Omega-P, Inc.
Final Report on DoE 2006 Phase II grant DE-FG02-05ER84368
Topic 37a: Radio Frequency Acceleration Structures
DIELECTRIC-LINED HIGH-GRADIENT ACCELERATOR STRUCTURE

Omega-P, Inc.
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**DIELECTRIC-LINED HIGH-GRADIENT
ACCELERATOR STRUCTURE**

Final Report on Phase II DoE SBIR grant DE-FG02ER84368
Topic 37a: High Energy Physics Accelerator Technology
Radio Frequency Acceleration Structures

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Material in this Report was developed by Omega-P senior scientist Dr. Vyacheslav P. Yakovlev (now at FNAL), former Omega-P employee Dr. C-B. Wang, Omega-P Senior Consultant Professor Thomas C. Marshall; and Dr. Michael A. LaPointe and Dr. Yong Jiang, both working under a sub-grant from Omega-P to Yale University. Dr. Hirshfield, in his role as Principal Investigator, coordinated activities of the participants and edited the Report.

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I. EXECUTIVE SUMMARY

Rectangular particle accelerator structures with internal planar dielectric elements have been studied, with a view towards devising structures with lower surface fields for a given accelerating field, as compared with structures without dielectrics. Success with this concept is expected to allow operation at higher accelerating gradients than otherwise on account of reduced breakdown probabilities.

The project involves studies of RF breakdown on amorphous dielectrics in test cavities that could enable high-gradient structures to be built for a future multi-TeV collider. The aim is to determine what the limits are for RF fields at the surfaces of selected dielectrics, and the resulting acceleration gradient that could be achieved in a working structure. The dielectric of principal interest in this study is artificial CVD diamond, on account of its advertised high breakdown field (~ 2 GV/m for dc), low loss tangent, and high thermal conductivity.

Experimental studies at mm-wavelengths on materials and structures for achieving high acceleration gradient were based on the availability of the 34.3 GHz third-harmonic magnicon amplifier developed by Omega-P, and installed at the Yale University Beam Physics Laboratory. Peak power from the magnicon was measured to be about 20 MW in 0.5 μ s pulses, with a gain of 54 dB. Experiments for studying RF high-field effects on CVD diamond samples failed to show any evidence after more than 10^5 RF pulses of RF breakdown up to a tangential surface field strength of 153 MV/m; studies at higher fields were not possible due to a degradation in magnicon performance. A rebuild of the tube is underway at this writing.

Computed performance for a dielectric-loaded rectangular accelerator structure (DLA) shows highly competitive properties, as compared with an existing all-metal structure. For example, comparisons were made of a DLA structure having two planar CVD diamond elements with a all-metal CERN structure HDS operating at 30 GHz. It was shown that the ratio of maximum surface electric field to accelerating field at the metal wall is only 0.35-0.4 for DLA, much smaller than the value 2.2 for HDS; and the ratio of surface magnetic field to accelerating field is 3.0 mA/V for DLA, compared with 3.45 mA/V for HDS. These values bode well for DLA in helping to avoid breakdown and to reducing pulsed surface heating and fatigue. The shunt impedance is found to be 160-175 M Ω /m for DLA, as compared to 99 M Ω /m for HDS.

Conclusions are reached from this project that CVD diamond appears promising as a dielectric with a high threshold for RF breakdown, and that rectangular accelerator structures can be devised using planar CVD diamond elements that could be operated at higher acceleration gradients with low probability of RF breakdown, as compared with corresponding all-metallic structures.

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II. IDENTIFICATION AND SIGNIFICANCE OF THE PROBLEM OR OPPORTUNITY, AND TECHNICAL APPROACH

IIa. Introduction

The DoE 2004 SBIR Phase I Program Solicitation requested grant applications under Topic 37a on *Radio Frequency Acceleration Structures*, wherein proposals were sought for RF structures with acceleration gradients >100 MeV/m for electrons. Omega-P, Inc. in response submitted Phase I and, subsequently, Phase II proposals entitled “Dielectric-Lined High-Gradient Accelerator Structure,” and was awarded Grant DE-FG02-05-ER-84368 for both phases, including a no-cost extension to Phase II. The present document is the Final Report on the Phase II portion of the project.

Accelerating structures for superconducting linacs for the proposed International Linear Collider ILC are to have an accelerating gradients of about 32 MV/m, and a maximum energy reach of 500 GeV [1]. Yet, interest persists in a technology to allow the much higher accelerating gradient needed to allow practical design of a multi-TeV collider. The most active idea under study to achieve higher accelerating gradient is the CERN two-beam room-temperature concept CLIC (Compact Linear Collider) [2]. In CLIC, an acceleration gradient of 150 MV/m had been sought, by using a much higher frequency (30 GHz), a structure geometry with moderate surface fields, and alternative structure materials such as molybdenum [3,4]. Since, the operating frequency and gradient goal have been reduced to 12 GHz and 100 MV/m. In the meantime, Omega-P proposed an alternative rectangular dielectric-lined uniform slow-wave accelerating structure [5] that uses low-loss, high-breakdown-field amorphous dielectric to support strong electric fields, yet in which transverse evanescent gaps would force down field magnitudes at the conducting walls, and thus reduce surface losses and surface fatigue.

