Preliminary Statistical Analysis of CEBAF's Cavity Pair Assembly Process Data

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ABSTRACT

CEBAF has been collecting much data during the cavity pair assembly process. Some process data has been entered and analyzed during the last two years as part of our attempt to apply statistical process control methods. Analysis is presented here on mechanical tolerances achieved by the industrial fabricator of the CEBAF superconducting rf cavities (Siemens). Suggestions for tolerances obtainable in future procurements are made. Influence of cooldown conditions during vertical test on field emission onset gradient is discussed. An increase in the mean gradient of 2 MV/m was seen after a simple change in procedure.

Mechanical Data

The outline of the CEBAF cavity is shown in Figure 1. Cavities are measured upon receipt and sorted into pairs according to window height (C), overall length (A) and window flange location (B). Specifications are in Table 1. The interaction of these specifications and the interface to the cryostat is substantial, and sorting was needed to meet the cryostat interface requirements. About 10% of the assemblies require custom beam tubes to meet the cryostat length interface. The pair length constraint was set at ±0.5mm early in the design process. (1) While this was relaxed in early 1992 to ±1.5mm, it could not be increased further without cryostat redesign. The waveguide interfaces for the two cavities are bolted to the inside of the stainless steel helium vessel. The differential contraction of the niobium and stainless steel puts a torque on the indium vacuum joints. The mechanical response of the system is such that the tops of the waveguide interfaces must lie between two parallel planes 0.4 mm apart in order to maintain an adequate safety factor on the indium seal integrity. This 0.4 mm tolerance is difficult to achieve in a bolted sheet metal assembly of this sort, so custom waveguide interfaces must be machined, causing a two day delivery delay, about 5% of the time. Another 15-20% of the pairs are brought into the interface tolerance band without delay by selection of waveguide interface parts from two sets of non-standard parts, one set with a 0.1 mm tilt and the second with a 0.2 mm tilt on the mate to the window flange.

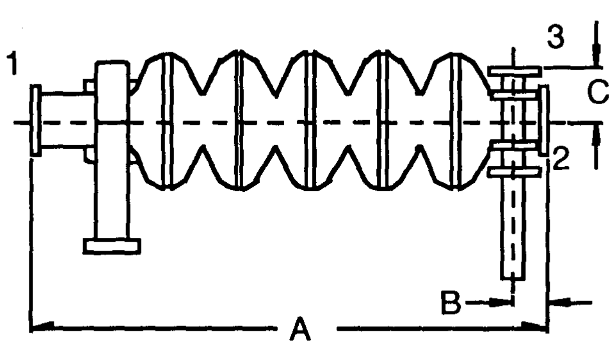


Figure 1. CEBAF cavity

Table 1 - Interface dimensions and tolerances (mm)

Overall length (A)	717.55±6
Coupler location (B)	46.33± 0.07
Coupler height (C)	76.20±0.1
Perpendicularity of flanges (1, 2) to beam axis	0.2
Parallelism of coupler flange (3) to beam axis	0.2

Means and standard deviations achieved on the three lengths shown, as measured by CEBAF and Siemens, are given in Table 2. The first two columns represent the first 36 units and the last two the remaining 324 units. It seems reasonable to conclude that the latter are more representative of series production, and that the first 10% can be considered the early part of the learning curve, so only the last 90% will be discussed below.

Table 2 - Cavity lengths (mm)

	Cavities 1-36		Cavities 37-360	
	Mean	σ	Mean	σ
Overall length (A)				
CEBAF measurements	720.74	1.73	721.48	0.97
Siemens	720.44	1.57	721.47	0.98
Window flange location (B)				
CEBAF	46.33	0.14	46.28	0.07
Siemens	46.35	0.05	46.32	0.05
Window height (C)				
CEBAF	NA	NA	76.28	0.06
Siemens	76.12	0.12	76.25	0.07

The agreement between the measurements made of overall length (A) is excellent. Only six cavities (2%) fall outside ±2 mm for the last 90% of the production run. Since this was achieved even though the span allowed was much broader, a length tolerance of ±2 mm is reasonable for future acquisitions. Agreement between CEBAF and Siemens measurements on dimensions B and C is not as good. It is believed that this is due to the difference in the way the cavities were supported on the table of each organization's coordinate measuring machine. CEBAF supported the cavity at the first and fifth cells while Siemens supported three of the five cells. Cavities are held by one beam tube and the coupler flange in the cryostat, so the CEBAF measurement is more representative of use. The cavities sagged. This is shown in Table 3, which gives the angles at points 1, 2 and 3 on Figure 1. Future acquisitions should include explicit descriptions of the measurement setup to be used, including supports. Nevertheless, the tolerances achieved are quite acceptable.

