Asymmetric Bimodal Accelerator Cavity for Raising rf Breakdown Thresholds

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We consider an axisymmetric microwave cavity for an accelerator structure whose eigenfrequency for its second lowest TM-like axisymmetric mode is twice that of the lowest such mode, and for which the fields are asymmetric along its axis. In this cavity, the peak amplitude of the rf electric field that points into either longitudinal face can be smaller than the peak field which points out. Computations show that a structure using such cavities might support an accelerating gradient about 47% greater than that for a structure using similar single-mode cavities, without an increase in breakdown probability.

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This Letter describes a new type of cavity for a high-gradient accelerator structure that can be expected to have a breakdown threshold higher than that for a conventional cavity. The threshold increase is to be brought about by designing the cavity to operate simultaneously in TM_{010}- and TM_{020}-like modes of a modified axisymmetric pillbox, whose end walls are profiled so that the second mode's eigenfrequency is twice that of the first. Hereafter, we refer to this as a bimodal cavity. It will be shown below that, when fields of a bimodal cavity are longitudinally asymmetric, the peak value of the composite rf electric field that points *into* one cavity wall (i.e., the "cathodelike" wall) can be markedly smaller in magnitude than that which points *away from* the opposite wall (i.e., the "anodelike" wall).

Creating this anode-cathode asymmetry could be beneficial since the onset of rf breakdown in an accelerator structure is probably initiated and fed by field emission, photoemission, secondary emission, and/or positive ion bombardment—distinctly cathodelike phenomena [1]. Thus, a structure composed of asymmetric bimodal cavities whose highest surface fields are anodelike might allow one to sustain a higher net acceleration gradient than for a structure using symmetric cavities.

The validity of this conjecture can be tested to provide evidence as to whether indeed cathodelike phenomena dominate the initiation of rf breakdown [2], since experiments driving such a cavity will show different breakdown probabilities if the phases of the two rf drive signals are shifted by π. No change in breakdown probability would be an indication that neither cathode nor anode dominates; whereas finding specific phases where the breakdown probability is minimized would indicate whether cathodelike or anodelike effects dominate. If the bimodal cavity concept can be shown to be valid, it should add an important item to the menu of ideas being pursued to establish a working accelerator gradient significantly greater than 100 MV/m in a warm structure for a future e^+-e^- linear collider with a breakdown probability below 1 in 10^7 pulses/m [3].

The menu of ideas currently under study includes improved structure and coupler designs [4], improved fabrication [5], improved conditioning regimens for copper structures [6], use of alternate metals such as stainless steel or molybdenum in structure areas subject to damage from breakdown [7], use of insulating coatings to reduce rf electric fields at metallic surfaces and to impede melting [8], and use of multimode excitation of longitudinally symmetric cavities to reduce exposure times to high fields during each rf cycle [9].

Use of an asymmetric bimodal cavity is motivated by analogy with breakdown in a dc vacuum diode, with a high potential U applied between the two electrodes, as depicted in Fig. 1. In Fig. 1(a), the negatively biased cathode is the outer electrode, while in Fig. 1(b), it is the inner electrode. The magnitude of electric field on the inner electrode is higher than that on the outer electrode (inversely as the square of radii for a spherical diode), so that one might anticipate different dc breakdown strengths for the two polarities. Indeed, it is established [1] that case (b) usually

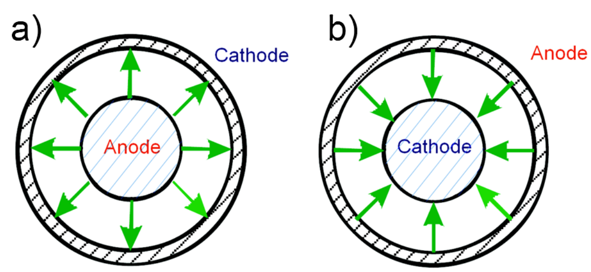

FIG. 1 (color online). Schematic of a high-voltage dc spherical diode. Polarity (b) is more vulnerable to breakdown than is (a), since for the same potential U it has a higher electric field on the cathode than does (a).