The present project is for basic studies of RF breakdown on amorphous dielectrics in test cavities that could enable high-gradient structures to be built for a future multi-TeV collider. The aim is to determine what the limits are for RF fields at the surfaces of selected dielectrics, and the resulting acceleration gradient that could be achieved in a working structure. The dielectric of principal interest in this study is artificial CVD diamond, on account of its advertised high breakdown field (~ 2 GV/m for dc), low loss tangent, and high thermal conductivity. But other dielectrics with promising parameters could be studied as well.

Omega-P’s ability to carry out high-field studies on materials and structures for achieving high acceleration gradient is based on the availability of the 34.3 GHz third-harmonic magnicon amplifier [6] developed by Omega-P, and now installed at the Yale University Beam Physics Laboratory. This magnicon had a design power of over 40 MW in 1 μ sec pulses, and was used to drive test structures containing dielectric elements. An early photograph of the magnicon is shown in Fig. 1. RF conditioning allowed the magnicon to be reported as having achieved an output power of about 20 MW in 0.5 μ s pulses, with a gain of 54 dB. Fig. 2 shows a sample output waveform. Slotted line measurements confirmed that the output is monochromatic to within a margin of at least 30 dB. The Yale Ka-band test facility has been available to users, including Omega-P, under DoE-sponsored auspices within the US Collaboration on High-Gradient Accelerator R&D, beginning in the latter half of 2006.

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Figure 1. A general view of the 34.3 GHz magnicon.

Figure 2. Sample RF output waveform from the 34-GHz magnicon (blue) and magnicon beam current (red). Noise on RF trace is mostly instrumental.

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IIb. Technical Approach

In our prior publication, properties of a five-zone rectangular dielectric-lined waveguide structure [5] were elucidated, showing that the structure has great promise for sustaining high acceleration gradients. A representative version of this structure is shown in Fig. 3, in a cavity configuration. On the next page, a configuration to operate in the traveling-wave (TW) mode is described. Fig. 3a shows the cutaway view of a cavity with two planar dielectric slabs (CVD diamond) between which electrons or positrons would be accelerated along z . Beyond the dielectric slabs, vacuum zones are provided wherein RF fields of the cavity's operating mode decay, thus reducing Ohmic wall losses and providing access for side-wall couplers. Fig. 3b is

(a)

(b)

Figure 3. (a) Dielectric-lined test cavity layout; (b) E -field contours for LSM₂₁₆ design mode.

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a color contour plot of the distribution of RF electric field strength in the cavity, operating in the LSM₂₁₆ design mode. Earlier, an example of this structure operating in the traveling-wave (TW) mode (labeled “DLA”) was analyzed by us, and its properties were compared with those of the HDS structure then under development at 30 GHz at CERN [7]. Table I summarizes some of these comparative properties, for the 34.27 GHz DLA, parameters given in Table II.

Table I. Characteristics of DLA and the CLIC structure HDS, in traveling-wave modes.

	DLA (34.27 GHz)	DLA (30.0 GHz)	HDS (30.0 GHz)
shunt impedance R (M Ω /m)	175	160	99
$E_{\text{diel-surf}}/E_{\text{accl}}$	2.5	2.4	-
$E_{\text{metal-surf}}/E_{\text{accl}}$	0.4	0.35	2.2
$H_{\text{metal-surf}}/E_{\text{accl}}$ (mA/V)	3.0	3.4	3.45

Table II. Parameters for a 5-zone diamond-lined (DLA) Ka-band accelerator structure.

waveguide height $2d$	12.0 mm
waveguide width $2b$	29.6 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 $\tan\delta$	4×10^{-5}

Since HDS was designed for 30 GHz, rather than 34.27 GHz, values for DLA are shown in Table I for 30 GHz as well. It is seen that the ratio of maximum surface field to accelerating field at the metal wall $E_{\text{metal-surf}}/E_{\text{accl}}$ is only 0.35-0.4 for DLA, much smaller than the value 2.2 for HDS, and the ratio $H_{\text{metal-surf}}/E_{\text{accl}}$ is 3.0 mA/V for diamond structure, compared with 3.45 mA/V for HDS. These values bode well for DLA in helping to avoid breakdown and to reducing surface heating and fatigue. It is important to note, however, that the DLA structure is not free of electric-field enhancement, since $E_{\text{diel-surf}}/E_{\text{accl}} = 2.4$ -2.5. But this occurs in DLA at the dielectric surface where higher electric fields may be better tolerated, and not at the metal surface as in HDS. The shunt impedance R is found to be 160-175 M Ω /m for DLA, as compared to 99 M Ω /m for HDS. For DLA in the TW mode with parameters as in Table II, the maximum electric field at the surface and within the diamond would reach 500 MV/m, well below the cited breakdown field of 2 GV/m [8], at a drive power level of 230 MW/m. It can be noted, however, that available data on diamond breakdown do not distinguish unambiguously between fields on the surface and fields within the volume; experiments at high fields in accelerator-relevant geometries as proposed here are needed to determine actual limits.

