Abstract

Arc faults were first recognized as a major, unexpected limitation on CEBAF performance in 1994. An arc-gradient team was formed to characterize and solve the problem. This report will briefly summarize the conclusions of that team. It will then cover in detail the statistical work I've done on cavity arc faults in the last six years, including methodology; general results and their utilization in lem++; special analyses on beam current dependence and other topics; RF performance projections as a function of beam energy and current; and suggestions for future work.

1. Background

1.1 History

The SRF group wished to prepare particulate-free cavity pairs to minimize field emission effects. The design chosen included ceramic windows 7.6 cm from the beam axis on the input RF coupler. It was recognized that window charging by field emitted electrons might be a problem, so at least two methods of applying a conductive coating to the ceramic were used during window production. A careful balance was needed between RF heating of the conductive coating, with the heat dissipated at 2K, and removal to ground of field-emitted electrons. Resistances of order $10^{12}$ ohms/square were required. This balance proved impossible to sustain, and it was decided to err in the direction of lower heat load and higher resistance coatings.

The cavity pairs were tested in vertical dewars. RF was typically applied for 10-20 minutes, to the limit of a critically coupled power supply capable of delivering ~80W to the cavity. The limiting gradient of the cavity was generally set at that which generated one watt of dissipation via field emission. After vertical test, the cavity pairs were installed in cryounits and these assembled into cryomodules.

Cryomodule commissioning in the tunnel was of somewhat longer duration than vertical test, but time at the highest gradient was of order of an hour, that needed for calorimetric measurements. Gradients were generally limited either by the watt of field emission or a radiation limit of 1 R/hour specified due to concern about long term radiation damage to niobium. The latter has now been discounted.

A number of interlock systems were installed on the cryomodules. The two with which this work is concerned are:

a. the arc detector, a photomultiplier mounted on a window on a tube beyond cutoff intended to sense RF-induced arcs in the waveguide. If light is above a threshold for more than 500 µs, that cavity's RF is turned off.

b. waveguide vacuum, via ion pump current. A single vacuum pump is used per cavity pair, so if there is a vacuum excursion in one cavity, both trip.

Beam testing began, first in the injector and then in the North Linac, as those machine sections were filled. These were the first instances in which the cavities were operated at gradient for long periods. It soon became apparent that there was a problem with arc trips. Much work was done by the arc-gradient team to find the source of the problem, in situ and in vertical dewar tests. (1) The arcs are due to field-emitted electrons charging the ceramic windows until the
ceramic can no longer sustain the induced voltage, at which point an arc occurs. The charge required to arc was found to be quite reproducible for a given cavity/window in vertical test.

An instance of the EPICS archiver was created which wrote a record each time the RF on bit in the RF control microprocessor changed. These records were then used to find gradients at which the cavities would arc relatively infrequently. These gradients were stored in the EPICS field GSET.DRVH. The original lem (linac energy manager) summed the DRVH values, divided 800 by the sum, and multiplied the DRVH value for each cavity by the result to determine GSET (gradient set) for each cavity. During late 1994 and the first half of 1995, this work was mostly empirical. The machine was running at 400 MeV/linac in this period. The cavities are 0.5 m long, so the energy gained in a cavity is half the gradient in V/m. If one wants 400 MeV, the sum of the gradients set for each cavity must be 800 - hence the 800 mentioned above.

Beginning in mid-1995, I began statistical analysis of cavity faults. Two field emission models were used, one physics-motivated and one empirical (see section 1.2). As data accumulated, field emission models were derived for the third of the cavities which were the worst offenders. DRVH values at which the models predicted one fault per cavity every four days were calculated and downloaded into the control system. By mid-1996, total arc fault rates of 12/day at 4 GeV were achieved using a combination of modeled and empirical DRVH values with lem. C. Reece then took over responsibility for linac cavity data. I wrote three tech notes, 95-059, 96-004 and 98-045, documenting the statistical work I had done. I retained responsibility for injector gradients and analyzed that region of the machine periodically.

In April 2000, when the Division was re-organized, I was asked by Andrew to assist in preparations for the August 2000 6 GeV test (TN 00-028). I dusted off my stat tools and summarized the data in the RF fault logger tables. In the period Jan. 30, 1995 through Jan. 31, 2001, 173915 faults were recorded in which the arc detector or waveguide vacuum fault bit was set. Of these, 88479 had the arc detector bit set and will be analyzed below. The remainder had only the vacuum fault bit set. Almost all of these vacuum-only records are paired, so these represent about ~42700 faults. Thus there were ~131200 arc and/or waveguide faults during this six year period. The rate increased substantially as the machine gradient increased during the last few years, as seen in figure 1.

1.2 Physical mechanism of arcs

As mentioned in 1.1, a substantial program of vertical dewar tests was initiated when the arcs became a problem. The most definitive test was the substitution of a kapton gasket for the usual indium gasket between the window and cavity. Insulated bolts were also used. This allowed a picoammeter to be connected directly to the niobium flange containing the ceramic window. As discussed in (1-3), field emission current to the window scaled exponentially with gradient and the total charge at which an arc occurred was roughly constant over a range of gradients. In the statistical analysis that follows, I assume the stored charge at which an arc occurs is constant.

The field emitted electrons actually bounce up the input waveguide to the ceramic window, as evidenced by negative currents read in the experiments summarized in (3). Moving the ceramic window from 7.6 cm from beam axis to ~20 cm from beam axis did not affect arc behavior. Moving the window to ~20cm and putting a dogleg in the waveguide to eliminate line of sight cut the current measured on the window flange by three orders of magnitude. (3)
Figure 1. Arc and/or waveguide faults. Upper trace, simultaneous arc and waveguide faults, falls from 1995 to 1996 due to early statistical work. It rises thereafter due to increased beam energy and the simple models used through June 2000. Middle trace, vacuum-only faults, are assumed to occur in pairs so only half the total recorded is plotted. Arc-only faults are believed to be false positives, as discussed in section 3.1.
1.3 Field emission models

The canonical field emission model is that of Fowler and Nordheim (4,5) based on quantum tunneling. The fields required for tunneling are higher than the average field at the niobium surface, so field enhancement due to sharp points is inferred. Sharp points have observed microscopically. Expansion is done in the small parameter (electron energy - Fermi energy)/(work function). If the model is applicable to our situations, a "Fowler-Nordheim" plot of ln(j/E^2) vs. 1/E should result in a straight line, where j is the field-emitted current and E the electric field. Analogous plots, using RF power balance to infer j, were made for all cavities in vertical test. Those which did not quench showed excellent fit to the Fowler-Nordheim model over one to three orders of magnitude of the dependent variable.

