Status Report: SRF Activities at CEBAF

John Mammosser

Continuous Electron Beam Accelerator Facility
12000 Jefferson Avenue
Newport News, VA 23606 USA

Abstract

The construction of the Continuous Electron Beam Accelerator Facility (CEBAF) is nearing completion in Newport News Virginia. The accelerator consists of 42.25 cryomodules in which 338 5-cell niobium cavities are to be installed. Presently 38.25 cryomodules are installed in the accelerator, 32 have been commissioned and all meet or exceed design criteria for energy gain and dynamic heat load.

Introduction

CEBAF will provide a low emittance electron beam with a current of 200 μA and electron energies up to 4 GeV for fundamental experimental studies in high energy nuclear physics.[1] The accelerator consists of a 45 MeV injector and two anti-parallel accelerating linacs arranged in a racetrack design as illustrated in Figure 1. Each linac contains 80 meters of accelerating cavities which are to provide 400 MeV of energy gain. Five passes through both linacs will provide the 4 GeV of energy gain needed.

Accelerating cavities (Figure 2) were manufactured from high thermal conductivity Nb with RRR values of ≥ 250. The design criterion for the accelerating gradient is $E_{acc} \geq 5$ MV/m with a Q value of 2.4×10^9 and a frequency of 1497 MHz at 2 K. Each 5-cell cavity is equivalent to 0.5 meters of accelerating length. Cavities are processed, assembled into pairs, tested vertically and assembled together with proper diagnostic hardware into a helium vessel called a cryounit. Four cryounits, and supply and return end cans are then connected together to form a cryomodule. Each linac consists of 20 cryomodules and the injector contains 2.25 cryomodules.

Vacuum Integrity

In production, cavities are paired to satisfy dimensional constraints, chemically processed, assembled into a hermetically sealed pair, evacuated and maintained under vacuum. Indium wire seals are used for 16 flange connections and two conflat-type seals are used for connecting the isolation valves at the ends of the pair. Figure 2 indicates the location of the indium seals connecting the Nb cavity pair.

Once installed into the accelerator, the cavity pairs must remain leak tight in superfluid He over the lifetime of the machine and through repeated thermal cycles if the integrity of the machine is to be maintained. To accomplish this goal, strict attention was paid to flange smoothness and cleanliness, cleanliness of the indium gaskets and bolt torquing procedures.[2] The use of appropriate leak checking techniques assured that assemblies, which did not meet leak rate specifications were eliminated at an early stage. Table 1 lists the leak rate specifications used at CEBAF for components and assembled pairs. It also lists the leak rate requirements for the cavity pair which corresponds to a He in-leakage rate necessary for a formation of one monolayer in a full year. Once a monolayer is formed, the beam line pressure would rise abruptly.

	CAVITY PAIR	COMPONENTS
REQUIREMENTS	$\leq 1 \times 10^{-7}$ atm cc/s	
SPECIFICATION	$< 2 \times 10^{-8}$ atm cc/s (@ 2 K)	$< 2 \times 10^{-10}$ atm cc/s (Room Temperature)
DESIGN OBJECTIVE	$< 2 \times 10^{-10}$ atm cc/s (@ 2 K)	$< 2 \times 10^{-10}$ atm cc/s (Room Temperature)

Table 1. Leak rate specifications.

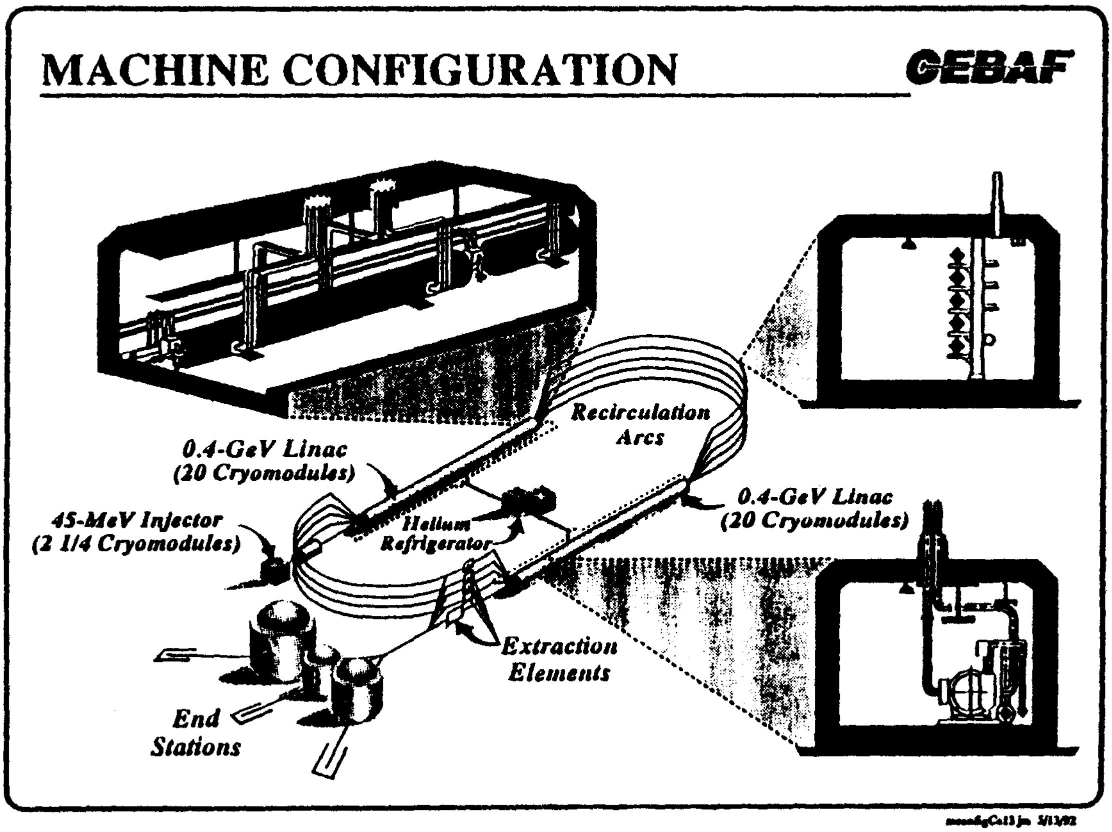

Figure 1. Machine configuration.

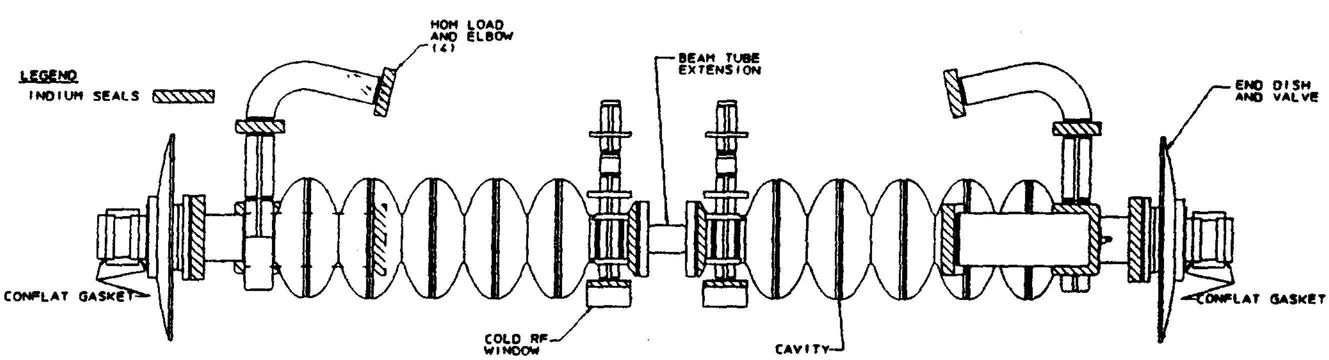

Figure 2. Cavity pair showing locations of vacuum seals.

