A Statistical Model for Field Emission in Superconducting Cavities*

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SUMMARY

A statistical model is used to account for several features of performance of an ensemble of superconducting cavities. The input parameters are: the number of emitters/area, a distribution function for emitter β values, a distribution function for emissive areas, and a processing threshold. The power deposited by emitters is calculated from the field emission current and electron impact energy. The model can successfully account for the fraction of tests that reach the maximum field Epk in an ensemble of cavities, for eg, 1-cells @ 3 GHz or 5-cells @ 1.5 GHz. The model is used to predict the level of power needed to successfully process cavities of various surface areas with high pulsed power processing (HPP).

INTRODUCTION

Field emission is the most important gradient limiting mechanism operative in SRF cavities. Over the last 5 years, a large amount of data has accumulated on the performance of cavities limited by field emission. At the same time, there have been significant advances in understanding of the nature of field emission, the Fowler Nordheim (FN) properties of field emitters, their density of occurrence and their microscopic nature. Significant advances have also been forthcoming in understanding the nature of processing. Field emission currents increase with increasing field to initiate a microdischarge. This is an explosive event that leaves behind molten craters, surrounded by starburst shape patterns[1]. We present here a statistical model that encompasses a large body of known data on emitter properties to simulate a variety of features about the known behavior of SRF cavities limited by field emission.

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THE MODEL

The surface of a SC cavity is divided up into a large number of segments (typically 20 per cell). Each segment i is sprinkled with a random number of emitters n_i, proportional to the surface area of the segment. The maximum emitter density, $n_i/area_i$ is the one free parameter of the model. As is well known from DC and RF studies of field emisison, the FN properties (β and emissive area S) can fall within a range of values; typically β is between 40 - 600, and log S (m^2) is between -8 and -16. We also chose β and S randomly, but the distributions for β and S values were chosen to mimic observed distributions from DC field emission studies[2]. Accordingly, (see Fig.1)

$N(b) \sim \exp(-.01*\beta)$
N(Log S) is a gaussian with half width of 2

After chosing 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[3]. We then compare the total power for all emitters to the available CW rf power. For example, 10 watts for a 1-cell 3 GHz cavity, or 100 watts for a 5-cell 1.5 GHz cavity. If the simulated total power is less than the available rf power, the test is declared a "success". As a final feature, if the power deposited by a single emitter exceeds 100 watts, that emitter is declared to be processed and extinguished. The cut-off value corresponds reasonably with the recent discovery that when the total field emission current drawn from an emitter exceeds 10 mA, there is a significant processing factor[4].

RESULTS

By choosing 0.3 emitters/cm^2 for the single free parameter, we show in Fig. 1 the simulated performance for several sets of cavities: 1-cell @ 3 GHz, 1-cell @ 1.5 GHz and 5-cell @ 1.5 GHz. We calculate the fraction of cavities that "successfully" reach a field value, given by Epk. The simulated resluts are compared to the data from 100 tests at Los Alamos on 1-cells @ 3 GHz[5], 25 tests at Cornell on 1-cells at 1.5 GHz[6], and 100 tests at CEBAF on 5-cells at 1.5 GHz[7]. All data used are from cavities prepared by nominally the same standard chemical treatment. No advanced treatment data are used (eg. heat treatment or high pressure rinsing or high pulsed rf power processing).

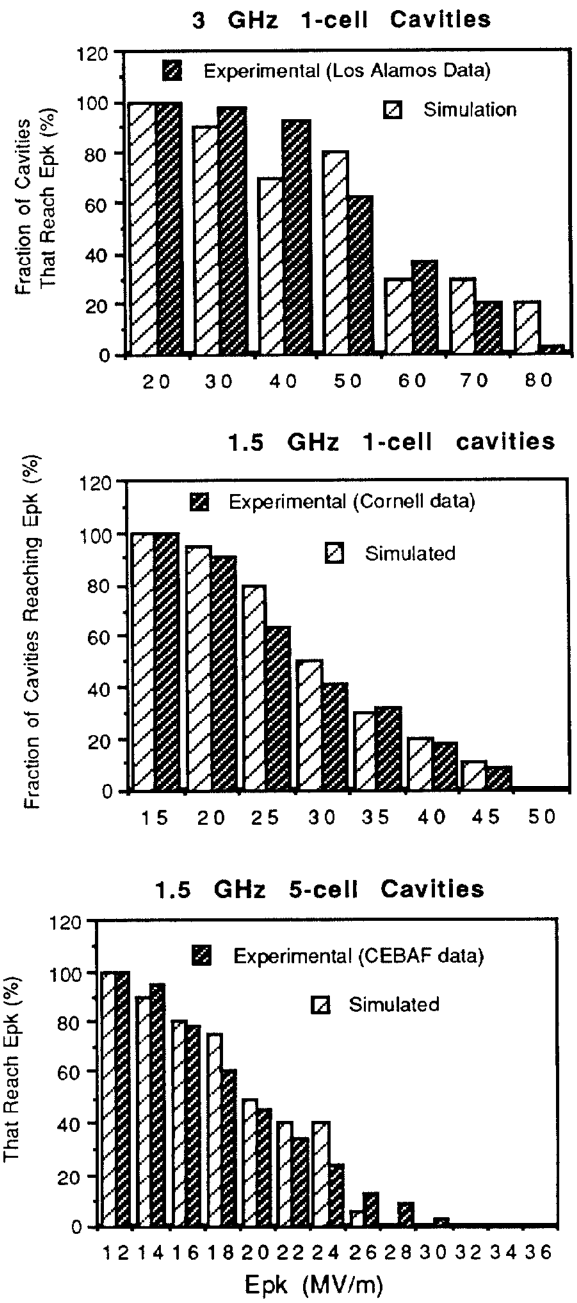

Fig. 1: Comparison between model and experiments

We see remarkable agreement betweeen simulations and data over the 3 sets of data. The most important feature is that, as the area of cavities increases, the successful fraction of cavities at a desired field level decreases. Note that the 5-cell 1.5 GHz cavites have 20 times the surface area of the 1-cell 3Ghz cavities.

