Recently, additional testing of 15 cavities was performed after 2–3 years of operations. There has been no performance degradation in any of the cavities tested. Of the 15 cavities tested, 8 had been rf pulse processed using a 5 kWatt klystron, just prior to the testing. In one of these 8 cavities the performance was measurably improved. Figure 2 shows the Q_o vs. gradient curves for the initial commissioning and the recent test results.

An additional limit imposed on current operations is a reduction from 5 kWatts to 1.7 kWatts of available rf power for each cavity as a cost savings measure. Figure 3 shows the summed gradient for each cryomodule installed for the current operating limits, the projected limits for 5 kWatt operations, and the limits defined during vertical testing. The values for the current operational and projected 5 kWatt operational limits are continually being updated with operating experience.

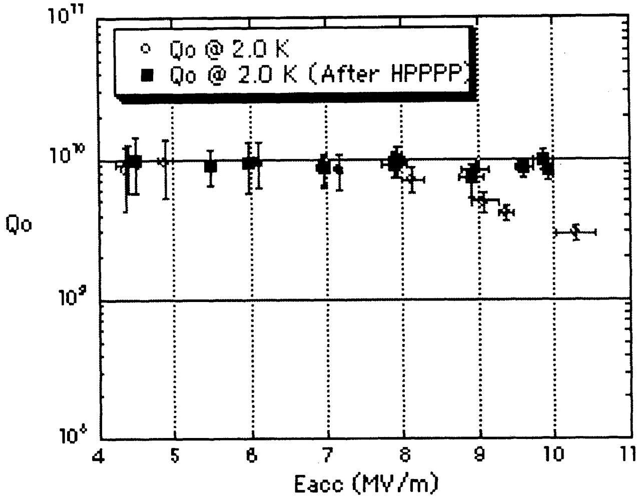

FIGURE 2 Q_o comparison before and after RF processing SL03–8.

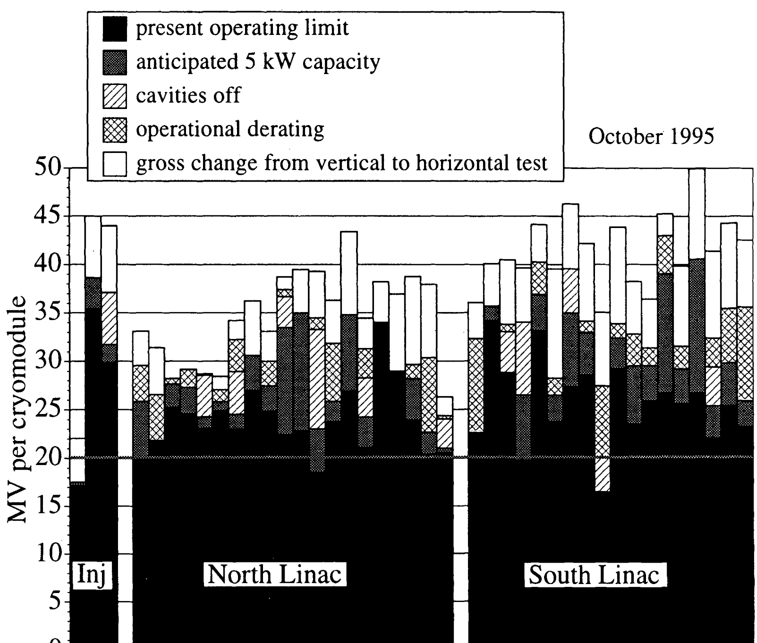

FIGURE 3 CEBAF cryomodule performance limits.

4 CAVITY SUPPORT SYSTEMS

4.1 MACSE

During early operations cavity phase fluctuations of 60–70 degrees were present. The root cause of the phase instabilities was identified as a mechanical vibration driven by the cryogenic supply internal to the cryostat. The rework of the helium supply piping in the cryostat reduced the vibrations to an acceptable level. The rf control system was then able to control the cavity phase to less than 0.1 degree of jitter.

Also during early operations the rf input coupler on one cavity failed. This resulted in the cavity remaining inoperable from that point on. The rf input couplers have been redesigned[6] and implemented on the three cell cavities presently installed in the accelerator.