For reliable leak checking of cavity pairs, a highly sensitive He desorption leak detection method was developed for the pairs during cryogenic testing.[3] Figure 3 shows the distribution of desorption leak rates for the pairs turned over for installation into the accelerator with a mean value of 3.5×10^{-11} atm cm^3 s^{-1}. A normal distribution curve is also plotted for comparison.

Vertical Test Results

The performance of each cavity was measured prior to installation into the accelerator. The pair was installed into a vertical fixture, lowered into a cryogenic dewar and tested at 2 K. To avoid "Q-disease", the cool-down to 4.2 K was accomplished ≤ 1.5 hrs. and the ambient magnetic field in the vicinity of the cavity was shielded to ≤ 10 mG.

As an example, the vertical test results of one cavity, IA333, are shown in Figure 4 along with a plot of the dissipated power. This figure illustrates two measures of E_{acc} used at CEBAF:

a) E_{acc} at the onset of field emission loading was defined as the point where the dissipated power rises off the constant Q_0 line. For Figure 4, this would be E_{acc} FE_{onset} =10 MV/m.

b) The usable gradient was defined as the accelerating field at which there was 1 watt of extra power due to field emission loading or 1 MV/m below the thermal magnetic quench field, whichever limited performance during vertical test.

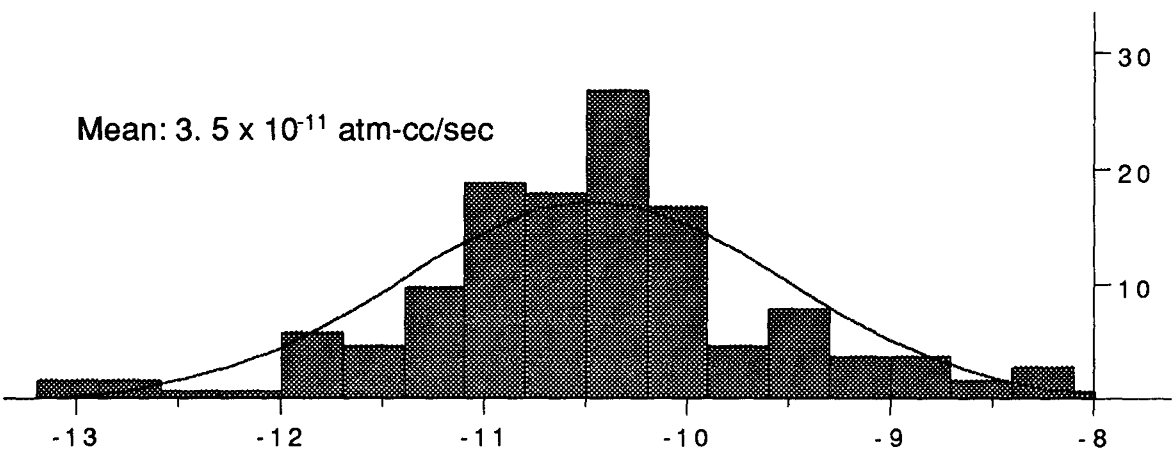

Figure 3. Integrated leak rates during vertical test, showing the number of cavities vs the log of the measured leak rate (atm cm^3 s^{-1}).

Figure 5 shows a distribution of Eacc and Q at the onset of field emission loading for all cavity pairs tested and installed into cryomodules. The mean accelerating gradient was 8.7 MV/m and the mean Q value was 8.5×10^9 which easily met our requirements of 5 MV/m and a Q value $\geq 2.4 \times 10^9$. As seen in Figure 5 there exists a wide range of accelerating gradients. Field emission loading has been detected as low as Eacc ~ 3 MV/m and as high as Eacc ~ 19 MV/m, even though the cavities received nominally the same surface treatment and assembly procedures. At this time we suspect random particulate contamination as the culprit for this wide spread, as indicated by recent studies[4,5] but the sources and nature of the contamination are not well quantified and further investigations are needed. Although most cavity performances showed field emission loading, 20% were limited by quench. Figure 6 shows the distribution of quench fields for cavities installed into the accelerator. Once again there was a large distribution which is not understood. It is likely that the quench limits of some cavities would improve with further chemical processing or heat treatment of the Nb.[6,7]

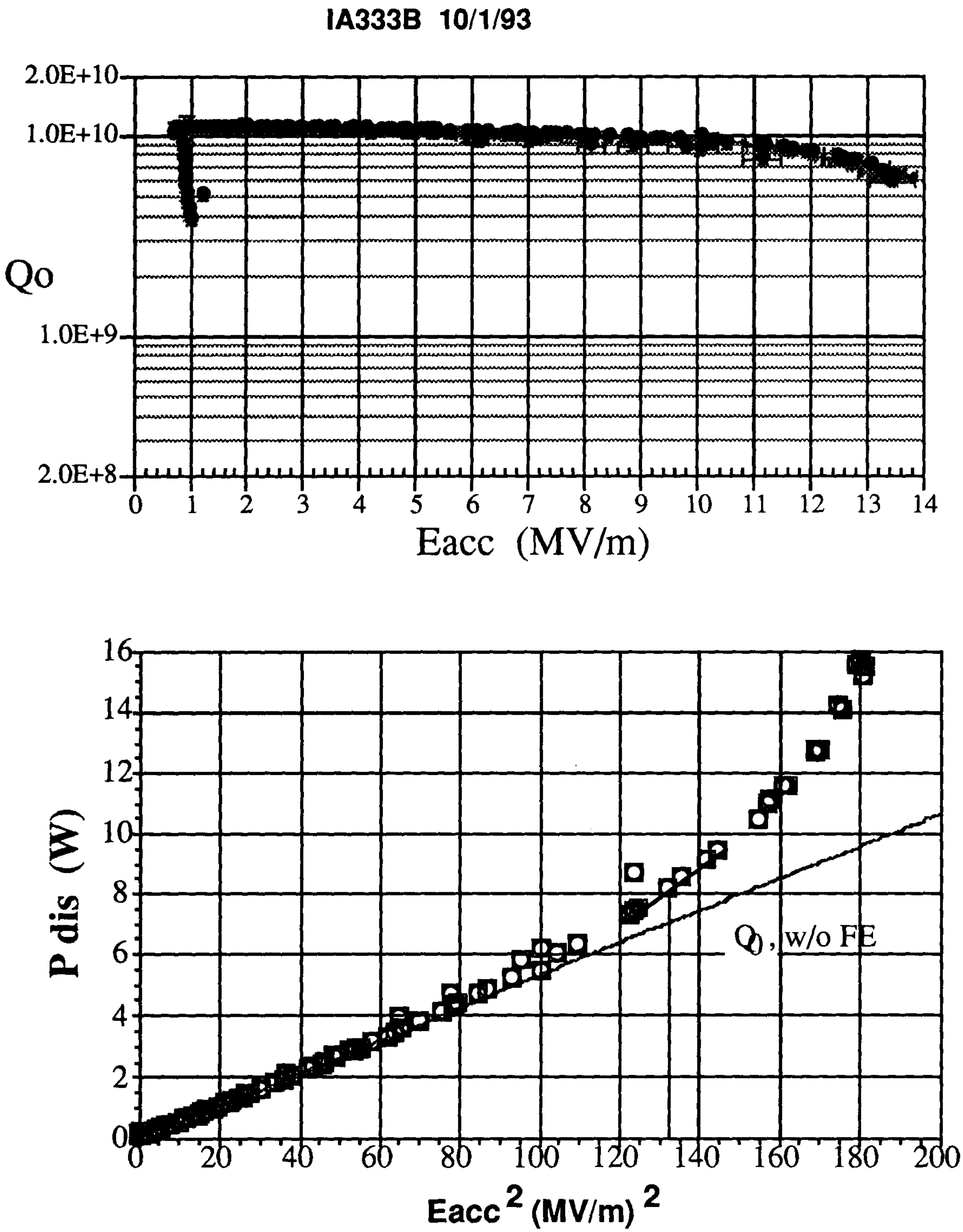

Figure 4. IA333 vertical test results.