Table 3 - Interface Angles

	mean	σ
Beam flange angle at HOM (1)	89.93°	0.04°
Beam flange angle at FPC (2)	89.92°	0.04°
Coupler flange angle to beam (3)	0.04°	0.03°

One can loosen the tolerances for dimensions B and C without custom machining of interface components if one maintains an inventory of 40 to 50 cavities and sorts. Since CEBAF generally had at least this quantity of unused cavities on site during full rate assembly, the variations measured by CEBAF were not a problem. Tolerances of ±0.15 mm and ±0.12 mm for dimensions B and C, with appropriate measurement protocols, are deemed achievable for future acquisitions.

The thinness (9 mm) of the flanges of the Cornell design did not allow for substantial machining after welding to obtain better length tolerances, better perpendicularity of flanges 1 and 2, and better parallelism of flange 3 to the beam axis. The thinness of the flanges also has been implicated in problems with the integrity of the indium vacuum seals used in the assembly of the cavity pairs.(3) An increase in flange thickness to 15 mm before final machining would stiffen the flange by a factor of three and allow adequate material for final machining to form and position. Since the fabrication cost of the cavities is ten times the raw material cost, this addition of material is insignificant and cost effective in reducing assembly labor. With thicker flanges, the form tolerances in Table 1 (parallelism and perpendicularity) could be tightened from 0.2 mm to 0.1 mm, perhaps eliminating the need for custom interface components altogether. Some development work was done on the obvious alternative, fabrication of niobium bellows for inclusion in the interface components, but when it became clear that this development could not be completed in time for production custom machining was adopted. (4)

Effects of Vertical Test Cooldown on Field Emission Onset

CEBAF's vertical test system and its rf test results are discussed elsewhere (2). We wish here to address one simple change made in our vertical test procedure which revealed that the cavities were capable, on average, of 2 MV/m higher accelerating gradients than originally thought.

It has been found that the lower of the two cavities in a vertical pair test tends to exhibit greater field emission loading than the upper unless the initial cooldown conditions are controlled so that the assembly is cooled as uniformly and as quickly as possible. The enhanced field emission is attributed to locally concentrated adsorbed gas from the residual components of the cavity vacuum. The required uniformity has been achieved by shrouding the cavity pair with mylar to insure that a 7cm pumping line connecting an ion pump atop the dewar lid to the bottom cavity cools before either cavity. (A room temperature valve in this line is closed at 100 K when cryopumping overtakes the ion pump base vacuum.) In Figure 2 we show field emission onset gradients for 290 cavities divided into four sets: top and bottom, with and without the mylar shroud. The effect of the change in vertical test setup is clear: mean field emission onset gradient has increased by 2 MV/m and the means of the top and bottom cavity distributions are now the same. In Figure 3 we plot the same data as histograms, to show that the distribution of the bottom cavities without shroud was skewed while the other three distributions are close to normal. In Figure 4 we plot field emission onset gradient versus time. It should be noted that the standard deviation of this value has remained constant at about 3 MV/m as the mean has increased by 50% over the last two years. This is unfortunately not understood.

