Statistical Analysis of Cavity RF Faults*

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Abstract - During commissioning of the CEBAF accelerator it was found that cavities could not be operated reliably at the gradients achieved for short periods during individual cavity commissioning. The principal hypothesis for the cause of about two thirds the faults seen is charging of the cold ceramic RF window, which is 7.6 cm off the beam axis. Beginning in February 1995, most RF systems faults were automatically logged. Simple statistical analysis of the accumulated fault data was first applied in July 1995, with a substantial drop in fault rate recorded. The intent of the analysis was to predict the gradient for each cavity at which it would fault once every ten days, leading to a fault rate for the machine of about 33/day (330 cavities). This analysis method was pursued through July 1996 with substantial benefit. Cavity gradients were increased thereafter to obtain information for an upgrade to 6 GeV, with concomitant fault rate increases. In late 1996 and early 1997, in situ helium discharge processing was employed in 88 cavities to reduce field emission. The methods used for the analysis of 30000+ faults recorded between February 1995 and December 1997 are presented. Comparisons of performance before and after helium processing are presented.

I. BACKGROUND

CEBAF's SRF cavity manufacturing experience is described in (1). The results described there were obtained in vertical dewar testing. Mean gradient at the onset of field emission was 8.7 MV/m. Mean gradient which was thought to be usable, at 1 W of field emission, was 10 MV/m. Final testing of the cavities by the SRF group took place in the accelerator tunnel (2). Cavity gradients were measured using a field probe in the evanescent field of the cavity. Cavity Q's were measured calorimetrically. A few minutes were spent at each gradient, with about 1 MV/m steps between gradients, for the calorimetric measurements. These measurements showed a mean gradient of 8 MV/m, given both additional constraints placed on operating envelope and degradation of performance during the cryostat assembly process. (2) Since the CEBAF accelerator was designed to supply 4 GeV using 5 MV/m gradient cavities, these tests immediately after installation in the tunnel promised an easy path to an accelerator energy of 6 GeV.

Unfortunately, another phenomenon became apparent during accelerator commissioning, when the RF systems were first run in parallel for long periods of time: RF system faults characterized by light and or vacuum excursions in the waveguide transition from 2K to 300K. These were attributed to discharges in the waveguide or at the ceramic window which terminates it at 2K. Empirically, it was found that reducing the operating gradient of an offending cavity reduced the arc rate. Since the accelerator had substantial margin for 4 GeV operation, this was accomplished and Accelerator Operations got on with commissioning the accelerator. In parallel, investigations were undertaken in vertical dewar tests to determine the cause of the discharges. (3-5). These investigations were consistent with the hypothesis that discharges were occurring at the surface of the cold ceramic windows. Discharges occurred only in the presence of field emission from the cavity and occurred at roughly constant charge on the window.

During the first stage of the work to be described here, the log of the interval between RF faults including light output was plotted against the gradient at which the fault occurred. Linear regression produced fits to these plots, so intervals as a function of gradients could be predicted. These were used to adjust the cavity settings for one year beginning in July 1995, resulting in a factor of five decrease in the number of faults per day during the next year. However, the statistical fits resulting from this data transformation were not always good and the residuals often appeared skewed. A model which includes physics input was therefore adopted for further analysis: the Fowler-Nordheim model of field emission (6). This model had proved to be an excellent fit to the cavity behavior in vertical tests. A "Fowler-Nordheim" plot of $\ln(j/E^2)$ vs. $1/E$ will result in a straight line if the physics model is appropriate to the experiment, and did in vertical tests over 2-4 orders of magnitude.

II. DATA ACQUISITION

Almost all the data was acquired passively during normal operation of the machine via an RF Fault Logger. This archiving tool recorded a few RF system variables, including RF power and gradient, each time the cavity state changed, from on to off or off to on. Infrequently, during periods devoted to accelerator studies, cavities were taken to higher gradients to gain information about their behavior there.

No record was kept of RF system on and off times. This information had to be inferred from the RF fault logs as described below. Further, electron current in the linac was not acquired in a manner which made it easy to connect to cavity faults, due to limitations in our control system, so this variable was not included in the analysis.

III. ASSUMPTIONS OF THE STATISTICAL ANALYSIS

1. Discharges with visible light, known as CWAD (cavity waveguide arc discharge) faults, occur at fixed charge on the cold ceramic window. The interval between discharges is thus inversely proportional to the field emission current.
2. The cavity was operating throughout the preceding interval with the gradient at which the fault occurred. The

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initial faults on dates of known high-gradient tests were therefore discarded.

IV. ANALYSIS OF THE RAW FAULT DATA

Substantial numerical experimentation was undertaken with the fault sequence to correct it for periods in which the RF was off. This experimentation resulted in a decision to substitute the 50-point running mean for any interval which exceeded that mean plus six standard deviations and exceeded six hours. The resulting table had each fault listed with type of fault, date, time, gradient, forward power, and "corrected" fault time.

