MULTI-HARMONIC CAVITY FOR RF BREAKDOWN STUDIES

Y. Jiang, J. L. Hirshfield, Yale University, New Haven, CT 06511, USA
S.V. Kuzikov, Institute of Applied Physics, Nizhny Novgorod, Russia
S.Yu. Kazakov, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

Abstract

An axially-asymmetric cavity to support several modes at harmonically-related frequencies is predicted to sustain higher RF breakdown thresholds than a conventional pillbox cavity, when driven by two or more external RF phase-locked harmonic sources. Experimental efforts are underway at Yale Beam Physics Lab to study RF breakdown in a bimodal asymmetric cavity. Such a cavity could be a basic building-block for a future high-gradient warm accelerator structure.

INTRODUCTION

A multi-TeV linear accelerator is considered needed for future research in high energy physics to explore the energy frontier beyond that that can be reached currently by LHC. However, RF breakdown appears to be a major hurdle preventing accelerator structures from reaching higher gradients. Any mechanism that shows promise for increasing RF breakdown thresholds is of great interest to the accelerator physics community.

This paper describes a bimodal asymmetric cavity with properties that may allow operation at higher acceleration gradient than a conventional single-mode cavity, without an increase in the breakdown probability [1]. In the present context, the term “bimodal” refers to a cavity operating simultaneously in two eigenmodes, where the eigenfrequency of one is twice that of the other. (Ref. [2] gives an example for a cavity design with more than two harmonically-related eigenmodes). Should success result from research on the bimodal cavity concept described here, it should help to illuminate the underlying physics of RF breakdown. Following that, it is conceivable that elements in a structure for a future two-beam design could evolve with nearly breakdown-free acceleration gradient in the 150 MeV/m range, or greater [2].

RF BREAKOWN THRESHOLD

The goal of the experimental studies on RF breakdown is the evolution of a viable warm structure design for an electron/positron accelerator structure with an acceleration gradient >150 MeV/m and a breakdown probability of $<10^{-7}$ m^{-1} per RF pulse (i.e., one event per meter structure length per 24-hour day with a 120 Hz pulse repetition rate). Certainly deeper understanding of breakdown physics is needed before a viable structure can be built to support such high acceleration gradient.

One of the appealing hypotheses as to the onset of RF breakdown is that, by analogy to DC vacuum breakdown, it is initiated by electron emission from walls of a metal structure supporting strong RF fields. When the RF electric field is directed towards the wall, electrons can be accelerated to overcome the work function barrier, then escape from the wall, and thence to stimulate (e.g., via multipactor and/or impact ionization) further emission that leads to a rapid expulsion of atoms (assisted in this by ion sputtering), creation of dense plasma, surface melting, and ultimately a breakdown event that grows as the plasma absorbs RF energy and terminates RF power flow along the structure. The onset of this runaway process would be promoted at surface irregularities, such as dislocations and grain boundaries, which are accentuated by stresses induced by pulsed heating due to surface RF magnetic fields.

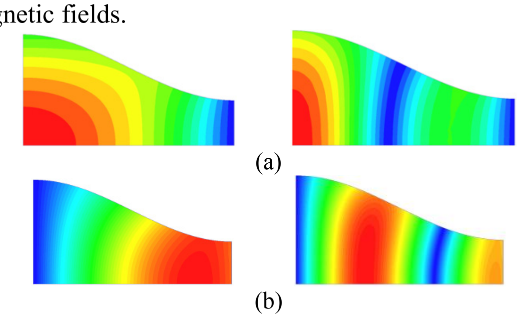

Figure 1: (a) The electric field map and (b) the magnetic field map for 2.856 GHz TM_{01} and 5.712 GHz TM_{02} modes.

In order to test the above hypothesis, systematic investigations of RF breakdown are described here using a bimodal test cavity [1-6], as shown in Fig. 1. In this cavity, phase-locked two-frequency operation allows the electric field pointing into one wall (cathode-like) to be significantly smaller than the field pointing out of the opposing wall (anode-like); it also allows the superposition of two harmonic modes to narrow the time span of peak field exposure and delocalize the spatial distribution of the peak field. The objective of the tests is to show that RF breakdown thresholds in bimodal, asymmetric cavities can exceed those in conventional single-mode cavities, and reveal the correlation between the electric field orientation (directed towards or away from metal walls) and the RF breakdown threshold, as well as the correlation between the field exposure at the micro-pulse ps time scale and the RF breakdown threshold. Furthermore, the influence of pulsed heating on RF breakdown as described above can also be tested using a bimodal cavity. For if the exposure time to peak surface RF magnetic fields is shortened and if the peak fields are less localized by use of a bimodal cavity, it is speculated that fatigue induced by pulsed heating will be lower than would be otherwise, thereby resulting in a reduced accentuation of surface irregularities with concomitant reduced breakdown rate for a given accelerating field.

BIMODAL CAVITY DESIGN

The design object of the bimodal cavity is to support the experiments aiming to explore RF breakdown and accumulate breakdown statistics in a demountable cavity without beam tunnels or irises, and test possible virtues of multi-harmonic cavity concept.

