

Field Emission in CEBAF's Superconducting RF Cavities and Implications for Future Accelerators

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Abstract

Field emission is one of the key issues in superconducting RF.¹ When present, it limits operating gradient directly or via induced heat load at 2K. In order to minimize particulate contamination of and thus field emission in the CEBAF SRF cavities during assembly, a ceramic RF window was placed very close to the accelerating cavity proper. As an unintended consequence of this, it has been possible to monitor and model field emission in the CEBAF cavities since in-tunnel operation began. From January 30, 1995, through February 10, 2003, there were 64 instances of spontaneous onset or change in cavity field emission with a drop in usable gradient averaging 1.4 (σ 0.8) MV/m at each event. Fractional loss averaged 0.18 (σ 0.12) of pre-event gradient. This event count corresponds to 2.4 events per century per cavity, or 8 per year in CEBAF. It is hypothesized that changes in field emission are due to adsorbed gas accumulation. The implications of this and other observations for the International Linear Collider (ILC) and other future accelerators will be discussed.

Monitoring Field Emission in CEBAF

The CEBAF cavity pair and helium vessel are shown schematically in figure 1. The features of interest for this work are the high resistance ($> 10^{12}$ ohms/square) cold ceramic RF window 7.62 cm from the beam axis, a fundamental power coupler (FPC) with substantial magnetic dipole field, and sensors attached to the waveguide at room temperature. The FPC induces a transverse kick of ~ 20 milliradians–MeV/c when the electron is on-crest in the adjacent accelerating cell, 147° away, and the cavity gradient as a whole is set at 7 MV/m.² While little trajectory modeling has been done³, it is clear conceptually and has been demonstrated in vertical test dewar experiments that field emitted electrons from either cavity in a pair can reach and accumulate on the cold ceramic window.^{4,5} The same set of vertical dewar experiments demonstrated that the interposing of an elbow or dogleg waveguide between the fundamental power coupler flange and the ceramic window dropped the electron current to the window by three orders of magnitude.

During CEBAF commissioning, arc discharges were seen at the cold ceramic windows via photomultipliers and vacuum sensors attached to the warm-to-cold transition waveguide. These were verified with spectroscopic observation in vertical dewar tests⁶ to occur at the ceramic and may be either surface flashover or punch-through. The latter is demonstrated by leak testing – most of the cold ceramic windows in the accelerator now have holes in them. In vertical tests, with a picoammeter available to monitor field emission current to the window, the discharges occurred at roughly constant charge.⁵ There is no way to monitor field emission current directly in the accelerator as all the vacuum seals are metal and there is no direct access to the cold ceramic window. All that can be recorded is the incidence of arc and vacuum faults and the gradient in the cavity at the time each fault occurred. Such records have been maintained since Jan. 30, 1995. The data set contains 427,400 RF faults through May 30, 2005.

This analysis assumes that the cold ceramic window is a perfect capacitor and that the charge at which a discharge occurs is constant. The interval between discharges is then inversely proportional to a constant field emission current. If the cavity gradient is constant throughout the interval and the RF is on throughout, one can easily apply a simple exponential or more rigorous Fowler-Nordheim¹ model to the data directly to obtain a field emission model for each cavity.

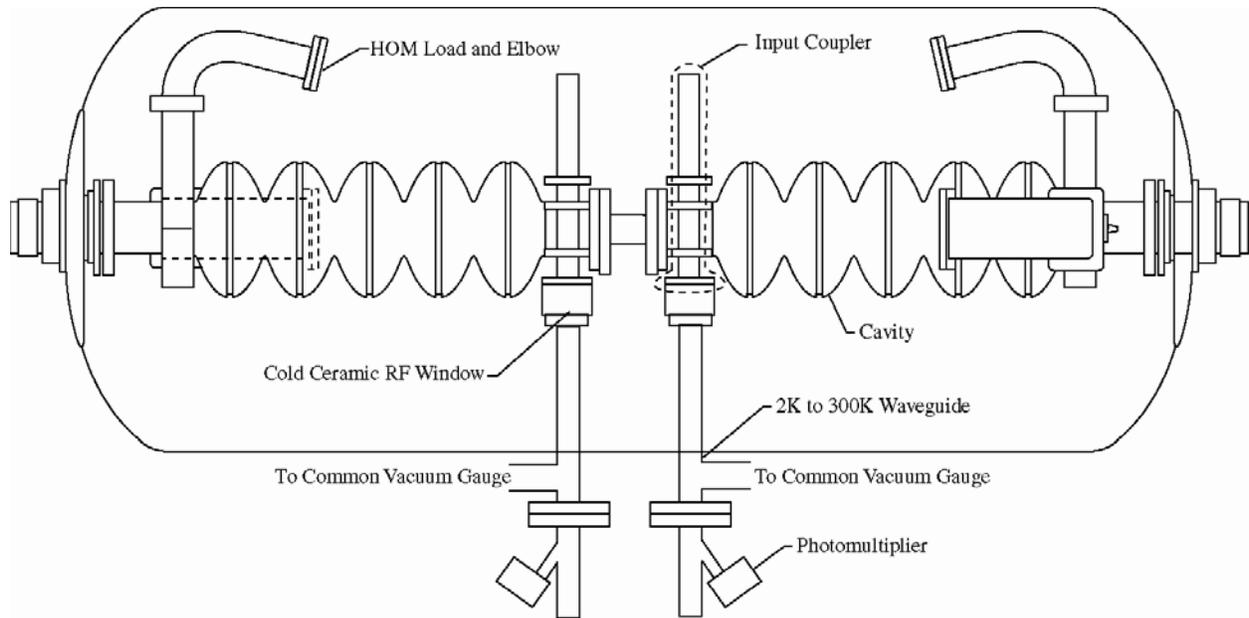


Figure 1. Cavity pair in helium vessel and room temperature sensors used in study.