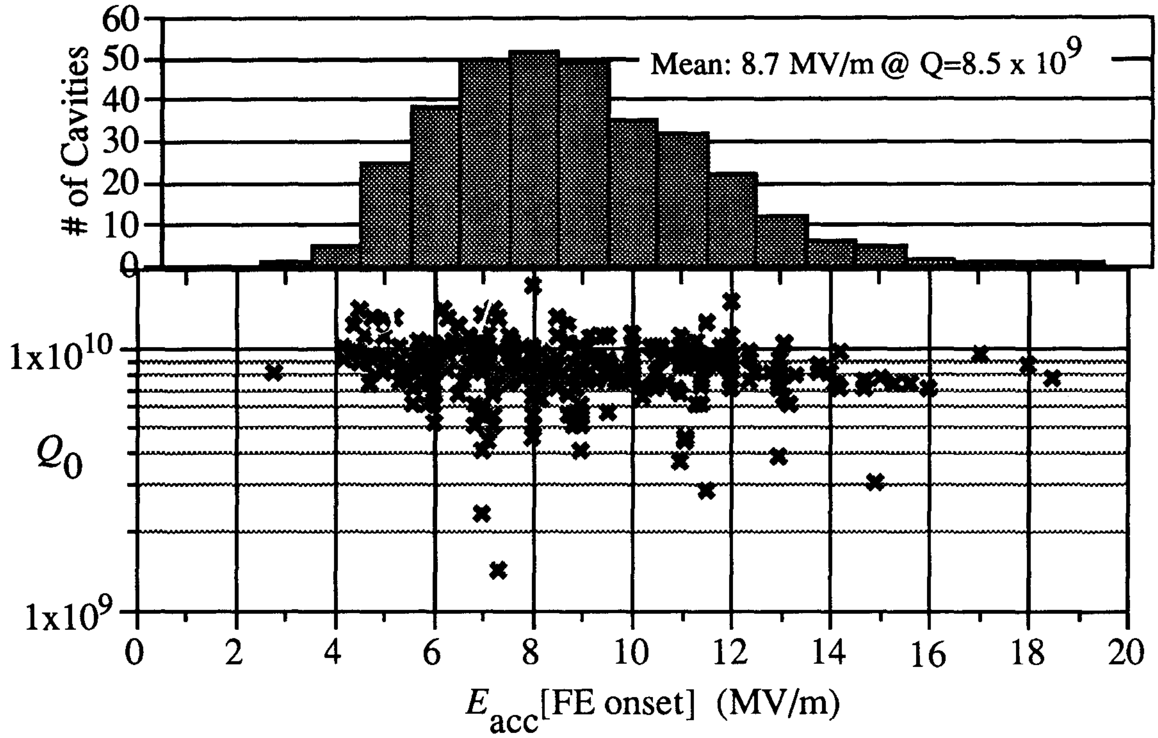

Figure 5. E_{acc} and Q_0 at field emission onset for all cavities in vertical test.

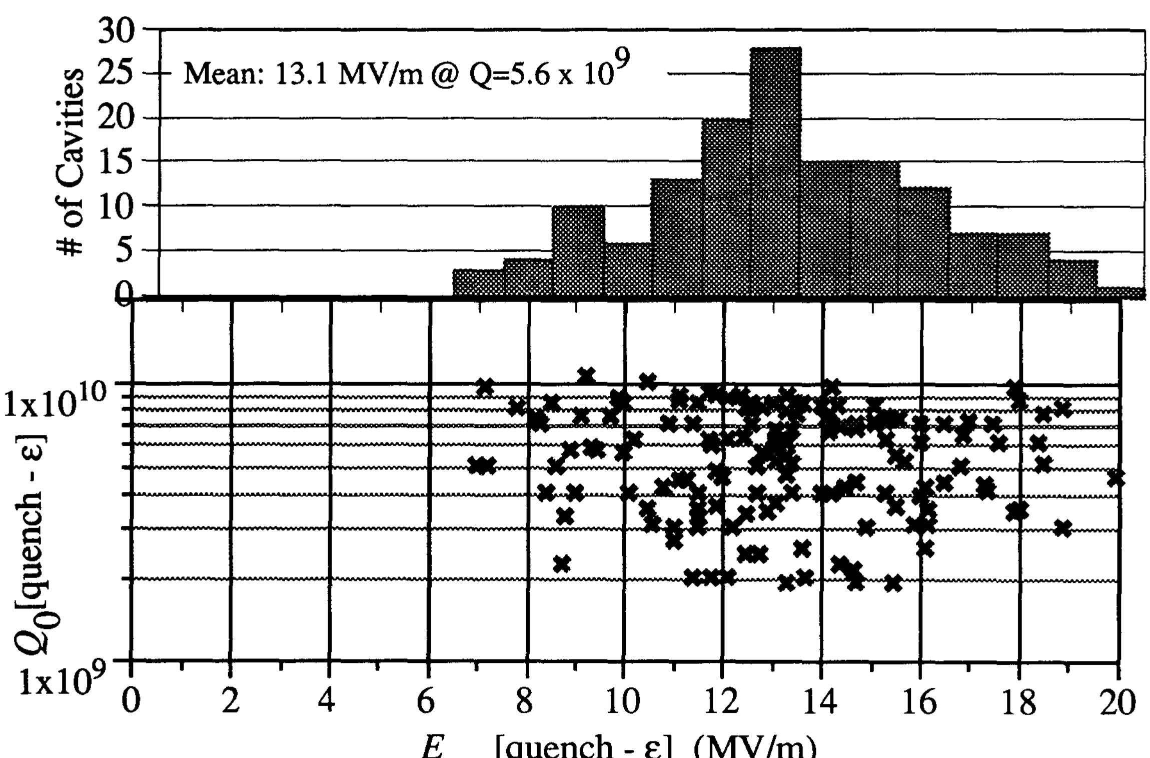

Figure 6. E_{acc} and Q_0 close to the quench field for 146 cavities in vertical test.

Production Issues

In mid 1990 CEBAF started production of cavity pairs to find problem areas and to develop procedures needed for the assembly of 169 pairs into cryomodules. CEBAF's cavity pair production experience is shown in Figure 7. It depicts assembled pair yields during the production period from startup through August 1993. A 100% yield represents a pair that was assembled, tested, turned over for cryomodule assembly and which met requirements without a retest or reassembly. At the bottom of Figure 6 the number of successfully produced cavity pairs is shown. During the first year, several major problems were encountered such as isolation gate valve leaks, unreliable indium seals, a few ceramic window leaks, and production problems with the HOM absorber material. At this point production was halted, the problems were addressed and production was restarted at the end of 1991.

During the remainder of the production period several new problems appeared, such as leaks in the end dish bellows and leaks in the Nb foil in the ceramic window, which had to be addressed during sustained production. Although Figure 7 represents the most serious production problems, there were many minor details which had to be dealt throughout the production period. Below is a list of all problems encountered, from startup to August 1993, which encompasses 225 cavity pair assemblies. Starting with the most prevalent of difficulties, each problem category and the number of events is summarized below.

RF WINDOW LEAKS [23]

The fundamental power coupler on the CEBAF cavity uses a ceramic window made of several components. A polished high purity alumina is metallized at the edges and brazed to a thin Nb foil which is then electron beam welded to a bulk Nb flange. In this rather complex assembly, several types of leaks were encountered; leaks through the ceramic, which is often correlated with excessive field emission loading of the cavity, weld leaks, and cracks in the Nb foil related to impurities and H-embrittlement in the foil. The window assembly procedures are still under study in order to improve the window reliability.[8]

TEST STAND PROBLEMS [13]

The next most prevalent problem was test stand problems such as cable breakdowns and malfunctioning variable input couplers. During early production it was discovered that RF cables were glow discharging inside the connectors in the He gas region of the dewar. This problem caused early termination of RF tests due to input cable failure. The problem was solved by installing a He leak-tight cable connector assembly.[9]

The variable input coupler also contributed to many early terminations of RF tests. The coupler consists of a Nb half-wave, "top hat" waveguide with a variable coaxial coupling probe which allowed operators to critically couple the cavity. The top hat probe assembly was very sensitive to alignment. Misalignment would cause the coaxial probe to short at certain positions or cause the drive system to become immobile.

