DESIGN OF DIAMOND-LINED ACCELERATOR STRUCTURE TEST CAVITY*

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Abstract

For a high-gradient normal-conducting accelerator structure for a future multi-TeV linear collider, the main limitation to achievement of high acceleration gradient is RF breakdown. In an attempt to increase the gradient beyond limits that are acceptable for metallic structures, a diamond-lined structure is suggested. The published DC breakdown limit for CVD diamond is ~2 GV/m, but the limit has never been determined for RF fields. Here we present a design for a 34-GHz diamond-lined symmetric rectangular test cavity, operating in the LSM_{216} mode with a side-wall input coupler. The goal is to produce electric fields up to 1 GV/m at the diamond surfaces with ~10 MW of RF input power supplied by the Omega-P/Yale 34-GHz magnicon for experimental tests to determine the breakdown strength of CVD diamond at mm-wavelengths.

INTRODUCTION

Interest grows in developing a technology to sustain the high accelerating gradient in a warm linac needed for practical design of a multi-TeV collider. The most active idea to achieve high accelerating gradient is the CERN two-beam room-temperature concept CLIC (Compact Linear Collider) [1]. In CLIC, an acceleration gradient of 150 MeV/m is sought, by exciting the accelerating structure at high frequency (30 GHz), by using a structure geometry with moderate surface fields, and by using alternative structure materials such as molybdenum [2,3]. Recently [4], we proposed a rectangular dielectric-lined accelerating structure that uses low-loss, high-breakdown-field chemical vapor deposition (CVD) diamond to support strong electric fields, yet in which transverse evanescent gaps force down field magnitudes at the conducting walls, and thus greatly reduce surface losses and surface fatigue. Prior work deepened understanding of this novel structure, reinforced expectations of its potential to sustain an accelerating gradient approaching 200 MeV/m, but led ineluctably to need for measurements of RF breakdown limits for CVD diamond. In this paper, a design for a diamond-lined test cavity is presented. The cavity geometry has evolved from the accelerator structure geometry, but is intended chiefly for measurements of the breakdown threshold on diamond, and confirmation of the input coupler concept.

THEORETICAL ANALYSIS

A sketch of the cavity discussed in this paper is given in Fig. 1, where only one-half is shown for clarity.

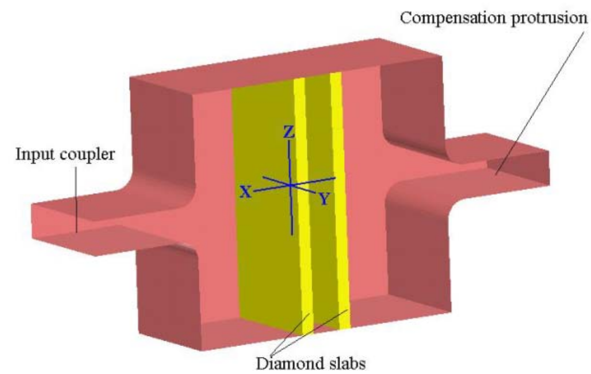

Figure 1: Sketch of cavity design (half shown). Seen are two diamond slabs surrounding the beam channel, the input coupler, and the opposing compensation protrusion to symmetrize the fields. Parameters for the example discussed in this paper are given in Table 1.

Design optimization began with theoretical analysis of an idealized cavity not taking into account a coupler. This approach helped to identify potential competing modes near the design mode, recognizing that spurious modes can be excited when the coupler and wall slots are introduced. The cavity parameters were optimized for a length along z of three wavelengths (26.2 mm).