The data is not perfectly clean, of course, so one pre-processing step and five data cuts are applied before statistical analysis. Until November 2004, there was no recordable signal giving RF-on time for each cavity. The pre-processing step approximates RF-on status by removing periods of 6+ hours in which no fault occurs anywhere in the machine from a running total of elapsed seconds. This assumes that all cavities are turned on and off at the same time, which is not the case – often one linac is on and the other off. This increases the noise in the data. The five cuts in the data and their justification are:

- a. exclusion from analysis of faults with gradient under 3 MV/m due to limitations in RF control system stability which decrease fault interval
- b. exclusion from analysis of faults with intervals under 30 seconds due to variation in reset time from 7-30 seconds; reset was manual during most of the data collection
- c. exclusion from analysis of faults with intervals more than 12 days due to data plots suggesting that the assumption of perfect capacitors begins to break down at this interval. 12 days = 1036800 s. Data analyzed thus spans 4.5 orders of magnitude in interval.
- d. exclusion from analysis of faults in which the gradient change from the preceding fault is more than 15%. There would be insufficient data to analyze if the assumption that the gradient is constant across the full interval were rigorously enforced. Both 10% and 15% cuts have been used with little difference in results. Since the gradient enters in the first power in the exponent in the simple exponential model and as the 5/2 power in the exponent in the Fowler-Nordheim model, no larger allowances were tested.
- e. exclusion of simultaneous (within timing resolution) faults of cavities in multiple helium vessels as due to beam strike or control system effects rather than field emission.

Photomultiplier and vacuum sensors were mentioned above. The first is termed the arc detector and is a simple threshold detector – if a PMT signal greater than a fixed level is detected for more than 0.5 ms, the RF is shut off and a fault bit set. The second is connected to a pair of cavities and the actual pressure archived as a function of time. About 20% of the faults show only vacuum faults and cannot be assigned to a single cavity, only to a pair. Inclusion of these faults in the analysis of either member of the pair has always decreased correlation coefficients, so these faults are discarded. Some fraction of these are likely accompanied by sub-threshold

PMT signals and should be included but there is no way to determine which. About 75% of the faults show simultaneous arc and vacuum faults.

About 5% of the faults show only an arc detector bit. In early 2003 the archiving rate for the vacuum data was increased to 10 Hz. This allowed the addition of a data pre-processing step which determines if there was a sub-threshold vacuum event at the same time as the arc detector fault and reclassifies about half of these 5% as true arcs. An increase in vacuum reading at least equal to background is required for the reclassification. When plotted, all such vacuum traces show classic burst and recovery patterns. For the data set ending in February 2003, the author determined by visual inspection in the data exploration program JMP⁷ which of the arc-detector-only faults would be included in the analysis.

The analysis which follows therefore begins with about 77% of the faults recorded and makes the cuts described above to this subset, ending with ~71% of the total faults. Known noise sources include, as discussed above: imprecision in RF-on intervals, changes in gradient during intervals, variation in window charge at discharge, and nonassignable vacuum-only faults.

Figure 2 below is the first cavity in CEBAF which varies in gradient; the two preceding cavities take the beam from 0.5 MeV to 5 MeV and are invariant. Only seven points were removed by the data cuts discussed above. Residuals of the fit are shown in figure 3 left. It is close to normal visually but does not satisfy the Shapiro-Wilk W test for normality. Removing two outliers from the high side and eight from the low, followed by refitting, results in the residual distribution in figure 3 right, which is consistent with normality.

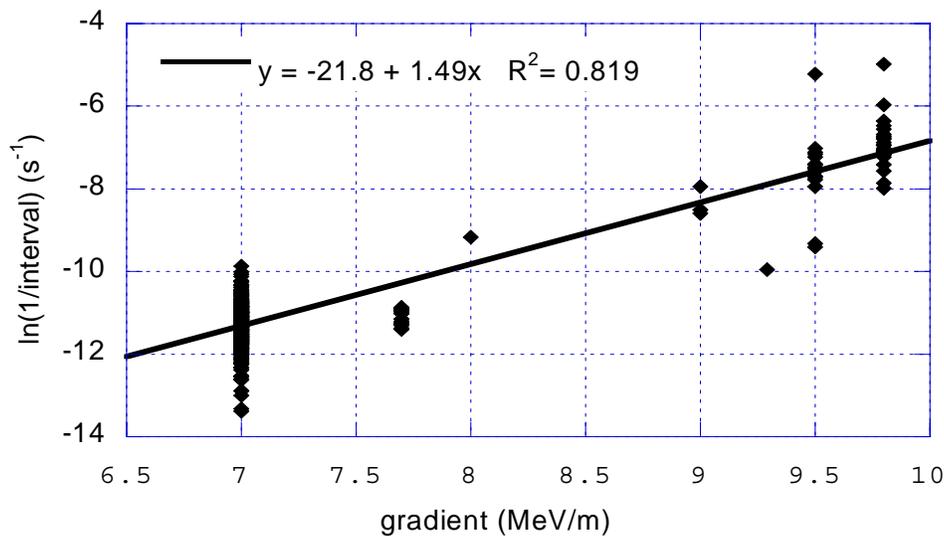


Figure 2. Fit to 0L031 data, automatic cuts only

This labor-intensive process of exploration of the data sets for outliers and development of exponential and Fowler-Nordheim models for each of 338 CEBAF cavities has been repeated many times since the beginning of 1995. The exponential models are used in a program which sets the gradient distribution along the linacs to minimize arc rate.⁸ The Fowler-Nordheim models were used through August 2003 during outlier removal as residuals tended to be closer to normal (Shapiro-Wilk W test). After the hurricane-induced temperature cycle to room temperature in August 2003, such niceties were abandoned due to lack of time and only the exponential models were developed since those are the only ones used in machine setup.