In view of the desire for high accelerating fields in a very low-loss DLA structure, it should be natural to eventually operate working accelerator modules in the TW mode, exciting the structure with two power inputs [9] separated by a distance $L = (n + 1/4)\lambda$, where n is an integer and λ is the free space wavelength. The RF phases in the two inputs must differ by 90°.

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This method of coupling allows one to avoid a hybrid coupler, which would be challenging to build for high power at Ka-band. A schematic of this TW arrangement is shown in Fig. 4. An oversized or quasi-optical feedback waveguide is used to circulate the stored RF energy, as in a resonant ring. High-power mode launchers would be used to excite the operating mode in the structure. The dielectric slabs have tapers on the ends in order to reduce the fields on the structure end metallic walls. The structure has two non-radiating longitudinal slots for pumping and for transverse wake field suppression. Future realization of this attractive concept for a working high-gradient accelerator requires confirmation of the electrodynamic properties of this class of multi-zone waveguides in a practical structure, and determination of limits to the RF field strengths that can reliably be sustained, especially at and within the dielectric slabs. Those requirements constitute the main long-term goals of the project reported here.

Figure 4. (a) Schematic for a future TW DLA accelerator module; (b) structure cross section.

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**III. DEGREE TO WHICH PHASE II HAS
DEMONSTRATED TECHNICAL FEASIBILITY**

IIIa. Technical Objectives

The overall goals for this project were to design, build, test, and evaluate a version of the rectangular dielectric-lined accelerator (DLA) structure, to operate at Ka-band. This structure is designed so that the highest strength RF fields occur at the dielectric, CVD diamond in this case, rather than at the surrounding metal walls. In this way, it is intended to learn if CVD diamond can sustain higher surface fields than can metals and, as a consequence, whether structures loaded with CVD diamond can sustain reliable acceleration gradients that are higher than those that can be sustained in conventional metallic structure. During Phase I, a design was optimized for a cavity test structure with a length of ~2.62 cm, to be powered by the then-available pulsed 34.27-GHz magnicon. Measurements of dielectric constant and loss tangent were made on CVD artificial diamond samples obtained from Gycom Ltd., which will likely supply the requisite diamond slabs during future tests. A cold-test model of the structure was built, using alumina in place of diamond, to confirm calculations of the eigenmode spectrum of the cavity. Furthermore, a dedicated test cell was built and operated to determine high-power RF breakdown limits on CVD diamond using 34.3 GHz power from the Yale/Omega-P magnicon; these results failed to observe any breakdowns at tangential field strengths up to 153 MV/m. Fields higher than this could not be applied due to deterioration in magnicon performance that arose during the breakdown tests. At this writing, the magnicon is undergoing rebuilding so as to restore and improve upon its initial performance, thereafter to resume the breakdown and accelerator structure tests.

IIIb. Project Results

Major issues that were addressed during the project included the following:

1. A design optimization procedure was developed, in which all parameters of five-zone rectangular dielectric-lined cavity structures were collectively varied, so as to maximize each of the following quantities: normalized characterized shunt impedance R/Q , structure quality factor Q , shunt impedance R , power absorption length A , and acceleration gradient E_{z0} .
2. Measurements of dielectric constant and loss tangent as a function of frequency have been made on diamond samples prepared by Institute of Applied Physics (RAS).
3. Design procedures were worked out, using rf field simulations, for the input couplers, adjusted for a good match to the WR-28 feed waveguides, with waveguide wall protrusions (stubs) as needed to symmetrize the fields and minimize reflections.
4. Candidate designs that optimize structure parameters have been optimized for five-zone rectangular dielectric accelerator structures, integrated with input couplers. From two types of these designs, one will be selected for testing during Phase II.
5. A preliminary engineering design has been made of a high-vacuum, high-power test cell for the rectangular diamond-lined accelerator structure to be tested during Phase II. Design is being coordinated with the supplier of the diamond slabs.

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6. Aforementioned test cell was built and tested, and initial RF breakdown tests were conducted.
7. A comprehensive theory for operation of 3- and 5-zone dielectric-lined rectangular waveguide structures was carried out, and examples developed that are relevant for design of a high-gradient accelerator structures.

IIIb.1. Design optimization for five-zone rectangular structures

Design optimization began by analyzing theoretically the cavity structure without a coupler; this amounts to analysis of eigenmodes of the idealized cavity. This approach also helps to identify potential competing modes near the design mode, although some spurious modes can be excited when the coupler and wall slots are introduced. In the Phase I proposal, a six-wavelength (52.5 mm) cavity mode was discussed. However, to reduce cost during Phase II, but still to arrive at the same goal, the cavity was re-optimized with a length of three wavelengths (26.2 mm) and a newly-measured diamond loss tangent of 3×10^{-5} . (See Sub-Section IIIb.2.) The full theoretical analysis behind results shown here is given in Sub-Section IIIb.7.