The cold to warm transition waveguides for adjacent cavities share a common vacuum system and ion pump. A discharge in one cavity will cause an vacuum excursion in the common system, tripping both off. For use in a parallel statistical analysis of faults which occur without light, vacuum faults without light in one cavity simultaneous with faults with light in the other cavity of the pair were removed from the fault table.

Cavity gradients were initially calibrated with field probes as described above. The gradients have subsequently been recalibrated twice using beam and the large radius arcs as magnetic spectrometers. The gradients recorded by the fault logger were corrected to reflect the change in calibration constants within the RF system hardware. These changes occurred on known dates, and occasionally the statistical analysis shows a discontinuity at these dates.

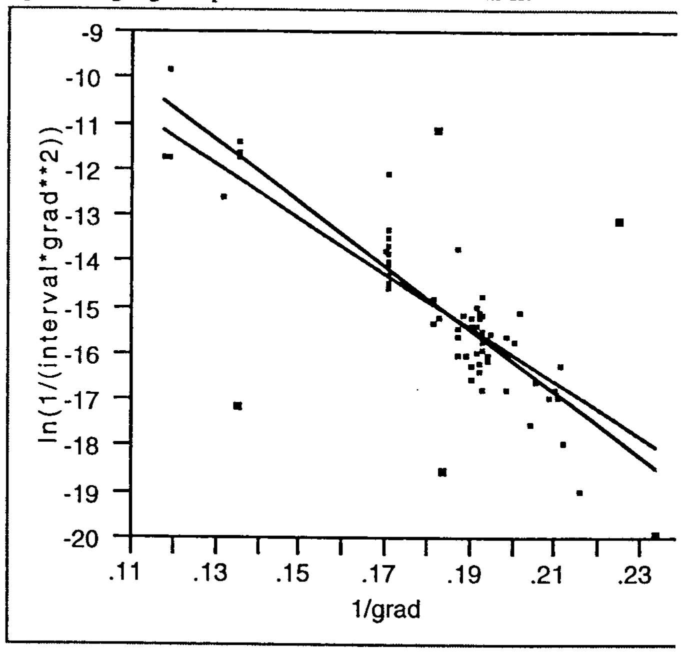
The resulting table of faults has about 60000 entries during the period Jan. 30, 1995 through December 24, 1997. Of these, about half have light. The others have only waveguide vacuum excursions, and occur in pairs, representing about 15000 actual faults. The analysis below considers only faults in which light was detected, since we have no simple means of determining in which cavity of a pair the discharge occurred if no light is present.

The 30454 CWAD faults were then sorted by cavity and time. The differences between corrected fault times were computed on a cavity by cavity basis. The data were then moved to a Mac for analysis with JMP, an exploratory data analysis package sold by SAS. Recalling the assumption that field emission current is inversely proportional to the interval between faults, and that the term gradient is used for E in the SRF cavity literature,

$\ln(j/E^2) \approx \ln(\text{interval}*\text{gradient}^2)$. This was plotted for each cavity versus (1/gradient). (6)

Figures 1 and 2, data from the eighth cavity in the North Linac, illustrate the approach taken to each of the 306 cavities for which CWAD faults were recorded. First, all the data was plotted and fit linearly. This is the lower slope line in the figure, and includes all data points recorded. Outliers (highlighted) were located by eye via residual plots and the raw data for that fault examined. Faults for other cavities in that module were checked to see if something affected all simultaneously. Daily summaries of machine operations written beginning 8/11/95 were consulted to determine if any special testing was done around the time the fault occurred. In this case, the cluster at the upper left occurred during such tests. The point at the lower left is the first fault during the test, so the gradient plotted for that point is not representative of the long interval preceding the faults (assumption 2 above). The remaining outliers were the first faults after a month-long maintenance down, indicating that the methods used to correct for the time the RF systems were off during these downs was not entirely effective. When the five points in question are removed from the data set for this cavity, the fit becomes very robust, as shown in the tabulated statistical parameters in figure 1. Figure 2, with its normal distribution of residuals, shows it likely that the chosen statistical transformation isolates an appropriate random variable. In other cavities, outliers with very high residuals were removed without external information to justify the removal; only the statistical analysis drove their exclusion.

