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TITLE: VOLTAGE-BREAKDOWN TESTING FOR AN RFQ STRUCTURE

MASTER

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VOLTAGE BREAKDOWN IN A 420 MHZ RFQ STRUCTURE*

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Summary

Designs for Radio Frequency Quadrupole (RFQ) accelerators of reasonable length require operation with surface fields above the threshold of Kilpatrick's Sparking Criterion.[1] A cavity was designed using SUPERFISH to test the validity of this criterion and to determine operating limits for the Los Alamos Proof-of-Principle (POP) RFQ. The testing was done near 420 MHz, with varying qualities of surface finish on the electrodes. The experimental set-up and procedure are described, as are the data and results. A method of calibrating the test is presented.

Introduction

The experimental series known as the Sparking Test has been completed. The usefulness of this test relates to the focusing-gradient selection and voltage-breakdown safety factors for RFQ designs near 420 MHz. The data also are applicable to general accelerator design where high fields are a concern.

An RFQ's expected performance is strongly dependent on the maximum surface field chosen for its design. It is important to select the highest field levels consistent with avoiding voltage breakdown. As the operating field increases, the radial acceptance, the rate of energy gain, and the current-carrying capacity are all increased.[2] Higher surface fields also allow for shorter accelerator designs.

The series comprised three tests. In the first, the high-voltage electrode finish was a machined surface hand-polished with 320-grit aluminum oxide paper. These electrodes were chemically polished to remove a mil of the surface for the second test. For the third measurement, these electrodes had about a mil of copper electroplated onto the surface. In each case, measurements were made to determine the surface rms microfinish and the breakdown fields at 420 MHz.

Background Information

For this work, sparking is defined as an abrupt change in the dissipation of energy stored as electric field across a gap between electrodes. The field magnitude required to initiate sparking depends on the electrode geometry, RF frequency, vacuum properties, and the nature and condition of the electrode surfaces. For gradients less than 10 MV/cm, the electron current caused by field emission is small. Field-emitted electrons in the gap, however, accelerate to strike the cathode, causing the emission of neutral gas atoms and electrons from that surface. The result is a localized expanding volume of increasing gas pressure, ionization within this volume, increased emission from back-bombardment, more gas, more ions, and so on. Such a cascade process may result in spark formation, causing an abrupt change in the stored energy to occur.

Kilpatrick's Sparking Criterion defines the frequency for which sparking may occur at a given gradient:

$$f = 1.64 \times 10^4 E^2 e^{-0.085/E}$$

where
f = frequency in MHz
E = gradient in MV/cm.

Thus, at 420 MHz, sparking is predicted at 19.7 MV/m. The conditions for which this Criterion applies are:

- single-gap sparking
- no effects involving the quantity of stored energy
- vacuums of 10^{-3} to 10^{-7} mm mercury
- metal electrodes not specially prepared
- no external magnetic fields.

The usefulness of this relation is that it determines a threshold below which no sparking should be observed during, or prior to, conditioning of the electrodes. This lower limit may be raised by procedures such as outgassing, electrode preparation, or spark cleanup.

The work presented here differed from Kilpatrick's test in several respects. First, the RFQ configuration had not one gap but four, as shown in Fig. 1. Second, the magnetic field component near the electrode tips was nonzero, although small. Third, the metal electrodes were prepared to maximize the field stand-off. Thus, the results were not directly correlative to Kilpatrick's. Rather, Kilpatrick's was used as the unit of measure for a test that employed a special geometry and nonexotic but modern vacuum and fabrication technique.

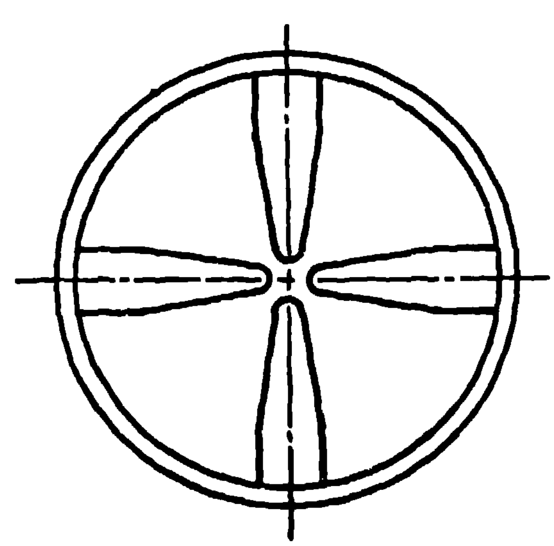

Fig. 1. Sparking cavity configuration.