As discussed in (5), an empirical exponential model in which only the current appears in the log term is often used in the study of field emission.

The key assumptions made in this analysis are:

a. arc faults occur when a fixed charge is accumulated on the cold ceramic window
b. the value of this charge is unchanged over years
c. the charge is reset to the same low value after each arc.
d. the ceramic window has very low leakage current
e. the clock intervals between faults may be approximately corrected to include only periods when RF was on via a method discussed below

These allow me to write:

\[ \text{Charge} = \text{constant} = j \times \text{(corrected fault interval)} \]
\[ j = \text{constant}/\text{(corrected fault interval)} \]

Plotting ln(1/(interval*E^2)) vs. 1/E should then result in a straight line if the Fowler-Nordheim model holds. If the empirical exponential model holds, ln(1/interval) vs. E should be a straight line.

1.4 Basic statistics

Figures 2 and 3 are samples of the statistical analysis done for all cavities. The software is SAS's JMP. The portions of the tables used as indicators of statistical significance are (6):

- RSquare: Correlation coefficient. Proportion of the total variance explained by fitting the model
- Model: Comparison is between the regression line and the horizontal line equal to the mean. If the regression is a better fit than the horizontal line, the slope of the line will test significantly different from zero. The value in the Analysis of Variance table is the difference between the sum of squares error in the two models (the mean-line model and the sloped regression line).
- Error: Sum of squared residuals after fitting the line
- Mean square: Sum of squares divided by respective degrees of freedom
F ratio is the ratio of mean squares for model and error. If the regression model explains substantially more of the variation than random errors do, it is significant even if the correlation coefficient is relatively small.

t ratio is a test that the true parameter is zero. It is the ratio of the estimate to its standard error. If the absolute value of the t ratio is greater than 2, the chance that the parameter is really zero is generally less than 5%. The t ratio is the square root of the F ratio.

I sometimes use models even if the F ratio is below 4 in the hope of acquiring more data for the next analysis iteration a year or so later. lem++ uses the empirical exponential model. For the 209 such models I've derived, the mean t ratio is 12 and the standard deviation is 10 - there is large variation in the accuracy of the statistical models.

At the bottom of Figure 2 the residuals are plotted against the independent variable. The residual is the difference between the data and the model. The dependence explained by the independent variable has been removed from the residuals. Dependencies on other random variables remain captured in the residuals. If all other variables affecting the data are normal, the residuals will be normal. In figure 3, the distribution of the residuals is plotted in three ways: histogram, box-outlier plot, and normal quantile plot. The second and third allow one to identify outliers and points which deviate from normality (straight line in plot). The test for normality provides a numerical evaluation of the probability that the distribution is normal. One would like this number to be very close to unity, i.e. to have good agreement with the hypothesis that the residuals are normally distributed, unless there is a reason to expect a non-normal random process influencing fault rate. No such reason is known for cavity arcing.
\[
\ln\left(\frac{1}{\text{interval} \cdot \text{grad}^2}\right) = -4.1657 - 62.2099 \frac{1}{\text{grad}}
\]

**Summary of Fit**
- RSquare: 0.372332
- RSquare Adj: 0.369999
- Root Mean Square Error: 1.302807
- Mean of Response: -14.2408
- Observations (or Sum Wgts): 271

**Analysis of Variance**

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<th>Mean Square</th>
<th>F Ratio</th>
<th>Prob&gt;F</th>
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**Parameter Estimates**

| Term      | Estimate | Std Error | t Ratio | Prob>|t| |
|-----------|----------|-----------|---------|-----|
| Intercept | -4.165706| 0.801491  | -5.20   | <.0001 |
| 1/grad    | -62.20988| 4.924736  | -12.63  | <.0001 |

Figure 2. SL021. All data since helium processing Jan. 97 shown. Points excluded by automatic cuts highlighted. Will cut points with large residuals after looking at data table.
Figure 3. Residuals of fit to SL021 data in figure 2. Ten points highlighted are clearly distinct from the 261 in the rest of the distribution.

In the data table, I see that six of the points at the top have intervals under fifteen minutes. The two at the bottom with long intervals occurred during startup after the January 1997 maintenance down and likely have poor correction for RF off condition. These eight will be eliminated in the next cut.
2. Methodology

2.1 Data collection and processing

Data collection is via an instance of the EPICS archiver labeled the RfFaultLogger. A process is created for each cavity which monitors the status of the RF on/off bit. A file is written with the value of eight EPICS variables each time the RF on/off bit changes. The variables are: two summary variables containing information on the type of faults which occurred, FLT1 and FLT2; forward and reverse RF power, CRFP and CRRP; gradient set and measured values, GSET and GMES; the bolometer readback CWWT; and the total beam current in the SL, R2XXITOT. The date and time of the fault are in the header of the entry. FLT2 includes information on the arc and waveguide vacuum fault indicators.

A series of scripts are used to extract and process fault data from the logs. The first discards faults which do not show either an arc or waveguide indicator, perhaps a tenth the total. Since the archiver records on each change of state, two records are written for each fault, one on the good to bad transition and one on the bad to good transition. The script discards all but one of multiple cavity records within four seconds of each other to eliminate this duplication.

A second script does a rough correction for long periods when the RF in the entire machine is turned off, e.g. maintenance days and downs. All recorded faults are placed in time order. Running fifty point means and standard deviations of the fault intervals are computed. If the interval between faults is greater than six hours and greater than (mean plus six standard deviations), the running mean is substituted for actual clock interval. This approximation was arrived at by spreadsheet experimentation in the mid-90's. Until 1999, the injector was not included in the fault list because it was often on when the rest of the machine was off, rendering this correction algorithm ineffective. Since then, this condition has obtained less frequently and the injector data is included in the data set. This script also removes cavities which show only a waveguide vacuum fault at the same time as the other cavity in the pair shows an arc detector fault, under the assumption that the fault likely originated where the light was. Waveguide vacuum faults occur in cavity pairs due to a common vacuum sensor. There are individual arc detectors on each cavity.

Approximating the true interval between faults in a given cavity in this manner rather than directly recording power on/off for each cavity with another method and using that information to individually correct each cavity is the most obvious flaw in the analysis. It was adopted because we don't have the power on/off data and because the programming task was so daunting even if the data became available.

Once the corrected fault times are computed for each of the faults, they are sorted into four bins: everything which the first script accepts; arc detector only; waveguide faults only; arc and waveguide faults. Intervals between faults for each cavity are then calculated by a third script. Analysis used to include all faults which showed arc detector response. For reasons discussed in section 3.3 below, it is now applied only to faults which show both arc and waveguide faults, those with FLT2 = 72.

