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Improvements in Field Emission: An Updated Statistical Model for Electropolished Baked Cavities

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Introduction

In 1993, Hasan Padamsee et al. simulated field emission in superconducting Niobium cavities with a statistical model program. This program simulated a specified distribution of emitters and calculated the total power loss due to field emission and subsequently the success rate of cavities as a function of the accelerating electric field. They compared the simulated success rates to data from many 1-cell, 1.5 Ghz, 1-cell 3 GHz and 5-cell, 1.5 GHz CEBAF cavities. Setting the simulation's main free variable – the maximum emitter density per unit area – to 0.3 emitters per square cm - best reproduced the data. See Figure 1 for 1.5 GHz, 5-cell CEBAF cavity data simulation from the previous paper [1].

The simulation program took into account the ranges of values of effective emitter area (*Ae*) 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 field enhancement factor values had an exponential decay. These choice of these distributions was guided by available data on field emitters from DC scanning studies.

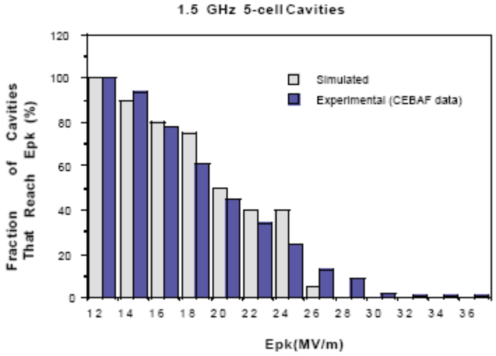


Figure 1: Simulated and. observed success rate from 1993 report [1]

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. Experience clearly shows that these higher standards of cleanliness have reduced field emission. One goal of this project is to determine quantitatively how much field emission now is different from field emission a decade ago. This requires adjusting the statistical model of the simulation to allow for possible changes in emitter density and emitter characteristics to fit the new data. We aim to compare different aspects of field emission, such as overall cavity success rate, the yield vs. gradient at different Q values, the onset field for emitters, and the number of emitters that must be processed to reach accelerating gradients of 35 MV/m. Thus the analysis here looks beyond the simple success rate comparison of the previous study.

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 (on 16 1-cell cavities and 10 9-cell cavities). These tests are listed in the Appendix. To minimize effects not due to field emission and also to ensure that any cavities analyzed underwent modern preparation techniques, only tests on cavities which were 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-drop from skewing the data. For some cavities which showed strong field emission and were re-treated with HPR only and retested, both tests before and after the second HPR were counted as separate tests.

The measured Q vs. E curves from the data base are then used to generate the success curves for comparison to the simulation. The success rate histograms used in the previous report were simply obtained, using only the maximum value of E_{pk} reached for each cavity test. Here we generate a more in-depth representation of the data which uses the entire Q vs. E curve for the tests. Instead of using the percentage of cavities which reached each given E-field, we 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 for various degrees of field emission loading (see Figure 2).

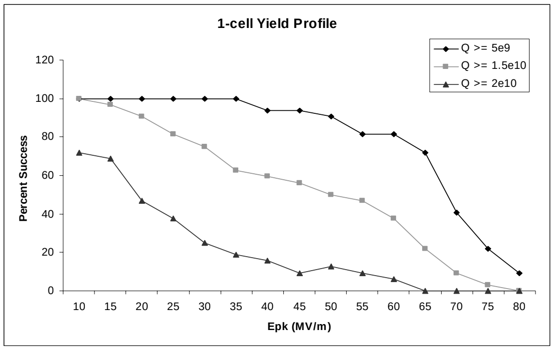


Figure 2: Graph showing the percentage of 1-cell cavity tests with Q greater than each of three values (data [2])

Modified Model

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

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

We expect that the number of strong emitters decreases with increasing beta value as suggested from DC field emission data [3], and that the log [emitter area] follows a random Gaussian distribution. These distributions are illustrated in Figures 3 and 4. The beta values ranged from 40 to 600, and the log-area values ranged from -18 to -8. The simulation runs as follows. The cavity rf surface is divided 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 between area and beta values [1].