Fig. 1. Initial (lower slope) and final fits to CWAD fault rate data for cavity NL01-8, plotting ln(1/(interval*grad**2)) vs 1/grad. Highlighted points are omitted from final fit



Linear Fit

ln(1/(interval*grad**2)) = -2.38 - 68.71 1/grad

Summary of Fit

RSquare	0.837478
RSquare Adj	0.834813
Root Mean Square Error	0.702844
Mean of Response	-14.8946
Observations (or Sum Wgts)	63

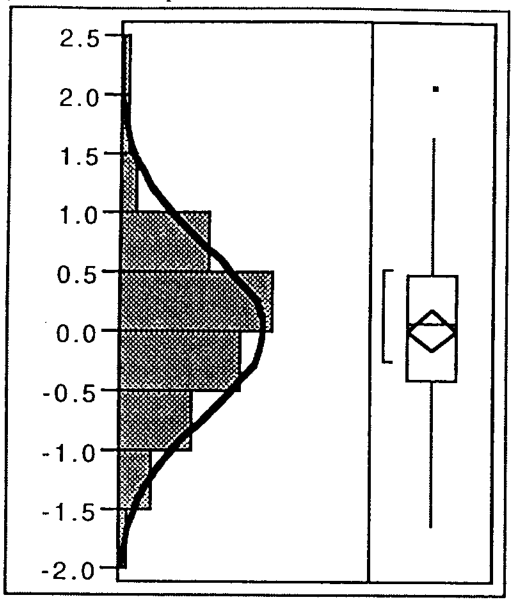
Analysis of Variance

Source	DF	Sum of Squares	Mean Squares	F Ratio
Model	1	155	155.3	314
Error	61	30	0.494	Prob>F
C Total	62	185.4		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-2.37	0.7116	-3.34	0.0014
1/grad	-68.71	3.875	-17.73	<.0001

Fig.2. Residuals of final fit from figure 1, with normal curve plotted for comparison.



Moments

Mean 0.02075 Std Dev 0.69877

Test for Normality Shapiro-Wilk W Test

W = 0.985124 **Prob<W** 0.8607

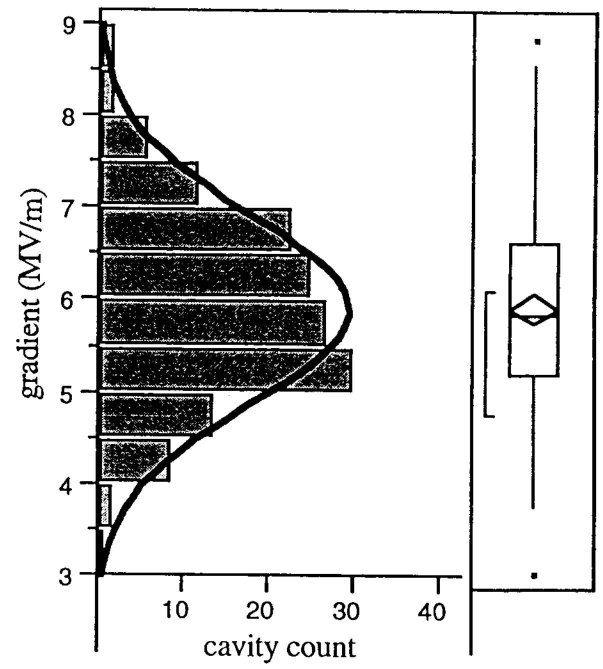
This process would have been laborious enough had no major changes in cavity condition occurred during the three years being analyzed. This was not the case: in an attempt to improve cavity performance by reducing field emission, in situ helium processing was performed on cavities in 12 cryomodules during the periods September 96-January 1997. These cavities were subjected to this analysis regime thrice: for the entire three years, for the period before helium processing, and for the period after helium processing. Thus the equivalent of 63 cryomodules of eight cavities each were examined, thrice each for 12 with helium processing (36) and once each for the other 27.

Results

Robust statistical models, reflected in high R-squared and F-ratios, were obtained for 153 1997-condition cavities. Of the remaining cavities in the linacs, 85% had too few real faults to model robustly. Eight had a sharp onset of trips with gradient, with no functional gradient dependence other than that "step function". Only 12 cavities had large numbers of faults yet showed no gradient dependence of any sort. Gradients for which faults intervals of four days are predicted are summarized in figure 3. The normal curve is included as a reference; the statistical test shows that a non-normal distribution cannot be excluded at the P = 0.05 level.

An attempt was made to extrapolate these models to all other cavities via the use of an empirically set (by others) gradient maximum. While good (>0.5) correlations were achieved between the model results and the empirical values or those cavities modeled, when the linear fit so arrived at was extended to the unmodeled cavities the net fault rate for the machine predicted was approximately a factor of two high.

Fig. 3. Modeled gradients for fault intervals of four days. With 312 cavities in the linacs, a four day fault interval per cavity is equivalent to 3.25 faults/hour, an acceptable rate.