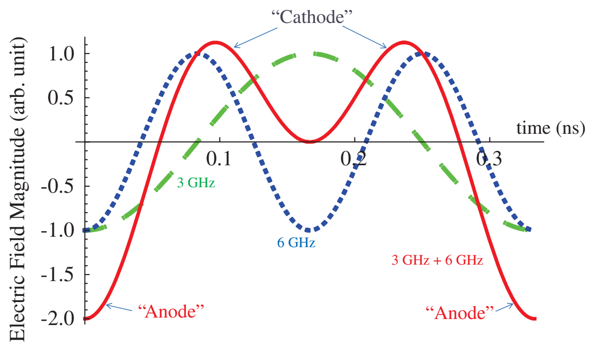

FIG. 2 (color online). Time dependence for a composite field (red solid line) excited at 3 (green dashed line) and 6 GHz (blue dotted line) with equal amplitudes and zero phase difference. Negative anodelike fields have twice the magnitude of positive cathodelike fields.

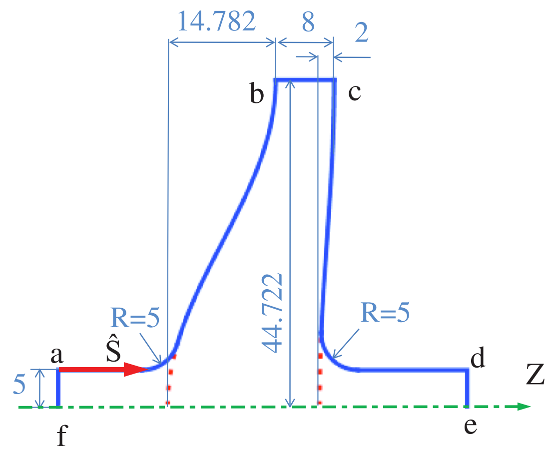

FIG. 3 (color online). Outline of axisymmetric bimodal cavity having 3.0 and 6.0 GHz TM_{010} and TM_{020} modes. Dimensions are in mm. Coordinate S measures distance around the cavity periphery, beginning at point a.

has lower breakdown strength than case (a). This is easily understood since it is the cathode that is the initial source for emitted electrons—through field emission, thermionic emission, or photoemission—and the source of sputtered atoms from energetic positive ion bombardment. If an electron beam were to cross the cathode-anode gap with polarity (a), particles could acquire a higher energy than they would in (b), since the applied potential U could be higher in that case without leading to breakdown.

If, however, instead of being a dc diode, this structure were to be driven with a high-voltage rf sinusoidal voltage, there is obviously no corresponding distinction between anode and cathode: anode and cathode will exchange roles each half cycle. But if the applied voltage were periodic but not sinusoidal there could be a distinction, leading to an increase in the breakdown threshold. This possibility is illustrated in Fig. 2. Here, with a periodic gap voltage consisting of a superposition of, for example, a 3.0 GHz fundamental and a 6.0 GHz second harmonic, one sees the peak negative field (at times when a negatively charged bunch would be accelerated) that is larger by a factor of 2 than the positive field that is present during the time interval between bunches.

For a microwave bimodal cavity, rather than a vacuum diode, operation is in TM_{010}- and TM_{020}-like modes of a modified pillbox, where the axisymmetric modifications consist of distortions of the (usually planar) end walls into profiles with sinusoidal variations along the radius. As will be shown, radial sinusoidal variations are found that provide the required 2:1 eigenfrequency ratio together with a high degree of axial asymmetry caused by unequal distortions of the two cavity faces. It can be noted that by reversing the phases of the two drive sources, the roles of "anode" and "cathode" would be exchanged, and a test of the efficacy of this idea could be easily carried out by comparing rf breakdown rates for the two conditions. Breakdown rates can also be compared with excitation of the same cavity using only one rf source, to confirm the essential distinction that can be realized using at least two harmonically related modes.

An example chosen to illustrate the underlying concept is shown in Fig. 3. Eigenfrequencies for the TM_{010} and TM_{020} modes in this configuration are 3.000 04 and 6.0003 GHz, with Q's of 7080 and 11 296. Electric field intensity maps in relative units for the modes are shown in Fig. 4.