The bimodal cavity can support 2.856 GHz TM_{01} and 5.712 GHz TM_{02} modes. The optimum ratio of electric field strengths of these two modes E_2/E_1 to maximize the ratio of anode field to cathode field (the anode-cathode effect) is 0.5812:1, where the anode field verse cathode field is 1.764. This implies—based on the same design idea described here—that an accelerator structure composed of bimodal cavities driven with this ratio of field strengths might sustain a 55% higher acceleration gradient than would a single-mode cavity, without an increase in breakdown probability [6]. It is that astonishing prediction that provides one of the main motivations for the study described here.

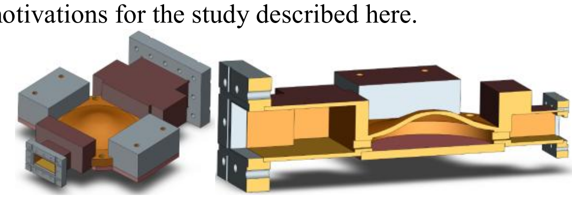

Figure 2: Bimodal cavity in a clamped structure with demountable bottom surface.

A bimodal asymmetric cavity design for the RF breakdown studies is shown in Fig. 2. In this design, peak electric field is located on the demountable flat plate, where the RF breakdown events occur most likely. This design allows convenient replacement of test plates for inspection and reassembling without disconnecting or changing the dual-frequency RF coupling and power feeding systems. The two input waveguides and the top portion of the cavity are to be reused for a series of tests with varying power levels and phases for the two RF sources, to gauge the validity of the anode-cathode imbalance conjecture. Reversing the relative phases between the second harmonic and the fundamental will change this surface to become anode-like, and thus provide a direct means to distinguish between the two states of operation. The tests can be carried out over a range of field amplitudes, and for surfaces prepared using different recipes. The cavity design includes allowance for vacuum pumping, as well as one or more ports for visual detection of breakdown.

Table 1: RF power requirements for 2.856 GHz and 5.712 GHz sources, assuming that breakdown would not intervene. P_{total} is the total power from S-band Klystron.

$E_{surface}$ (MV/m)	P_1 (MW)	P_2 (MW)	P_{total} (MW)
100	1.397	0.267	1.700
200	5.587	1.068	6.800
300	12.57	2.403	15.301

Table 1 shows the RF power requirements for 2.856 GHz and 5.712 GHz sources to sustain the desired peak surface fields using the dual frequency test stand to be operated at Yale Beam Physics Lab.

COLD TEST OF BIMODAL CAVITY

One key to demonstrate feasibility of building and operating bimodal cavities is to build a practical cavity with two harmonically-related operating modes with the accuracy of frequency matching good to be ~1 MHz or better. But fabrication to such a high tolerance can prove daunting. In order to show that in principle a cavity with two harmonically-related modes could be built, we describe here a demonstration in the laboratory of a weakly tunable cavity with provision to compensate small discrepancies that naturally arise during fabrication [6].

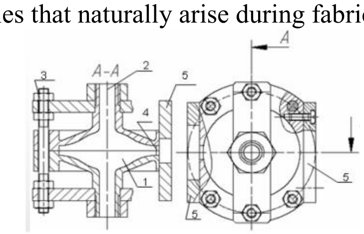

Figure 3: Drawing of the test cavity with a flexible wall: 1 – cavity body; 2 – simulated beam tunnel; 3 – tuning screw, 4 – coupling holes; 5 – waveguide flanges.

For simplicity in low-power tests, a symmetric, dual-mode cavity was built with its TM_{01} mode with frequency f_1 = 7.0 GHz and its TM_{02} mode with frequency f_2 = 14.0 GHz, for a greater sensitivity to fabrication errors. Tuning of frequencies was afforded by means of a 2-mm thick flexible wall in the copper cavity which could be easily deformed by ~1 mm without plastic deformation. A diagram of the actual cavity is shown in Fig. 3.

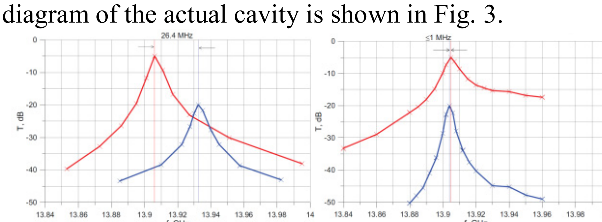

Figure 4: Measured transmission vs frequency: (a) before cavity deformation, (b) after cavity deformation. Red curve corresponds to 14 GHz mode, blue curve corresponds to 7 GHz mode, whose transmission is plotted as function of 2×f.

As a result a difference $\Delta f \sim 1$ MHz has been achieved, as shown in Fig. 4b. Results allow one to conclude that design of a cavity with a flexible, tunable wall can overcome the problem of mode equidistance in a future high-power experiment. Tuning to achieve a given value of f with high precision can be further achieved by temperature regulation of the entire structure, which in any case is probably required to compensate for ambient temperature variations.