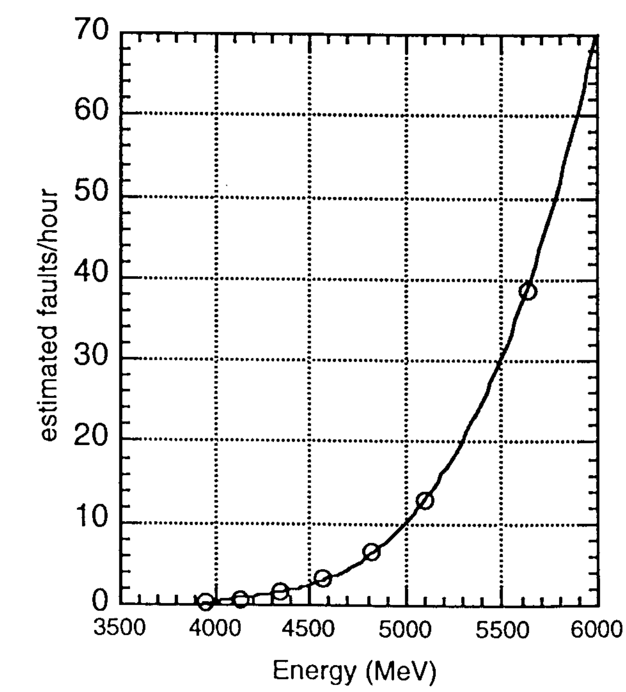
Moments

Mean 5.9208 Std Dev 1.0364

Test for Normality Shapiro-Wilk W Test

W. = 0.988794 **Prob<W** 0.9072

Fig. 4:.Modeled fault rate as a function of machine energy. A ten hour test without beam at 4996 MeV logged 5 faults/hour, half the number suggested by the model. Improvements from helium processing of 18 modules in 1998 are not included here.



Even before this analysis was done, it was clear that we could not deliver 6 GeV beam with the cavities in their 1996 condition. Eighty six cavities were subjected to some level of helium processing in the period September 1996 through January 1997.(7) For 44 cavities, no conclusion can be drawn from this analysis. The changes as a function of trip interval for the 42 cavities for which before and after models are sound are shown in Table 1, sorted by the change in gradient for a four day interval between faults. For six cavities, a mean degradation of 0.6 MV/m at four day fault interval was calculated. For the next five cavities, the change in model slope was such that some intervals shown improvement and some degradation. For the last 31 cavities, a mean improvement of 1.4 MV/m at the four day fault interval was calculated. Thus the minimum net increase in available energy at this fault rate due to helium processing was 20 MeV x 5 passes = 100 MeV. The maximum net increase cannot be assessed because of lack of data either before or after the processing.

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TABLE 1
MODELED CHANGE IN GRADIENT FOR TRIP INTERVALS SHOWN AFTER HELIUM PROCESSING

cavity	2 days	4 days	8 days	16 days
2L103	-1.48	-1.57	-1.64	-1.70
2L114	-1.13	-1.13	-1.13	-1.12
2L113	-0.38	-0.41	-0.43	-0.45
1L098	-0.11	-0.28	-0.42	-0.54
1L038	-0.22	-0.26	-0.29	-0.32
2L101	-0.28	-0.16	-0.06	0.03
1L097	-0.17	0.01	0.15	0.26
1L103	-0.01	0.01	0.03	0.05
1L102	0.16	0.07	0.00	-0.06
1L092	0.17	0.08	0.00	-0.06
1L061	0.26	0.14	0.03	-0.06
1L094	0.16	0.23	0.29	0.33
2L116	0.23	0.31	0.38	0.43
2L102	0.42	0.39	0.36	0.33
1L105	0.39	0.42	0.44	0.46
2L036	0.41	0.48	0.55	0.60
2L023	0.46	0.53	0.58	0.62
2L028	0.50	0.57	0.62	0.67
2L026	0.58	0.65	0.71	0.75
2L027	0.67	0.67	0.67	0.66
1L045	0.96	0.94	0.92	0.90
2L107	1.13	0.99	0.87	0.76
2L105	1.10	1.15	1.20	1.23
2L041	1.27	1.18	1.10	1.03
2L024	0.91	1.21	1.48	1.73
2L021	1.15	1.21	1.26	1.29
2L045	1.40	1.31	1.24	1.17
1L106	1.03	1.33	1.11	1.37
1L053	1.5	1.5	1.0	1.0
2L025	1.35	1.51	1.65	1.75
1L065	1.85	1.73	1.63	1.54
1L101	1.63	1.83	2.00	2.13
2L104	1.84	1.87	1.89	1.90
2L034	1.74	1.87	2.00	2.13
1L037	2.00	1.99	1.97	1.95
1L104	2.10	2.04	1.99	1.93
1L046	2.57	2.11	1.75	1.45
1L036	2.44	2.20	1.98	1.79
2L022	2.96	2.27	1.72	1.29
2L106	2.01	2.33	2.12	2.37
1L032	2.82	2.64	2.48	2.34
1L057	4.34	4.56	4.75	7.5