Fig. 2 compares the measured and simulated β distributions from 1-cell, 1.5 GHz Cornell cavity data. Measured β values were obtained from thermometry data[6].

Fig. 3 shows the location of processed emitter sites for a 1-cell 3 GHz cavity operated at 80 MV/m surface field.

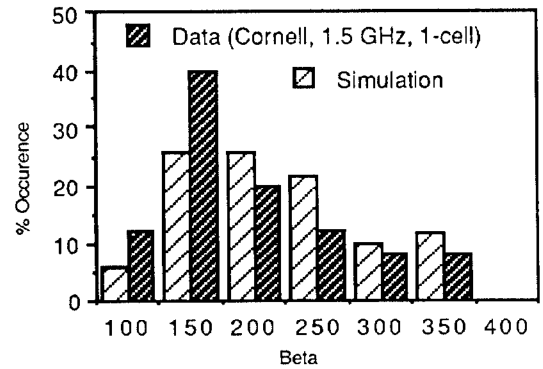

Fig. 2: Comparison between model and experiment

The distribution of processed emitter location corresponds well to the surface electric field, and compares favorably with the observed distribution of processed emitter sites (starbursts/molten craters) reported in [8].

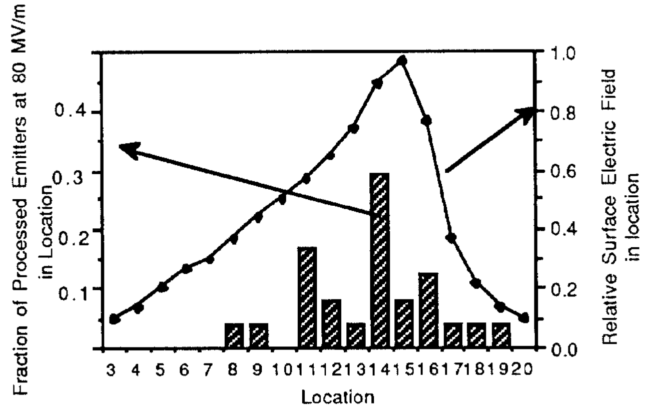

Fig. 3: Model predictions for location of processed emitters

The agreements obtained so far encourage us to examine the predictions of the statistical model for effectivenes of HPP (high pulsed rf power processing). We determine the behavior of a cavity at Epk = 40 MV/m, after it is processed at fields of 50, 60, 70 and 80 MV/m each. Table shows a list of emitters encountered in a 1-cell 3 GHz cavity at Epk = 40 MV/m. Because of the power into field emission the Q would drop to $5x10^8$. After processing at 50 MV/m and returning to 40 MV/m, some of the emitters are predicted to process. The remaining emitters and their deposited power are listed under the column headed 50 MV/m. The Q would rise to $3x10^9$. Note that the power and Q are re-calculated at the operating field of 40 MV/m. Similarly the result of processing at 60, 70 and 80 MV/m are listed under the appropriate columns. Again the predicted deposited power and Q are re-calculated at 40 MV/m.

The statistical model confirms that, for CW operation at Epk = 40 MV/m and with no field emission, it is necessary to carry out HPP at 80 MV/m. i.e [8]

Ecw = 0.5 Epulsed

Table 1: Single Cell 3GHz Monte Carlo HPP

Process at E (MV/m)	40		50		60	70	80
Watts at 40 MV/m for Run No. 1	5.8	25.9	5.8	0	5.8	5.8	0
2	8.5	0.6	0	8.5	0.6	0	0
3	23.3	1.6	0	1.6	1.6	0	0
4	0		0	0	0	0	0
5	78		0	0	0	0	0
6	1.7	3.6	5.3	1.7	0	0	0
7	3.9	0.3	0	1.3	0	0	0
8	1.5		1.5		1.5	0	0
9	18		0		0	0	0
10	7.5	0.6	0.6	0.6	0.6	0.6	0
Average power for one run (watt)	18.1		2.7		1.01	0.64	0
Q_0 at 40 MV/m	$5.5x10^8$		$3.1x10^9$		10^{10}	$2x10^{10}$	$> 10^{11}$

We carried out a similar evaluation for HPP on 1.5 GHz, 10-cell cavities, close to TESLA type cavities. We found that the relationship between Ecw and Epulsed is preserved. At Eacc = 12 MV/m, we first found that the Q would be lowered to $8x10^8$ because of field emission. Only 5 emitters/cavity would be successfully processed. If HPP were carried out to establish a surface Eacc = 40 MV/m, then 110 emitters would be processed, and there would be no remaining field emission visible at Eacc = 20 MV/m. At Eacc = 25 MV/m, the Q would be lowered to $5x10^{10}$. Hence the statistical model predicts that if TESLA cavities could be prepared with standard chemistry as the cavities today, it will be possible to reach the TESLA goal, provided HPP conditions could establish Eacc = 40 MV/m or Epk = 80 MV/m, if only for a short period, even μsecs[1]. Another work has shown[9] that a klystron and coupler that could provide pulsed power of 1 Mwatt for a pulse length of 1 msec would be sufficient to establish the desired field, even if the Q would fall to $2x10^6$ during HPP.

Conclusions

A simple statistical model using known data about emitters can explain the behavior of SRF cavities when they are limited by field emisison. The model can be used to predict the requirements for HPP.

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