4.2 S-DALINAC

During the last two years S-DALINAC also suffered the failure of a rf input coupler. This was accompanied by the coincidental failure of a rf pick-up coupler. This combination of failures led to significant contamination of the cavity surfaces and reduction in cavity performance. The input coupler failure produced an in rush of helium into the cavity vacuum space. During the investigation that followed the cryostat insulating vacuum was vented leading to an air exchange with the cavity vacuum space through the pick up coupler. Following this the main linac cavities were removed and reprocessed. During this rework operation new coupler designs[7] were installed on all cavities.

4.3 CEBAF

There have been three failures of rf input couplers during operations at CEBAF. On each occasion the warm polyethylene window has failed resulting in an air leak into the waveguide transition vacuum space. The input coupler configuration utilizes one vacuum manifold for two waveguide regions resulting in the loss of two cavities from operations when a single window fails. A single coupler is shown in Figure 4. Investigations of two of these failures identified procedures that effectively bypassed the interlocks intended to prevent this kind of failure. Without interlock protection, sustained arcing in the waveguide transition region coupled rf power into

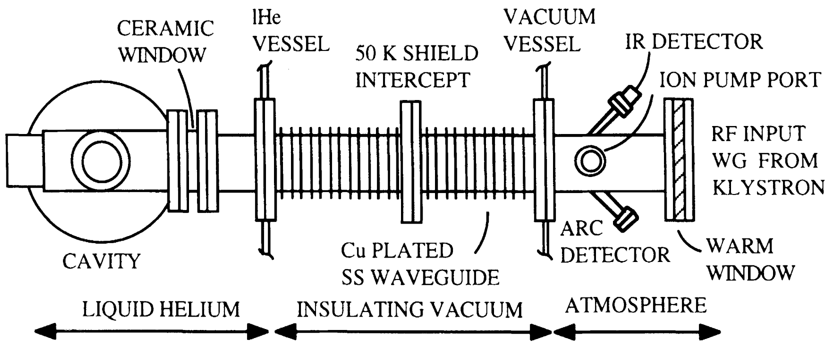

FIGURE 4 CEBAF waveguide transitions (not to scale).

the polyethylene window and melted them. Procedures have been reviewed and modified to eliminate a possible repeat of these failures. The recovery from these required the warm up of the cryomodule to allow for the replacement of the polyethylene windows and the clean up of the vacuum space. This effort requires 1–2 weeks to accomplish and returns the cryomodule to a fully operational state.

The third failure of the input coupler occurred in August 1995. This failure also included the melting of the polyethylene window but was not the result of sustained arcing in the waveguide region. A smaller vacuum leak developed which allowed enough time to stabilize the waveguide vacuum before we suffered a complete loss of cryogenic support. The cryomodule is still in operation without the two effected cavities. Continued operations precludes a complete investigation of the failure.

A partial investigation did include a 100% inspection of the input coupler flanges in the accelerator and the evaluation of the performance of the infrared interlock utilized in the waveguide region.[8] This interlock is intended to monitor heating in the region. During the inspection it was noted the warm windows had been creeping under load allowing gaps in the rf flange. As a result of these findings, all of the warm input coupler flanges in the accelerator have been tightened in an attempt to minimize rf heating in the region. Additional efforts have produced a better understanding of the infrared interlock and a modification of the associated electronics. The result of this work can be seen in the measurement of the infrared signal as a function of

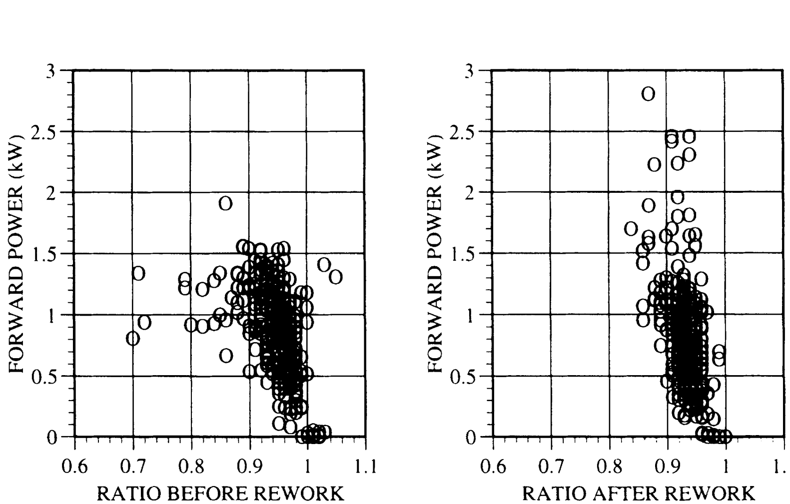

FIGURE 5 Waveguide infrared sensor response.

rf power before and after the changes to the system. Figure 5 shows these two cases where a decrease in the signal ratio results from a increase in heating. The elimination of outliers after the rework of the input couplers is attributed to the mechanical adjustment of flanges. Better control of this interlock system and control of the mechanical interface is expected to eliminate a repeat of this failure.