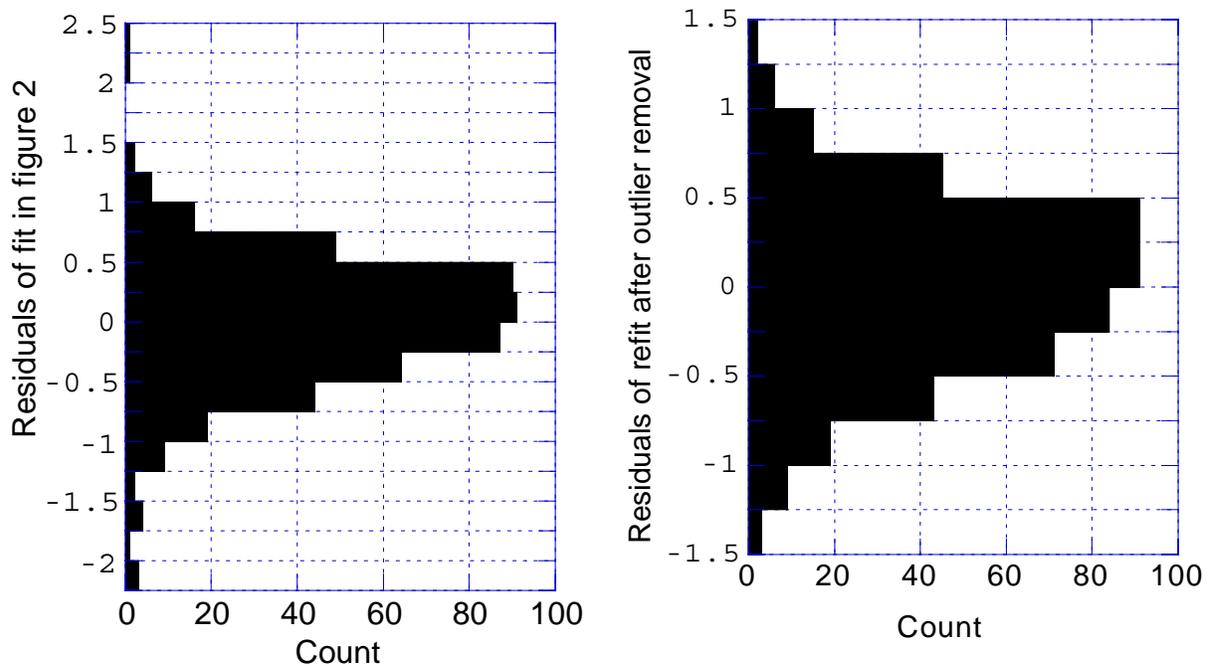


Figure 3. Residuals of fit in figure 2 before (left) and after (right) outlier removal.

Abrupt Changes in Field Emission

In figure 4 we show a change in cavity performance which does not correlate with any known external disturbance. Among the externally imposed changes which modify field emission and therefore mandate new statistical models are 30K warm-up, 300K warm-up and helium RF-discharge processing⁹. All of these will change adsorbed gas distribution. Inaccurately calibrated RF control hardware can also cause a change in apparent response as the gradient scale changes.

Sixty-four events with no external drivers were found with this distinct signature, including at least a factor of three change in fault interval at fixed gradient, in the data set encompassing Jan. 30, 1995, through February 10, 2003. Most of the changes in interval were at least an order of magnitude. Some were associated with a period of RF-off for magnet or other maintenance in the tunnel, but no recorded maintenance of any sort on the cavity or RF system in question. Figure 5 is one such change. This count of 64 is the minimum for the period and corresponds to 2.4 per cavity-century, or eight per year in CEBAF with 338 cavities. For an ILC with 20,000 cavities, the toll might be 500/year. Without similar long term performance data from TTF or other high performing cavities, it is not known whether the ~ 2.5 MV/m loss at fixed fault interval seen in figure 4 is best viewed as an offset or fractional loss of previous behavior. The former is much preferred for ILC.

The cavity performance changes are not subtle, providing confidence that the 64 events selected are a minimum set. Upper bound is perhaps half again this number. In figure 6 the distributions of absolute and fractional gradient loss for the 64 events are shown. Mean gradient loss is 1.4 (σ 0.8) MV/m and mean fractional loss 0.18 (σ 0.11). It is not clear whether the improvement in one cavity is real or a result of measurement error induced by unrecorded maintenance. Its inclusion renders the left distribution more consistent with normality. If excluded, losses are 1.4 (σ 0.7) MV/m and 0.18 (σ 0.10) fractional for the 63-event sets.

