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VOLTAGE BREAKDOWN IN S-BAND LINEAR ACCELERATOR CAVITIES

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ABSTRACT

Voltage breakdown is one of the major limiting factors in the design of a high accelerating gradient linear accelerator structure. A multiple-use cavity test system was developed to establish the criteria for voltage breakdown in S-band pulsed electron linear accelerator cavities, in terms of cavity geometry, accelerating gradient, RF pulse shape and repetition rate, surface finish, temperature and external magnetic field. The experimental set-up and test procedure, as well as the experimental results, are presented.

INTRODUCTION

In the past several decades, new accelerator developments have lead to an increase in accelerator beam energy by a factor of 10 in every six years. Although accelerator technology has been steadily progressing every year, it appears that we are reaching the limit of maximum energy level due to the limited availability of funding and space, as well as technical problems. As a result, new types of accelerators with higher efficiencies (lower cost) and higher gradients (less space) become interesting. Similarly, the medical and industrial linear accelerator world is seeking more efficient and more compact structures for their new applications.

One of the major technical problems in the development of high-gradient accelerator structures concerhs breakdown phenomena, which are not well understood at microwave frequencies. The study done by Kilpatrick is one of the few investigations of breakdown phenomena and is very often referred to by accelerator engineers[1]. He empirically derived the relationship between frequency and maximum electric field as

$$f = 1.643 \times E^2_{max}\, e^{-\frac{8.5}{E_{max}}}$$

where f is frequency in MHz and Emax is maximum electric field in MV/m. At f = 3000 MHz, this relation predicts Emax = 46.8 MV/m. Several recent studies show that Kilpatrick's Breakdown Criterion gives a relatively conservative Emax value[2,3].

It is of interest to determine the ultimate limitation of conventional accelerators in terms of efficiency and accelerating gradient. This paper describes the tradeoff situation between accelerator efficiency (shunt impedance) and accelerating gradient for side-coupled standing-wave linear accelerators. Also, a multiple-use cavity test system is described which has been developed to experimentally define the limitations of S-band, standing-wave linear accelerator structures.

STRUCTURE OPTIMIZATION

The side-coupled standing-wave linear accelerator structure developed at LASL has many advantages over other structures, such as high shunt impedance, being less sensitive to mechanical tolerances and beam loading, etc. One of the major advantages is that the shunt impedance can be optimized independently from the coupling cavity structure. By choosing properly the accelerating cavity contour and beam hole diameter, a theoretical shunt impedance as high as 130 MΩ/m can be acheived at S-band frequencies. However, as the shunt impedance increases, the peak electric field at the surface, especially at the nose, also increases. Using the LALA program, various cavity geometries were studied in terms of peak surface electric field and shunt impedance per unit length. Fig. 1 shows a plot of the ratio of the peak surface electric field, Ep, to the average axial accelerating electric field, Eo, vs. shunt impedance per unit length for a given beam hole diameter and web thickness. The figure clearly shows the tradeoff situation between the peak electric field and shunt impedance. The optimized shunt impedance with the constraints used (constant beam hole diameter and web thickness) appears to reach a limit of about 130 MΩ/m with Ep/Eo values of 8 or higher.