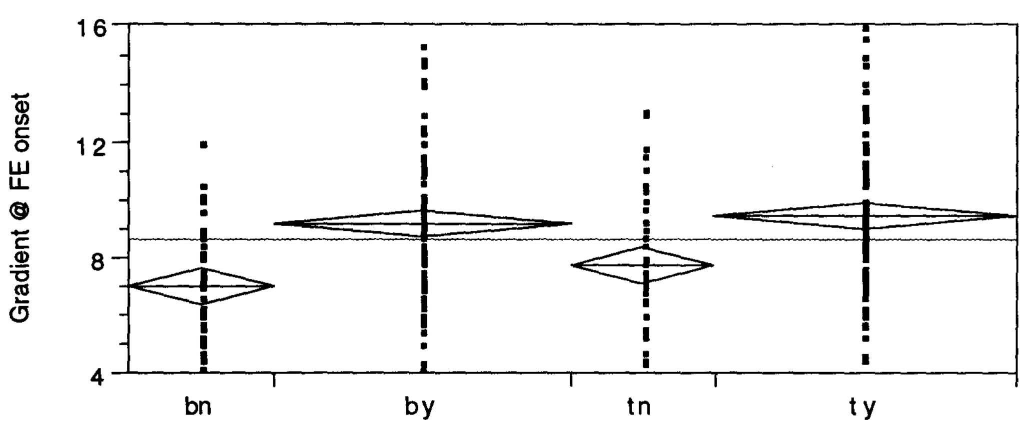


Figure 2 Effect of change in vertical test setup on cavity performance. bn: bottom, no shroud; by: bottom, yes shroud; tn: top, no shroud; ty: top, yes shroud. Gradient is given in MV/m. Diamond shows mean and 95% confidence levels for mean.

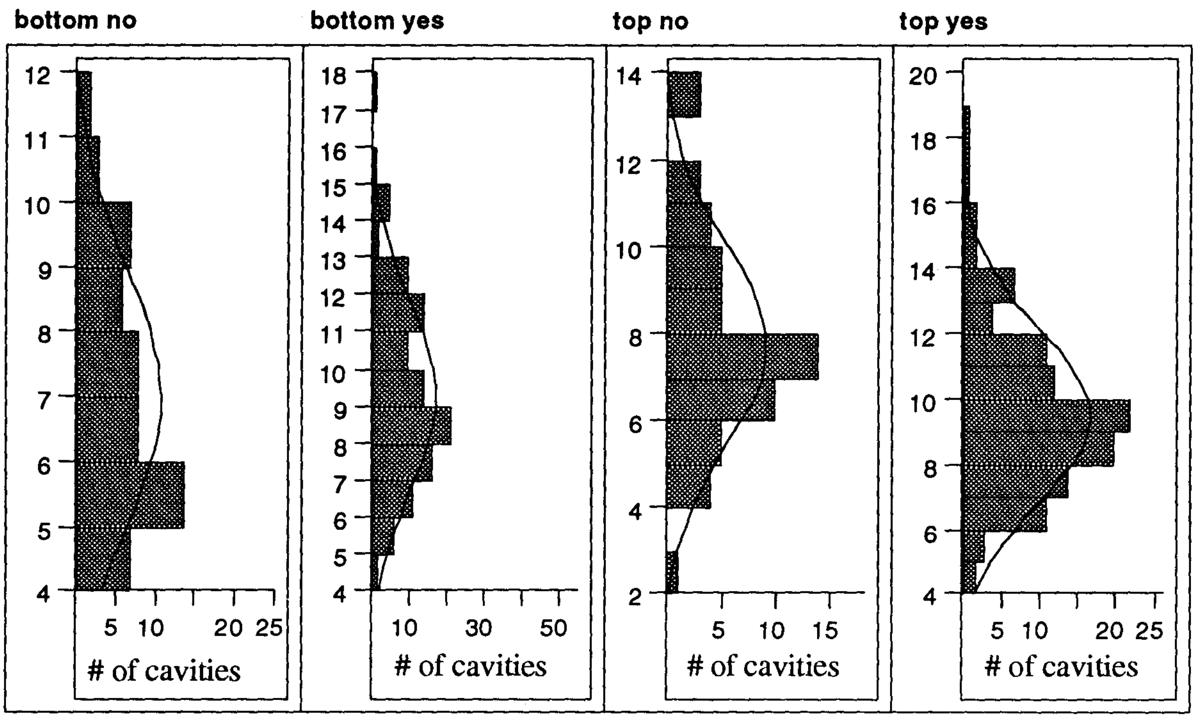


Figure 3. Histograms of field emission onset gradients for same cavities and conditions as in figure 2 Vertical axis is MV/m. The "bottom, no shroud" distribution is clearly skewed to low gradients, while the others are roughly normal.