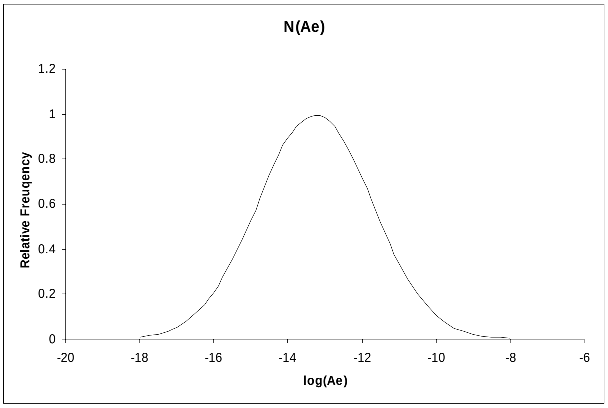


Figure 3: Emitter area distribution

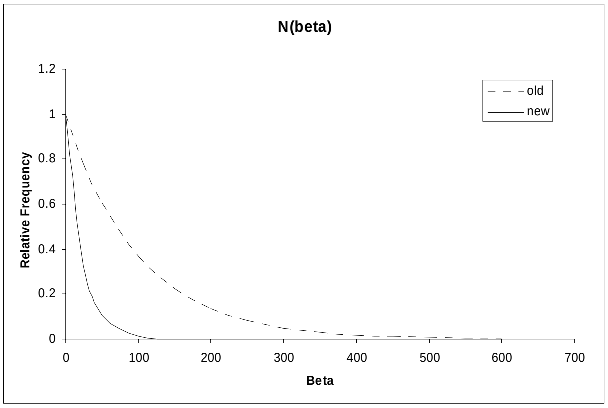


Figure 4: beta value distributions from old and new simulations.

After choosing an emitter set, we calculated at a given operating field, the trajectories of the emanating electrons and determined the power deposited on the wall of the cavity by the impacting electrons according to established techniques [4]. After many such simulations we found that the power deposited by a field emitted electron can be simply approximated by

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

where E is the E-field at the emitter's location in MV/m. The total power from all the emitters is added up and recorded. During the cavity rf tests, emitters are often seen to be rf processed as the cw power rises, which also needs to be simulated. The processing condition for an emitter cannot be determined purely from its Fowler Nordheim characteristic I-V curve. It is necessary to know in addition the local gas pressure which develops at high fields near the emitter due to desorption or local melting to create the discharge event that causes the processing [5]. Without knowing these important conditions we used in the previous simulation a simple processing criteria that any emitter depositing more than 100 W will process. We use the same criteria to shut off the strong emitters which the distributions select.

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.

To make a comparison against the experimental yield profiles, the Q value of each run must be recorded during the simulation. We assume a Q of 2 x10^{10} due to BCS and residual losses, 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 (shunt impedance) which equals 1000. We calculate Q from the total power due to field emission and wall losses from:

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

The goal of the simulation is 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 from the extensive DESY data set. Please note at this point that due to occurrence of quench in the data sets, which is not simulated in the program, the simulated yields at high E-fields are expected to be higher than the data.

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, all due to the benefit of higher cleanliness from HPR, and possibly additionally from smoother EP surfaces. The cavities in the older simulation were all prepared by BCP.

