SLAC-PUB-14153

A DUAL-MODED CAVITY FOR RF BREAKDOWN STUDIES*

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Abstract

The phenomenon of rf breakdown presents a technological limitation in the application of high-gradient particle acceleration in normal conducting rf structures. Attempts to understand the onset of this phenomenon and to study its limits with different materials, cell shapes, and pulse widths has been driven in recent years by linear collider development. One question of interest is the role magnetic field plays relative to electric field. A design is presented for a single, non-accelerating, rf cavity resonant in two modes, which, driven independently, allow the rf magnetic field to be increased on the region of highest electric field without affecting the latter. The design allows for the potential reuse of the cavity with different samples in the high-field region. High power data is not yet available.

INTRODUCTION

The field of particle accelerators has, from its inception, been driven toward achieving higher and higher energies. Since multi-turn circular accelerators approached a practical size limit for electrons due to synchrotron radiation, lepton machines have focused on one-pass linear accelerators, such as the SLAC linac. Efforts to push toward the TeV scale in the past couple of decades have strained the limits of linac technology as well, as required lengths of tens of kilometers and the associated costs impede efforts to fund and build a collider.

As a result, a major thrust of accelerator physics R&D has been aimed at reliably sustaining higher accelerating gradients in accelerator structures to limit length. Superconducting technology is one approach, with its unique challenges and limitations as well as benfits. Gradients exceeding 30 MV/m are being achieved more regularly in L-band superconducting cavities. Normal conducting accelerator structures, at X-band, have been shown to be capable of 65-100 MV/m gradients. At their frontiers, the parameter to be improved for superconducting cavities is yield, limited by Q drop, whereas for normal conducting structures the limiting factor is breakdown rate (see e.g. [1–5]).

At high field levels, copper accelerator structures (or other materials/alloys), have some probability on each pulse of exhibiting rf breakdown. This involves arcing, a vacuum burst, disruption of the field pattern, and reflection and absorption of rf power. This disruptive phenomenon must be kept to a minimum for efficient operation of a machine comprised of many structures.

As gradient is pushed higher in test structures, breakdown rate increases exponentially. The ratio of peak surface electric field to accelerating field is obviously a factor, long taken into account in accelerator structure design. Another factor that has become apparent is the peak surface magnetic field. This seems to be related to pulsed heating of the surface, the cyclical temperature rise between the beginning and end of each rf pulse. This can be rather large due to the very small duty factor, the heat being deposited in a time short relative to its diffusion time through the bulk material. Plots of breakdown rate vs. accelerating gradient shift upward for a given structure, with a strong exponential dependence as the pulse width and thus pulsed heating, is increased.

The phenomenon (phenomena?) of rf breakdown, however, and the relative roles played in it by electric and magnetic surface fields, are not completely understood. High magnetic fields, for example, have been known to cause evident surface melting in regions where no breakdowns occurred. Is it only through pulsed heating that magnetic field is relevant, or does the field itself play a role in the surface physics resulting in breakdown?

This paper presents a design for a unique resonant cavity which we hope will prove useful in studying this aspect of rf breakdown. The cavity is not itself of a geometry applicable to particle acceleration. However, it may provide information on the basic physics relevant to optimization of accelerator structure designs.

CONCEPT AND INITIAL THOUGHTS

The idea was to produce an rf cavity for high power testing in which the surface electric field and surface magnetic field could be independently varied via the excitation of different modes. In order to be driven by sources of the same type, the modes should be degenerate or nearly so; for our purposes, they should be resonant at within a few megahertz of 11.424 GHz to accommodate the use of XL4 klystrons.

The obvious choice for magnetic field control is a TE_{01} mode in a pillbox cavity, which has no surface electric field. With a diameter of 3.5092 cm and a height of 3.2005 cm, TE_{011} is degenerate with TM_{012}. However, the peak electric field of the latter, where breakdown is likely to occur, is on the end walls, whereas the peak magnetic field of the former is around the center of the circumference. In fact, the magnetic enhancement it provides at the peak electric field point is zero. At 2.1429 cm diameter and 3.7686 cm height, TE_{112} and TM_{011} are degenerate. While the peak magnetic field of the former coincides with the peak electric field of the latter, their different symmetries means the net peak magnetic field will be offset in a direction determined by the former's polarization and the relative phase, creating uncertainty.

Another possibility considered was the use of two cross polarized TE_{111} modes. The peak electric and magnetic fields of this mode are separated by 90˚ in azimuth on the side wall. One could imagine varying the relative phase to

*Work supported by the U.S. Department of Energy under contract DE-AC02-76SF00515.

go between linear and circular polarization, and thus from separated to uniform pulsed heating and electric field. However, keeping the peak amplitudes constant would require simultaneously ramping power. Knowing the relative phase would be difficult, and imperfections would cause uncontrolled beating between polarizations. It would be easier to work with cross-polarized 110 modes in a rectangular cavity, driving them at different amplitudes to achieve different combinations of magnetic and electric surface fields.