Table 1: Parameters for diamond-lined cavity structure

operating frequency for LSM_{216} mode	34.272 GHz
equivalent phase velocity v_{phase}	c
cavity height $2d$ (along y)	12.0 mm
cavity width $2b$ (along x)	29.6 mm
cavity length L (along z)	26.2 mm
beam aperture width $2a_1$	3.0 mm
width of dielectric slabs $a_2 - a_1$	1.29 mm
relative dielectric constant	5.7
loss tangent $\tan\delta$	3×10^{-5}
wall quality factor Q_w	51,000
dielectric quality factor Q_d	140,000
overall quality factor Q	37,000
characteristic shunt impedance R/Q	53.8 Ω
shunt impedance R	1.99 MΩ
input RF power	10 MW
peak RF electric field on axis	340 MV/m

Diamond slabs with precise dimensions as in Table 1 ($12.0 \times 26.2 \times 1.29$ mm^3) can be supplied by the intended vendor.

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Modes for rectangular cavities with dielectric slabs can fall into two classes: LSM modes with no magnetic field normal to the dielectrics, and LSE modes with no electric field normal to the dielectrics [5]. With a sinusoidal field pattern along *z* having a periodicity equal to the vacuum wavelength (as to simulate a standing-wave accelerator for relativistic particles), transverse field variations are oscillatory along *x* in the two dielectrics and evanescent along *x* in the three vacuum zones. The LSM_{216} mode that is discussed here has a nearly-uniform symmetric E_z field along the central beam channel with six half-wavelength variations along *z*, and anti-symmetric E_x and E_y fields. To illustrate, plots of electric and magnetic field patterns are shown in Fig. 2, at *z* locations where their magnitudes have peak values, and for a cavity input power of 10 MW.

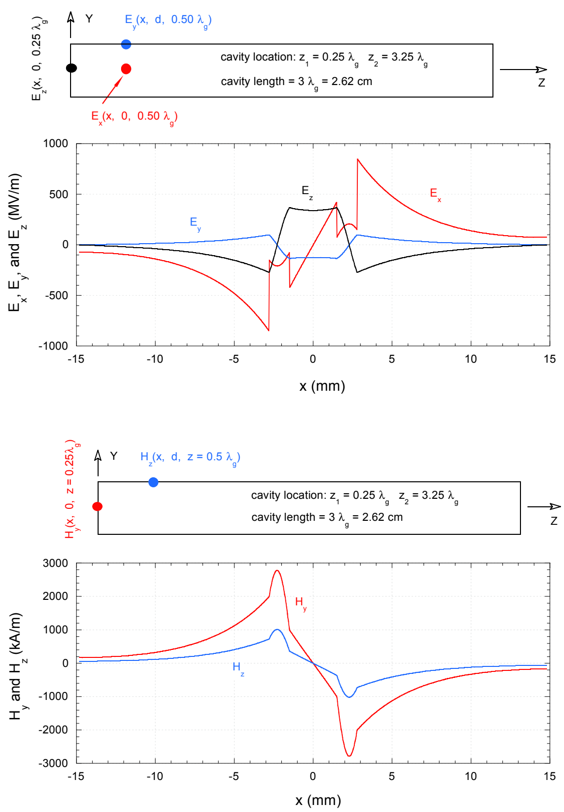

Figure 2: RF field profiles for the idealized LSM_{216} cavity mode with parameters as in Table 1 for an input power of 10 MW, at (*y*,*z*) coordinates shown in the accompanying diagrams. Top figure shows peak *E*-fields at the diamond surfaces of $E_{y\text{-max}}$ = 133 MV/m, and $E_{x\text{-max}}$ = 848 MV/m; E_z on the axis is 340 MV/m. Bottom figure shows *H*-field profiles with $H_{y\text{-max}}$ = 2783 kA/m and $H_{z\text{-max}}$ = 1014 kA/m; these values will be greatly reduced in the test cavity by use of wall tapers and profiled slots.