Achievement of optimum field asymmetry for a given cavity geometry requires computations over a range of magnitudes for E_2/E_1, the second-harmonic to fundamental field amplitude ratio. Phases for each are set to maximize energy gain. Results are shown in Fig. 5, which depicts as functions of E_2/E_1 the ratios E_a/E_c, G/E_c, and $R = (G/E_c)/(G/E_c)_{PB}$. Here E_a and E_c are peak magnitudes of fields directed away (anode), and towards (cathode), a cavity surface, and G is the average gradient, namely, the energy gain per unit charge for a velocity-of-light particle that crosses the gap, divided by the effective gap width. The quantity $(G/E_c)_{\rm PB}$ is the stated ratio for a 3.0-GHz pillbox with effective gap, irises, and roundings equal to that of the bimodal cavity. R is a measure of the

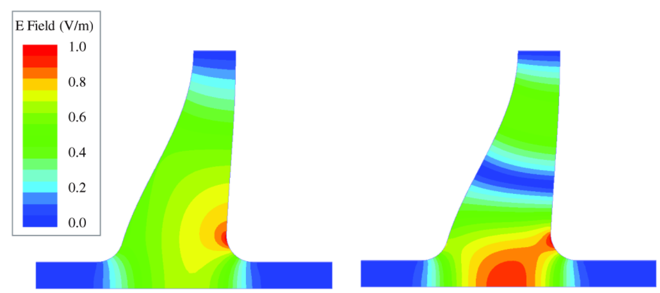

FIG. 4 (color online). Electric field maps for the 3.0-GHz TM_{010} (left) and 6.0 GHz TM_{020} (right) modes.

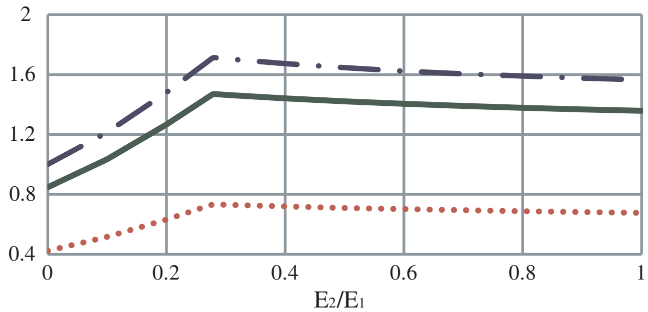

FIG. 5 (color online). Computed values of the ratios E_a/E_c (blue dot-dashed line), G/E_c (red dotted line), and R (green solid line) as functions of E_2/E_1. Peaks are at $E_2/E_1 = 0.28$, where $E_a/E_c = 1.71$, $G/E_c = 0.73$, and $R = 1.47$. This latter result suggests that an accelerator structure comprising axisymmetric bimodal cavities could support an acceleration gradient up to 47% higher than that for a similar conventional pillbox at the same fundamental frequency, without an increase in breakdown rate.

benefit that could arise by use of bimodal asymmetric cavities.

Figure 6 shows plots of the electric field around the cavity periphery and in the beam tunnel for the case with $E_2/E_1 = 0.28$, at times when a bunch to be accelerated would enter the cavity (negative fields) and one-half period later (positive fields).

Table I shows the rf powers needed to achieve acceleration gradients G of 100, 150, and 200 MV/m for excitation using rf frequencies of 3 and 6 GHz (S band and C band), and of 6 and 12 GHz (C band and X band). The former is for the cavity profile shown in Fig. 3, while the latter is for a replica with half-scale dimensions.