Figure 5. Shunt impedance and acceleration gradient (for 10 MW input power) for the LSM₂₁₆ mode at a frequency of 34.272 GHz in a five-zone diamond-lined cavity structure.

Figure 5 shows the computed shunt impedance and acceleration gradient for the LSM₂₁₆ design mode as a function of the half-width of the central acceleration zone a_1 , with the phase velocity fixed at the speed of light c . Parameters are $\mu_{r1} = \mu_{r2} = 1$, $\epsilon_{r1} = 1$, $\epsilon_{r2} = 5.7$, $d = 4a_1$, wall conductivity $\sigma = 5.56 \times 10^7 \Omega\text{-m}$, and $\tan\delta = 3 \times 10^{-5}$. The vacuum gap width $b - a_2$ is fixed at 12 mm, for RF field decay sufficient at the conducting walls to consequently reduce wall loss.

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Table III lists these parameters for the optimized case with $a_1 = 1.5$ mm. As is seen, this analysis predicts an acceleration gradient of 170 MeV/m for 10 MW of input power.

TABLE III. Parameters for a five-zone diamond-lined cavity structure.

operating frequency for LSM ₂₁₆ mode	34.272 GHz
phase velocity v_{phase}	c
cavity height $2d$	12.0 mm
cavity width $2b$	29.6 mm
cavity length L	2.62 cm
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 M Ω
input RF power	10 MW
peak RF electric field on axis	340 MV/m
acceleration gradient	170 MeV/m

The field strength profiles throughout the cavity in this example are shown in Figs. 6 and 7. Figure 6 gives profiles of RF electric fields as functions of transverse coordinate x at the designated (y,z) coordinates, while Fig. 7 gives profiles for the RF magnetic fields.

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Figure 6. RF electric field profiles for the cavity structure with parameters given in Table III. The input power is 10 MW. $E_{\text{surf}} = E_{y\text{-max}} = 133$ MV/m, $E_{\text{diel}} = E_{x\text{-max}} = 848$ MV/m; E_z on the axis is 340 MV/m, while the acceleration gradient is 170 MV/m.

Figure 7. RF magnetic field profiles for the cavity structure with parameters given in Table III. $H_{\text{surf}} = H_{y\text{-max}} = 2783$ kA/m and $H_{z\text{-max}} = 1014$ kA/m.

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Figure 8 is a color-contour plot showing the axial electric field profile in the x - y plane on the end conducting wall. A relatively uniform zone in the center of the acceleration zone is seen.

Figure 8. RF electric field contours for the LSM₂₁₆ design mode in an idealized cavity.

Figure 9 shows eigenfrequencies for some of the cavity modes; LSM modes are shown in red; LSE modes in blue.

Figure 9. Mode spectrum for the ideal cavity with parameters as given in Table III, for mode indices $1 \leq n_x \leq 5$, $0 \leq n_y \leq 3$, and $n_z \leq 12$) This idealized spectrum can be expected to be modified when input couplers are included, both in the frequency pulling of these modes, and with the introduction of spurious modes.

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The means of excitation can help to de-select some of the modes, and wall slots should serve to suppress others. LSM_{515} mode is a fast-wave mode, but it has a different symmetry in the z -direction from the design mode. LSM_{117} mode is a slow wave and decays faster in the vacuum gaps than the design mode and thus would be weakly coupled using a coupler on the outside walls. Both competing modes have odd symmetry in x , and would be further suppressed by a central wall slot running along z . But couplers and wall slots will distort this spectrum, and could allow introduction of other spurious (or “ghost”) modes.

For a TW structure based on use of the same LSM_{21} design mode, similar analytic solutions can be found. A selected parameter set from this analysis is shown in Table V.

Table V. Parameters for a five-zone diamond-lined traveling-wave (TW) structure.

operating frequency in the LSM_{21} design mode	34.272 GHz
phase velocity v_{phase}	c
waveguide height $2d$	12.0 mm
waveguide width $2b$	29.6 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	130,000
dielectric quality factor Q_d	140,000
overall quality factor Q	68,000
characteristic shunt impedance R/Q	4.10 k Ω /m
shunt impedance R	278.5 M Ω /m
flowing rf power	6,100 MW
energy velocity	0.62 c
dissipated power	104 MW/m
power attenuation length $\Lambda = Qv_{\text{group}}/\omega$	58.6 m
acceleration gradient	170.3 MeV/m

From Table I, one sees that the ratio of field at the diamond surface to the accelerating field is 2.4:1. (At the side-wall conducting surface the ratio is only 0.35:1.) Thus, once it is proven that the CVD diamond slabs can sustain a surface electric field of $2.4 \times 170.3 = 409$ MV/m without an undue frequency of breakdown events, then it should be possible to build a test accelerator module with a length of 10-20 cm to demonstrate energy gains in the range of 17-34 MeV, using 10-20 MW of RF power from the Yale/Omega-P magnicon. Once the rebuild of the magnicon is completed, tests at this power level should be possible.