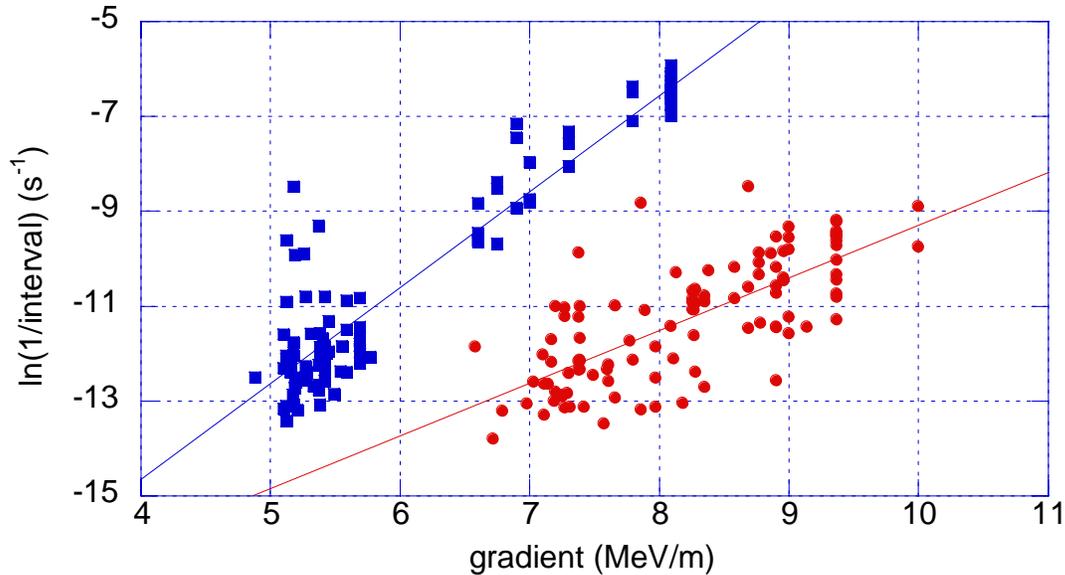


Figure 4. Blue points are after 0440 9/21/2004. Interval at 8.1 MV/m changed from ~80,000 seconds to ~500 seconds. Linear fits for the data sets before and after are shown. Cavity 2L145

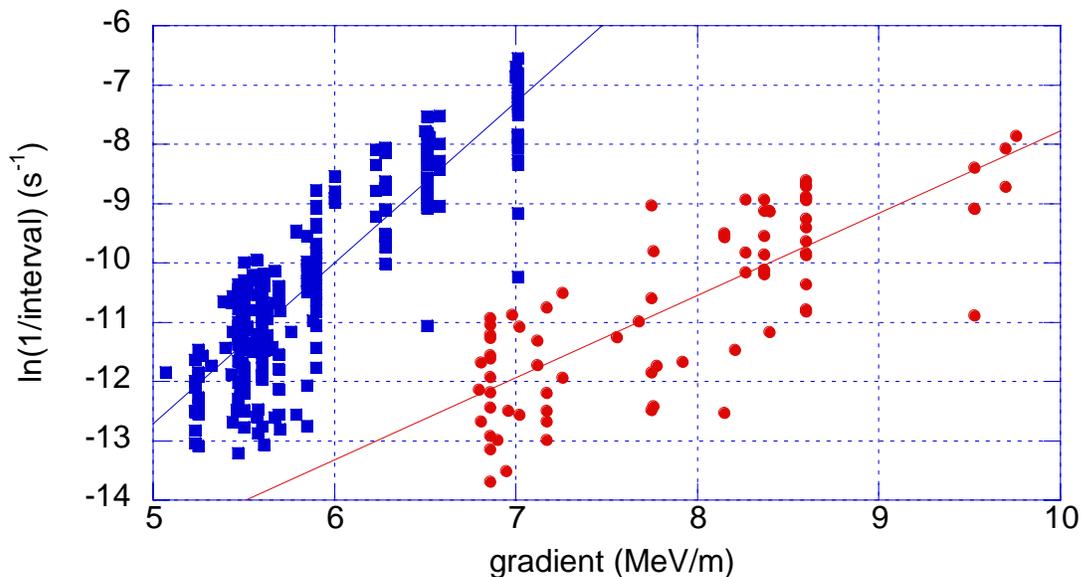


Figure 5. Data (blue) sloping across left of figure is after 5/18/2004. This change in behavior occurred across a maintenance period during which nothing was done to the cavity except turn RF off and on. Such episodes are counted in deriving the 2.4/cavity-century value. Cavity 1L087

Seventeen such events were counted between October 2003 resumption of operations after warm-up to ambient due to a hurricane and the end of March 2005, a period of 18 months. Since data was not recorded for the first two years after original cooldown in CEBAF, it is not known whether this increased rate, almost 12/year, is appropriate for a new accelerator. These events cannot be quantified in the same manner as those in figure 6 because there wasn't enough data to create a model for most of the "before" states. For instance, there may be a dozen points at fixed gradient with an interval of 50000 seconds which suddenly changes to 100 seconds. Data is sufficient for an "after" model but not "before".