It is likely that there are false negatives buried in the waveguide-only fault data, i.e. that some of these faults were caused by an arc at the ceramic window. Since the arc detector didn't fault, one can't say which of the pair arced. I have been unable to find any patterns in this data. Assistance would be welcome.
Summarizing, Unix scripts are used to extract fault records with waveguide or arc faults; eliminate duplication; correct for periods in which the RF was off; and calculate intervals between faults for the full set and subsets of data. The data is then taken to my desktop machine for further manipulation using the exploratory data analysis package JMP sold by SAS.

In JMP, I make further cuts to the data:

- fault intervals less than 8 seconds or more than 12 days are excluded. In one or two cases, intervals up to a month appear to be valid. 12 days, roughly one million seconds, is semi-arbitrary. One rationale was the bi-weekly maintenance days the machine used to schedule.

- gradient change between faults greater than 10% as the interval between faults won't be representative of the gradient at the second fault. Since the gradient is in the exponent in both fits, this is a loose cutoff.

- gradient below 2.05 MV/m, as these generally occur during startup after a long maintenance down and lem++ isn't supposed to set gradients this low for operation

On a cavity by cavity basis, I examine the arc faults using the Fowler-Nordheim model as discussed in section 1.3. Six years ago, when I began this work, I could afford the time to look at each outlier, examining my daily meeting reports, the elogs, and other data sources to determine if the outliers should be included in the analysis or excluded as artifacts. Taking these pains generally resulted in normal distributions of the residuals of the Fowler-Nordheim fits. Now, with 88000+ arc faults to deal with, I reverse the procedure. I assume that the residual distribution should be normal and look at the outliers that distort it to decide what to include and what to exclude. I look at the plot of residuals versus independent variable for patterns. I sometimes look at a listing of faults ordered by time within cryomodule because beam strikes will cause multiple pairs to fault simultaneously. Generally, I look at the data for each cavity in isolation. This is not good statistical practice, but the goal is adequate models to feed to lem++ (see section 4.1), not publication in statistical journals.

2.2 Example - analysis of cavity 2L021

Figures 2 and 3 above and 4 to 10 below are those created during the analysis of cavity 2L021. In figures 2 and 3 one clearly sees that a few percent of the data appears to be very different from the bulk of the distribution. As discussed in the caption to figure 3, eight of the points were eliminated after examining the data. The fit to the remaining data is shown in figure 4. The process of examining outliers and removing them is repeated until the residuals are normal or there is no rationale available to remove outliers which distort the residuals.
$\ln\left(\frac{1}{\text{interval} \cdot \text{grad}^2}\right)$ By $1/\text{grad}$

Linear Fit

$\ln\left(\frac{1}{\text{interval} \cdot \text{grad}^2}\right) = -2.1027 - 75.5852 \frac{1}{\text{grad}}$

Summary of Fit

- **RSquare**: 0.697059
- **RSquare Adj**: 0.695898
- **Root Mean Square Error**: 0.778523
- **Mean of Response**: -14.3558
- **Observations (or Sum Wgts)**: 263

Analysis of Variance

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<th>Mean Square</th>
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Parameter Estimates

| Term  | Estimate | Std Error | t Ratio | Prob>|t| |
|-------|----------|-----------|---------|------|
| Intercept | -2.102728 | 0.502299 | -4.19 | <.0001 |
| 1/grad  | -75.58522 | 3.084331 | -24.51 | <.0001 |

Figure 4. SL021 regression after removal of eight points discussed in figure 3 caption.
Residuals $\ln(1/(\text{interval}\times\text{grad}^+)$

![Graph showing residuals](image)

**Quantiles**

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<td></td>
</tr>
</tbody>
</table>

**Moments**

- Mean: -0.0000
- Std Dev: 0.7770
- Std Error Mean: 0.0479
- Upper 95% Mean: 0.0943
- Lower 95% Mean: -0.0943
- N: 263.0000
- Sum Weights: 263.0000

**Test for Normality**

- Shapiro-Wilk W Test: W = 0.950424, Prob<W = <.0001

Figure 5. 2L021 residuals after cut of eight points and refit. Two points at top, with intervals under thirty minutes, will be removed next.
\[ \ln\left(\frac{1}{\text{interval} \times \text{grad}^2}\right) \text{ By } \frac{1}{\text{grad}} \]

**Linear Fit**

\[ \ln\left(\frac{1}{\text{interval} \times \text{grad}^2}\right) = -2.0271 - 76.2281 \frac{1}{\text{grad}} \]

**Summary of Fit**

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**Analysis of Variance**

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<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F Ratio</th>
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**Parameter Estimates**

| Term    | Estimate | Std Error | t Ratio | Prob>|t| |
|---------|----------|-----------|---------|-----|
| Intercept | -2.02707 | 0.456608  | -4.44  | <.0001 |
| 1/grad   | -76.22812| 2.804294  | -27.18 | <.0001 |

**Figure 6.** 2L021 third cut. A total of ten points have been removed manually. 56 were removed by the automatic data cuts referred to in the text.
Figure 7. 2L021 third cut residuals. The hypothesis that this distribution is normal cannot be excluded at the p=0.05 level. Stop cutting.
\[ \ln(1/\text{interval}) = -23.634 + 2.06943 \times \text{corr \_ grad} \]

Summary of Fit

- **RSquare**: 0.804654
- **RSquare Adj**: 0.8039
- **Root Mean Square Error**: 0.69341
- **Mean of Response**: -10.7323
- **Observations (or Sum Wgts)**: 261

Analysis of Variance

- **Source**: Model, Error, C Total
- **DF**: 1, 259, 260
- **Sum of Squares**: 512.96187, 124.53179, 637.49366
- **Mean Square**: 512.962, 0.481, 637.49366
- **F Ratio**: 1066.853
- **Prob>F**: <.0001

Parameter Estimates

- **Term**: Intercept, corr\_grad
- **Estimate**: -23.63425, 2.0694286
- **Std Error**: 0.39733, 0.063358
- **t Ratio**: -59.48, 32.66
- **Prob>|t|**: <.0001, <.0001

Figure 8. 2L021 third cut data fit with empirical, exponential model used by lem++
Figure 9. 2L021 third cut, empirical exponential fit, residuals.
This process is repeated for each of the cavities in the machine. 2L021 was analyzed here simply because I finished the North Linac before beginning this paper. Thus the first cavity in the South Linac was next in sequence. This cavity happens to be one with much data and a good fit. It thus provides a good example of the stability of models. The previous modeling iteration resulted in the fit $\ln(1/\text{interval}) = -24.167 + 2.16253 \text{ corr}_\text{grad}$, about two standard deviations in slope estimate and one standard deviation in intercept estimate from that in figure 8 above. Cavities in which the number of faults increases substantially from one modeling iteration to the next change more radically, of course.