The field patterns shown in Fig. 2 indicate that the peak electric fields do indeed occur at the dielectric slabs, as desired for determining breakdown limits on the dielectric. But strong electric and magnetic fields (especially E_z and H_y) that are would occur at the end walls and at the dielectric-wall joints, respectively, must be moderated to avoid breakdown and undue pulsed heating. It is planned to achieve field moderation at these locations by introducing gradual tapers-beyond-cutoff in *z* to replace abrupt end walls, and by use of rounded-edge quarter-wave slots to capture the dielectric slabs at the conducting walls. These strategies are to insure that field limitations imposed by breakdown and/or pulsed heating at metallic surfaces within the cavity will be superseded by field limitations at the dielectric surfaces, where it is the deliberate intention of the experiments to determine field limits. The use of judiciously-placed wall slots along symmetry planes as used in the cold test cavity discussed below can have an added advantage. This arises since higher-order transverse deflecting modes that could pose stability problems for a traveling-wave accelerator version of this structure can be suppressed by these slots.

DESIGN FOR INPUT COUPLER

An RF simulation design study for the cavity with an input coupler has been carried out for the 3-D numerical model shown in Fig. 1. The model does not include central narrow wall slots along *y* and *z* that would be introduced to help suppress deflecting modes in the corresponding TW structure, for pump-out, and to facilitate precision fabrication and assembly; and tapers which might be necessary to avoid high RF fields on the metal ends of the cavity and at interfaces between the dielectric and the wall. The model is based on cavity dimensions taken from values given in Table 1 with, in addition to the coupler, a short-circuited compensation protrusion with dimensions of 3.56×12×10 mm^3; coupler and protrusion are joined to the cavity with corner radii of 2 mm. The simulated field patterns in the three symmetry planes, including fields in the coupler and compensating protrusion, are shown in Fig. 3. For operation with short pulses (e.g., 50-100 ns) the coupling factor would be about 4 in order to achieve reasonable energy flow during the pulse, and the temperature rise on the copper side walls would be about 170° C (for a 50 ns pulse).

COLD TEST MEASUREMENTS

A test cell using alumina slabs in place of diamond was constructed to confirm design calculations for modes in a dielectric-lined cavity with wall slots. Segments of the brass test cavity were held together with polycarbonate rods which also served as alignment fixtures. A photo of the separated halves of the test cavity is shown in Figure 4. The alumina slabs with dimensions 1×13×24 mm^3 were not quite long enough for a LSM_{216} mode cavity; as a consequence the cold-test cell was built to operate in the LSM_{215} mode. The cavity dimensions were 29×12×21.9 mm^3, with slot thicknesses of 0.5 mm. The calculated eigenfrequency is 35.107 GHz, and the unloaded *Q*-factor is 4200, based on the alumina's dielectric constant of 9.7 and loss tangent of 4×10^{-4}. RF input/output coupling was via 2.4 mm coax probes placed in opposite sidewalls, beyond the dielectric slabs. Mode properties and field patterns were measured, the latter *via* a bead-pull method. Results led to identification of the LSM_{216} design mode, based on the "5-1" symmetry of its fields.