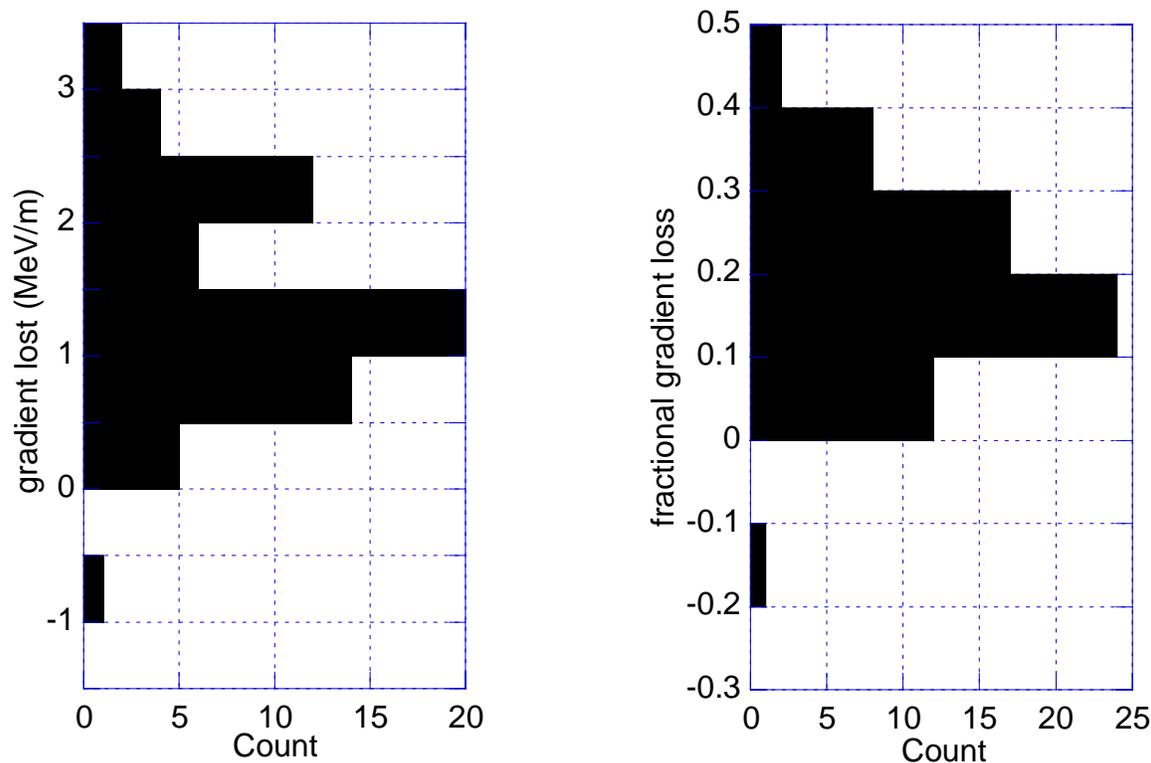


Figure 6. Abrupt loss distributions in two formats for January 30, 1995, through February 2003.

Another phenomenon of interest: fratricide

In addition to field emission in a cavity charging its own ceramic window and causing arcs, it is possible for an adjacent cavity to do so as well. The most striking example of this is the cavity pair 2L12 - 7,8 in which the gradient in each cavity controls the fault rate in the other. In figure 7 the inverse fault intervals for cavity seven are fit by gradients in cavity 7 and cavity 8. The fit is poor and of the wrong sign physically for cavity 7 intervals fit by cavity 7 gradient. The fit is good and of the right sign for cavity 7 intervals fit by cavity 8 gradient. Figure 8 has the same pair of graphs for cavity 8 intervals. Such fratricide may extend beyond the other member of a cavity pair to adjacent helium vessels. Fratricide is found and quantified by stepwise regression of multiple cavity gradients in JMP. The need to check for fratricide is one of the reasons for the large amount of human input to the analysis.

Most at Jefferson Lab, including the author, were reluctant to believe in the effect. The author was convinced by the abrupt changes in the performance of cavities 6 and 7 in zone NL04 when an accidental introduction of N_2 into cavity 8 forced its gradient to drop from 10 MV/m to 5 MV/m. Retrospective analysis of previously misunderstood data showed that when cavity 8 was below 7.5 MV/m, fault vs gradient behavior in cavities 6 and 7 was consistent with field emission models. The physical mechanism of interaction between cavities which are not in the same pair is unknown. When fratricide is statistically found in cavity response and the culprit is located, a maximum culprit gradient is estimated and tested in the machine.

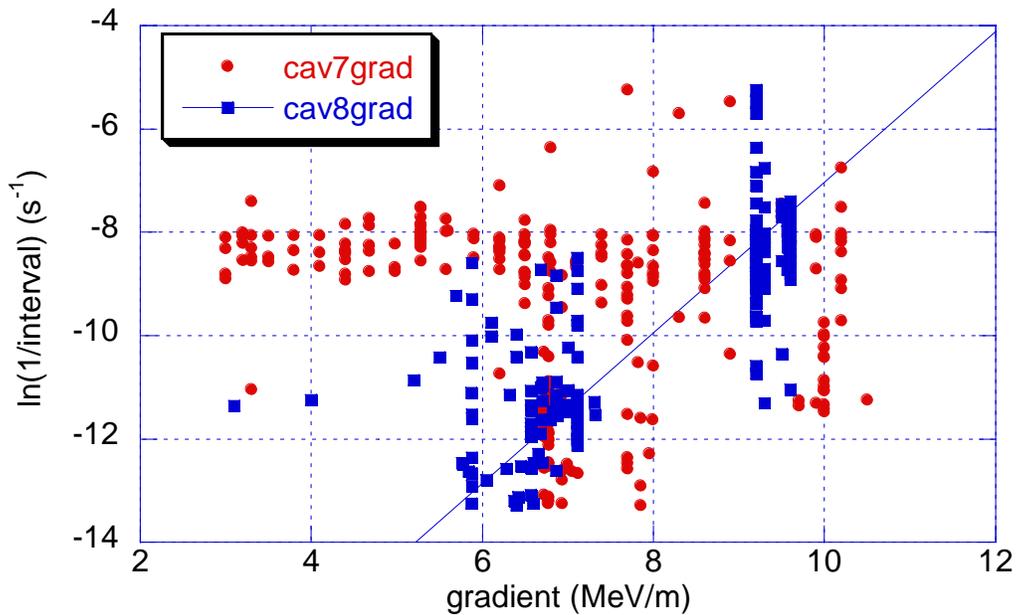


Figure 7 Fits of cavity 7 intervals by cavity 7 gradient (cav7grad, red) and cavity 8 gradient (cav8grad, blue)