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IIIb.2. Measurements on diamond samples.

Preparation of CVD-diamond disk. The synthesis of quality diamond disk was performed in a microwave plasma-assisted CVD reactor invented by Fraunhofer Institute for Applied Solid State Physics (IAF) [10] and manufactured by AIXTRON company (Germany). The base of the AIXTRON reactor is an ellipsoidal cavity excited with a flagpole antenna situated near one of the focuses of the ellipsoid. The discharge is ignited near the surface of the substrate in the vicinity of the other focus. The resonator is fed by a magnetron operating at the frequency of 2.45 GHz and maximum power 6 kW. Design of the reactor provides the possibility to deposit diamond films in the three-component mixture, $H_2+CH_4+O_2$, on substrates up to 75 mm in diameter. The substrate holder is rotating, which improves homogeneity of the deposited diamond film. Diamond disk was deposited on polished silicon substrate 75 mm in diameter. The standard growth conditions (temperatures between 700 and 900C and pressures ranging from 150 to 200 mbar) were used. After growth process to get a free-standing diamond disk, the Si substrate is removed by etching in acid. Figure 10a shows the unpolished CVD diamond disk with thickness 1.6 mm in central part of the disk. Then the polycrystalline CVD diamond disk was polished using a mechanical lapping method. As a result diamond parallel plate of 1.35 mm thickness was obtained. The mean surface roughness (Ra) was 150 nm on both sides of polished disk. The general view of polished CVD diamond disk with thickness 1.35 mm is shown in Fig. 10b.

Fig. 10a. Unpolished diamond disk, with diameter 75 mm, and thickness 1.6 mm.

Fig. 10b. Polished diamond disk, with diameter 75 mm, and thickness 1.35 mm.

Measurements of the dielectric losses in the 36-330 GHz frequency range. Measurements of the dielectric losses in the obtained disk, which are characterized by $\tan\delta$ (ratio of the imaginary to real part of the dielectric permittivity) have been accomplished using the method described below [11,12]. The dielectric properties of the disk were determined on a specialized setup based on a quasi-optical Fabry-Perot resonator (see Fig. 11) designed to characterize materials with low dielectric losses. The resonator was fed with radiation from a backward-wave oscillator (BWO). To control the BWO frequency, two synthesizers were used: a microwave (MW) synthesizer that determined the central frequency of the BWO radiation and a fast radio-frequency (RF) synthesizer for fast precise scanning of the BWO frequency near the central frequency set by the MW synthesizer. The RF synthesizer operation was controlled by a specialized microprocessor. To determine the coefficient of microwave

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absorption for the sample positioned in the resonator, the width of the resonance curve was measured, from which the Q -factor of the loaded and unloaded resonator was obtained.

Figure 11. Resonator spectrometer for measurements of millimeter wave absorption in the frequency range 36-330 GHz [12].

Interpretation of measurements and results. The measurements were carried out at the resonance frequency of the disk, when its optical thickness is divisible by half-wavelength of the electromagnetic radiation. The disk was positioned in the resonator center, perpendicular to its axis. Two principally different cases of disk positioning relative to the standing wave in the resonator are possible, as shown in Fig. 12. In the first case, both surfaces of the disk are in the field maxima of the standing wave. In the second case, the surfaces coincide with the zeroes of the field. The Q -factor is measured at the same frequency for an unloaded (empty) resonator (Q_0) and for two positions of the disk in the resonator (Q_1 and Q_2). The values Q_0 , Q_1 and Q_2 depend on the coefficient of own ohmic losses of the resonator, δ_{ohm} , the loss tangent in the bulk of the diamond disk, $tg\delta_{pl}$, the loss tangent in the near-surface region of the diamond disk, $tg\delta_{fil}$, resonator length, L , disk thickness, L_{pl} , thickness of the near-surface region of the disk, L_{fil} . Also these expressions contain the refraction index of diamond, n , and the wavenumber of the electromagnetic wave, $k = \omega/c$:

$$Q_0 = k \frac{L + n \cdot L_{pl}}{\delta_{ohm}}; \quad Q_1 = k \frac{L + n^2(L_{pl} + L_{fil})}{\delta_{ohm} + n^2 k L_{pl} tg\delta_{pl} + 4n^2 k L_{fil} tg\delta_{fil}}; \quad Q_2 = k \frac{L + L_{pl}}{\delta_{ohm} + k L_{pl} tg\delta_{pl}}.$$

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Using the measured values Q_0 , Q_1 and Q_2 , the losses in the bulk of the diamond disk and the absorption in the thin near-surface region are calculated.

Figure 12. The distribution of electric field in the resonator for two cases of disk positioning: a) disk surfaces coincide with the field maxima of the standing wave in the resonator, b) disk surfaces coincide with the field zeroes of the standing wave.

