VOLTAGE BREAKDOWN TESTING FOR THE RADIO-FREQUENCY QUADRUPOLE ACCELERATOR*

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Summary

Designs of radio-frequency quadrupole (RFQ) accelerators with reasonable length require operation with surface fields above the limit imposed by Kilpatrick's Criterion. A cavity was designed using SUPERFISH to test the validity of this criterion and to determine operating limits for the RFQ. The experimental setup and procedure are described, as are the data and results. A method of calibrating the test is presented.

Introduction

The choice of an RFQ as the low-beta accelerator in the Fusion Materials Irradiation Test (FMIT) linac depends on the successful demonstration of operational feasibility by a prototype RFQ, the Proof-of-Principle (POP) structure. In the design for this structure, questions arise concerning the field strengths that will exist in the cavity during excitation. Because of the very small beam-channel dimensions and the constraint that useful structures have reasonable length, the fields during operation must exceed those predicted by Kilpatrick[1] as breakdown levels. The question that follows, then, is a basic issue concerning RFQ design: to what field levels may RFQs be designed so that the field strengths are maximized and so that breakdown occurrences are tolerable?

Test equipment designed to determine the maximum standoff voltage in an RFQ was subject to several constraints. As in all high-voltage rf equipment, vacuum and cleanliness considerations were important. It was necessary that the resonant frequency be between 400 and 450 MHz for compatibility with the available klystron power unit and controller. Scheduling commitments were such that rapid test completion was necessary. Finally, to provide useful information, the cavity design was required to be capable of developing fields several times those predicated by Kilpatrick as the breakdown limit for 400-450 MHz with the available 1-MW power level.

Background Information

For this work, sparking is defined as the abrupt dissipation of energy stored as electric fields across a gap between electrodes. For a practical vacuum system such as that used in this study, there exists a definite threshold gradient for which electrodes of a given metal may spark. The breakdown mechanism is dependent on this gradient at the electrode surface for spark initiation.[2]

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

$$f = 1.643 \times 10^4\ E^2 e^{-\frac{0.085}{E}} \qquad (1)$$

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

Thus, at 425 MHz, sparking is predicted at 20 MV/m.

The restraints imposed on the use of this criterion are several in that it:

- deals only with single-gap sparking
- ignores effects involving the quantity of stored energy
- includes practical vacuums of 10^{-3} to 10^{-1} mm pressure
- includes metal electrodes that are not specially prepared
- does not include the presence of external magnetic fields.

The work presented here differs from these restraints in two respects. First, the RFQ configuration has not a single gap, but four, as shown in Fig. 1. Second, although it is small,

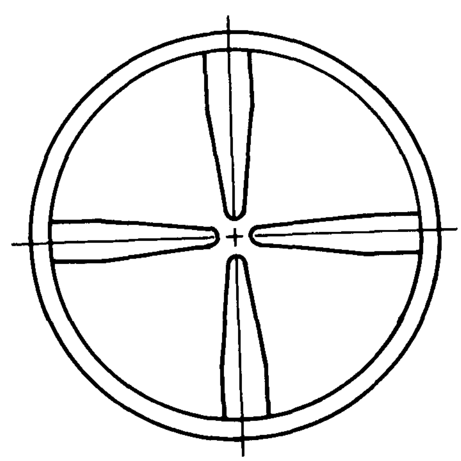

Fig. 1. Sparking cavity configuration.

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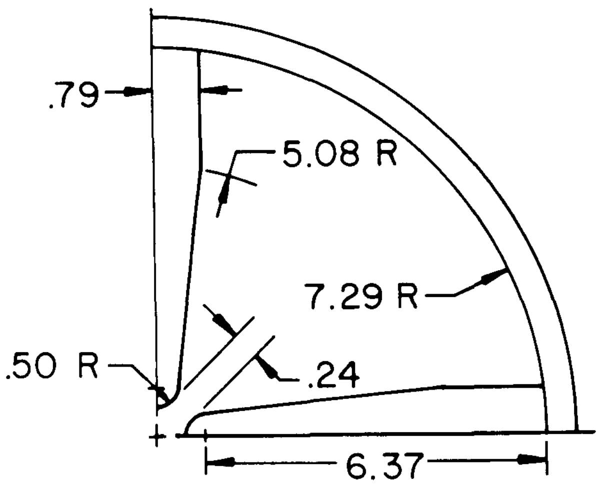

Fig. 2. Sparking cavity quadrant (cm)

the magnetic field component near the electrode tips is non-zero. To first order, however, neither of these differences has much effect on the final gradient achieved before breakdown occurs.

For gradients less than about 10 MV/cm, the electron current caused by field emission is small. Ions in the gap, however, may be accelerated to strike the cathode, causing the emission of electrons and neutral gas atoms from the cathode. A cascade process follows which may result in the formation of a spark, by which an abrupt change in the stored energy dissipation occurs. Such a breakdown mechanism is characteristic of vacuum systems having a high enough ion population for the cascade process to work.