Sources of error in these models include:

- technique used to correct for periods when RF is turned off
- technique used for outlier removal
- faults not recorded by RF fault logger
- changes in gradient calibration when RF control modules are replaced or repaired

The last two of these have not been discussed above. There are periods when the RF fault logger process stops and remains inactive for days in spite of a Unix chron (chronic) task which checks status of the logger every fifteen minutes. Such intervals are removed by the technique used to correct for the time RF was off even though RF was on and faults occurred. In addition to periods when the entire fault logger was non-functional, there are questions about its functionality in general. A technique for inducing arcs in all cavities in the machine simultaneously was tried on March 20, 22 and 23, 2001. The RF fault logger recorded only 20% to 80% of the faults registered by the RF commander MEDM display. It is hoped that this occurs only when many cavities fault simultaneously. The number of RF FSD faults recorded by BOOM and the RF fault logger agree well during normal circumstances.

RF control modules fail and must be replaced and repaired. Module to module calibrations are good, but there is occasionally a change in arc behavior versus gradient which falls within model error on the day when the control module for that cavity was replaced. The last time the gradients of each cavity in the machine were calibrated using the transport arcs as spectrometers was July 1997. Data was taken last year on most cavities but has not been fully analyzed by the colleague who took it.

### 2.3 Summary results

This methodology has been applied to all cavities in the machine during the year beginning April 2000. The North Linac has been completely evaluated twice and the South Linac once in that period. Individual cavities may have been modeled more often, as Operations staff notice changes in performance or that a particular model does not accurately reflect the cavity behavior. I recognized that arc-only faults were likely false positives (section 3.3) only in cryomodule NL17, so 80% of the North linac had to be checked after that discovery. Below I summarize the set of models as they exist at this writing.

206 out of 320 linac cavities and 5 of 18 injector cavities have fault models. *lem++* deals only with the linacs. Of the 320 linac cavities, six are disabled long term. The number of unmodeled cavities will drop somewhat after the next analysis pass through the South Linac.
In figure 10, I show the range of cavity fault interval versus gradient seen in the empirical exponential models. The mean and two extremes in the ensemble are shown. With 338 cavities in the machine, one would like to run at gradients producing one fault every 4 days per cavity, less than four faults/hour for the whole machine. For these cavities, the "4 day" gradients are ~4.5, ~6.7 and 8 MV/m. Note that the cavity with the steepest slope will be very sensitive to gradient calibration errors.
Figure 11 contains histograms of the slopes of the empirical fault models and modifications of these actually used in lem++. The lem data input includes eight cavities in the South Linac analyzed in another manner by C. Reece and not yet analyzed by me. Reece calculates a gradient for 8 hour fault interval and assigns a canonical gradient of 2, about a quarter standard deviation above the mean of the combined distribution. Four models with slopes above 6 were reduced to 4 in the lem++ input file, causing the spike there in the lem_slope histogram.
Figure 12 shows the empirical model slopes and associated goodness of fit parameters. Quantiles rather than moments are shown for the F ratio because they are more informative for such a distribution.

Figure 12. Distribution of statistical fit parameters for empirical models, highlighting those modified in the lem++ input data table.
2.4 Discussion of summary results

Figure 12 shows that the statistical models derived to date have a wide range of robustness. In roughly one sixth of the cases, as shown in figure 11, manual intervention is made. These interventions include reduction of slopes to within +/- two standard deviations of the mean and omission of models which, however high their goodness of fit parameters, are determined by only a few data points taken during off-normal conditions, for example the 6 GeV test in August 2000. Other models are omitted because their F ratios are extremely low. These last two are reflected in the lower of number of points in the first histogram of figure 11 (197) versus that in the first histogram of figure 12 (209), though these are taken from the same data set.

3. Specific analyses

3.1 Fratricide

One of the most frustrating results of this study, because the hypothesis seems so far-fetched physically, is "fratricide". By this is meant a cavity whose field emission drives arc trips in another cavity, not itself. As mentioned in section 1.2, the field emitted electrons make a right angle turn at the input coupler and travel several centimeters to the ceramic window. When fratricide occurs, the field emitted electrons from one cavity charge the window of another. This is hard enough to believe when the two cavities are paired, with ceramic window centerlines 18.7 cm apart along the beamline. Cryomodule NL4 provides evidence, as shown below, that field emitted electrons from one cavity can cause arcs in two others. NL04-8 gradient was lowered from 10 MV/m to 5 MV/m when nitrogen was inadvertently introduced into the beamline during attempted maintenance on the adjacent warm beamline. NL04-8 seems to have caused arcing in cavities NL04-6 and NL04-7. NL04-6 is in the adjacent cryounit. A field emitted electron from NL04-8 will have to move upstream across two full cavities and two "drifts" to reach the input coupler of NL04-6. These electrons have to arrive with the right phase to get deflected into the input coupler and move to the ceramic window. I don't believe this occurs, but I don't have another explanation for what is seen in the data below. Suggestions are solicited.

Additional evidence: During November and December 2000, trip rates were very high. Twenty cavities which do not themselves arc but which were near cavities showing little or no gradient dependence of arc rate were clamped at lower values in January 2001. Even though the cavities in the machine for which arc models exist had to make up for the lost energy, the fault rate in January was about half that in November. Since NL04 provides evidence that cavities can "kill" at a distance of two meters, not just twenty centimeters, I have as yet been unable to determine which subset of the twenty cavities turned down are guilty. Parasitic tests will be possible again during the high energy run which begins in June 2001.

In Figure 13a, all arc fault data since helium processing is shown for cavity NL04-6. There was a change in character of the dependence at the end of 1998, as is seen by inspection. Figure 13b shows the January 1999 through November 2000 data, showing no gradient dependence. Cavity 8 in that module was running at high gradient during this period. At the end of November 2000, as mentioned above, nitrogen was inadvertently introduced into NL04-8 and it had to be turned down to 5 MV/m. Figure 13c shows this cavity's behavior in December 2000 and January 2001. Gradient dependence similar to that seen in 1997 and 1998 is again seen, with good statistical fit.
Figure 13a. NL046 1997 and 1998 data highlighted clearly differs and will be removed.

In(1/(interval*grad**2)) By 1/grad

Figure 13b. NL046 Jan. 1999 through Nov. 2000, with cavity NL048 at high gradient. No gradient dependence here.

