IMPROVEMENTS IN FIELD EMISSION: A STATISTICAL MODEL FOR ELECTROPOLISHED BAKED CAVITIES

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Abstract

A statistical model for field emission developed in 1993 has been applied to characterize the improvement in field emitter properties and field emitter occurrence due to improvements in treatment methods for 9-cell TESLA-style cavities. The improved treatments are electropolishing, high pressure rinsing and baking (120C, 48 hours). We model the Q vs. E_{acc} data from 24 9-cell tests and 32 1-cell tests, all conducted at TTF by DESY. The statistical model is able to successfully simulate the observed yields by applying a factor of 3 decrease in emitter density over the emitter density prevailing for treatments in 1993, which did not include high pressure rinsing. Both simulation and data show that at E_{acc} = 70 MV/m the yield for field emission power less than 100 watts ($Q > 8 \times 10^9$) is less than 20%. To raise this yield to 80% will require new treatments that will reduce the emitter density by another factor of 3 at least. Further comparisons of field emission behaviour will be made with data for alcohol rinsed cavities.

INTRODUCTION

In a previous simulation of field emission statistics [1] the program simulated a specified distribution of emitters and calculated the total power loss due to field emission and subsequently the success rate of the cavities as a function of the accelerating electric field. They compared the simulated success rates to data from 1-cell and 5-cell 1.5 GHz and 3 GHz CEBAF cavities. Setting the simulation's important variable – the maximum emitter density per unit area – to 0.3 emitters per square cm best reproduced the data (see figure 1) [1].

The program also accounted for the ranges of values of effective area (A_e) and field enhancement factor (β) among the emitter population. The specific distributions of these values were chosen based on available data at the time. According to this statistical model, the log effective area values had a Gaussian distribution, and the enhancement factor values had an exponential decay.

Objectives of New Simulation

In the fifteen years since these results were reported there have been significant improvements in cleaning methods, such as high pressure rinsing and electropolishing. Such higher standards of cleanliness is to determine quantitatively how field emission now is different from field emission a decade ago. This includes adjusting the statistical model of the simulation
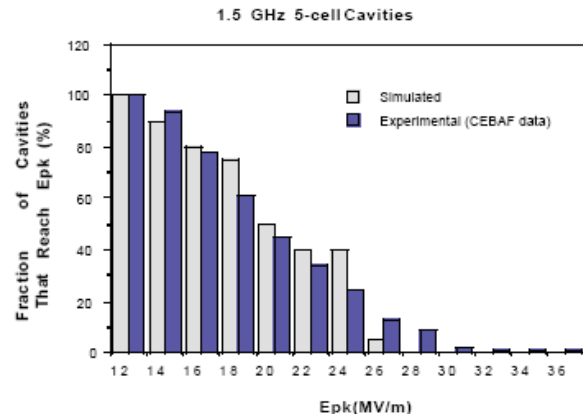

Figure 1: Simulated vs. Measured success rate (CEBAF data) [1].

to allow for possible changes in emitter density and characteristics, to fit new data, and compare different aspects of field emission. The resulting analysis looks beyond the success rate comparison and single free variable of the previous report.

DATA

All data used in this analysis were taken from the Tesla RF cavity database [2]. Quality factor vs. E-field curves were taken from 32 1-cell and 24 9-cell 1.3 GHz cavity tests (16 1-cell cavities and 10 9-cell cavities). To minimize effects not due to field emission and also to ensure that any cavities analyzed underwent modern preparation techniques, only cavity tests on cavities which had been electropolished, high pressure rinsed, and baked were included in the data set. By restricting the data set to tests on only baked EP cavities, we prevent high-field Q-slope from skewing the data. For some cavities which showed strong field emission and were retreated with HPR only and retested, both tests were counted as separate tests.

These Q vs. E curves are then used to generate the success curves used for comparison to the simulation. The success rate histograms used in the previous report are simply obtained, using only the maximum value of E reached for each cavity test. However we can generate a more in-depth representation of the data which uses the entire Q vs. E curve for all of the tests. Instead of using the percentage of cavities which reached each given E-field, we can consider the percentage of cavities with quality factor greater than a given Q at each E-field. This can be done for a few threshold values of Q, producing a yield profile of the data.