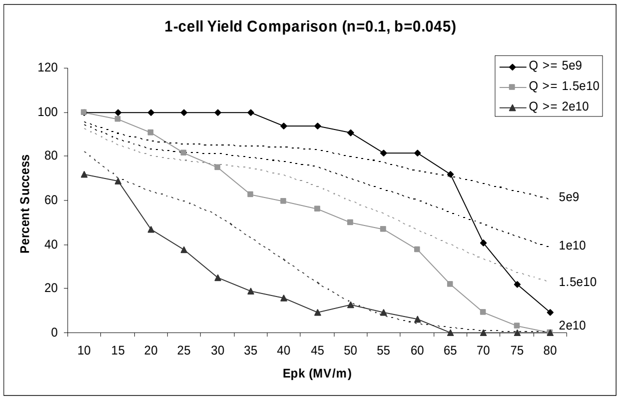
The gradient yield comparisons at various Q are shown in Figures 5 and 6 for the 1-cell and 9-cell simulations and data. We discuss the comparisons for three cases: field-emission free, strong field emission and acceptable field emission.

First look for gradient yields for the *low field emission* case, i.e.. Q > 1.5 x 10^{10}. The simulated yield agrees rather well with the data for 9-cell cavities. The yield at Epk = 70 MV/m is rather small (10% or less). The yield at 50 MV/m is 40% for 9-cells. For 1-cell cavities the agreement between simulation and data is also good for E_{pk} = 50 MV/m (yield about 60%). At E_{pk} = 70 MV/m, the simulation predicts a higher yield (40%) than the 1-cell data reach (10%), but this is due to the fact that quench dominates the yield for the data. The FE simulations show that significant improvements must be made to get *field emission free cavities* both for ILC (E_{pk} = 70 MV/m) and XFEL (E_{pk} = 50 MV/m).

If we allow lower Q values (say 5x10^9) due to the *strong field emission regime*, higher gradients are reached, and the yields are also higher. However, such low Q's may not be allowed for operation, due to the high radiation dose. The simulated yield at E_{pk} = 70 MV/m, Q > 5x 10^9 is about 70% for single cells, and about 60% for 9-cells. The agreement between simulation and data are good for 1-cells out to E_{pk} = 65 MV/m, with yields of about 80%. At higher fields the data fall off faster most likely due to the dominance of quench limitations. The simulations show that if FE was the only limitation yields would be as high as 75% at E_{pk} = 70 MV/m. For 9-cells the simulations agree out to E_{pk} = 45 MV/m, where the yields are above 90%. At higher fields, the data yields fall off rapidly to about 20% at E_{pk} = 70 MV/m, again due to the dominance of quench. But if FE were the dominant limitation, the simulations suggest yields > 60% at E_{pk} = 70 MV/m. Note that at 70 MV/m, Q = 5x 10^9 corresponds to P_{FE} = 184 W for a 9-cell cavity, which would clearly be unacceptable.

The third comparison of simulation with data is to determine what fraction of tests are "successful", where success is defined as 10 watts of FE power into field emission for a 1-cell, and 100 watt of FE power for 9-cells. After adding the resistive losses of 60 watts (Q = 2x10^{10}) this would mean a net Q of 7.6x10^9 for 9-cells. This is close to the allowed Q for ILC at E_{pk} = 70 MV/m. Figures 7 and 8 compare the simulated and observed success rates. The 1-cell comparison is good out to E_{pk} = 65 MV/m, when quench takes over for the data. For 9-cells the agreement is quite good out to E_{pk} = 80 MV/m, suggesting that for this level of allowed field emission the emission still dominates the data.

To summarize, the field emission simulations reveal an important result. To reach the ILC goal of 95 percent, we need to improve field emitter density further.