Powers for a comparable conventional pillbox operating at 3.0 GHz to achieve equivalent gradients of 100, 150, and 200 MV/m would be 5.5, 12.4, and 22.0 MW, while for a

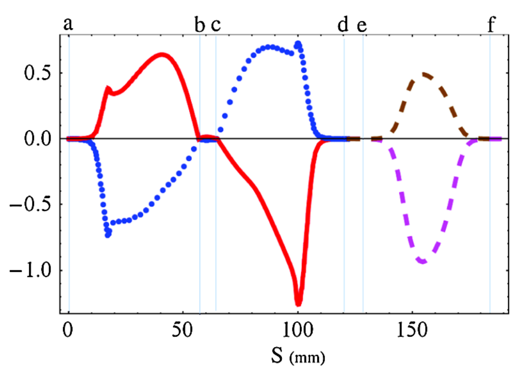

FIG. 6 (color online). Electric field around bimodal cavity periphery as coordinate S advances between points a and d, and along the cavity axis between points e and f (see Fig. 3). Negative fields are during acceleration of a bunch, positive fields are half a cycle later. Red (solid) segments are anodelike, while blue (dotted) segments are cathodelike. Dashed segments are fields along the cavity axis.

TABLE I. rf powers (in MW) for cavities with S-band–C-band and C-band–X-band excitation needed to achieve acceleration gradients of 100, 150, and 200 MV/m, for the cavity profile shown in Fig. 3.

	S band and C band		C band and X band	
G (MV/m)	P_S	P_C	P_C	P_X
100	7.60	0.55	2.69	0.20
150	17.1	1.25	6.05	0.44
200	30.4	2.22	10.7	0.78

6.0 GHz pillbox powers would be 2.0, 4.4, and 7.8 MW. Of course, these figures are only meaningful if rf breakdown does not occur

Bimodal excitation implies that a means is found to couple power from two phase-locked high-power rf sources into cavities in an accelerator structure without higher frequency radiation leaking through and being transmitted back towards the lower frequency source. A coupling design has been found to accomplish this aim, using a high-frequency choke on the low-frequency input waveguide. Details are shown in Fig. 7 for 6-GHz excitation in a 3/6 GHz bimodal cavity. Coupling 3-GHz power would not require any exceptional design features. In practice, a weakly coupled probe would be built into each cavity to test for optimum phase difference for the two modes and for correct polarization with respect to the "cathode."

In conclusion, a novel bimodal, asymmetric cavity concept has been described that shows promise of sustaining a 47% higher acceleration gradient than in a conventional

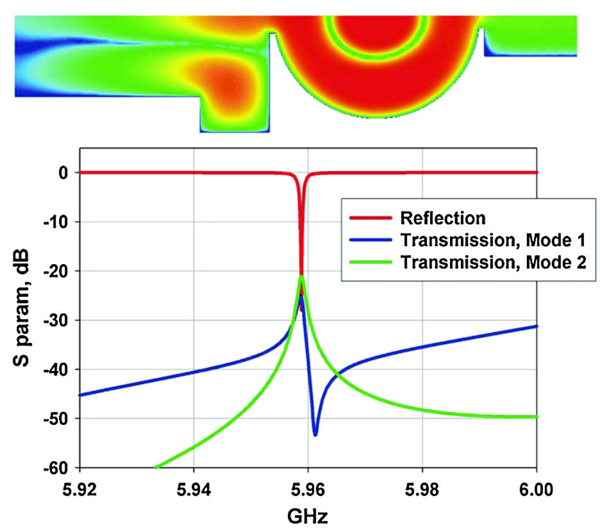

FIG. 7 (color online). Power coupling from waveguide at right into bimodal cavity near 6.0 GHz. Field map along central plane in the cavity is shown at top, and S parameters at bottom. Only limited penetration occurs of 6.0 GHz radiation into the above cutoff waveguide at left. Here, the influence of irises is neglected.

pillbox cavity with the same gap, irises, and roundings. This increase comes about because the cavity surface where the peak electric field points *into* the surface has a lower field magnitude than the opposite surface where the peak electric field points *out of* the surface. Use of two harmonically related frequencies ensures that this asymmetry prevails throughout the rf cycle. The first surface is akin to a cathode, the second to an anode. Since cathode phenomena such as electron emission and positive ion sputtering probably initiate breakdown, an asymmetric field distribution should allow operation with net acceleration gradient higher than what can be achieved using a conventional cavity, without an increase in the probability of breakdown.

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