In(1/(interval*grad**2)) = -13.637 – 0.73001 1/grad

Summary of Fit
- RSquare = 0.000117
- RSquare Adj = -0.00345
- Root Mean Square Error = 1.34468
- Mean of Response = -13.7601
- Observations (or Sum Wgts) = 282

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F Ratio</th>
<th>Prob&gt;F</th>
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<tbody>
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<td>Error</td>
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<td></td>
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<tr>
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<td>506.34546</td>
<td></td>
<td>0.8564</td>
<td></td>
</tr>
</tbody>
</table>
\[
\ln\left(\frac{1}{\text{interval} \cdot \text{grad}^2}\right) = -2.6596 - 85.8805 \frac{1}{\text{grad}}
\]

**Summary of Fit**
- **RSquare**: 0.150855
- **RSquare Adj**: 0.147458
- **Root Mean Square Error**: 1.101405
- **Mean of Response**: -12.9558
- **Observations (or Sum Wgts)**: 252

**Analysis of Variance**

<table>
<thead>
<tr>
<th>Source</th>
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<th>Mean Square</th>
<th>F Ratio</th>
<th>Prob&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
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<td>53.8780</td>
<td>44.4138</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>250</td>
<td>303.27321</td>
<td>1.2131</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C Total</td>
<td>251</td>
<td>357.15124</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Parameter Estimates**

| Term      | Estimate | Std Error | t Ratio | Prob>|t| |
|-----------|----------|-----------|---------|------|
| Intercept | -2.659638| 1.54651   | -1.72   | 0.0867|
| 1/grad    | -85.8805 | 12.88652  | -6.66   | <.0001|

Figure 13c: NL046 after cavity 8 turned down. Gradient dependence appears. The cavity is running at 8-9 MV/m here, versus 5 MV/m in November 2000.
Figure 14 shows cavity NL047 behavior January 1999 - November 2000. There is a small but statistically significant gradient dependence. This slope of the empirical exponential fit to this data is 0.54, at the low end of the distribution shown in figure 11a. I would use it as input to lem++ were it not for other information that cannot be graphed: this cavity has operated at 9.5 MV/m since the adjacent cavity NL04-8 was turned down November 30, 2000, and NO arc faults have been recorded. NL04-8 has only three recorded faults, in early November 2000, at 9.5 - 10 MV/m.

\[
\ln(\frac{1}{(\text{interval} \cdot \text{grad}^2)}) = -12.232 - 11.3519 \frac{1}{\text{grad}}
\]

**Summary of Fit**
- RSquare: 0.032958
- RSquare Adj: 0.029323
- Root Mean Square Error: 0.984083
- Mean of Response: -13.9999
- Observations (or Sum Wgts): 268

**Analysis of Variance**
- Source: Model
- DF: 1
- Sum of Squares: 8.77941
- Mean Square: 8.77941
- F Ratio: 9.0657
- Prob>F: Prob>0.0029

**Parameter Estimates**
- Term: Intercept
- Estimate: -12.2323
- Std Error: 0.590133
- t Ratio: -20.73
- Prob>|t|: <.0001

- Term: 1/grad
- Estimate: -11.35194
- Std Error: 3.770242
- t Ratio: -3.01
- Prob>|t|: 0.0029

Figure 14. NL047 January 1999 through November 2000. Mild gradient dependence. Most recent operation is the middle cluster at 6 MV/m. NO faults at 9.5 MV/m since cavity 8 was turned down November 30, 2000.
Figures 13 and 14 demonstrate that a dramatic change in the arc behavior of nearest and next-nearest neighbor cavities may be obtained by a reduction in gradient in a cavity which rarely or never itself arcs and thus is run at the highest gradient available RF power allows. There are no direct diagnostics which allow one to determine which cavity is causing others to arc, no way of measuring window charging directly as a function of gradient of nearby cavities. One can only reduce the gradients on suspects and see if the analyses of victims change from that in figure 13b to that in 13c. Since the field emitted electrons in NL04-6 from NL04-8 have already traversed two meters and two cavities, another twenty centimeters, to the third-closest ceramic window, must be considered. With one third of the cavities rarely or never arcing, fingering suspects for gradient reduction is difficult. We cannot afford to turn down all suspects because the fault rate from the known arc-ers would increase too much to deliver acceptable beam for physics.

M. Tiefenback suggested changing the phase of suspects as this would change the arrival phase of field emitted electrons at the victim's windows. Keeping track of phase changes during a month of testing, including putting selected cavities off phase after Krest runs put them on phase, is problematic operationally so I haven't tried this approach.

Fractricide is a painful reality which will take much time to pin down well enough for true machine optimization.

### 3.2 NO arc rate dependence on beam current

The question of direct beam current dependence of arc rate has long been open. Accelerator arc rate is known to be indirectly dependent on linac beam current via input power limitations. If cavities which do not arc are limited in gradient by beam current loading due to insufficient RF power coupled to the cavity, other cavities that arc more frequently have to be turned up to provide the total energy needed and the total number of arcs increases. Improved coupling from klystron to cavity and beam via increased input Q remains very important for accelerator availability. I demonstrate here that there is no dependence of arc rate on beam current on a cavity by cavity basis.

As discussed in sections 1 and 2, two models are used for analysis of the gradient component of cavity arc faults, an empirical exponential model and the Fowler-Nordheim model of field emission. Table 1 below shows the correlation coefficients and F ratios of these fits on eight cavities.

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Fowler-Nordheim model</th>
<th>Exponential model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R^2$</td>
<td>F ratio</td>
</tr>
<tr>
<td>NL15-1</td>
<td>0.29</td>
<td>74</td>
</tr>
<tr>
<td>NL15-2</td>
<td>0.055</td>
<td>8.2</td>
</tr>
<tr>
<td>NL15-4</td>
<td>0.40</td>
<td>92</td>
</tr>
<tr>
<td>NL15-6</td>
<td>0.26</td>
<td>65</td>
</tr>
<tr>
<td>NL15-7</td>
<td>0.29</td>
<td>24</td>
</tr>
<tr>
<td>NL15-8</td>
<td>0.64</td>
<td>136</td>
</tr>
<tr>
<td>NL16-1</td>
<td>0.56</td>
<td>160</td>
</tr>
<tr>
<td>NL16-2</td>
<td>0.18</td>
<td>39</td>
</tr>
</tbody>
</table>
The $R^2$ values for the gradient fits show that there are variables other than gradient which affect the arc rate. In NL15-2, the gradient explains only a small portion of the arc rate, but still a significant one (via F ratio). The other variables involved are not known.

Forward power, CRFP, is recorded for each fault in addition to gradient. It is composed of two major terms, $V^2/R$ and $I^2R$. The gradient analysis summarized above yields residuals which contain information about the cause of the remaining variation. If there is dependence of arc rate on beam current, it should be seen when one regresses the forward power against the residuals of the gradient fits. Table 2 below summarizes the results of such regressions for the cavities in table 1. None of these fits are significant.