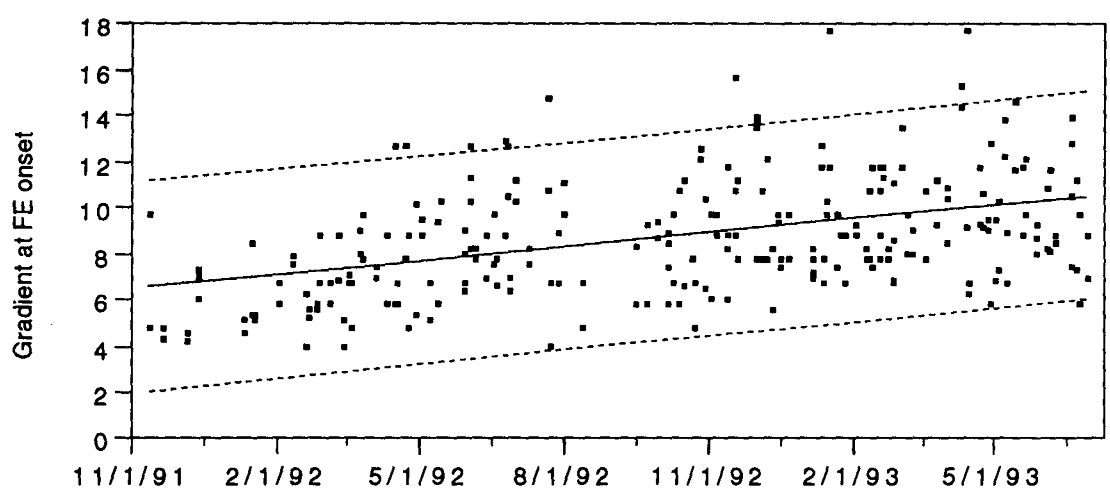


Figure 4. Improvement in gradient at field emission onset versus time. Gradient is given in MV/m.

The improvement in field emission onset and usable gradients with the addition of the mylar shroud is more easily seen in a graph of the quarterly average of these values (Figure 5) rather than the individual points given in Figure 4. The shroud was first used near the end of the third quarter of FY92, on May 31, 1992. The increase is dramatic. The drop in performance during the last quarter of FY93 is due to a combination of cold rf window difficulties and "end effects", principally personnel shifts as temporary employees find new positions elsewhere.

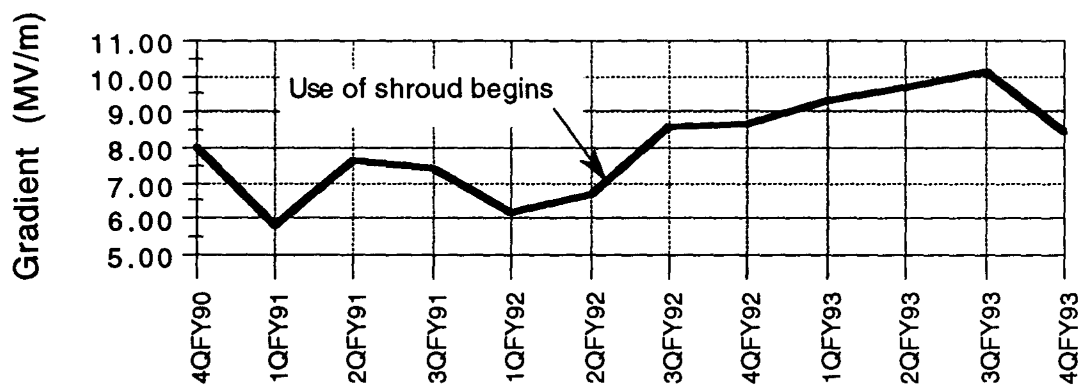
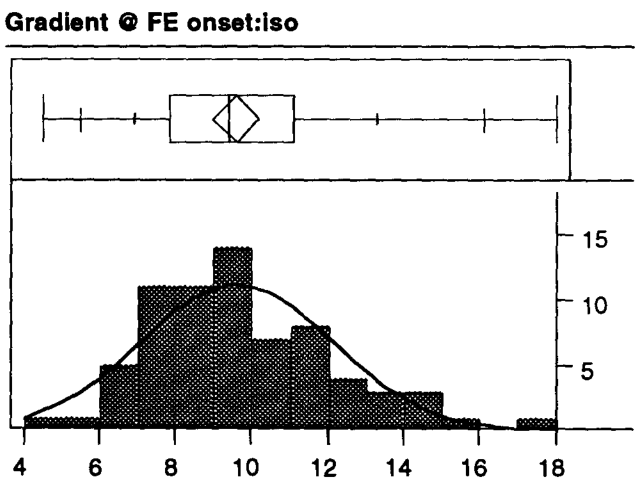
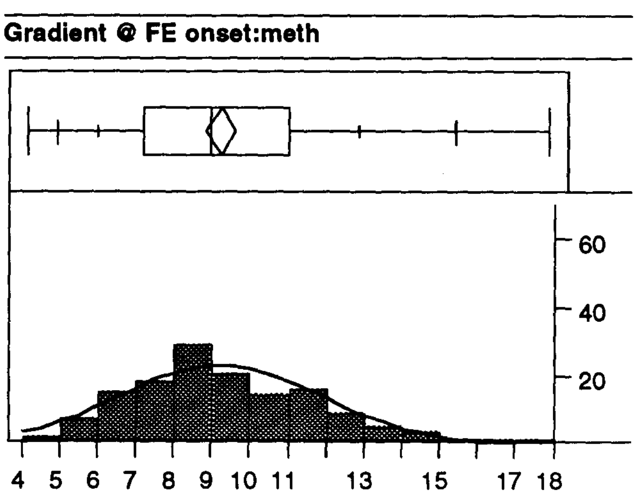