COAXIAL CAVITY

After such considerations as the above, the configuration that finally appeared best was a combination of TE_{011} and TEM_3 in a coaxial cavity (see Fig. 1), for which the peak fields are azimuthally symmetric and located clearly on the center conductor. A degenerate solution at 11.424 GHz was found with inner and outer diameters of 1.270 cm and 4.179 cm and a length of 3.928 cm. The modes could be independently excited through appropriate iris pairs from either end wall, thanks to their orthogonal magnetic field orientations, radial and azimuthal, respectively.

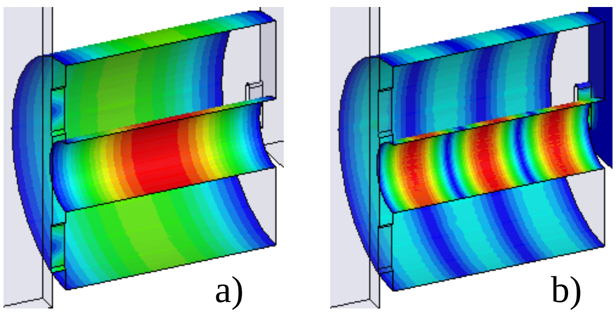

Figure 1: a) Surface magnetic field pattern for the TE_{011} mode and b) surface electric field pattern for the TEM_3 mode in a coaxial cavity dimensioned to achieve the same resonant frequency for both.

The peak magnetic field of the TE_{011} mode surrounds the midpoint of the center conductor, lying atop the middle of three electric field peaks of the TEM_3 mode. From the latter mode alone, one would expect an equal distribution of breakdown craters to be formed around each peak. One could not tell during testing where breakdowns were occurring, but would have to determine afterward whether adding more magnetic field concentrated them at the middle.

It would be more useful and simplify experiments if there were one peak electric field region, co-located with the one peak magnetic field enhancement region. To this end, the center conductor was shaped, with a larger 1.588 cm diameter near the ends necked down to 0.953 cm in the middle, as shown in Fig. 2. This has the effect of dropping the field of the outer lobes. As stepping the diameter sharply between the electric field lobes creates very high magnetic fields, and thus pulsed heating, as this is the location of the TEM_3 magnetic field peaks. Therefore, the shaping had to be done using gentle slopes with rounded ends. An added benefit of this shaping is that it breaks the unwanted degeneracy of TE_{011} with TM_{111}. The nearest parasitic modes in the modified cavity are TM_{110} and TM_{111} at 11.06 GHz and 11.90 GHz, respectively, far enough away not to be of concern.

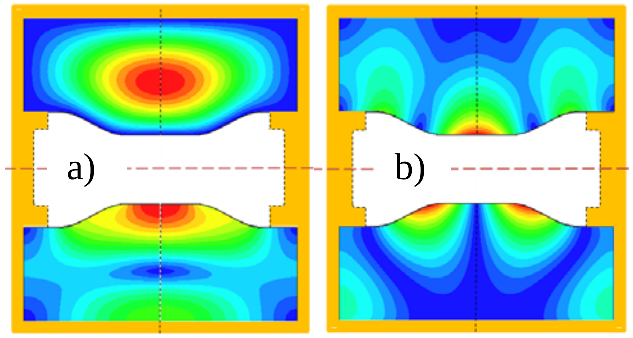

Figure 2: Electric field pattern (top) and magnetic field pattern (bottom) for a) the TE_{011} mode and b) the TEM_3 mode with necked center conductor. The white region suggests a removable center conductor.

Coupling to the TE_{011} mode is accomplished through two narrow radial slots, centered on either side of the center conductor and connecting the cavity to the narrow wall of a rectangular waveguide. The width of the input waveguide is reduced through an asymmetric mitered bend from 2.286 cm (WR90) to 1.504 cm to match the half guide wavelength to the spacing between the slots, for optimal coupling with the guide appropriately shorted. The TEM_3 coupling uses two 58.5˚ azimuthal slots in the opposite cavity end, just beyond the center conductor, coupling into the broadwall of an appropriately shorted WR90 waveguide.

A fortuitous feature of this combination of cavity modes is that neither mode has longitudinal fields across the center; the TE_{011} currents are purely azimuthal, and the longitudinal TEM_3 currents have a node at the center. It is therefore conceivable to split the outer cavity wall at the centerline to be connected by flanges. The middle of the center conductor is the experimental area and should not be split. However, the two additional magnetic field/current nodes of TEM_3 provide locations near the ends of the center conductor which could be discontinuous (see Fig. 2). Thus the center conductor can be made removable; it can screw into a base one side of the cavity and slip fit into one on the other side as the cavity halves are brought together with bolted conflat vacuum flanges. A tiny hole on either end will serve to vent the volumes where the center conductor is inserted to the coupling waveguides to relieve virtual leaks. With this construction, the main cavity should be reusable. Multiple center conductor inserts can be subjected to different high power processing, with different combinations of field amplitudes and pulse lengths, and their surfaces and breakdown histories compared after removal.