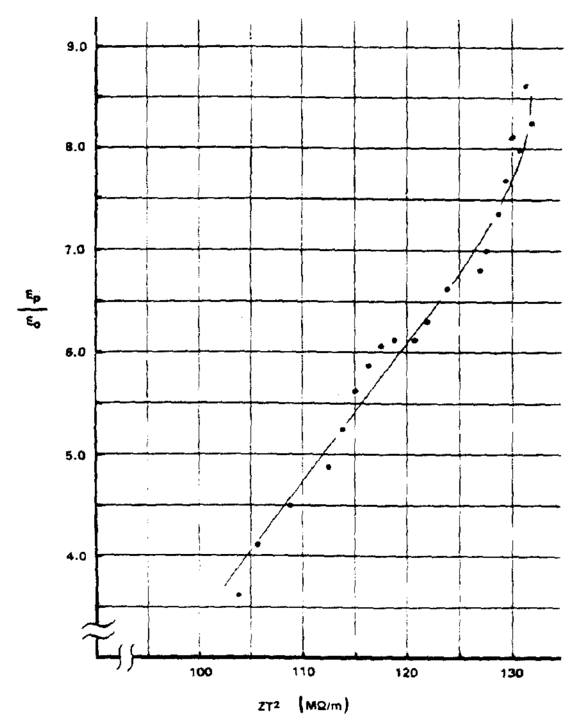

Fig. 1 A plot of the ratio Ep/Eo vs. shunt impedance per unit length for various cavity geometries.

EXPERIMENTAL SET-UP

To establish the voltage breakdown criteria in terms of accelerating gradient, cavity geometry, surface finish, RF pulse shape and repetition rate,

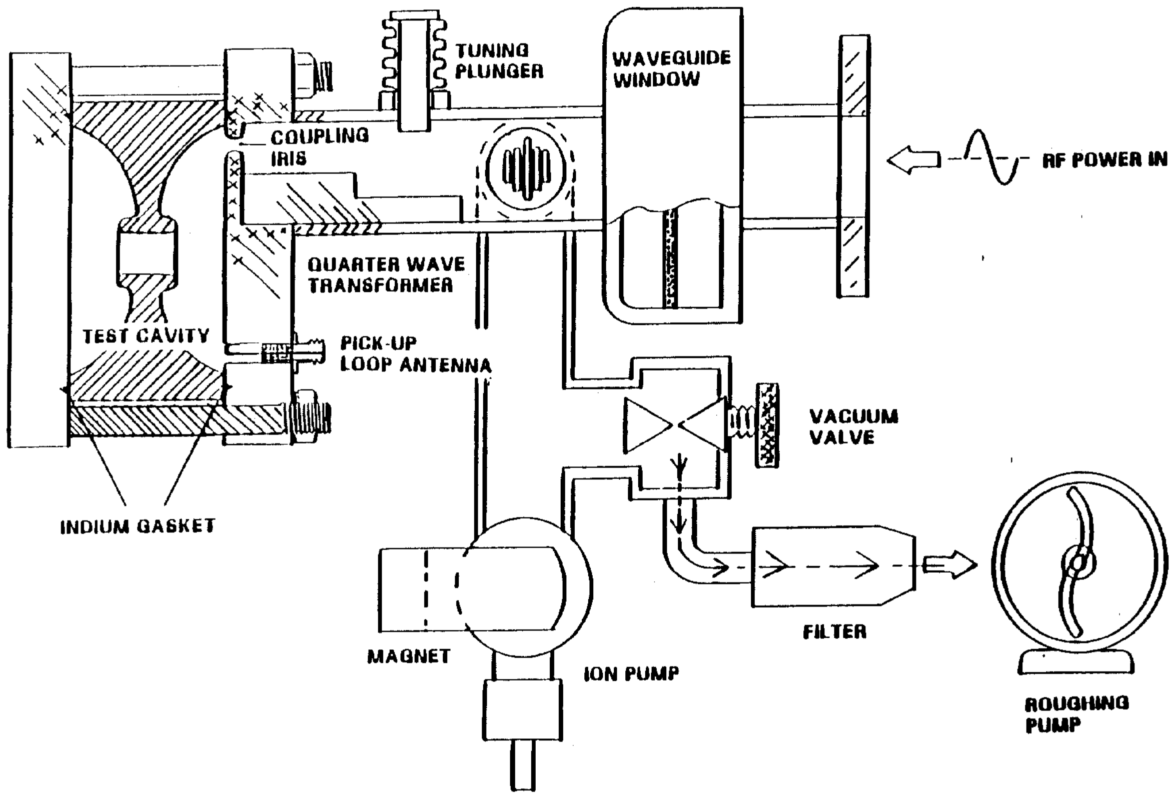

Fig. 2 A cross sectional view of the cavity test system.