Test Apparatus

The computer code SUPERFISH[3] was used to design the sparking cavity. The first set of runs was a frequency/power scan for a suitable cavity configuration. The goal was to determine cavity dimensions for a 425-MHz resonator that would require a substantial fraction of the klystron's 1.2-MW capacity when the surface gradients were about 50 MV/m. This study showed that the main cavity body could be constructed from an available length of 15-cm i.d. copper tubing if the vanes were sized properly.

The SUPERFISH-aided design produced the cross-section for which a single quadrant is shown in Fig. 2. In the structure that was tested, the vanes were 30.48 cm long and located in the center of the copper cavity that was 76.20 cm in length. Figure 3 is a diagram of the cavity with the vanes installed and the support feet and flanges in place. The flanges at each end were connected to ells of the same inside diameter as the cavity.

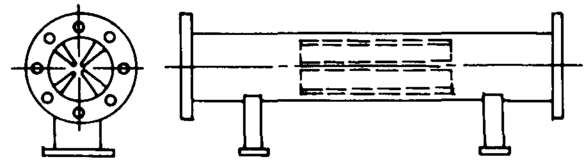

Fig. 3. Cavity with vanes in place.

A 600-ℓ/s ion pump was hung on one of the ells and the other had ports for an ion gauge and a liquid-nitrogen-trapped roughing pump. A screen-covered copper gasket was installed between each ell flange and cavity flange. This device was designed to contain the rf fields inside the test cavity but was shown to be only marginally necessary.

Power was coupled into the cavity from the klystron unit through a waveguide. This setup terminated with a vacuum window attached to a transition piece brazed onto the cavity wall. Inside the transition, a slot was bored through the cavity wall to provide inductive coupling between the waveguide and the resonator volume. After tuning the waveguide, the load presented a VSWR of 1.3:1 to the klystron, at a resonant frequency of 417 MHz.

A 450-ℓ/s turbomolecular pump was connected to a port in the sidewall of the rf vacuum window. Using this pump and the ion pump, an operating pressure of 6 x 10^{-7} mm was achieved. The entire test setup is diagrammed in Fig. 4.

Test Procedure

The first part of the test procedure 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. For all pieces, the procedure involved surface cleaning first with acetone, then methanol, then ethanol, each a reagent-grade solvent. Smaller parts were cleaned in an ultrasonic bath using ethanol as the solvent.

After assembly, the resonator was excited at low power with high duty to heat the rf surfaces. The cavity external wall was heated to about 150°F for two hours to drive out most of the volatiles.

The procedure for determining the RFQ breakdown gradient was to increase the power delivered to the cavity until the level was reached that produced sparking. The gradient magnitude was determined by measuring the power and using the relation:

$$E_{spark} = (P/k)^{1/2} \qquad (2)$$

where k was an experimentally-determined constant.