MODIFIED MODEL

According to the previous model, the area and beta values of the emitters had specific distributions:

$$N(\beta) \sim \exp(-0.01*\beta)$$
$$N(Ae) \sim \exp\{-([\log(Ae) + 13.262]/2.175)^2\}$$

These are shown in Figures 2 and 3. The beta values ranged from 40 to 600, and the log-area values ranged from -18 to -8. The simulation runs as follows. A cavity is split up into a number of regions (typically 20), and each region is given a random emitter density between zero and the maximum density specified. Area and beta values are distributed so the entire emitter population has the distributions given above. There is no correlation made between area and beta values [1].
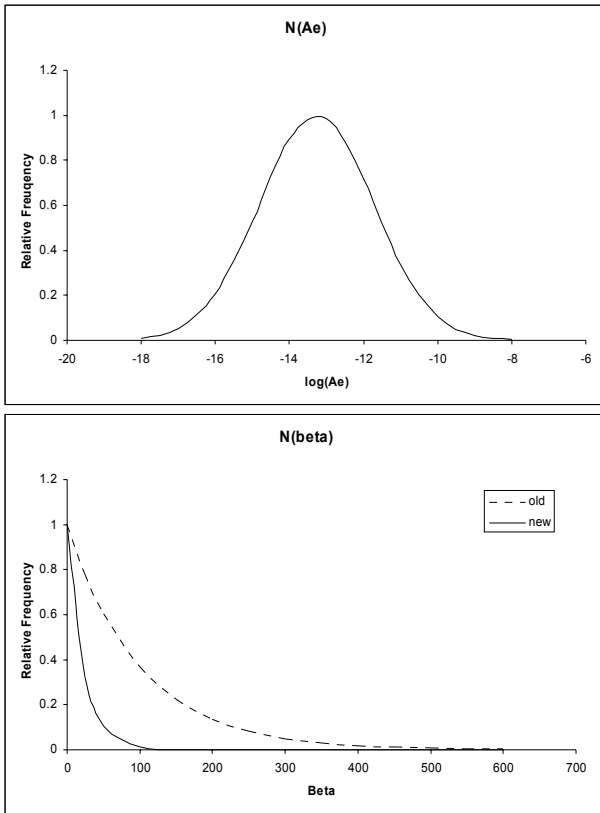
Figures 2 & 3: Area and beta value distributions.

The cavity is then run at a given accelerating field, and the power in watts from each emitter is calculated using

$$P = Ae*10^{12}*(1500/freq)^{1.5}*1.8 \times 10^7*\exp(-7.4 \times 10^4/\beta E)$$

where E is the E-field at the emitter's location in MV/m. Individual emitters running more than 100 W were considered processed. The total power from all the emitters is added up and recorded. A test was considered "successful" if the total emitted power was under 10 W for 1-cell cavities and 100 W for 5-cell cavities. The only free parameter was the maximum emitter density.

When this is set to 0.3 cm^{-2}, the simulated success rate fit the data well [3].

The new model differs from the old model mainly in the free parameters used. Varying only the maximum density was found to be insufficient to account for the new data, and so the exponential coefficient of the beta value distribution was also varied. A higher coefficient implies less emitters with high values of beta. The range of beta values was left unchanged. The effective area distribution and emitter processing criteria were also kept the same. The condition for success was mainly the same – a total emitted power of under 10 W constitutes success for a 1-cell cavity, under 100 W is success for a 9-cell cavity.

Also, to make a comparison against the yield profiles, the Q value of each cavity must be recorded during the new simulation. We assume a Q factor of $Q_0 = 2 \times 10^{10}$ in the absence of field emission. The cw power in watts dissipated in the cavity walls is then

$$P_D = L*E_{acc}^2/[(R/Q)*Q_0]$$

where L is the length of the cavity, E_{acc} is in V/m, and R/Q is a constant which equals 1000. We can now calculate Q from the total power due to field emission

$$Q = L*E_{acc}^2/[(R/Q)*(P_D + P_{FE})].$$

The goal was to find the combination of parameters – density and beta coefficient – which best fit the yield profiles for both the 1-cell and 9-cell cavity test data. Please note at this point that due to quench in the data, which is not simulated in the program, the simulated yields at high E-fields are expected to be higher than the data. Basically, the yield profiles from the data are constrained by the success rate curve, whereas the simulation has no such restriction.

The best fits were found using a maximum emitter density of 0.1 cm^{-2} and a beta coefficient of 0.045. These suggest a reduction by a factor of 3 in the number of emitters since the previous report, as well as a shift in the emitter population towards lower values of beta. The comparisons to the 1-cell and 9-cell data are shown in figures 5 and 6. See also the success rate comparisons using these same parameters in figures 7 and 8.