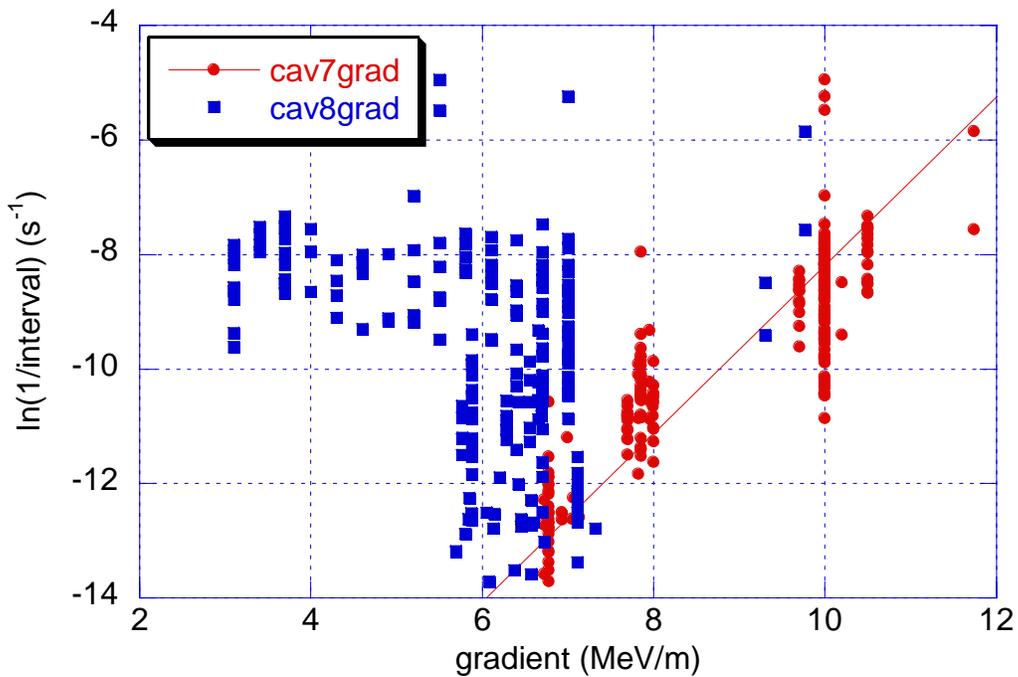


Figure 8 Fits of cavity 8 intervals by cavity 7 gradient (cav7grad, red) and cavity 8 gradient (cav8grad, blue)

Characteristics of the set of models now in use

The ensemble of statistical models which were used in the operation of CEBAF⁸ in early 2005 will now be characterized statistically. Perhaps the most striking feature is an exceptional correlation of the slope and intercept of the exponential models (figure 9). The physical source of this correlation is unknown. It may be a function of cavity and FPC geometry.

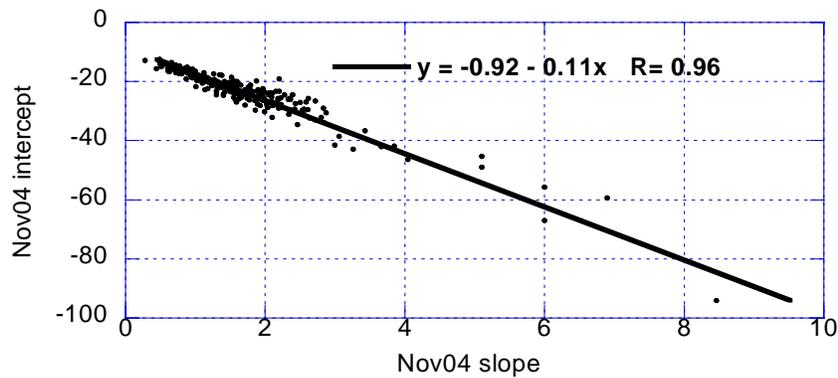


Figure 9 Intercept vs slope for 247 cavity models in use in CEBAF

Statistical measures of the quality of these models are shown in figure 10. t value is equal to parameter divided by standard error and so is a measure of the significance of the model. Minimum t value of 2, which for these samples corresponds to excluding the null hypothesis at $P=0.05$, is enforced for model use in the machine. 90% of the models used have $t > 7.9$ for slope and $t > 10$ for intercept: "7.9 sigma" and "10 sigma" in the usual physics parlance. R^2 is the square of the usual correlation coefficient. While some of these correlation coefficients are low, additional data can best be obtained if some model is used in setting up the gradient distribution in the accelerator. To increase data acquisition rate, up to half a standard error has been added to the slope values input to the code⁸ used to establish the gradient distribution in the accelerator.

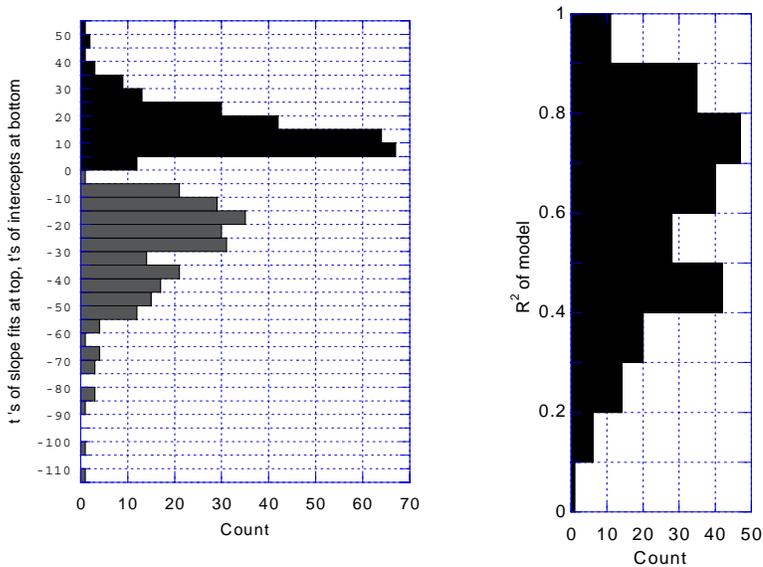


Figure 10. Statistical measures of model quality for 247 cavity models. t values for slopes and intercepts are at left and R^2 values at right. Statistical measures of model quality for 247 cavity models.