COLD LEAKS [9]

Cold leaks were detected by a residual gas analyzer during warm-up of the pair from a cryogenic test. Pairs or test stands which had leak rates > 10^{-8} atm cm^3 s^{-1} were leak checked subsequently at room temperature and were repaired if a leak could be localized by exchange of the failed gasket or component. Not all leaks were found and a few pairs had to be disassembled.

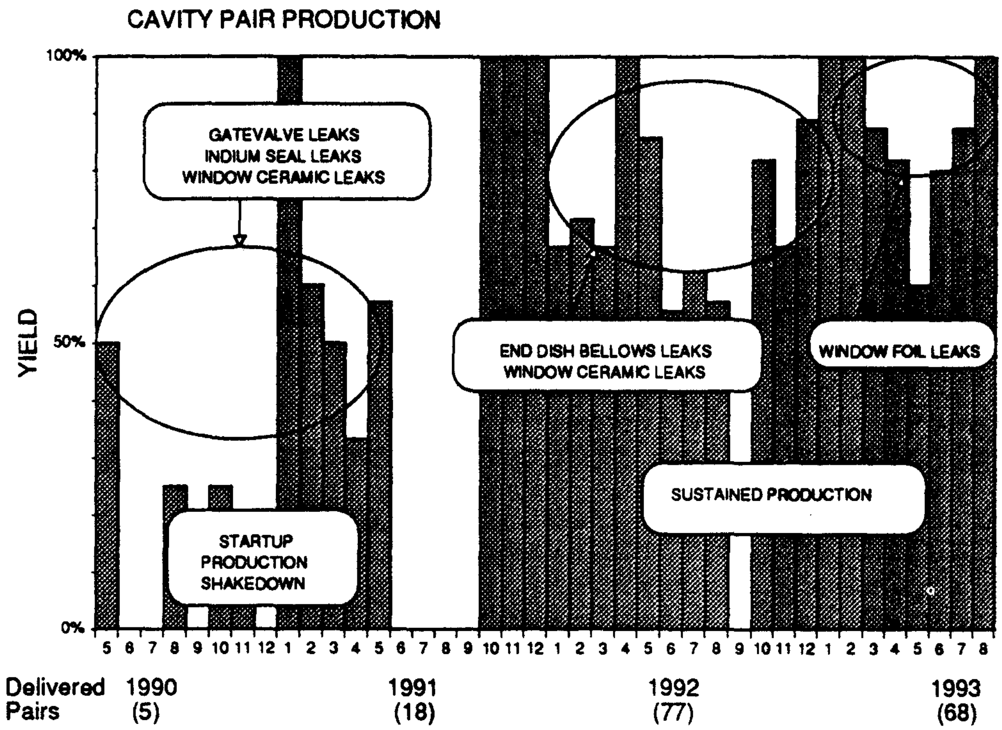

Figure 7. Cavity pair production bar chart.

LOW Q_0's [9]

Several cavities had Q_0 values below specification of 2.4×10^9. It was later discovered that most of these cavities did not receive sufficient material removal during chemical processing and the rest could be due to particulate contamination. Disassembly and reprocessing fixed the problem.

ISOLATION GATE VALVE LEAKS [8]

Most isolation gate valve leaks occurred early in production. These valves were added at the beam-pipe ends of a cavity pair to isolate the pair while being assembled into or out of a cryomodule. Even though initial prototype valves performed very well, it was found later that the reliability of the production valve sealing after the cryogenic RF test was low. The valve used a Viton o-ring as its sealing mechanism. It was discovered that the tolerances of the valve body carriage and camover mechanism were not good enough to repeatedly seal the paddle in which the o-ring was located. This problem was solved by using a valve of a different manufacturer, which had a more reliable sealing mechanism.

INDIUM SEAL LEAKS [8]

During assembly most indium seals were pressed onto the auxiliary parts prior to assembly in order to reduce the assembly time. Most indium seal leaks were attributed to particulate contamination in the seal, scratches across the sealing area or stains from chemistry in the sealing area. In all cases leaks were discovered in a bagged leak check and the suspect component was removed and replaced.

Q_0 SWITCHES [6]

In several cavities the Q-value dropped irreversibly to a lower value at certain field levels. Six pairs were disassembled because the drop in Q_0 in one cavity was significant enough that the pair could not be utilized in the machine. Many other cavities also had small Q_0 switches but the cavities still met specifications. The cavities with significant Q_0 switches were inspected after disassembly, but no obvious reasons for the degradation were found. Conceivably they were caused by surface imperfections and "temperature mapping" will be needed to identify the defective areas.

FIELD PROBE LEAKS [6]

During assembly, a field monitoring probe was installed in the higher order mode coupler waveguide for pi-mode field sampling and phase locking the cavity. This probe was a stainless ceramic feed through with a screwed-on copper probe on the center conductor. Several leaks on the field probe occurred due to mechanical damage to the ceramic during handling.

PAIR LEAKS AFTER TURNOVER [5]

Several leaks were found after pairs were turned over for installation into a cryomodule. These leaks occurred early in production and they were due to improper sealing techniques in combination with less sensitive leak detection devices. As discussed above, more stringent assembly procedures eliminated this early difficulty.

STAINS IN SEAL AREA [3]

During chemistry Nb oxide stains occurred on flanges that were covered with polyethylene blanks at the end of the cleaning process. The stain occurred during ultrasonic cleaning at flange locations where de-ionized water passed between the Nb and polyethylene. Even though the growth mechanism for the Nb-oxide is not understood, the occurrence of stains was prevented by modifying the final rinsing step to a static water bath with ultrasound, rather than having the ultrapure water flowing through the cavity and polishing loop.

PROBE SHORTS [2]

Field probe shorts were caused by indium creeping out of flange areas and shorting the probe antenna. This problem was solved by using smaller diameter indium, thus reducing the creep distance.

OTHER [9]

The category "Other" represents single occurring events such as resonant frequencies or probe Q external values being out of specification.

Overall, most production problems were easily overcome, but some are still under investigation such as certain window ceramic failures. Although most production problems occurred early during startup phase, 31% of the pairs had to be repaired during sustained production because they did not meet all requirements after the first RF test, as shown in the pie chart in Figure 8. They had to be repaired by replacing a component, retested or reprocessed and reassembled. However, 69% met requirements for the accelerator after the first RF test.

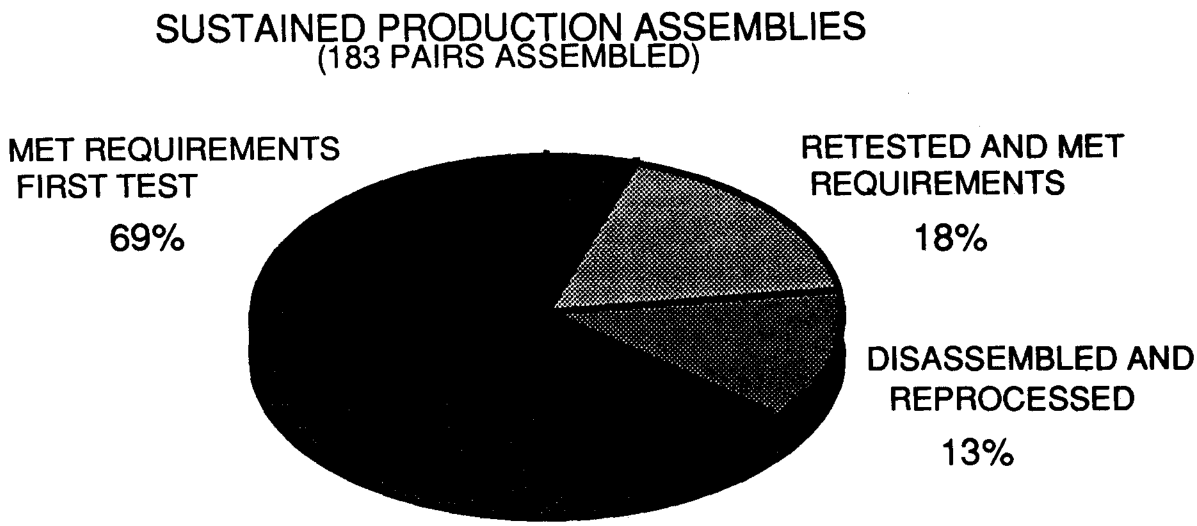

Figure 8. Sustained production assemblies.