The simulated yield at $Epk = 70$ MV/m, $Q > 5 \times 10^9$ is about 70 percent for single cells, and about 60 percent for 9-cells. The observed yields are of course even lower because several tests are also limited by quench or power. To reach the ILC goal of 95 percent, we still need to improve field emitter density further. Note that at 70 MV/m, $Q = 5 \times 10^9$ corresponds to $P_{FE} = 184$ W for a 9-cell cavity, so the simulated yield is higher than the simulated success rate, which uses the 100 W cutoff.
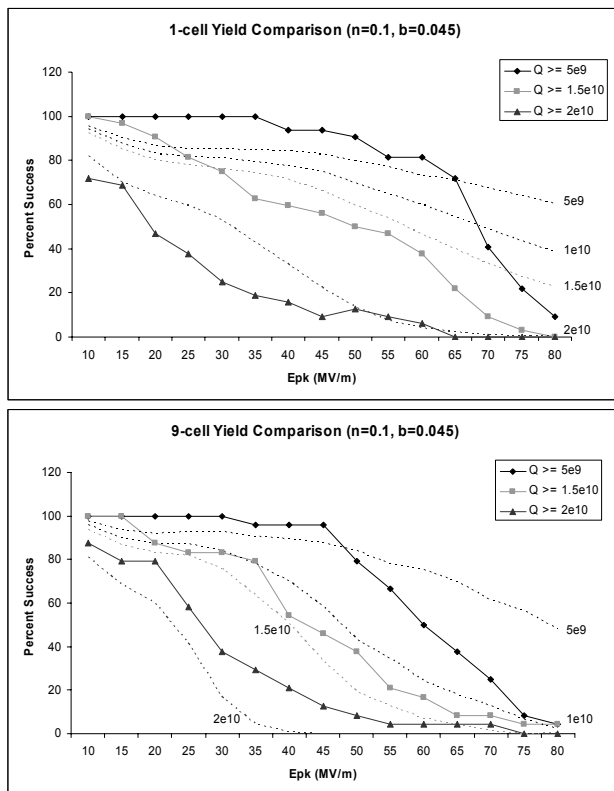
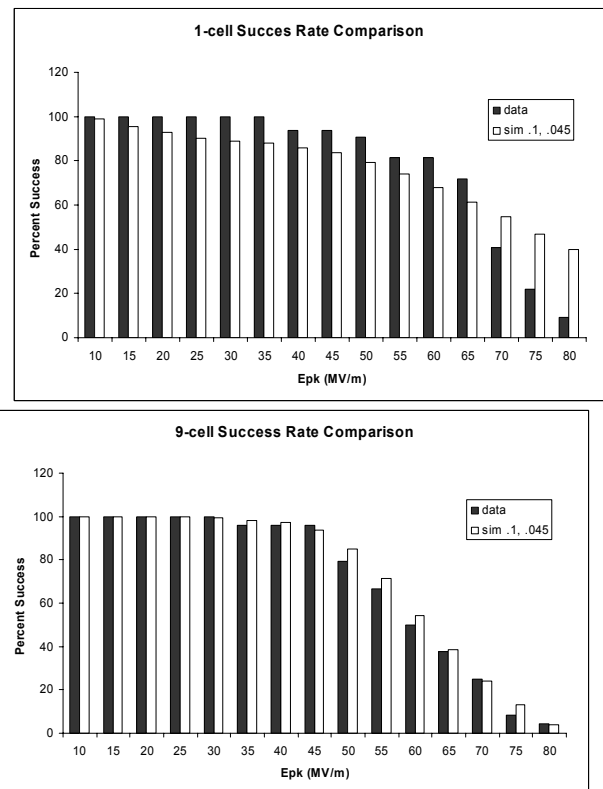Figures 4 & 5: New simulated vs. observed yield profiles for 1-cell and 9-cell tests.

FUTURE IMPROVEMENTS

Simulations show that a maximum emitter density of 0.035 cm^{-2}, i.e. another factor of 3 improvement, is necessary to obtain an 80 percent success rate for 9-cell cavities at $Epk = 70$ MV/m. At this density, the average number of emitters processed up to 70 MV/m is just under 2. To reach this result, cleaning techniques would have to improve to reduce the number of emitter sites to roughly a third of current standards. Candidates for improvement are ethanol rinsing, soap and water ultrasound, and dry ice cleaning. It would be useful to compare new data on these treatments with future simulations once more than 20 tests are available.

CONCLUSION

Improvements in cavity cleaning techniques have reduced field emission over the past years. This improvement can be evaluated by matching the computer simulation to more recent test data. Fitting the same parameters to both 1-cell and 9-cell data sets shows that the typical emitter density has been reduced, from a maximum of 0.3 cm^{-2} to 0.1 cm^{-2}, and that higher-beta

emitters are more preferentially eliminated than in the past.

Figures 6 & 7: New simulated vs. observed success rates for 1-cell and 9-cell tests.

Both data and simulation show that several emitters need to be rf processed in 9-cell cavities to reach $E_{pk} = 70$ MV/m. The simulations show that cleaning techniques need to be improved further to reach $E_{pk} = 70$ MV/m with an 80 percent success rate.

REFERENCES

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[3] H. Padamsee et al. *RF Superconductivity for Accelerators*, Cornell University, Ithaca, NY 1998