Models are lacking for the remaining 91 cavities in CEBAF for a variety of reasons: 8 failures requiring cryomodule remanufacturing; field emission onset above RF control or RF power upper bound; culprit in fratricide so upper bound set below effect of gradient on a cavity itself; room temperature RF window heating; insufficient data; and 7 injector cavities which haven't been pushed to limits due to fixed ratio between injector and linac energy.

Further attempts at automation of analysis

In an attempt to reduce the labor required, the author has been working with a Jefferson Lab programmer to automate as much as possible. All of the processing and data cuts described above are applied via a perl script. An additional cut proved necessary to deal with delays in resetting during short system problems: remove intervals under 1800 seconds with gradients below average. A list of cavities in which such points are more than 10% of the total is kept for manual check in JMP so abrupt changes like figures 4 and 5 are not ignored. Four fitting routines from the open source statistics environment R¹⁰ are then applied via an R script: standard least squares and three robust regression algorithms, M-estimator, MM-estimator and least trimmed squares. Numerical output is directed to a summary file and a graph of the data and the four fits is produced as a postscript file. If all four models agree and the statistical measures of the models indicate reliability, any of the models can simply be copied into the input file for the machine setup code. If they don't agree or if the statistical measures are poor, the plot is examined for signs of fratricide, sudden change of field emission characteristics, etc., and a decision made whether to repeat the analysis in JMP manually. This should reduce the effort needed in the future to develop new models when cryomodule perturbations force a change. The graph for 0L031 is shown in figure 11.

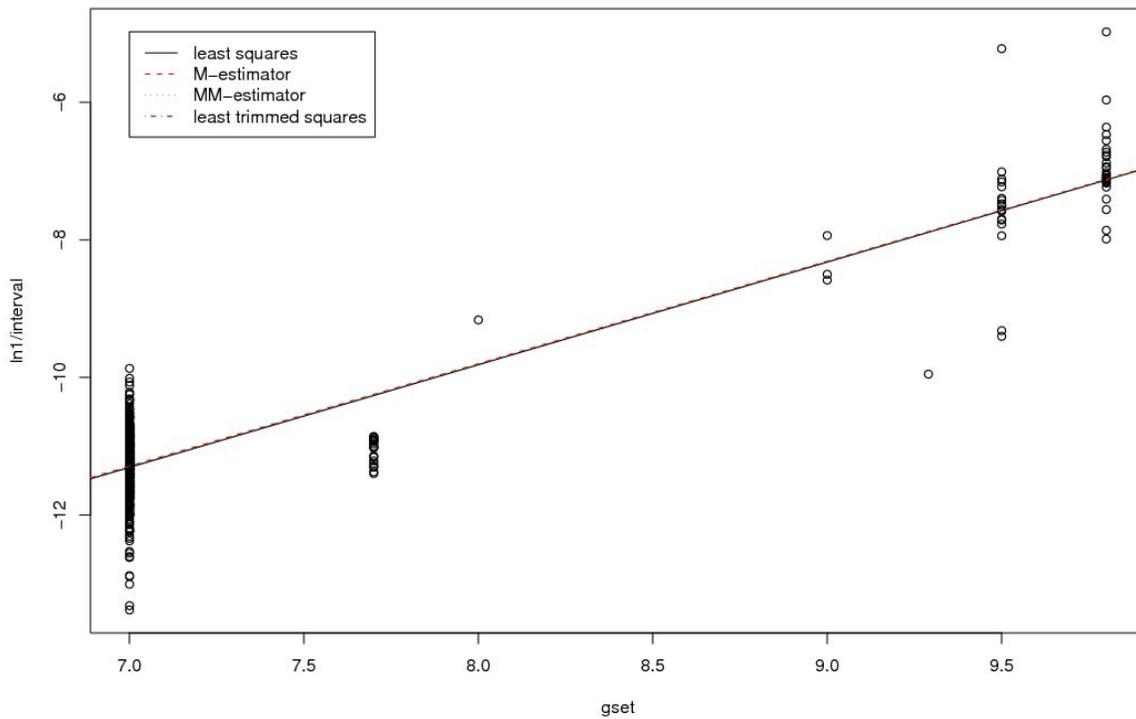


Figure 11. 0L031 data (figure 2) analyzed and plotted in R environment. Horizontal axis is the control variable equivalent to gradient (MeV/.m)

Effects of cryomodule perturbations

Two recent events have resulted in major perturbations of multiple cryomodules. In August 2003, hurricane Isabel caused a four day power outage and all cryomodules warmed to room temperature. In August 2004 maintenance of the main helium liquefier forced the cryo load to be shifted to a much smaller 4K refrigerator. The smaller capacity of this unit, in

combination with main electrical substation maintenance, forced nine cryomodules to be warmed to room temperature. Change out of room temperature RF windows, requiring 30K cycle, occurred in four more modules in August 2004. Comparisons among models in March 2003, July 2004 and November 2004 were made. Due to poor statistics in the interval October 2003 - June 2004, comparisons with July 2004 models proved less than useful. In figure 12 gradients predicted to yield one day fault intervals are compared for March 2003 and November 2004 models in two ways, with intercept as a free parameter and with zero intercept forced. The second is not valid statistically but looks good and provides a simple estimate of the degradation due to the perturbation: 10%. The August 2004 excursions appear to have no effect on these comparisons as the same correlations are seen for the full set of cavities, the set which was unperturbed in August, and the set perturbed in August. Thus only the full set is shown.