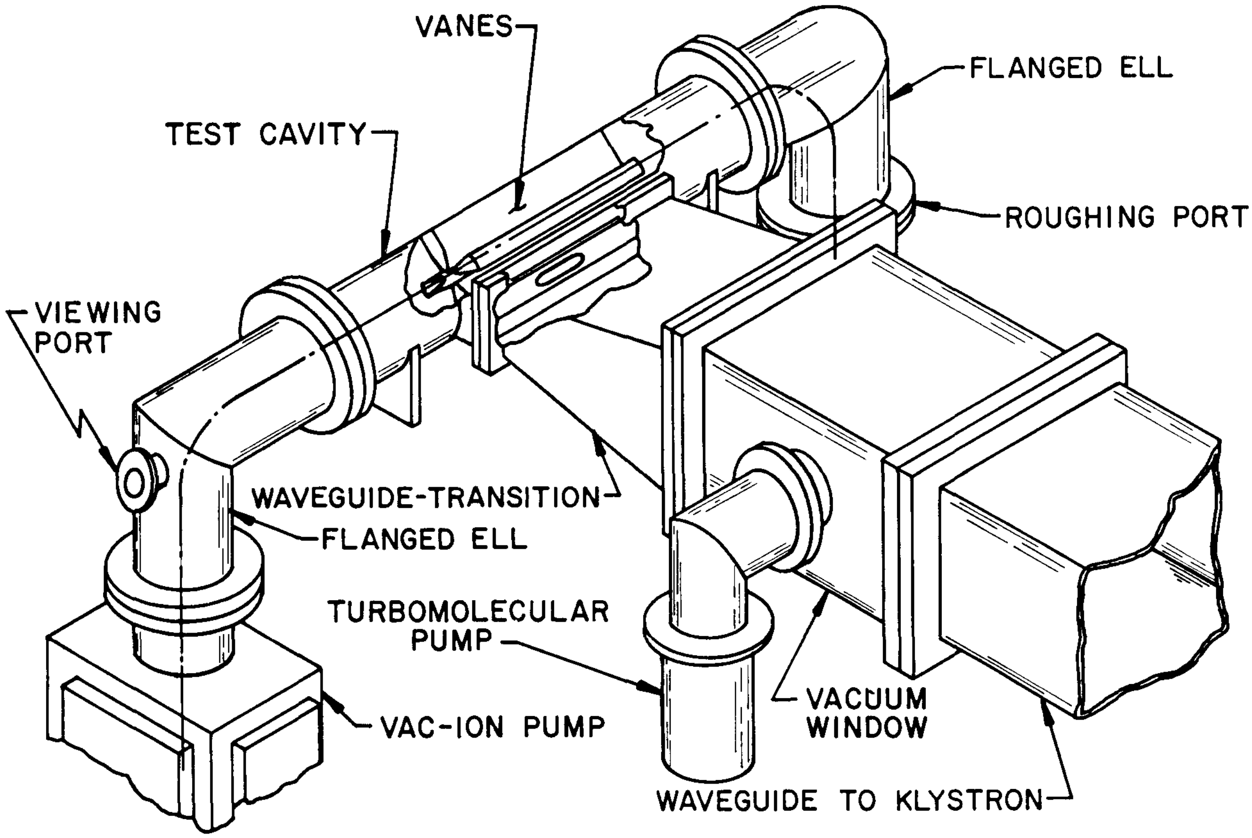

Fig. 4. The 440-MHz RFQ sparking cavity schematic.

Results and SUPERFISH Correlation

The method for evaluating k used a SUPERFISH simulation, and a measurement of the quality factor, Q, of the cavity. The simulation analysis showed the geometry had a field-enhancement factor of 1.63; that is,

$$\frac{E_{max}}{E_{pole\ tip}} = 1.63 \quad .$$

The analysis also predicted a theoretical Q of 8665, and, 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 so pole-tip fields of 0.347 MV/m theoretically required 11.96 W of drive. This power was adjusted for the actual Q of the cavity, which was measured as 5400. Therefore,

$$K_{sf} = \frac{11.96\left(\frac{8665}{5400}\right)}{(0.347 \times 1.63)^2} = 59.9\ \mathrm{W/(MV/m)}^2 \quad . \qquad (3)$$

An observed cavity input power of 62.2 kW (duty factor = 0.2%) was required to initiate sparking. The resultant maximum electric field using Eqs. 2 and 3 was, then, 32.2 MV/m. Kilpatrick's Criterion predicted that sparking was possible at 19.7 MV/m for f = 417 MHz.

Error Analysis

Because the dimensions of the spark gaps were small (see Fig. 2) and the cavity body had a cylindricity error of ± 0.008 cm, the gap spacing between the four vanes varied. An analysis using the measured-gap spacing for each of the four quadrants was done using SUPERFISH. The error was assigned an rms value according to the comparison between the four quadrants. Other sources of error were the measured values for the cavity Q and the effective length of the vanes. Table I lists the sources and values for the errors as percents of the breakdown field. Thus, the total error is 19.6% and the observed breakdown field is $32.2 \pm 9.8\%$ MV/m or 32.2 ± 3.2 MV/m.

In the absence of any quantitative data, no corrections were made for the quadrant asymmetry introduced by the drive iris or the longitudinal field distribution. Such adjustments would increase the estimate of the voltage required to cause a spark. Inspection of the spark

TABLE I

	RMS ERROR (% E_s)
SUPERFISH Results	
Cavity Q	0.6
Power/length	7.7
Field intensity	7.9
Measured Results	
Cavity Q	3.2
Cavity length	0.001
Measured Power	0.16

discoloration density on the vanes showed that most sparks had indeed occurred opposite the iris, as would be expected. Also, electron loading was observed during the approach to the sparking threshold, accompanied by soft x-ray radiation of 10^3 R/hr. Correcting for this effect would lower the sparking assignment.[4]

Acknowledgments

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References

1. W. D. Kilpatrick, "Criterion for Vacuum Sparking Designed to Include Both RF and DC," UCRL-2321 (Sept. 1953).
2. W. D. Kilpatrick, "Sparking and X-Rays in a Mercury Pumped Vacuum System," UCRL-1907 (Aug. 1952).
3. K. Halbach, et al., "Properties of the Cylindrical Rf Cavity Evaluation Code SUPERFISH", Proc. 1976 Proton Linear Accel. Conf., 122, Chalk River, Canada, AECL-5677.
4. T.J. Boyd, unpublished note, Los Alamos Scientific Laboratory (July 1979).