*Work performed under the auspices of the US Department of Energy.
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Test Apparatus

The computer code SUPERFISH was used to design the RF structure. This code identifies modes and resonant freqencies for RF cavities. The first set of runs was a frequency/power scan for a suitable resonator configuration. The goal was to find the dimensions for a 425-MHz cavity that would require a substantial fraction of the klystron's 1.2-MW capacity when the surface gradient was about 50 MV/m.

This computer-aided design produced the cross section for which a single quadrant is shown in Fig. 2. The electrodes, or vanes, were 30.5-cm long and made from OFHC copper. The 76.2-cm-long cavity body was made of 15-cm diam drawn copper tubing. The vanes were centered longitudinally in the cavity and attached with bolts through the wall.

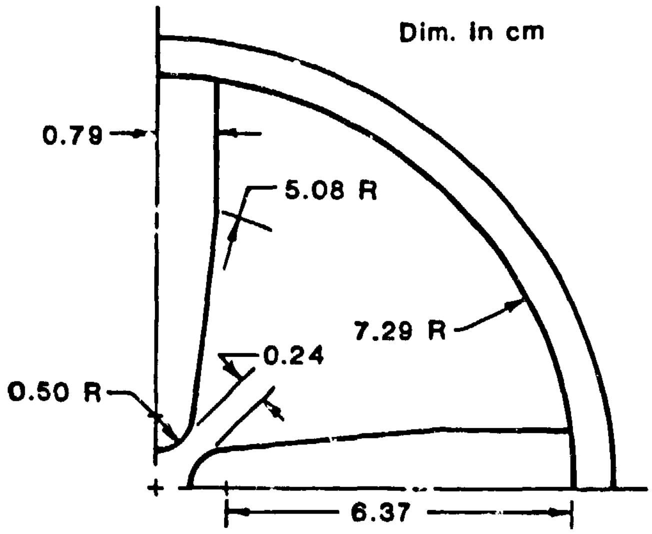

Fig. 2. Sparking cavity quadrant.

Power was coupled into the cavity from the klystron through a waveguide. This setup terminated with a vacuum window attached to a transition piece brazed onto the cavity. Inside the transition, a slot was bored through the cavity wall to provide inductive coupling between the waveguide and the resonator volume.

The vacuum was provided by two pumps, one on each side of the RF coupling slot. A 600-ℓ/s ion pump was coupled to the RF cavity. A 450-ℓ/s turbomolecular pump was connected to a port in the sidewall of the RF vacuum window. The entire test setup is diagrammed in Fig. 3.

Test Procedure

The first task was the assembly of the vacuum envelope. All parts that would be exposed to vacuum were cleaned, using a three-step procedure, then stored in plastic bags until required for assembly. Using reagent-grade solvents and lint-free wipes, all pieces were surface cleaned first with acetone, then methanol, then ethanol.

After assembly and RF circuit tuning, the resonator was excited at low power with high duty factor to heat the RF surfaces. The external wall temperature was held at 150°F for two hours to drive out the solvents in the vacuum envelope.

The procedure for determining the breakdown gradient was to increase the power delivered to the cavity until the sparking level was reached. Power was then reduced to the highest stable drive level