Table 2. Goodness of fit for regressions of forward power against residuals of gradient fits.

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Fowler-Nordheim model</th>
<th>Exponential model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R^2$</td>
<td>F ratio</td>
</tr>
<tr>
<td>NL15-1</td>
<td>0.0012</td>
<td>0.22</td>
</tr>
<tr>
<td>NL15-2</td>
<td>1.4E-7</td>
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</tr>
<tr>
<td>NL15-4</td>
<td>0.0085</td>
<td>1.2</td>
</tr>
<tr>
<td>NL15-6</td>
<td>0.00043</td>
<td>0.079</td>
</tr>
<tr>
<td>NL15-7</td>
<td>0.015</td>
<td>0.90</td>
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<tr>
<td>NL15-8</td>
<td>0.002</td>
<td>0.16</td>
</tr>
<tr>
<td>NL16-1</td>
<td>0.002</td>
<td>0.26</td>
</tr>
<tr>
<td>NL16-2</td>
<td>0.000033</td>
<td>0.0063</td>
</tr>
</tbody>
</table>

Figures 15 through 17 show representative graphs, for the last cavity in the table, NL16-2. In figure 15 I plot arc rate versus forward power directly, to show that a dependence is seen before the gradient dependence is removed via the Fowler-Nordheim and exponential models. In Figures 16 and 17, the residuals of the exponential and Fowler-Nordheim fits are plotted against forward power. The gradient dependence having been removed, there is no longer any correlation. Since the only other major component of forward power is beam loading, I conclude that there is no dependence of arc rate on beam current. The source of the variation in arc rate seen in the residuals remains unexplained.
\[ \ln(1/\text{interval}) = -12.998 + 0.60617 \text{ crfp} \]

**Figure 15. Direct dependence of arc rate data on forward power, NL162**

**Summary of Fit**
- RSquare: 0.177521
- RSquare Adj: 0.173193
- Root Mean Square Error: 0.854158
- Mean of Response: -11.4785
- Observations (or Sum Wgts): 192

**Analysis of Variance**

<table>
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<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F Ratio</th>
<th>Prob&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>1</td>
<td>29.91966</td>
<td>29.9197</td>
<td>41.0091</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>190</td>
<td>138.62142</td>
<td>0.7296</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C Total</td>
<td>191</td>
<td>168.54108</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Parameter Estimates**

| Term   | Estimate | Std Error | t Ratio | Prob>|t| |
|--------|----------|-----------|---------|------|
| Intercept | -12.99786 | 0.245133  | -53.02  | <.0001 |
| crfp   | 0.6061725 | 0.094658  | 6.40    | <.0001 |
Residuals $\ln(1/\text{interval})^2$ By crfp

Residuals $\ln(1/\text{interval})^2 = 0.04729 - 0.01887 \text{ crfp}$

Summary of Fit

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F Ratio</th>
<th>Prob&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
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<td>0.02898</td>
<td>0.028982</td>
<td>0.0463</td>
<td></td>
</tr>
<tr>
<td>Error</td>
<td>190</td>
<td>118.92616</td>
<td>0.625927</td>
<td>Prob&gt;F</td>
<td></td>
</tr>
<tr>
<td>C Total</td>
<td>191</td>
<td>118.95514</td>
<td></td>
<td>0.8299</td>
<td></td>
</tr>
</tbody>
</table>

Parameter Estimates

| Term  | Estimate | Std Error | t Ratio | Prob>|t| |
|-------|----------|-----------|---------|------|---|
| Intercept | 0.0472867 | 0.227052  | 0.21    | 0.8352 |
| crfp   | -0.018866 | 0.087676  | -0.22   | 0.8299 |

Figure 16. Regression of forward power against residuals of exponential gradient fit
Residuals $\ln(1/(\text{interval}^*\text{grad}^*)$ - By crfp

Linear Fit

Residuals $\ln(1/(\text{interval}^*\text{grad}^*) = 0.0175 - 0.00698 \text{ crfp}$

Summary of Fit

| Term       | Estimate | Std Error | t Ratio | Prob>|t| |
|------------|----------|-----------|---------|------|
| Intercept  | 0.0175009| 0.22761   | 0.08    | 0.9388|
| crfp       | -0.006982| 0.087891  | -0.08   | 0.9368|

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F Ratio</th>
<th>Prob&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
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<td>0.00397</td>
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<td>0.9368</td>
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<td>Error</td>
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<tr>
<td>C Total</td>
<td>191</td>
<td>119.51554</td>
<td>0.629008</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 17. Regression of forward power against residuals of Fowler-Nordheim fit.
3.3 False positives

As mentioned in the caption of figure 1, fault records in which only the arc detector registers are thought to be false positives. This section will provide the justification for this hypothesis.

When I reached cryomodule NL17 in my most recent analysis pass through the North Linac, I noticed in analyzing NL17-2 that there were many points with short intervals between arcs which did not show simultaneous waveguide vacuum faults. With these points included, there was no gradient dependence. With these points excluded, there were only seven faults. I then produced figure 1, showing a significant upsurge in the number of arc-only faults in 2000, when many cavities that had not arced were pushed further into field emission in order to support higher beam energy for physics. I decided to remove such faults from my analysis. In figures 18 and 19 I show analysis of NL17-7 with and without such faults. For the data set including arc faults with and without accompanying vacuum faults, figure 18, no significant arc rate dependence on gradient is seen. The sign of the poor fit is unphysical: fewer faults at higher gradients. When only faults with simultaneous arc and vacuum faults are considered, figure 19, gradient dependence is evident.

Prior to this analysis, it was thought such faults were on the cavity side of the ceramic window. As can be seen in figure 1, they represented 2-4% of the total arc faults prior to 2000. In 2000, such arc-only faults were 10% of the total arc faults, accounting for about thirty hours of lost beam time. Even if only the increase from 4% to 10% of total arc faults is assumed to be false, this is still about twenty hours of lost beam time.

The working hypothesis is that x-rays produced by field emission are hitting the glass envelopes of the photomultipliers, causing scintillation pulses. The detector circuitry may saturate with too high a pulse rate. (The design engineer thinks it does, but hasn't run tests on as-installed arc detector cards.) If this hypothesis is correct, shielding the photomultipliers will reduce the false positives. Copper tubing with 1.6 mm wall thickness conveniently fits over the photomultipliers. An erroneous analysis showed they would provide about two orders of magnitude attenuation for x-rays with energy spectrum (7) measured several years ago. For $7 each, 80 copper tubes were cut to length and had a slot machined to admit the desired light. Seventeen of these were installed in the machine. It should be noted that all seventeen arc detectors were found to be improperly positioned when AES installed the copper sleeves. Since a better analysis showed the copper provides little attenuation and the detectors were found mispositioned, the seventeen installed sleeves will be removed in May.