DUAL FREQUENCY TEST STAND

This dual-frequency source now under construction in the Yale Beam Physics Laboratory is based on an XK-5 24-MW S-band klystron, an S-band waveguide transmission line with provision for power splitting into two portions with adjustable amplitude and phase, and a second-harmonic frequency multiplier to produce the C-band power, as shown in Fig. 5. Thus, the two sources would be automatically phase-locked, and no new modulator or C-band driver would be needed.

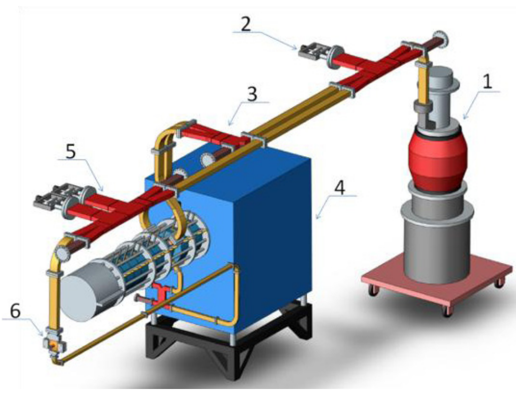

Figure 5: Layout of dual-frequency RF source, shown feeding a bimodal test cavity. 1 – S-band klystron; 2 – variable power splitter; 3 – 3-dB hybrid splitter; 4 – 250-kV electron gun tank; 5 – variable power splitter and phase shifter; 6 - bimodal test cavity. Gray structure attached to gun tank is the magnetic circuit, within which the two-cavity source is positioned.

The frequency multiplier is built with a demountable output cavity, to allow substitution of different output cavities to operate at different harmonics. For this project, a TE_{211} 5.712 GHz cavity is to be used, shown in Fig. 6.

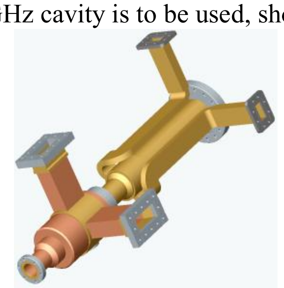

Figure 6: RF structure for second harmonic power source.

Simulations indicate that the 2nd harmonic multiplier should have an 88% RF-to-RF conversion efficiency, so that more than enough 2.856 and 5.712 GHz power should be available, at levels indicated in Table 1, based on the available S-band power of 15-20 MW from the XK-5 S-band klystron.

The existing S-band waveguide transmission line at the Yale Beam Physics Lab contains a variable power splitter and phase shifter that allows a wide range of coherent power divisions to be directed at two loads, in this case to the test cavity and the input of the 2nd harmonic frequency multiplier, which are needed to give the field strength levels in the cavity at each frequency, and for monitoring of reflected power to signal a breakdown event. The C-band waveguide systems will be constructed to bring RF power to the cavity test stand.

Planned experiments to be conducted are to involve excitation of the bimodal asymmetric cavity with varying amplitudes and phases for the two fields E_1 and E_2, and accumulate breakdown statistics for different scenarios following the conjectures discussed in the previous section.

CONCLUSION

In this paper we discussed several processes that can occur in multi-harmonic (bimodal) cavities which may help illuminate basic principles of RF breakdown, and might lead to an increase the RF breakdown threshold in an accelerator structure composed of such cavities. Experimental efforts are underway to confirm that multi-mode cavities can have higher breakdown threshold than single-mode cavities. Such a proof could lead to improved designs for an accelerator composed of such cavities for a future multi-TeV collider with higher acceleration gradient. Excitation of multi-harmonic cavities can be either using external RF sources at each frequency, or using an intense drive beam; but only the former has been discussed in this paper.

*Work supported in part by the U.S. Department of Energy, Office of High Energy Physics.

REFERENCES

[1] S.V. Kuzikov, S.Yu. Kazakov, Y. Jiang, and J.L. Hirshfield, Phys. Rev. Lett. 104, 214801 (2010).

[2] S.Yu. Kazakov, S.V. Kuzikov, Y. Jiang, and J.L. Hirshfield, Phys. Rev. ST – Accel. & Beams, 13, 071303 (2010).

[3] S.Yu. Kazakov, S.V. Kuzikov, V.P. Yakovlev, and J.L. Hirshfield, AAC2008, AIP Conference Proceedings, v. 1086, pp. 439-444 (2009).

[4] Y. Jiang, S.Yu. Kazakov, S.V. Kuzikov, and J. L. Hirshfield, AAC2010, AIP Conf. Proc. v. 1299, pp. 324-329 (2010).

[5] S. V. Kuzikov, S. Yu. Kazakov, Y. Jiang, M. E. Plotkin, A. A. Vikharev, and J. L. Hirshfield, AAC2010, AIP Conf. Proc. v. 1299, pp. 307-312 (2010).

[6] Y. Jiang, S.Yu. Kazakov, S.V. Kuzikov, and J. L. Hirshfield, AAC2010, AIP Conf. Proc. v. 1299, pp. 319-323 (2010).