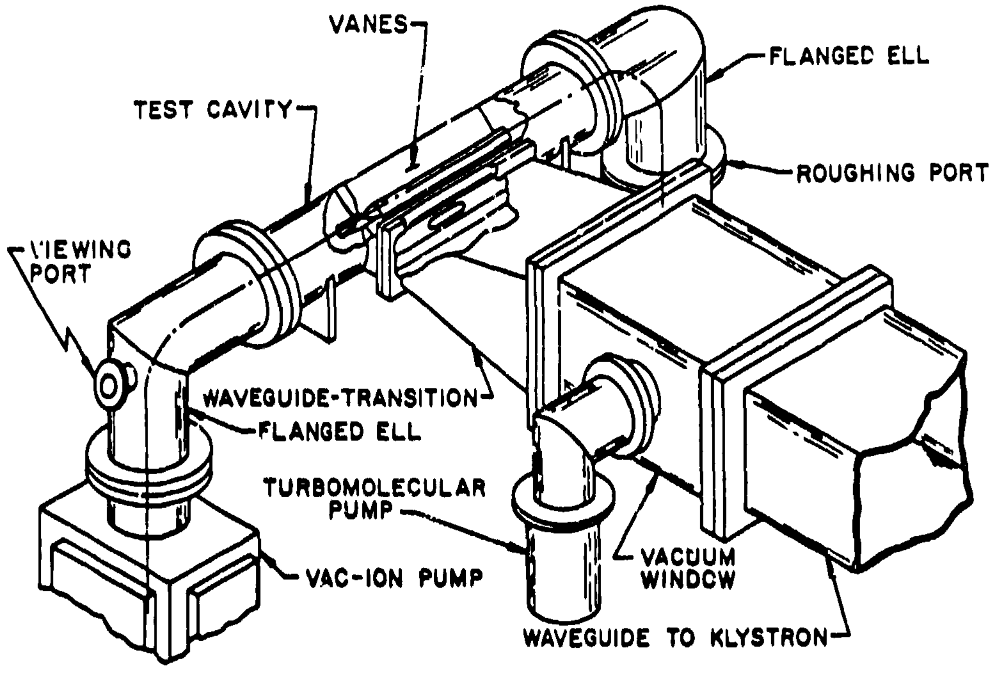

Fig. 3. The 420 MHz RFQ sparking cavity test stand

Fig. 3. The 420-MHz RFQ sparking cavity test stand.

and measurements were made of the forward and reflected powers. The existence of sparks was observed visually, by x-radiation monitors, by cavity field monitoring, and by reflected power measurements. The surface gradient magnitude was calculated by measuring the RF power to the cavity and using the relation:

$$E_{spark} = (P/_k)^{1/2} \quad , \qquad (2)$$

where k was experimentally determined.

After these measurements were taken, the cavity was disassembled for vane removal. The vane-surface microfinish was measured by a recording stylus profilometer. This measurement was taken at 45° from the vane tip; that is, at the region of highest electric field.

The original vane surface was a machine finish hand-polished with 320-grit aluminum oxide paper. After observing the sparking threshold for this surface,[3] the vanes were electropolished to remove 0.001 in. of copper and gradient measurements followed. Then the vanes were electroplated for the third test.

Results

The results of the three tests are shown in Table I. The electropolished vanes were most effective for holding off high voltage. The cavity resonant frequency varied slightly because of the different vane dimensions in each test.

The method for evaluating k in Eq. (2) used a SUPERFISH simulation and a measurement of the quality factor, Q, of the cavity. The simulation showed that the geometry had a theoretical Q of 8665 and a field enhancement factor of 1.63, relative to the pole tip at the point of highest field. The analysis also showed that a structure excitation of 39.2 W/m would produce pole-tip fields of 0.347 MV/m.

The active length of the structure was 0.305 m; thus pole-tip fields of 0.347 MV/m theoretically required 11.96 W of drive. This power was adjusted for the Q of the cavity, which was measured as 5406 for the first test setup. Therefore,

$$k = \frac{11.96 \frac{8665}{5406}}{(0.347 \times 1.63)^2} = 59.9 \ W/(MV/m)^2 \quad . \qquad (3)$$

An observed cavity input power of 62.2 kW (0.2% duty) was required to initiate sparking in this case. The resultant maximum electric field, using Eqs. (2) and (3), was 32.2 MV/m. Table I includes results for the other two tests.

Conclusions and Comments

The threshold for sparking was increased by special electrode preparation. The electroplated vanes had the lowest measured rms microfinish, but did not have the greatest resistance to arcing. Inspection showed the plating process was more susceptible to imperfections in the final product than the electropolishing process. The plated vanes were delivered with 0.005- to 0.020-in. diam nodules deposited as clusters in several locations. Before testing, these nodules were removed by sanding with AlO_3.

Several effects were not considered that could influence the sparking gradient assignments in Table I. Those effects whose influence would increase the assigned value were corrections for the quadrant asymmetry introduced by the drive iris, longitudinal field distribution, and field asymmetry due to dimensional variations. Effects that would decrease the assigned values were corrections for RF power circulating between the drive iris and the RF tuning slugs, and electron loading observed during the approach to sparking thresholds.

Acknowledgments

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TABLE I

SPARKING TEST RESULTS

VANE FINISH	RMS FINISH (μin.)	SPARKING FIELD (MV/m)	CAVITY FREQ. (MHz)	VSWR	Q	PRESSURE (torr)
Machine/ $Al\ O_3$ Hand Polish	50-60	32.2	417.2	1.3 under	5400	6×10^{-7}
Electropolished	15-20	47.0	420.7	1.2 over	4900	4×10^{-6}
Electroplated	10-15	40.5	407.3	4.0 under	4500	4×10^{-6}