A design has been finalized, with simulations giving each mode within 0.2 MHz of 11.424 GHz and critically coupled to $0.96 < \beta < 1.04$. The edges of the coupling slots are rounded to 76 μm to reduce slot pulsed heating.

Table 1 gives the quality factors, time constants and steady state peak surface field amplitudes for each mode. To achieve an electric field of 200 MV/m requires 3.3 MW driving the TEM_3 mode. The unenhanced magnetic field level would be 549 kA/m, offset from the peak electric field. To raise the peak magnetic field to 1 MA/m at the middle of the center requires 18.3 MW driving the TE_{011} mode (see Fig. 3). While this adds no electric field in the cavity proper, it does create slot fields at the level of 84 MV/m.

Parameter	TE_{011}	TEM_3
Q_0	15,162	9,591
τ (ns)	205	135
$\|E_s\|_p/\sqrt{Pin}$ (kV/m / $W^{1/2}$)	19.62	110.2
$\|H_s\|_p/\sqrt{Pin}$ (A/m / $W^{1/2}$)	233.6	302.4
$\|E_s\|_p/\|H_s\|_p$ (V/A)	84.0	3644.4

TABLE 1: Cavity Mode Parameters.

While it might be more efficient to use one power source, dividing the power with a variable splitting circuit, effective use of this cavity really calls for two independently driven klystrons. Critically coupled, the bandwidths of the resonances are on the order of a couple of megahertz, narrower than that of the klystron. To accommodate fabrication errors and change with temperature, each klystron will have to be independently tuned to and track its cavity frequency by minimizing the reflection; drifting a little off frequency can greatly reduce the power going into the cavity.

Separate klystrons will also allow adjustment of the timing of the pulses to accommodate the difference in the mode fill times or to study the effect of separating them temporally. By pulsing the TE_{011} mode first and then reversing its drive phase, we might discharge it at the start of the TEM_3 pulse, thus preheating the surface to distinguish the effect of pulsed heating from that of added magnetic field. To bring it up faster and reduce its own pulsed heating, TEM_3 mode's drive, which requires less power in the regimes given above, can start perhaps four times high and drop down at steady state.

CONCLUSION

A resonant X-band rf cavity has been designed, after consideration of various options, which supports two modes close enough in frequency to be driven by the same type of klystron. One mode produces a focused surface electric field maximum in a region where the other mode provides peak magnetic field and thus pulsed heating. This region is on a center conductor in the modified coaxial geometry. The purpose of the design is to allow a series of rf breakdown experiments to be conducted with independent control of electric and magnetic field. The wall current patterns associated with the chosen modes permit breaks allowing the cavity to be opened at the midplane and the center conductor to be removed. Multiple experiments can thus be performed with the same cavity by simply replacing the center conductor. With rf design complete, mechanical drawings are being produced.

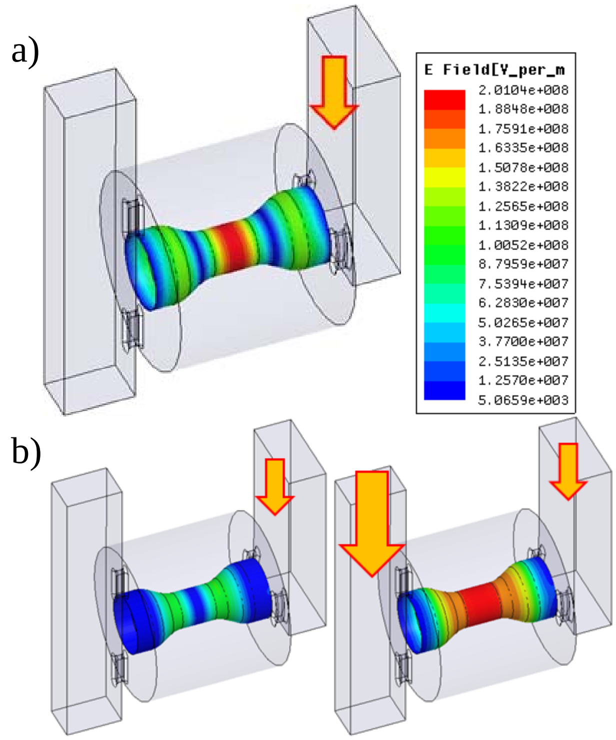

Figure 3: Full geometry of the dual-moded cavity with coupling waveguides showing a) electric field on the center conductor with TEM_3 driven with 3.3 MW and b) magnetic field on the center conductor before and after adding 18.3 MW of TE_{011} drive, shown on the same scale with a peak of 1 MA/m.

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