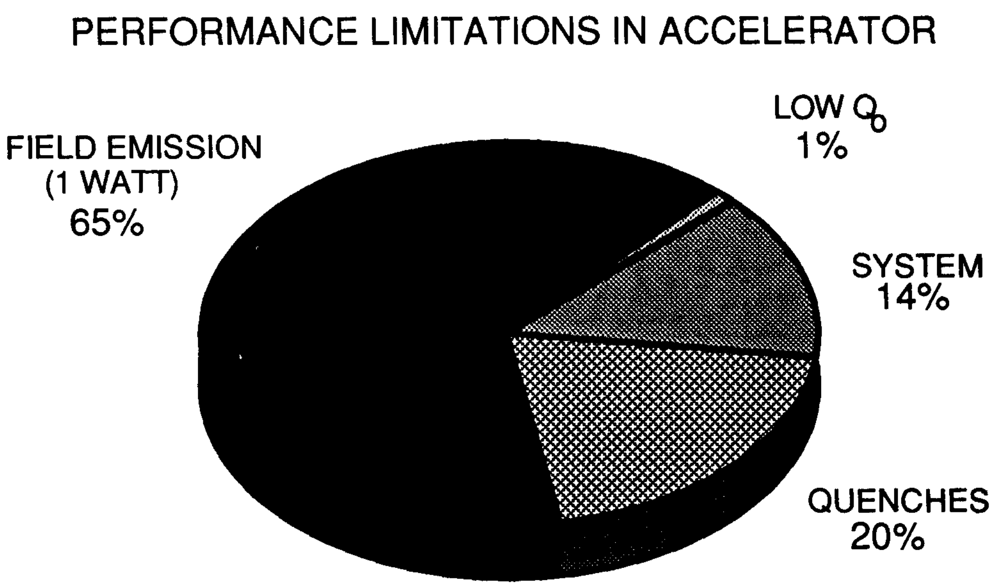

Figure 10. Performance limitations in the accelerator.

COMPARISON OF VERTICAL TEST TO COMMISSIONING DATA

The comparison of usable gradients obtained during vertical test to commissioning data obtained on cryomodules in the tunnel is shown in Figure 9. The vertical test E_{acc} is approximately 2 MV/m higher on average than cavities installed into the accelerator. The cause of reduced cavity performance in the accelerator is not obvious but in most cases field emission on-set starts at lower fields and in some cases system interlocks, which are not present in the vertical test, prevent further increase in field level. Figure 9 shows the same comparison, but here the interlock limitations are removed. The difference between vertical test performance and accelerator performance has been reduced to 1 to 1.5 MV/m. In Figure 10, a look at the performance

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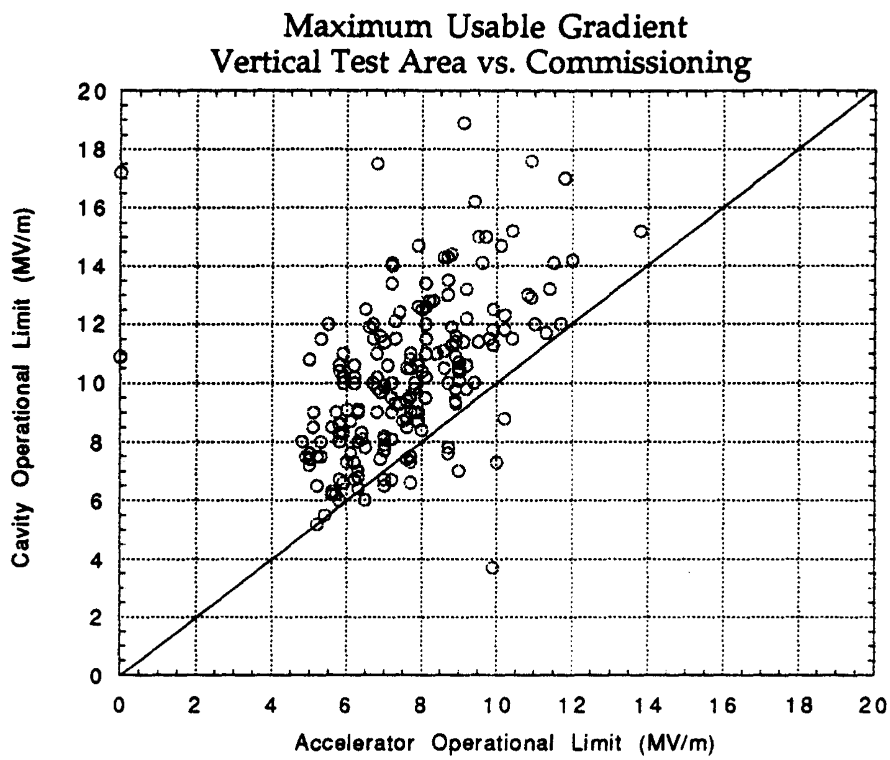

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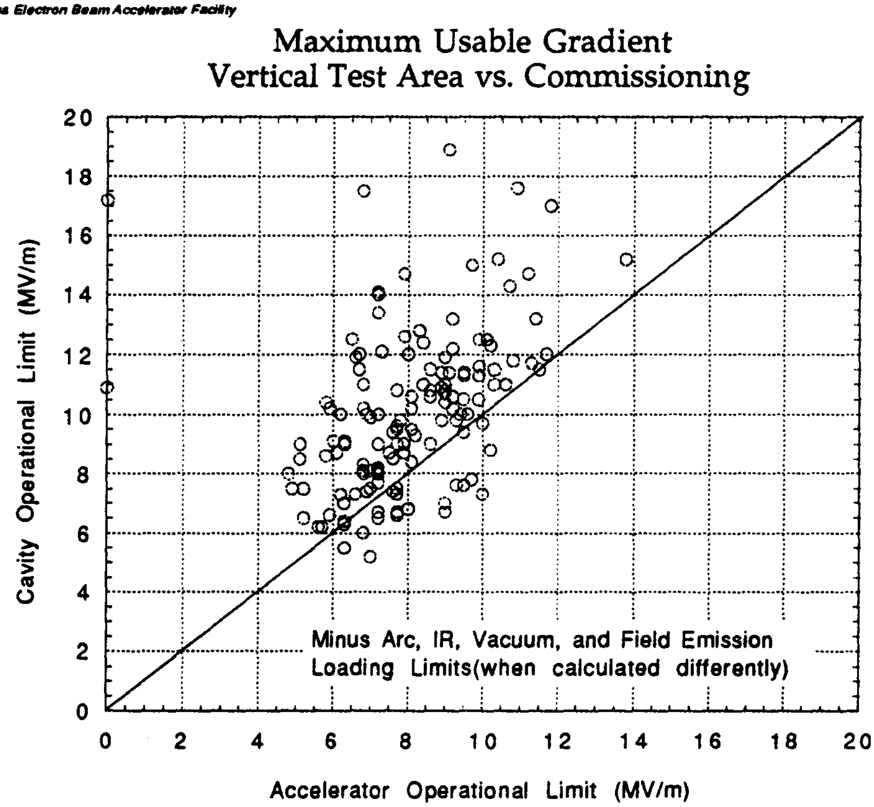

Figure 9. Comparison of usable gradients.

limitations of 24 cryomodules installed in the accelerator shows that 65% of the cavities are limited by field emission loading as determined by calorimetric measurements in the tunnel (see below). The remainder of the limitations are: 20% quenches and 14% interlock trips. The remaining 1% of the cavities of this group have Q_0 values below specification. Cavities with low Q values have recently been encountered during commissioning of cryomodules and are now under investigation. There are several modules in a series with low Q_0 cavities in the 4th position or middle position of the cryomodule.[10] Because of the correlation of the occurrence of this problem with position we suspect a cooling rate induced Q-disease as the most probable cause.