This method of dielectric loss measurements was used for test of CVD diamond disk grown at the Institute of Applied Physics. The measured values of dielectric losses in the bulk of the 1.35 mm thick diamond disk at different frequencies from 36 GHz to 330 GHz are shown in Fig.13. Loss tangent at a frequency of 36 GHz equals to 3×10^{-5} . It can be seen that the disk grown at the IAP in the CVD reactor operating at a frequency of 2.45 GHz has the loss tangents comparable to those of the best De Beers' disks in frequency range 110-170 GHz.

Figure 13. Measured loss tangent of the polished diamond disk as a function of frequency.

It is known [4] that for CVD diamond disks the loss tangent frequency dependence (at room temperature) is as $\sim 1/f$ at frequencies less than 100 GHz. From our measurements an empirical approximation $\tan \delta \sim 1/f$ for the low end of the band (36-50 GHz) was confirmed. For the frequency band below 50 GHz the observed loss frequency dependence in the tested sample can be well described by simple approximation $\tan \delta = (a/f) \times 10^{-5}$, where $a = 109$ and f is in GHz. Using this extrapolation leads to a loss tangent at 34.3 GHz of 3.15×10^{-5} .

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IIIb.3. Design for input couplers

A 3D numerical model of the input coupler for the diamond-lined cavity is shown in Fig. 14. The model does not include the slits for the cavity pump out and to help to suppress deflecting modes in the TW structure, and tapers necessary to avoid high RF fields on the metal ends of the cavity. The model is based on cavity dimensions taken from analytical calculations described under Task 2, but with an input coupler and compensation protrusion added. Because the unloaded quality factor is high, the coupling should be small, thereby not much perturbing the field distribution. The computed amplitude reflection coefficient for the input coupler (in dB) is shown in Fig.15, and the simulated field patterns are shown in Fig. 16.

Figure 14. The model of the coupler for diamond test cavity, showing one half only.

Figure 15. Amplitude reflection coefficient S_{11} (in dB).

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Figure 16. Field pattern of the operating mode in each of the symmetry planes.

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IIIb.4. Design for test accelerator structure

The test structure is an LSM₂₁₆ cavity with two CVD diamond slabs, as depicted in Fig. 3, except that the input coupler could be in the configuration shown in Fig. 14, with the nearly-ideal coupling as in Fig. 15. The structure will be fabricated out of eight sections, to allow insertion of the diamond slabs and to provide for slots along symmetry planes to suppress competing (transverse) modes. Figure 17 shows views of parts of this test cavity, one-eighth in Fig. 17a; and one-quarter in two views in Fig. 17b.

Fig. 17a. Phase I test cavity, 1/8-th section.

Fig. 17b. Phase I test cavity, 1/4 sections.

To confirm the validity of the design procedures for this test cavity, a cold-test model was built that used alumina slabs in place of diamond, on account of the ready availability of alumina. A similar exercise will take place using the actual diamond slabs that will be incorporated into the high-power, high-vacuum test cell. However, the alumina slabs with dimensions $1 \times 13 \times 24 \text{ mm}^3$ that were procured during the Phase I cold-tests were not quite long enough to fit into a LSM₂₁₆ mode cavity; as a consequence the cold-test cell was built to operate in the LSM₂₁₅ mode. The cavity dimensions were taken to be $29 \times 12 \times 21.9 \text{ mm}^3$, with slot thicknesses of 0.5 mm. For this structure, 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} . The field pattern (in one-eighth of the structure) is shown in Fig. 19.

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Figure 18. Field pattern for LSM₂₁₅ operating mode (with five field variations along the z-axis. If the hole for antenna is placed on the cavity wall in the middle of the cavity at $y=0$ and $z=0$., the electric field here is about 3 times smaller than the maximal field in dielectric.

IIIb.5. Cold test measurements

The test cell for the alumina slabs was constructed of brass and held together with polycarbonate rods which also served as the alignment fixtures and had a 0.5mm disk machined in them in order to maintain the proper slot spacing. Pictures of the test cell are shown in Figure 19.

(a)

(b)

Figure 19. Photographs of the alumina test cell are shown. (a) The fully assembled test cell shown the mode suppression slots and one configuration of the RF input and sample ports. (b) The test cell is partially dismantled in order to see the alumina slabs as installed.

The system was driven from an HP 8350B swept frequency generator using an HP 83472A plugin. A frequency range of 32-36 GHz was observed to find the frequency response of the test cell. The RF was input into the cavity via a 2.4 mm coax to pin adapter with the pin

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inserted 1 mm into the cavity along the z-axis. A corresponding coax to pin adapter was used to monitor the cavity response and was placed in the sidewall of the cavity in the evanescent region. This orientation was chosen so as to only drive the symmetric modes and to minimize the perturbations of the sample port by placing it in a weak field region outside of the dielectric channel. The sample port was connected to an HP 8757D scalar spectrum analyzer which was used to measure the frequency and amplitude of the modes of interest. Once a mode was identified a more accurate frequency measurement was performed using an EIP 548B frequency counter.