Figures 5: Simulated vs. observed yield profiles for 1-cells

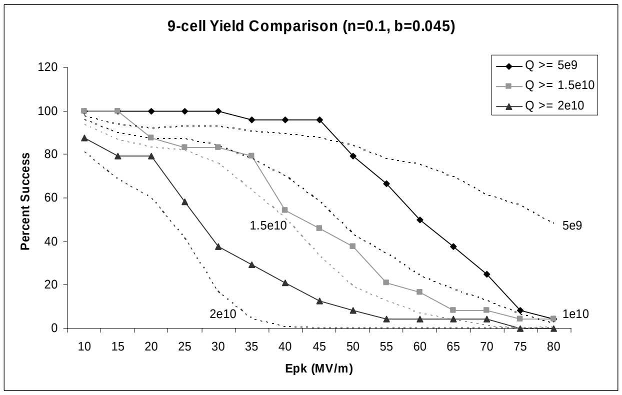


Figure 6: Simulated vs. observed yield profiles for 9-cells

Further Behavior

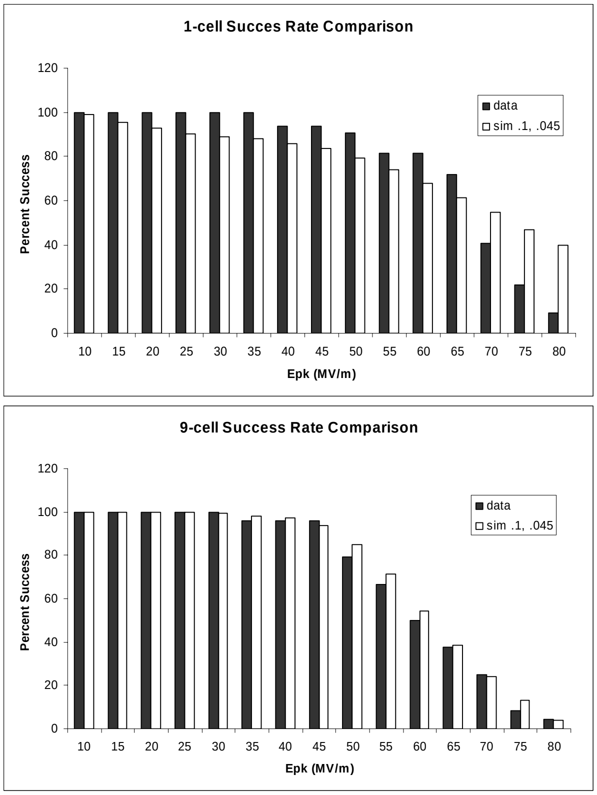
In addition to the above yield profiles, the onset of field emission was investigated. The accelerating field at which radiation is first detected for each test is recorded. For a given E-field level we can estimate what percentage of tests began field emitting. This can be compared to the simulation easily. It should be noted that the data as taken from the Tesla database conveys the fields at which a radiation level above $4x10^{-4}$ mGy/min. The simulation, having no such measure of radiation, uses a reasonable guess of 1 W total power output due to field emission.

The resulting comparison between data and simulation are shown in Figures 9 and 10. The correspondence is decent but could be improved. Both sets show some field emission onset earlier in the simulation than in the data. This suggests perhaps that the upper end of the range of beta values used in the simulation (40-600) is too high, causing field onset at lower E-fields than is accounted for in the data. Alternately, the one watt criteria may be more sensitive than the radiation level criteria used in the experiments.

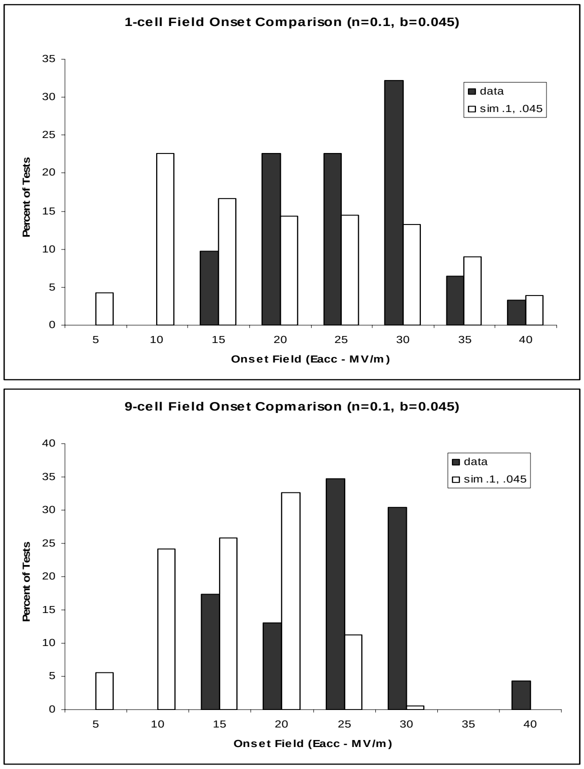
The average number of processing events up to E_{pk} = 70 MV/m in the simulation was 1 processed emitter per test for 1-cell cavities, and 4 to 5 processed emitters for 9-cell cavities. The present level of treatment technology thus requires some rf processing to reach 70 MV/m for 9-cell cavities. Although the simulation automatically processes emitters when P_{FE} > 100 W, this may not be true in experience. Therefore some 9-cell cavities may be eventually limited by strong emitters.