Figures 11 and 12 compare the performance of a cryomodule of the south linac with the cavity data taken in the vertical pair test. Even though this module is slightly better in performance than the average module, it is representative of the majority of the performance differences in most modules.

MEASUREMENT ERRORS

It is difficult to make a comparison of vertical test data to that of accelerator commissioning data because the systems, their interlocks, measurement techniques and errors in measurements are different. One must keep in mind that in the cryomodule commissioning procedure the Q_0 values are measured calorimetrically with a larger uncertainty than in the critically coupled vertical test. In addition, there is a somewhat slower cooldown through the dangerous temperature region for Q-disease. The following is an attempt to make such a comparison to show cavity performance discrepancies

IA50/284

The first pair analyzed was cavity number IA50/284 which was assembled on 14 January 1993. Both cavities were processed in buffered chemical polish (BCP) for 1 minute as a final cleaning before assembly. The chemical treatment and rinsing were both typical of most cavities and there were no recorded discrepancies in the production traveller. The cavities were then assembled in the cleanroom and once again the assembly was typical with no recorded problems. The pair was then placed in the vertical fixture with IA50 as the lower cavity, moved to the dewar and set in place. The cavities were then both RF tested on 20 January 1993.

Cavity IA284 (top cavity) was tested first and it had a Q_0 of 1×10^{10} out to 6.3 MV/m where field emission loading started. The performance was slightly improved by processing in the $2/5\ \pi$ mode. After several more minutes of RF processing the cavity had improved to 7.7 MV/m as the accelerating gradient for field emission onset. This was the limitation in vertical test for this cavity. The accelerator commissioning data also shows field emission as a limitation for IA284 but the onset of field emission loading started already at 6.0 MV/m. The Q_0 in the accelerator was also lower at 8×10^9.

Cavity IA50 (bottom cavity) was tested next and it had a Q_0 of 1×10^{10} up to a gradient of 14 MV/m; a quench at this gradient irreversibly lowered the Q value. The next few runs showed a slight improvement in the field emission onset and the last run started field emission loading at 11 MV/m. The accelerator results again showed field emission loading much earlier and the performance limitation at 9.7 MV/m. The Q_0 at low field was 8×10^9. Both cavities were field emission limited in both tests, which could indicate particulate residual contamination before the first vertical test.

IA64/142

The chemical treatment and assembly took place on 5 January 1993 for this pair. Final surface treatment for both cavities was 1 minute of BCP and no problems were recorded. The assembly had no problems and the pair was tested on 11 January 1993.

Cavity IA142 (top cavity) was tested first and it had an unusually low Q_o of 4.6×10^9 in the vertical test. Which remained at this value up to the quench field of 18.2 MV/m in the first run. The field had a slope to it, but there was no field emission loading. The second run showed a slight degradation with field emission loading starting at 15.2 MV/m and the cavity quenched at 18.1 MV/m. The accelerator test was similar with a Q_o of 6×10^9 and had field emission loading starting at 10.8 MV/m but there was no significant Q_o loading.

Cavity IA64 (bottom cavity) had a Q_o of 1×10^{10} and RF processed very little during vertical testing. The cavity test showed onset of field emission loading at 11.5 MV/m and quenched at 18.2 MV/m. In the accelerator, the cavity had a very low Q_o with a steep slope. The Q_o at E_{acc} of 2 MV/m was approximately 2×10^9; nevertheless the gradient could be increased to a quench field of 13.4 MV/m with a Q value of 2.6×10^8.

The cavity pair IA64/142 represents the best performance pair in vertical test with respect to accelerating gradient. In the accelerator performance of cavity IA64 has considerably degraded in Q and gradient. In the assembly traveller it was noted that the ion pump for this pair had tripped off several times after vertical testing and was eventually replaced before installation into the accelerator. Possibly particulates released from the pump, entered into IA64 to which it was attached and degraded the cavity.

IA203/210

Both cavities received a normal surface treatment and assembly on 7 January 1993, and were vertically tested on 14 January 1993. Cavity IA210 (top cavity) test results show a Q_o of 1.1×10^{10} and no field emission loading out to a quench at 11.6 MV/m. There was no processing recorded during the test. The accelerator also shows a good Q of 1.0×10^{10}, no field emission loading and a quench at 10.2 MV/m. Cavity IA203 (bottom cavity) had a Q_o of 9.6×10^9 and quenched at 10 MV/m in the vertical test. There was no recorded radiation during the test . In the accelerator test there was field emission just before a quench at 8.8 MV/m, and the Q_o was slightly lower at $\approx 7.8 \times 10^9$. The accelerator data for both of these cavities have error bars for Q_o within that measured in vertical test. This pair started as a field emission free pair with quenches as limitations and the integrity was maintained through installation into the accelerator.

IA40/255

Both cavities received a normal surface treatment and assembly on 12 January 1993 and were vertically tested on 15 January 1993. Cavity IA255 (top cavity) had a Q_o of 9×10^9 at low field and the gradient could be increased to 18.5 MV/m, where it quenched, with little or no processing. At 18.2 MV/m some radiation was recorded at the cryostat, but no degradation of Q_o typical for FE-loading was seen. The accelerator performance however was reduced. The cavity had a Q_o of 7×10^9 and was field emission limited at 10 MV/m. The cavity field was increased to a quench at 13.3 MV/m to find the limitation but no Q_o measurements were made. There was no radiation recorded until a field of 13.2 MV/m, just before the quench field. IA40 (bottom cavity) was tested with a good Q_0 of 1×10^{10} and in the first run Q_0 remained constant up to the quench field of 15 MV/m. This event degraded the cavity's performance and the final runs of the cavity started field emission loading at 13.3 MV/m and quenched at 15.7 MV/m. The accelerator test results showed lower Q_0 of 7×10^9 and field emission as the performance limit. Both cavities in this pair will be usable in the accelerator to 10 MV/m given no other constraints.