Figure 5. Field Emission Onset Gradient versus time



Gradient at FE onset, Isopropanol

Moments	
Mean	9.61871
Std Dev	2.52617
Std Err Mean	0.30193
upper 95% Mean	10.22106
lower 95% Mean	9.01637
N	70.00000
Sum Wgts	70.00000



Gradient at FE onset, Methanol

Moments	
Mean	9.2355
Std Dev	2.6368
Std Err Mean	0.2125
upper 95% Mean	9.6553
lower 95% Mean	8.8157
N	154.0000
Sum Wgts	154.0000

Figure 6 Effect of methanol vs isopropanol rinsing on field emission onset.

Effect of Isopropanol vs Methanol Final Rinsing

CEBAF has investigated the effect of the use of isopropanol versus methanol for final cavity rinse before assembly. Isopropanol is preferred because of its lower toxicity, but there was concern that cavity results would be poorer. In Figure 6 we plot gradients at field emission onset for cavities tested with the shroud. All cavities tested without the shroud were rinsed with methanol, so including them would bias the evaluation. As can be seen, there is no significant difference in the gradients achieved: the difference in the means is 15% of the standard deviation. On the other hand, mean Q at 5 MV/m is 6.6% lower for the isopropanol rinsed cavities, about one third of a standard deviation of the distributions, making this difference marginally significant. Other gradient comparisons show no significant effect.

Summary

CEBAF has more raw manufacturing process and performance data on superconducting cavities than any other organization, and recognizes its responsibility to distill and transmit this information to the community. An attempt has been made to demonstrate the uses to which this data has been put to date. A key result is the effect of cooldown procedure during vertical test, where a simple change caused a 2 MV/m increase in measured gradient. This result has clear implications for cryostat design for future SRF accelerators. There are many more questions raised by the process data on hand, which CEBAF hopes to explore during the coming year. The CEBAF SRF group also welcomes questions from others in the field on which this data set might be able to shed light.

Acknowledgments

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Figure 1 was provided by K. Yopp. Measurements of the cavities were made by K. Yopp, I. Daniels, A. Forrest and H. Ward. RF measurements were made by C. Reece, T. Powers and P. Kushnick. The use of the mylar shroud in vertical test was suggested by J. Susta after statistical analysis of the difference in top and bottom cavity performance by the author. Discussions with J. Mammosser, P. Kneisel, H.F. Dylla, C. Reece and W. Schneider were useful throughout this work.

References

1. P. Kneisel, W. Schneider and R. Sundelin set the cavity and interface specifications in various CEBAF drawings. See also discussion and figures in "RF Superconductivity at CEBAF", proceedings of the Fifth Workshop on RF Superconductivity, DESY M-92-01, pp 5-22.
2. C. Reece, T. Powers, J. Mammosser and P. Kushnick, "Production Vertical Cavity Pair Testing at CEBAF", these proceedings
3. H.F. Dylla et al. , Vacuum Integrity of SRF Cavity Pair Assembly. CEBAF Report, November 1991
4. P. Kneisel, personal coomunication