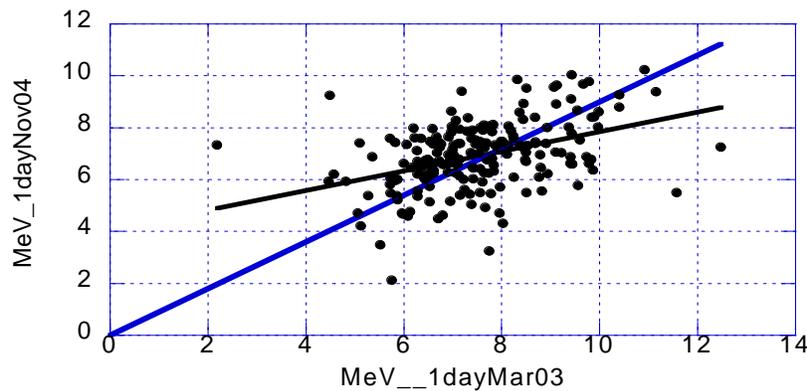


Figure 12. Comparison of pre- and post- hurricane gradients for one day fault interval by standard least squares (black) and fit forced through zero (blue). Latter has slope of 0.9. Former has equation $y=0.38x + 4.06$, $R=0.42$.

Implications for the Future Accelerators

The only hypothesis for abrupt field emission changes advanced by the author or anyone with whom he has discussed this work is a increase in geometrical electric field enhancement by “one more” gas molecule adsorbing to an asperity on the cavity surface. This mechanism should be independent of duty cycle, depending only on vacuum conditions. Leak rate of CEBAF cavity pairs was measured during superfluid helium vertical dewar tests via an integration method and average 4×10^{-11} std cc/s¹¹. The fact that CEBAF runs CW with RF on ~75% of the year and the ILC will run pulsed with ~1% duty cycle should be irrelevant for turn-on rate.

CEBAF runs with ~600W of 2K heating due to field emission at 5.8 GeV, or ~2.5W per cavity with field emission model. In vertical dewar tests, the author was able to run with up to 70W of field emission heating without quenching the cavity. Maximum field emission heat load allowable by the TESLA cryomodule design is not known to the author, but ~10W extra in one cavity probably won't choke the plumbing.

Improved surface preparation of the ILC cavities, including electropolishing, will reduce the asperity count per unit area orders of magnitude over that achieved in 1991–1993 in CEBAF. In the best case for ILC, this will cut the rate of abrupt changes to a level that is irrelevant for machine operation. If the 1995–2003 CEBAF rate holds in spite of this, undetected events could add up to 5 kW 2K heat load per year in ILC, but for a 1% duty cycle machine the increase in energy deposited to 2K is likely negligible. The heat load from new field emitters would be important for a future CW machine, for example ERL (energy recovered linac) based FELs or

light sources, despite the fact that the number of cavities involved in any of these is small compared to the ILC.

The CEBAF event rate increased to 17 in 18 months after the cycle to ambient in September 2003. We do not have similar data for the 18 months after first 2K cooldown and so cannot say which rate, if either, is appropriate for use in planning ILC. Long term x-ray observation of TESLA modules at DESY and other labs would be useful but the number of cavities is too small to provide useful information before the planned completion of the ILC Conceptual Design.

During helium glow discharge processing to improve field emission⁹ eight small G-M tubes were placed about the cryomodule and monitored. No pattern was found in x-ray emission with this small coverage. It was not possible to isolate the offending cavity to a single module using the x-ray detection alone, much less find the cavity. Observation of patterns of x-rays as a function of gradient was needed. The x-rays from many cavities didn't intercept the eight small detectors at all.

One mitigation implementation for this field emission change phenomenon in a future accelerator would require:

1. "4 π " x-ray detection in linacs
2. RF system capable of varying power to individual cavities
3. software to detect changes in x-ray patterns and use (2) to determine which cavity is at fault parasitically during normal operation. Energy lock assumed.

Item 1 can be retrofitted, for instance by applying sheets of plastic scintillator to the outside of the cryostat and guiding their light to appropriate detectors. Provision must be made in civil construction design for such a retrofit, e.g. cable and rack space. The decision whether to add (1) can be taken after observation of TESLA modules gains statistical significance. Item 2 must be part of the initial accelerator design. In-tunnel electronics, e.g. RF controls, would benefit from item 1 as they will have limits on integrated dose.¹²

Jefferson Lab is beginning a modest program to refurbish cryomodules. Improved surface preparation techniques will be applied in the hope of achieving at least 30 MV/m surface field (12 MV/m accelerating gradient) in refurbished cavities. The installed ensemble averaged 13 MV/m accelerating gradient with field emission in vertical test in 1991–1993. The best vertical test result was 21 MV/m, so 40 MV/m surface field average is not unrealistic after refurbishment with installed RF controls and klystrons, roughly half that needed for ILC. Cavity surface field could approach ILC specs with improved RF systems.

Another part of this refurbishment is installation of a waveguide with dogleg between the cavity and the cold ceramic window. This has been shown to eliminate arc faults due to field emission in one cryomodule so equipped and so will eliminate the method for monitoring field emission used here. Radiation detectors can be emplaced as discussed above to monitor field emission in the absence of charge/discharge cycles on the cold ceramic windows. A more ambitious refurbishment program might apply two to four surface preparation techniques of varying complexity and cost to twenty to ten cryomodules each. Three years of observation would then produce statistically significant results on the efficacy, cost effectiveness, and longevity (against spontaneous field emission changes) of each treatment. Such information would be valuable for the ILC and other future accelerators.

Summary

Insights gained from a decade of monitoring and modeling field emission in CEBAF have been discussed. Items possibly relevant to the ILC have been pointed out. Most importantly, 2.4

sudden changes in field emission, yielding onset at substantially lower gradient, occur per cavity-century in CEBAF. The phenomenon designated fratricide complicates diagnosis but can be dealt with using standard statistical techniques. Monitoring of field emission via dedicated x-ray monitors in tunnel is desirable for future accelerators using superconducting RF.

Acknowledgments

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