SOUTH LINAC CRYOMODULE-08

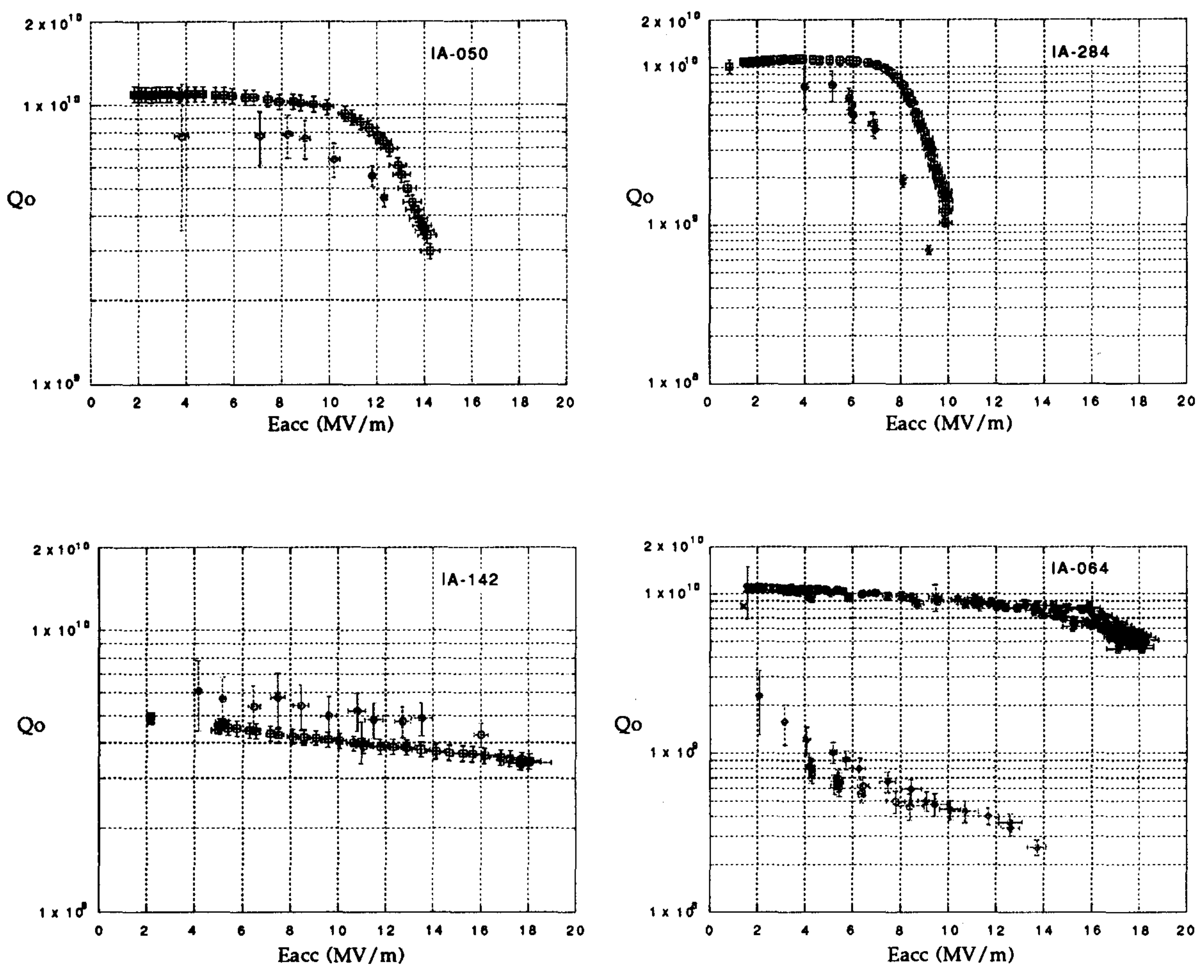

Figure 11. Comparison of vertical test RF data to cryomodule commissioning data.

Cryomodule Performance

The bar graphs (Figures 13 and 14) show accelerating voltage contributions of each cryomodule commissioned in the north and south linacs respectively. The dark bars represent maximum usable voltages, provided there are no other limitations. The lighter bars show voltage contributions that are optimized for a 45 watt dynamic heat load to the cryogenic system. Also on the bar chart is CEBAF's accelerating voltage specification of 20 MeV for a cryomodule. All the cryomodules commissioned easily fulfill specification for accelerating voltage contribution at 45 watts dynamic heat load.

Other Activities

Other ongoing SRF activities at CEBAF include several investigations either planned or underway in the area of understanding the phenomena associated with the RF windows. These include basic window performance studies and studies of the phenomenon at the windows and in the waveguide between 300 K and 2 K. Studies aimed at improved materials are in various stages. These include better antimultipacting coatings, new materials for warm and cold windows, and investigation of superconducting metallization of ceramics for low loss RF windows.[11]

SOUTH LINAC CRYOMODULE-08

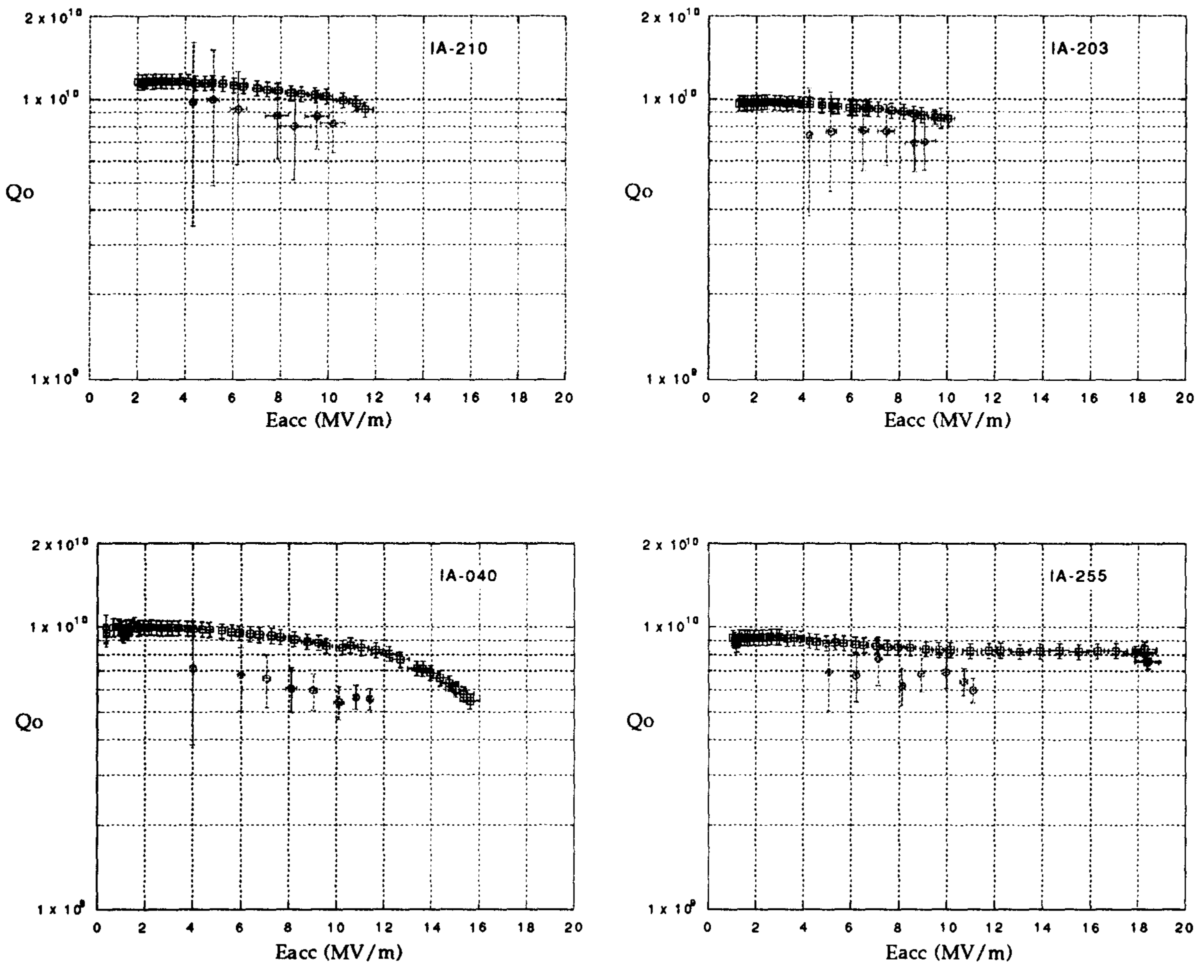

Figure 11. Comparison of vertical test RF data to cryomodule commissioning data.