temperature and external magnetic field, a multiple-use cavity test system was developed. Fig. 2 shows a cross sectional view of the cavity test system. The test cavities were made from OFHC copper. In order to test many different cavities using the same system, the test cavity was clamped between two parallel plates with 6 bolts torqued to 200 inch-pounds. Phospher bronze bolts were used to provide thermal expansion similar to that of the cavities. Indium gaskets were used to maintain vacuum as well as to provide a RF seal. The coupling iris dimensions were empirically obtained through cold test to match the RF source impedance to the cavity impedance. Precise matching was then obtained by tuning the stub plunger. This was necessary since different cavity geometries have different external Q's, i.e. different degree of coupling. A waveguide window separates the freon gas- pressurized (30 psi) RF system from the vacuum in the test cavity system. A vacuum system which includes a vacuum valve, a roughing pump, a filter and an 8 l/s vacuum ion pump was installed in the waveguide narrow wall.

EXPERIMENTAL PROCEDURE

After a careful chemical cleaning (vapor degrease, alkali soak, cyanide bath and water and methanol rinse) of the test cavity, and assembling the system in the clean room, the system was pumped down to the pressure level of 10^{-7} mmHg. Then the test cavity was wrapped with a heating blanket and kept at 200°C for 8 hours.

Fig. 3 shows a schematic diagram of the high power experimental set-up. A tunable magnetron was used as the RF power source. The peak output power was varied from 0.2 to 2.6 MW by varying the external magnetic field and the anode voltage. The RF pulse width was 4.4 microsecond. The pulse repetition rate could be varied between 70 and 300 pps, yielding an average output power from 0.06 to 3.1 KW. The forward and reflected RF power were monitored through the 60 db calibrated waveguide directional couplers. The transmitted RF power into the test cavity was monitored through the small loop antenna placed at the end plate as shown in Fig. 2. By measuring the vacuum ion pump current, one could estimate the test cavity pressure level. Due to the finite conductance of the vacuum system, a factor of 2.8 was used for this estimation. The test cavity was immersed in the circulating water bath in order to thermally stabilize it. The thermocouple was placed in the cavity body to monitor the temperature rise during the experiments.

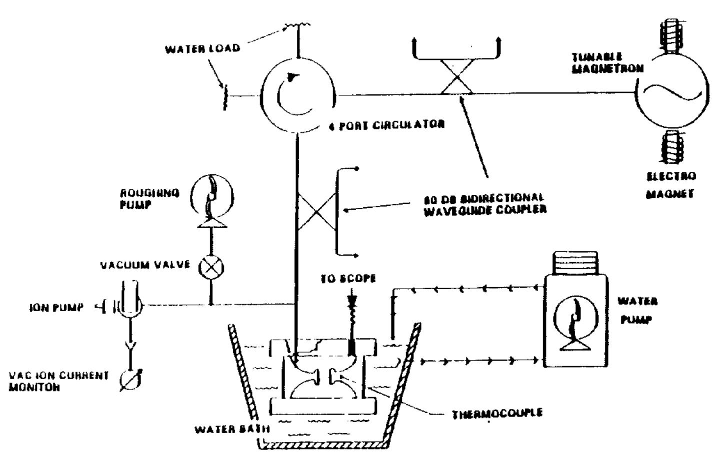

Fig. 3 A schematic diagram of the high power test set-up.

The test cavity was initially excited by low peak power at a high repetition rate for one hour to condition the cavity surface (RF processing). The breakdown power level was determined by monitoring the forward, reflected and transmitted power as well as vacuum ion pump current during the high power tests.

EXPERIMENTAL RESULTS

The maximum surface electric field can be estimated in the following way: Firstly estimate the effective shunt impedance of the cavity by using

$$Z_{eff} = \frac{Q_{exp}}{Q_{theor}} \times ZT^2$$

where Q_{exp} and Q_{theor} are the experimental and the theoretical Q values of the cavity respectively, and ZT^2 is the theoretical shunt impedance per unit length of the structure. Secondly, compute the average axial electric field by using the relation of

$$E_o^2 = \frac{P_t \times Z_{eff}}{l}$$

where Pt is the transmitted power at breakdown level, and l is the cavity length. Thus by using the Ep/Eo ratio obtained from a LALA computation, one can estimate the maximum surface electric field.