Several other cryostat components have failed during operations at CEBAF. These failures include infrared sensors, mechanical tuners, and rf pickup probe cables. In all cases the failures have caused little interruption to operations. The small impact of these failures is a result of the additional gradient capacity installed in the linacs. A single cavity can be bypassed while the remaining cavity gradients are increased slightly to maintain the linac voltage.

During the last two years we have had 4 infrared sensors fail. The failures result in the corresponding cavity being taken off-line until repairs can be made. With the sensor installed inside the waveguide vacuum space the repair requires the cryomodule to be warmed to room temperature.

Seven mechanical tuner failures have resulted from two failure modes. On two early tuner assemblies a bearing race would bind after cooldown making the tuner hard or impossible to move.[9] These cavities are not recoverable without disassemble of the cryostat. This problem was discovered during cryomodule production and eliminated by increasing the clearance for the bearing race. The other 5 tuners failed as a result of a air leak into a single cryostat. Air products, leaking through a electrical feedthrough, had built up on cold rotary feedthroughs inhibiting their operation. A gradual increase in resistance to operation finally made the tuner inoperable. After warming the cryostat and replacing the leaking feedthrough the tuners returned to normal operation.

The rf pickup probe signal is transmitted on a semi-ridged cable inside the cryostat. On two cavities the cable pulled out of its termination during cooldown. The cables that failed were at the short end of the specified length. At this time, all cables have been cooled down and no further losses are anticipated.

5 ACCELERATOR SYSTEMS SUPPORT

5.1 CEBAF

The large installation of SRF cavities in the CEBAF linacs have required the development of several tools to manage and optimize accelerator operations. Some of the more interesting ones include Auto-Tune, Linac Energy Management (LEM), and Auto-Krest.

The automated cavity tuning, Auto-Tune, has three routines that, find the cavity resonance over a 10 kHz range and tune it to $f_o \pm 200$ Hz, determine the 0 phase of the cavity, and maintain the cavity phase to $\pm$ 10 degrees.

The identification of the cavity resonance is accomplished by driving the cavity with a broadband, 10 kHz FM, signal and measuring the transmitted power to identify the resonant frequency. The mechanical tuner is then stepped in the appropriate direction to bring the cavity frequency closer to the operating frequency. This is repeated until the resonance frequency is within the 200 Hz of the operating frequency.

The 0 phase of the cavity is measured by sweeping the rf drive frequency to the cavity and measuring the transmitted power. The phase resulting in the maximum transmitted power is defined as the 0 phase.

The cavity phase is monitored by the control system during operations. When the phase shift between the cavity and the established 0 phase is measured to be more that 10 degrees the mechanical tuners step the cavity frequency until the phase shift is less than 3 degrees.

The Linac Energy Management system is an automated system that sets the operating gradient of each cavity. Normally each linac is set up to provide 400 MV per pass. On any given day a maximum operating gradient is identified for each cavity, determined by performance limitations and available rf power, LEM then sets the gradient of all cavities to a uniform percentage of the operating limits. The percentage of maximum gradient required to support the 400 MV linac is a good indicator of cavity performance. When operating with the gradients at less than 85% of the maximum a typical cavity trip rate is one per hour, summed for the entire machine. If the gradient percentage is greater than 90% the trip rate increases to two or more trips per hour for the entire machine.

Auto-Krest, the utility used to measure and optimize the cavity accelerating phases during operations is performed in real time and does not disrupt beam operations. This is possible by maintaining the beam energy constant throughout the optimization. The phase of the cavity being optimized is stepped $\pm 10^\circ$ producing an energy shift. This energy shift is measured in the following arc and then compensated by adjusting the gradient of the second cavity used. The peak accelerating phase is then computed using the energy measurement at the three phase settings.

6 SUMMARY

The operating experience with SRF electron linacs continues to grow at a rapid pace. This has been driven by the recent large scale installation at CEBAF and the continued work at HEPL, MACSE, and S-DALINAC. The increase in the amount of operational experience should continue at this rate for the near future. These continued efforts should support the continued development in SRF electron linacs by establishing present performance limitations and working to expand those same limits.

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