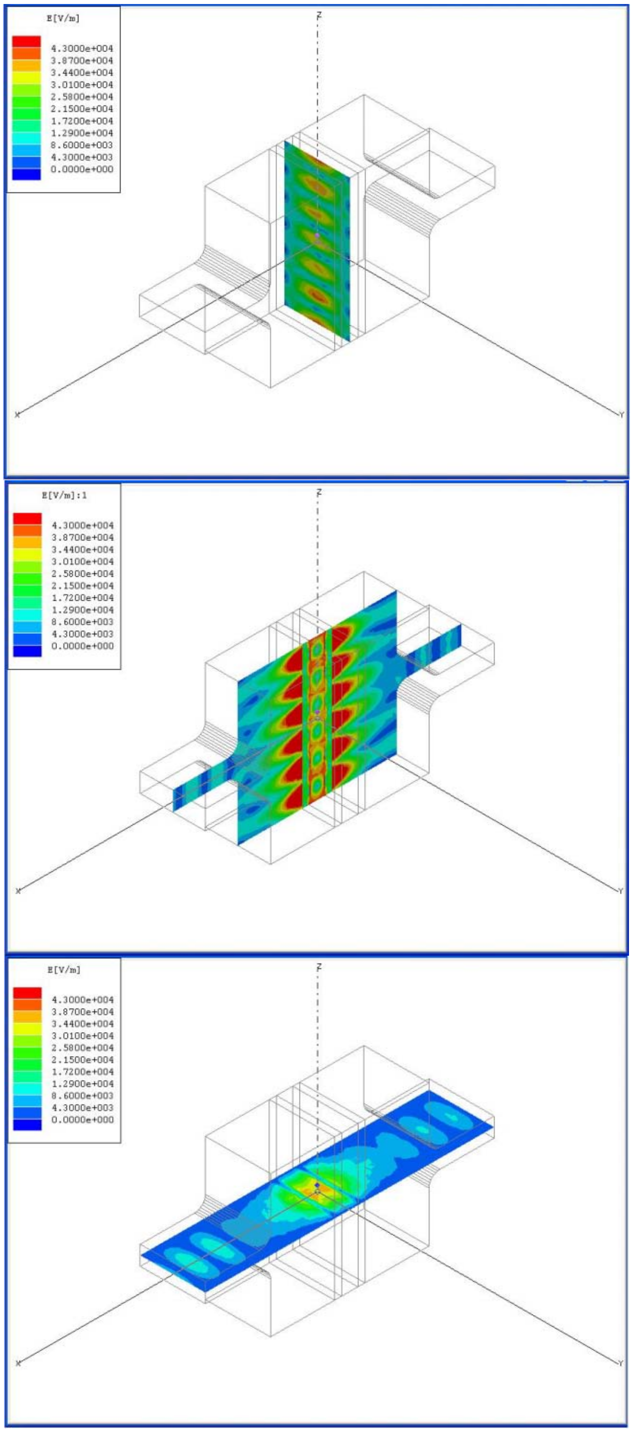

Figure 3: Field pattern in each of the symmetry planes of the operating LSM_{216} mode with an input coupler and a compensating protrusion.

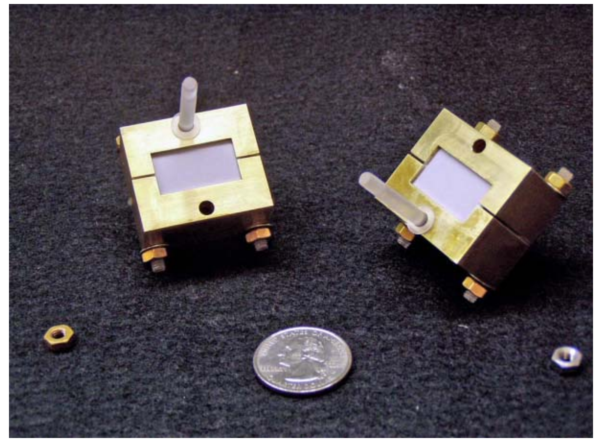

Figure 4: Photo of two halves of LSM_{215} mode test cavity that used alumina slabs in place of diamond.

SUMMARY

A design for a diamond-lined cavity test structure has been described. The overall goals for this project are to design, build, test, and evaluate at Ka-band a rectangular diamond-lined cavity that embodies features of a possible future high-gradient accelerator structure. The cavity is designed so that RF electric fields in the range 0.8 – 1.0 GV/m can be imposed on the CVD diamond slabs, with much weaker fields at the surrounding metal walls. In this way, it is intended to learn if CVD diamond can sustain significantly higher surface fields than can metals and, consequently, reliable acceleration gradients that are significantly higher than in conventional structures. For a traveling-wave structure with parameters as in Table 1, a accelerating field on axis of 340 MeV/m could evidently be sustained if cavity tests described here prove successful at input power levels up to 10 MW. Cold test measurements identified the LSM_{215} mode in a cavity with alumina slabs in place of diamond. Further work is planned on means to reduce electric fields on cavity end walls, means for mounting diamond slabs without electric field breakdown and metal fatigue from surface current heating, and designs for slots for pump-out and mode suppression that introduce minimal field distributions of the mode's field pattern.

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