Cavity performance studies are also continuing. Among these will be further work on high pressure rinsing, investigations of cleaning efficiency of various cleaning methods, Nb thermal conductivity studies[12], fabrication and testing of single cell cavities with RRR > 1000 material provided by IHEP, Protvino, and Q disease studies.[13] Basic research on superconducting thin films, aimed at reduction of field emission and improved economy of structure fabrication and operation, will also be undertaken at CEBAF. Finally, work relating to HOM loads will go forward, including tasks aimed at better thermal conductivity of ceramic materials, improved understanding of the sintering process, and designs which reject the heat generated by the HOM loads at 50 K rather than 2 K (for high current machines).[14]

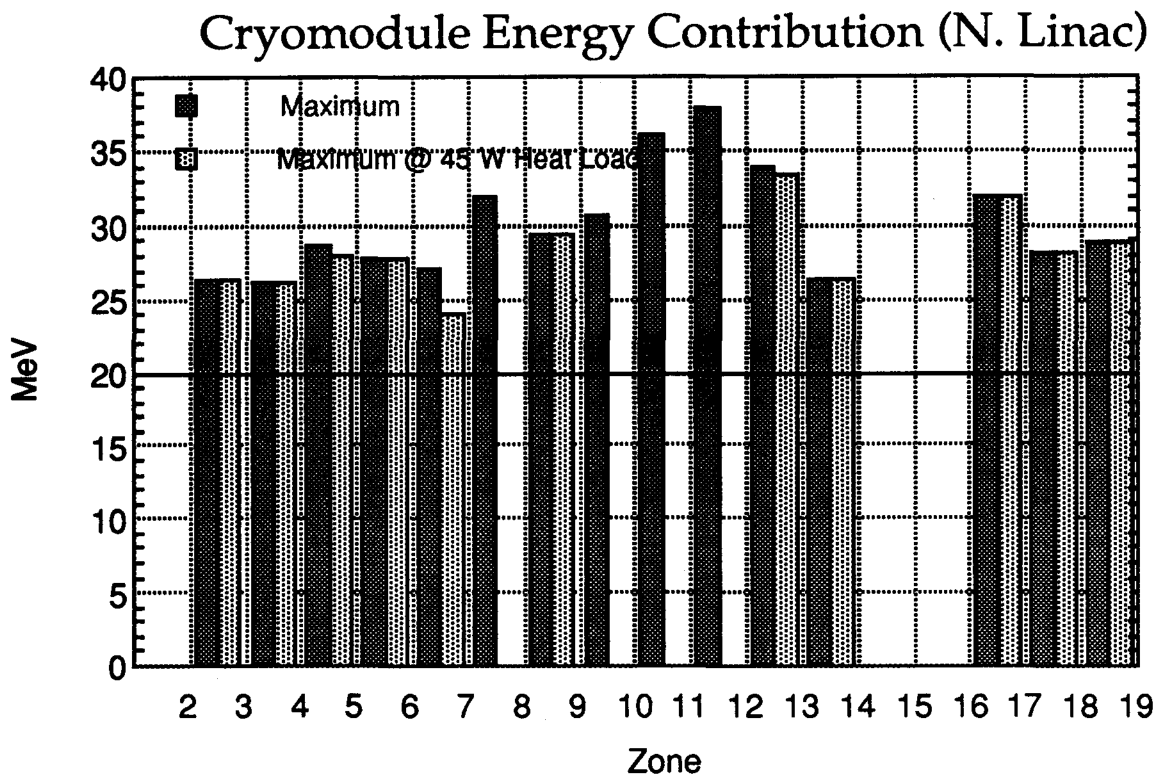

Figure 13. North linac's cryomodule performance.

Conclusions

All 169 cavity pairs for the CEBAF accelerator have been assembled and tested. The SRF Department will complete its production of 42 cryomodules by the end of 1993. Thirty eight of these were installed in the accelerator as of October 1, 1993, and thirty two modules have been commissioned. Five more modules will be commissioned by December, 1993. Commissioning of the last five modules will not occur until April and May of 1994 due to accelerator operations constraints.

In the vertical dewar test, the average gradient with one watt of field emission induced power dissipation was 9.6 MV/m at a Q of 7.3×10^9, compared to the specification of 5 MV/m at $Q = 2.4 \times 10^9$. In the accelerator, commissioned modules average an energy gain of 28.3 MeV at 45 W dynamic heat load, or 7.1 MV/m, which is 40% above specification.

Acknowledgments

The notable performance of CEBAF's superconducting cavities is attributable to many persons' efforts over a ten year span: CEBAF's technical staff for their expertise, creativity, flexibility, attention to detail, and most of all for never losing sight of our primary mission, building a high quality accelerator; L. Williams, G. Sundeen and G. Martinez for making the SRF office run smoothly and assistance in preparing this manuscript. I would also like to thank our industrial partner Siemens for cavities delivered on schedule and of the highest quality; and Cornell

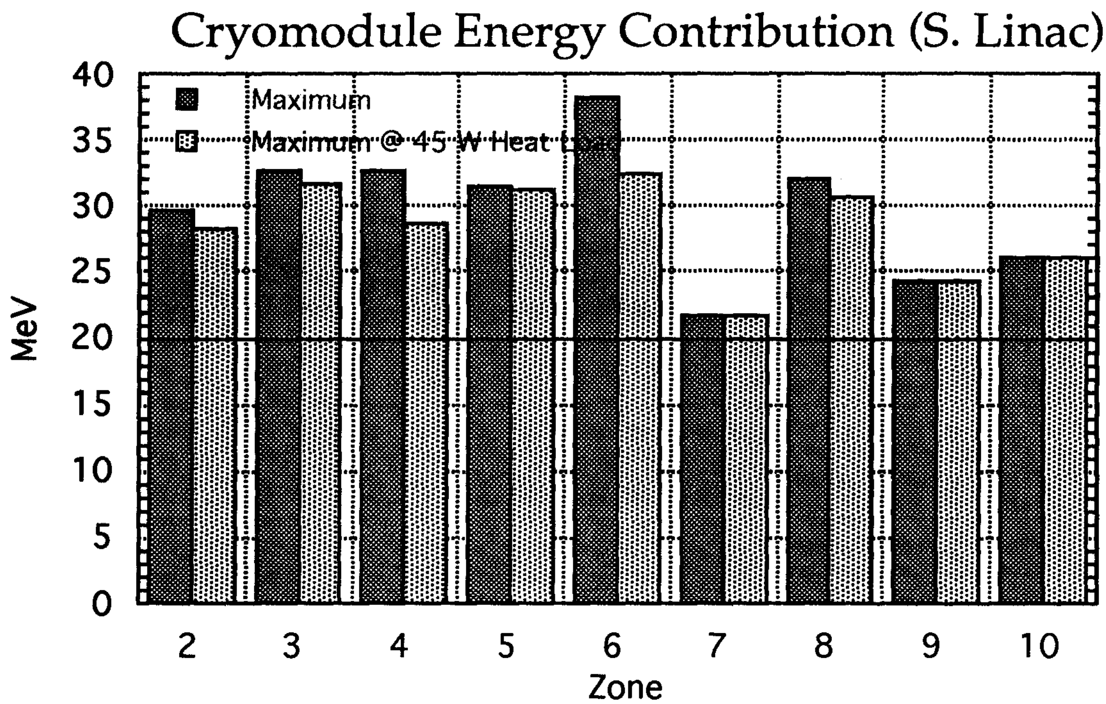

Figure 14. South linac's cryomodule performance.

University's labatory of nuclear studies for their contributions nurturing a developing technology. Most of all I would like to thank P. Kneisel and R. Sundelin, the principals who have made it possible for all of us to experience this innovative technology.

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1 H. Grunder, in Proceedings of the 1988 Linear Accelerator Conference, CEBAF-Report-89-001, June, 1989, p. 3.

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6 P. Kneisel, "TESLA Activities at CEBAF," contribution to this Workshop.

7 B. Bonin, "State of the Art in ß = 1 Superconducting Cavities," contribution to this Workshop.

8 L. Phillips, "Update on Windows, Couplers, HOM Damping, and Interlocks," contribution to this Workshop.

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12 P. Kneisel, "TESLA Activities at CEBAF," contribution to this Workshop.

13 P. Kneisel, "Observation of Q-Degradation in Superconducting Niobium Cavities due to Cooldown Conditions," contribution to this Workshop.

14 I. Campisi, "Artificial Dielectric Ceramics for CEBAF's Higher-Order-Mode Loads," contribution to this Workshop.

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