Bead pull experiments were performed to identify the LSM₂₁₅ mode. Several modes were tested and the one near 32.7 GHz exhibited the required spatial responses as indicated in Figure 20. The five half-wavelength variation along the z-axis is clearly seen in Figure 20(a) and the half wavelength variation along y is also clear. A qualitative measurement moving the bead along x from the outside wall toward the alumina slab showed a monotonic change in the frequency and amplitude, which, together with the other results, demonstrate that this mode is indeed LSM₂₁₅. Imperfections from ideal sinusoidal variation in Fig. 20a is due to line sag.

Figure 20. Bead pull measurement results for the mode near 32.7 GHz shows the n15 nature of the mode. (a) shows the five variations in the frequency and amplitude of the mode as the bead is pulled along the z-axis. (b) show the single variation as the bead is pulled vertically (y-direction) near the center of the structure.

As was not wholly unexpected, the measured mode frequency of 32.7 GHz is different from the calculated frequency of 35.1 GHz because of known tight dimensional tolerances; this observation emphasizes need for careful design and (probably) iterative cold testing to evolve the final design. Still, this exercise shows the means as well as the challenges that need to be confronted when designing and building the actual test cavity for confirming the high-gradient potential for this class of dielectric-loaded structures.

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IIIb.6. Test cavity for CVD diamond breakdown investigations

Prior to building the accelerator test cavity described in Sub-Sections IIIb.3 and IIIb.4, it was decided to perform direct breakdown tests on CVD diamond; this was to provide confidence that surface field strengths anticipated in the accelerator structure could be sustained by the CVD diamond itself, since the highest fields in the accelerator structure are localized at the dielectric surfaces. But in order to avoid magnetic field enhancement on the metallic walls of the cavity, that would lead to premature surface fatigue due to pulsed heating, the sharp edges of the cavity needed to be rounded. However, simple rounding itself is not sufficient for achieving surface magnetic fields low enough to be acceptable for high-gradient experiments. It is necessary that the cavity lifetime, before surface fatigue begins to cause the unloaded Q -factor to drop, be sufficient for experiments with at least four different diamond samples. Two samples are to be hydrogenated, and two de-hydrogenated. It is desirable that each experiment allow for a minimum of 10^4 RF pulses at the highest achievable RF fields in the diamond, in order to obtain meaningful statistics for observed breakdown events.

A tentative experimental scenario with each sample would include runs of up to 10^4 RF pulses at each level of incident RF power, recording the breakdown rate at each power level. The experiment would be repeated at each RF power level up to the maximum that can be sustained before the breakdown rate exceeds some predetermined rate, say, $1:10^2$. Should a low breakdown rate be found for one sample, it would be advantageous to run for an even greater number of shots. The acceptable level of breakdown rate for an HG accelerating structure is about $1:10^6$, but this high number may not be possible before surface fatigue destroys the cavity (see below).

The outline drawing for the conceptual design of a cavity with reduced surface magnetic field that appears suitable for high-gradient tests is shown in Figure 21.

Figure 21. Conceptual design for a breakdown test cavity with reduced surface magnetic field.
Dimensions are in mm.

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The electric field map for this design is shown in Figure 22, and the magnetic field map in Figure 23. The input power is 2.9 MW for this example. One can see that the maximum electric field in the CVD disc is 500 MV/m, at which point the maximum surface magnetic field on the cavity wall is 0.77 MA/m (0.98 T). The surface magnetic field distribution along the conical part of the cavity near the field maximum is shown in Fig. 24.

Figure 22. Electric field map. The input power is 2.9 MW.

Figure 23. Magnetic field map. The input power is 2.9 MW.

Figure 24. Surface magnetic field along the conical side of cavity, between points **A** and **B**, including the field maximum. The input power is 2.9 MW.

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Computed input power reflection vs frequency is shown in Figure 25. Note that the cavity unloaded Q is 11,600, so that its filling time would be about 100 ns.

Figure 25. Reflection vs. frequency for the breakdown test cavity.

For a pulse width of 0.5 μ sec the temperature rise on the copper wall with 2.9 MW input power would be 500 $^{\circ}$ C, taking into account nonlinear effects [1]. For this temperature rise, the cavity should sustain about 2.5×10^5 pulses before surface fatigue causes irreversible damage [2]. That should be just sufficient for the series of breakdown experiments along lines of the scenario sketched above. A photograph of the breakdown test cavity is shown in Fig. 26.

Figure 26. Photograph of completed breakdown test cavity. RF feed from the magnicon is at right, and transmitted power is sampled using horn at left.

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IIIb.7. Results of CVD diamond RF breakdown experiment

As stated above, chemical vapor deposition (CVD) diamond is a dielectric of great promise for accelerator applications, on account of its advertised high breakdown field (~ 2 GV/m for DC), low loss tangent ($\tan\delta \sim 3.15 \times 10^{-5}$ at 34.3 GHz), and high thermal conductivity. Efforts were thus made in this project to determine the RF breakdown limits at 34.3 GHz, where it is planned to build the accelerator test cavity described above. Other dielectrics with promising parameters could be studied with similar experimental setup as well.