The root cause is likely to be a general circuit problem or an x-ray problem. Monitoring arc types during the June-August high energy run, after preventative maintenance, will provide useful information. An attempt will be made to measure the radiation spectrum in the tunnel. It may be that circuit changes and/or x-ray attenuation are needed. We should know by the end of the year.

The discovery of this problem necessitated a reanalysis of many North Linac cavities in which the arc-only faults were a significant component of the data set. A dozen cavities thought to be victims of fratricide were cleared. This delayed South Linac analysis to May 2001.
**Figure 18.** NL177 arc faults with and without accompanying waveguide vacuum fault

\[
\ln(\text{1/interval}) = -4.4253 - 0.3007 \text{ corr\_grad}
\]

**Summary of Fit**
- RSquare: 0.011471
- RSquare Adj: 0.006741
- Root Mean Square Error: 3.292959
- Mean of Response: -6.77561
- Observations (or Sum Wgts): 211

**Analysis of Variance**
- Source: Model
  - DF: 1
  - Sum of Squares: 26.2989
  - Mean Square: 26.2989
  - F Ratio: 2.4253
  - Prob>F: 0.1209
- Error: 209
  - Sum of Squares: 2266.3074
  - Mean Square: 10.8436
- C Total: 210
  - Sum of Squares: 2292.6062
  - Mean Square: 10.8436

**Parameter Estimates**
- Term: Intercept
  - Estimate: -4.42526
  - Std Error: 1.526142
  - t Ratio: -2.90
  - Prob>|t|: 0.0041
- Term: corr\_grad
  - Estimate: -0.300701
  - Std Error: 0.193087
  - t Ratio: -1.56
  - Prob>|t|: 0.1209
\( \ln(1/\text{interval}) \) By \( \text{corr\_grad} \)

![Graph showing the linear fit of \( \ln(1/\text{interval}) \) against \( \text{corr\_grad} \)]

**Linear Fit**

\( \ln(1/\text{interval}) = -24.756 + 1.96832 \times \text{corr\_grad} \)

**Summary of Fit**

- **RSquare**: 0.323384
- **RSquare Adj**: 0.30224
- **Root Mean Square Error**: 3.167792
- **Mean of Response**: -8.39805
- **Observations (or Sum Wgts)**: 34

**Analysis of Variance**

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<tr>
<th>Source</th>
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<th>F Ratio</th>
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<td>153.476</td>
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</tr>
<tr>
<td>C Total</td>
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<td>474.59296</td>
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<td></td>
</tr>
</tbody>
</table>

**Parameter Estimates**

| Term      | Estimate  | Std Error | t Ratio | Prob>|t| |
|-----------|-----------|-----------|---------|-----|
| Intercept | -24.75599 | 4.217915  | -5.87   | <.0001 |
| corr\_grad| 1.9683181 | 0.503306  | 3.91    | 0.0004 |

Figure 19. NL177 arc faults accompanied by waveguide vacuum faults.
3.4 Utility of helium processing

Tech Note 98-045 is an earlier summary of my statistical analysis of cavity arc faults. It includes an analysis of the gains due to helium processing of the first 86 cavities that were subjected to the process. One to two years of post-processing data were then available. In that note I used the gradient for which a fault interval of four days is predicted as a reference, equivalent to 3.5 faults/hour. I quote below a portion of the tech note.

_Eighty six cavities were subjected to some level of helium processing in the period September 1996 through January 1997. For 44 cavities, no conclusion can be drawn from this analysis. 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 [of these 42 cavities] was 20 MeV x 5 passes = 100 MeV._

This analysis has not been extended to the full machine or the data acquired subsequent to mid-1998 for the 42 cavities mentioned, with one exception. Twelve cavities have been helium processed twice. The first helium processing was done with a procedure which C. Reece states was sub-optimal. For the ten cavities for which statistical models could be derived for the period between first and second helium processing and the period since the second helium processing, the changes in gradient for two day fault interval ranged from -1.9 to + 2.6 MV/m, with a mean of 0.34 MV/m or 0.17 MeV. A soft upper bound to the gain from repeated helium processing is thus ~50 MeV/pass. The bound is soft because stub tuners have or will be added to 109 cavities in the machine, allowing better coupling of RF power into the cavities. This would make helium processing somewhat more effective in these cavities.

Two or four modules which were subjected to the final helium processing protocol will be processed a second time during the May 2001 maintenance down. It is not clear that a definitive answer to the question of utility of repeating helium processing will be derived from monitoring these modules because of confounding factors which began March 20: cavity coughing.

Cavity coughing is a procedure which causes arc faults by abruptly stepping the master oscillator 400 Hz, one to three input bandwidths, causing the RF control system to increase RF power abruptly to the maximum available. The idea is to discharge the buildup on ceramic windows throughout the machine simultaneously in under ten minutes each day, to eliminate or at least reduce the random faults which would otherwise cause beam trips throughout the day. The analysis methods described above clearly fail when cavity coughing is done regularly because the fundamental assumptions in section 1.3 are violated. I have not been able to devise new methods as yet. Suggestions are solicited.
4. lem++ and its predictions

lem++ is the program used to set the gradients of each cavity in each linac subject to beam energy, beam current in the cavities, and arc rate per shift. Heat input from the cavity RF losses to the LHe is evaluated and feasibility with LHe flow rates present checked. The program is described in a paper presented at PAC 1999 (8).

There are three main inputs to lem++. The file lem.dat, maintained by me, contains for each cavity: input Q; maximum allowable gradient; data on likely detuning due to microphonic vibration; two coefficients describing the empirical exponential model described above; the cavity Q; RF power available. The last is read from a table rather than the machine because the klystron voltage readbacks are poor. (A software modification has been requested to read the klystron voltage from a table; the klystron current from the machine; compute available RF power; and update the last column of lem.dat each time lem++ is invoked. No delivery date has been established for this modification.) I revise the lem.dat file three or four times per linac analysis iteration when we're running high energy and thus have many daily faults. If the lem.dat file includes an increase in cavity maximum gradient, the associated GSET.DRVH variable must be updated for lem++ to proceed to completion. lem++ does not check GSET.DRVH and so will attempt to set a cavity above this value. If DRVH is too low, the IOC will not allow the gradient to be reached and lem++ will wait forever.