Future Improvements

The simulation can be used to estimate how much improvement in field emission is needed to reach the ILC yield goal. Further 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 E_{pk} = 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.



Figures 7 & 8: New simulated vs. observed success rates for 1-cell and 9-cell tests



Figures 9 & 10: Value of E_{acc} at the onset of field emission, data vs. simulation

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 emitter 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.

Both data and simulation show that with present levels of cleanliness 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

[1] H. Padamsee et al. A Statistical Model for Field Emission in Superconducting Cavities, 1993.

[2] TESLA Technology Collaboration Cavity Database, RF Tests *http://teslanew.desy.de/cavity_database/rf_tests/index_eng.html*

[3] Ph. Niedermann, PhD thesis. Univ. of Geneva. 2197, (1986).

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

[5] G Werner, PhD thesis, Cornell University.

Table 1: List of Cavity Tests Used

Cavity Name - 9cell	Date and Time		Cavity Name - 1cell	Date and Time
A16	9/14/2000 17:46		1DE1	5/25/2005 12:41
A16	11/1/2000 11:22		1DE1	6/9/2005 11:20
AC63	11/22/2000 11:42		1DE1	1/10/2007 13:02
AC63	12/13/2000 12:42		1DE1	4/3/2007 13:47
AC63	1/10/2001 11:02		1DE2	6/29/2005 11:42
AC70	11/6/2003 14:55		1DE2	5/24/2006 11:39
AC71	2/21/2006 13:56		1DE3	8/4/2005 17:06
AC72	3/12/2002 12:25		1DE3	8/24/2005 16:09
AC72	5/27/2003 18:16		1DE3	3/9/2006 14:39
AC73	8/14/2002 12:45		1DE3	5/18/2006 14:05
AC76	10/9/2002 11:18		1DE3	9/12/2007 14:32
AC76	7/16/2003 17:26		1DE4	4/20/2006 15:32
AC76	10/27/2004 11:08		1DE5	2/9/2006 16:03
AC76	11/11/2004 11:42		1DE7	1/11/2006 16:12
AC76	5/10/2005 15:55		1DE7	2/16/2006 17:02
AC76	11/4/2005 12:52		1DE7	6/2/2006 12:03
AC78	9/4/2002 11:15		1DE8	4/26/2006 15:40
AC78	5/14/2003 16:38		1DE8	9/28/2007 14:15
AC78	9/3/2003 18:04		1DE9	3/1/2006 15:53
AC78	10/7/2003 16:14		1DE9	3/16/2006 13:51
AC80	3/12/2004 10:20		1DE10	3/28/2006 15:59
AC80	9/3/2004 12:04		1DE10	7/5/2006 14:20
AC81	10/22/2004 10:54		1DE11	9/13/2006 13:47
AC81	10/13/2005 18:08		1DE12	8/30/2006 18:17
			1DE13	10/31/2006 16:56
			1DE14	2/8/2007 14:55
			1DE16	9/14/2006 14:23
			1DE16	9/27/2006 15:20
			1DE17	3/7/2007 12:50
			1DE18	3/28/2007 12:58
			1DE18	6/6/2007 13:24
			1DE18	6/20/2007 13:16