Table I summarizes the high power test results for three different cavities. All cavities were made from OFHC copper with the surface processed as described before. These results show that one can operate an accelerator at power levels far exceeding the level of Kilpatrick's breakdown criterion for the pulsed operation case. Fig. 4 shows the reflected and the transmitted RF power pulse for both the normal operating condition and for operation at the breakdown level.

In order to study the effect of surface finish, several cavities were made differently and tested. The results showed that both mechanical (diamond polish) and electrical polishing had minor effect on the breakdown threshold.

The repetition rate was continuously varied from 70 to 300 pps during these tests. There was no noticeable dependence of the breakdown threshold level on the repetition rate.

Table I

	Cavity I	Cavity II	Cavity III
Frequency (MHz)	2997	2997	2997
ZT^2/L (MΩ/m)	104.0	117.1	130.2
E_p/E_o	3.61	6.04	8.08
Qtheor	18520	18411	16835
l (m)	0.025	0.025	0.025
Qexp (half cavity)	7780	7310	6670
Zeff (half cavity)	43.7	46.5	51.6
P_t (MW)	2.52	1.02	0.45
E_o (MV/m)	66.3	43.6	30.5
Emax (MV/m)	239.4	263.1	246.4

(Note) Operating Condition
Pulse Width = 4.4 μsec
Repetition Rate = 200
Cavity Starting Pressure = 2×10^{-7} mmHg
Cavity Surface Finish = 8 microinch

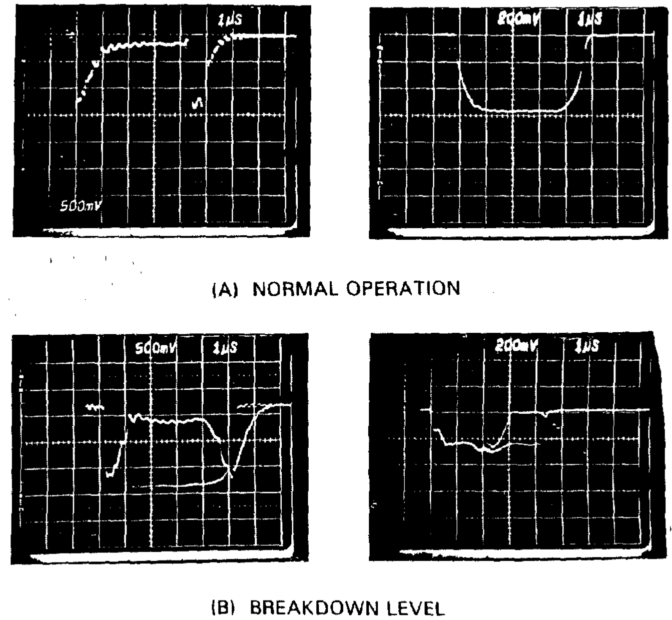

Fig. 4 Reflected and transmitted RF power: a) Normal operation, b) Breakdown level.

CONCLUSION

A multiple-use cavity test system was developed and successfully employed to study voltage breakdown phenomena in S-band pulsed linear accelerator cavities. The experiments demonstrated that the system is capable of testing many different types of cavities without brazing them. The high power test results indicate that the maximum surface electric field can be as high as 240 MV/m at S-band frequencies for pulsed operation. This is five times higher than the maximum field given by Kilpatrick's breakdown criterion. The surface polishing experiments show that neither diamond polishing nor electro polishing significantly enhanced the breakdown threshold. It was also found that the breakdown threshold did not depend on pulse repetition rate between 70 and 300 pps. Further experimental studies on other surface finish techniques, other materials, effect of RF pulse shape, temperature and external magnetic field are currently underway.

ACKNOWLEDGEMENTS

The author wishes to thank L. Nelson and F. Gordon who helped to develop the system and to conduct the tests.

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