The file _RFSTATUS is maintained by operators via the cavity history files. Here operators define the on/off status of the cavity and tuner and may impose lower maximum gradient values than contained in lem.dat. Reasons for lowering the gradient maximum include a new field emitter turning on; a bad 2.5 W amplifier or control module which limits available RF power well below that listed in lem.dat; a badly detuned cavity which cannot be retuned using the autotune script, etc. AES personnel review the cavity history files periodically to determine which RF systems need attention during the Tuesday RF recovery periods. I review them when I make a major update to the lem.dat file. Operator gradient limits which are supplanted by new cavity models or new maximum allowable gradients are overwritten. If operators set a tuner on manual and forget to update the cavity history file, lem++ will not run to completion - it will wait forever for the tuner to move.

The script cavm contains a few parameters maintained by me. This script creates the GUI the operators see when they invoke lem++. Default parameters for energy, current, arc rate, and cryogenic tune factor are defined within cavm. The matrix solver used by lem++ is not robust. It solves for the exact values you specify, not equality for most and <= for arc rate as one might expect. If the arc rate default is set too low, the solver may encounter a singular matrix upon initiation and fail, effectively crashing lem++. This condition sometimes occurs when a cavity must be turned off and the machine re-lemmed. It creates a tension between my desires to sleep and to minimize the number of faults. Recently, I have set the arc rate default 2-3 per shift above the minimum feasible value so lem++ won't crash during the night if a few cavities are bypassed. (A software modification request has been filed asking that the matrix solver be replaced with simplex, which can handle minimax and equality conditions, so this tension can be eliminated. Again, no delivery schedule. Once this improvement is in place, the default arc trip rate may be set high and the simplex algorithm will minimize it.)

The table below summarize output from lem++ runs. These runs were made April 26-27, 2001. Cavity history files were updated. _RFSTATUS was temporarily replaced with one in which the 314 functional cavities are all registered as on. Five different lem.dat files were created as described in the configuration column of the table. 76 stub tuners were installed as of April 26,
2001. 33 more are on hand and will be installed by May 20, 2001. The 33 stub tuners are to be placed in locations specified by C. Reece via analysis based on a lem.dat table of March; no input from cavity history files. There is agreement on 31 locations between Reece's analysis and direct use of lem++. The 55 additional stub tuners, if purchased, would be placed in locations where lem++ output shows cavities are RF power (current) limited with 800 kW beam.

The second and third columns of the table contain the predicted arcs/day at 6.0675 GeV with the specified linac current. Actual RF trips/day will be ~75 higher than shown in the table due to other types of faults and arc model uncertainties. 500 uA in the linacs represents 607 kW beam power. 660 uA is equivalent to 800 kW beam power, the operating envelope for CEBAF.

One sees that the addition of the stub tuners produces significant trip reduction at the highest beam loading. The stub tuners allow cavities which arc less to be operated at higher gradient due to better RF:beam coupling and others to be turned down.

During the 6 GeV test last summer, klystrons ran at 11.9 kV in 33 zones and 11.6 kV in 7 zones. We lost a klystron a day. For about a month after the run, klystrons ran at 11.3 kV in 33 zones and 11.6 kV in seven zones. We lost a klystron a week. Since the beginning of FY01, klystrons have been at 10.7 kV in 33 zones and 11 kV in 7 zones. There have been no tube losses since the second voltage reduction. The risk of increasing 33 zones to 11 kV is not quantified.

Table 3. Stub tuners, klystron voltages and arc rates

<table>
<thead>
<tr>
<th>Configuration</th>
<th>6 GeV 500 uA arcs/day</th>
<th>6 GeV 660 uA arcs/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/26/01, 76 stub tuners, 33 CM 10.7 kV, 7 CM 11.0 kV</td>
<td>273</td>
<td>426</td>
</tr>
<tr>
<td>add 33 stub tuners, same voltages</td>
<td>257</td>
<td>348</td>
</tr>
<tr>
<td>add 88 stub tuners (buy 55), same voltages</td>
<td>256</td>
<td>309</td>
</tr>
<tr>
<td>add 33 stub tuners, all CM at 11 kV</td>
<td>251</td>
<td>300</td>
</tr>
<tr>
<td>add 88 stub tuners, all CM at 11 kV</td>
<td>249</td>
<td>282</td>
</tr>
</tbody>
</table>
In figure 20, fault rate versus energy is shown for the second configuration above, that expected for June 2001. The points labeled 660 µA were calculated at that current. The points labeled 800 kW were calculated at that constant power. Note that this is a semi-log plot. At 567 MeV/linac, the two values are 120 and 134 arcs/day, respectively. One may thus expect about 8 RF faults/hour during the June-August run, including the 75/day mentioned above for other types and model errors.

Fig. 20
5. Guidance for Operations

A discussion with M. Joyce April 4 resulted in a change in the cavity history files. These files now include a second, persistent comment field. This field will be used to advise Operations when the normal response to frequent arcs is inappropriate due to fratricide or false positives. The normal response to frequent arcs should be to lower the Ops DRVH value 0.3 MV/m. The new comment field will identify the victims of fratricide and direct operators to a nearby suspect. Over time, given adequate resources to examine the data and subject to the same caveat about coughing as ends section 3.4, it should be possible to determine all of the cavities that cause others to arc.

6. Future work

6.1 False positives

Assess impact of May 2001 preventative maintenance on false positives during the June-August run. Gather additional data on radiation field and pulse pile-up issues.

6.2 Coughing

Develop statistical techniques to deal with the perturbation provided by cavity coughing if it becomes a daily occurrence during high energy runs.

6.3 Helium processing

Once 6.2 is accomplished, assess impact of second helium processing on four modules done in May 2001. Qualitative assessment may be possible if improvement is large.

6.4 Complete analysis of data obtained through March 20, when coughing began.

7.0 Conclusions

Statistical analysis has proven to be a valuable tool in dealing with cavity arc faults. It allows one to demonstrate that beam loading does not affect cavity arc rate except through lem++ optimization of the entire linac. It shows that about one day of beam time per year can be reclaimed once the root cause of a type of false positive can be eliminated. Iterations of the analysis have improved fault rates at high beam energy and power. It allows the identification of cavities whose arc dependencies are not related to their own gradient, so Operations does not unnecessarily reduce their set points. It is necessary but not sufficient to provide operation with less than 3% beam time loss due to RF faults at 6 GeV.

Acknowledgments

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References


2. V. Nguyen-Tuong et al., Electronic Activity at CEBAF Cold RF Window Induced by Cavity Operation; Proc. of 1994 European Particle Accelerator Conf.

3. T. Powers and P. Kneisel, Arcing Phenomena on CEBAF RF Windows at Cryogenic Temperature, CEBAF TN 96-002


7. D. Weisenberger and H. Fenker, X-ray Spectroscopy in the North Linac, CEBAF Detector Meisters note of 10/14/94