The synthesis of a high-quality diamond disk was performed in a microwave plasma-assisted CVD reactor, at Omega-P's vendor Microwave Discharge Physics Laboratory, Institute of Applied Physics, Russia. In this manner, a poly-crystalline diamond plate was produced and then polished to the required thickness of 0.715 mm. Four identical diamond disks, 16 mm in diameter, were laser cut out from it, as shown in Figure 27.

Figure 27. Four identical diamond disks were cut from a white clear diamond plate grown by CVD technology.

It is known that secondary electron emission (SEE) yield could have strong influence on the RF breakdown and multi-pactor limits for diamond [14]; evidence for the influence upon SEE of surface treatment is shown in Figure 28. Means to lower the SEE coefficient of the diamond sample are: (a) coat the diamond with a thin (few Å) layer of TiN to reduce the secondary yield, which is only good for planar dielectric geometry; or (b) remove the hydrogen by exposure of the finished diamond sample in chemical oxidation or air heating, which is more practical. This latter approach is followed in work described here.

Hence the experimental samples were subjected to the following treatment procedures: (a) Disk 1 hydrogenated: Without additional treatment, which has hydrogenated surface, as a result of the CVD process itself; (b) Disk 2~4 dehydrogenated: Disk 2, immersed in mixture $\text{CrO}_3 + \text{H}_2\text{SO}_4$, temperature T about $160\sim 165^\circ\text{C}$ for 10 min; Disk 3, mixture $\text{CrO}_3 + \text{H}_2\text{SO}_4$, $T\sim 100\sim 105^\circ\text{C}$ for 10 min; Disk 4, exposed in warm air $T\sim 600^\circ\text{C}$ for 10 min. Examination on whether these surface-treatment configurations show different RF breakdown probabilities at high RF fields could provide a guideline for proper surface treatment and the future choice of other cheaper and more available dielectric materials in accelerator applications.

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Figure 28. Selectron emission coefficient versus primary electron energy for diamond with and without de-hydrogenation [1].

The test structure for CVD diamond RF breakdown experiments is designed so that the highest strength of RF fields occurs at CVD diamond rather than at the surrounding metal walls, and a minimum of 10^4 RF pulses at the highest achievable RF fields in the diamond, are needed in order to obtain meaningful statistics for observed breakdown events. A biconical TE_{011} -like cavity, designed by V.P. Yakovlev and S.Yu. Kazakov and described in the prior Sub-Section, captures the 16-mm diamond disk at its center. A photograph of the test structure is shown in Figure 29a, and a drawing in Figure 29b. The conical features in this cavity are to allow high RF electric fields at the diamond surfaces without corresponding high RF magnetic fields at the cavity walls to avoid pulsed heating leading to surface degradation and diminution of cavity Q . The cavity spectrum is sparse, as there are no parasitic modes within a ± 500 MHz range around the 34.254 GHz of TE_{021} mode.

Cold test using spectrum analyzer to determine the cavity parameters with diamond disk installed shows that the loaded quality-factor $Q_L = 4.7 \times 10^3$, the Ohmic quality-factor $Q_0 = 9.86 \times 10^3$, and coupling parameter $\beta = 1.1$ at the magnicon operating frequency of 34.272 GHz [3]. Different diamond disks yield the same quality-factors. Calculations show that a surface field of 511 MV/m would be imposed on the CVD diamond when 5.0 MW of power is fed into the cavity.

The experimental setup with the breakdown test cavity install in the magnicon test bay at the Yale Beam Physics Lab is shown in Figure 30. External static magnetic fields can be applied tangentially or normal to the diamond surface to check the influence of magnetic field on the multipactor phenomena; one coil for providing magnetic fields is shown in the figure. RF transmission and reflection are used to tune the RF breakdown cavity into resonance with the magnicon output; mechanical tuning can be accomplished while experiments are running, using a remotely controlled stepper motor drive mechanism. RF breakdown event diagnostics include observation of transmission of RF through the cavity, and observations of visible light when a breakdown discharge occurs on the diamond surface.

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(a)

(b)

Figure 29. Photograph (a) and drawing (b) of TE_{011} -mode biconical test cavity used for breakdown studies on CVD diamond. 1. $TE_{11} \rightarrow TE_{01}$ mode converter, 2. evacuation port, 3. taper transition, 4. cylindrical waveguide, 5. jump-wise narrowing of 6-mm waveguide, 6. test sample, 7. fixing bush, 8. adjustment piston, 9. adjustment device, 10. evacuation port, 11. vacuum window.

Figure 30. CVD diamond test cavity in magnicon test bay, including microwave horn and fiber optics for diagnostic, stepper motor for mechanic tuning, and coil for future multipactor study.

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To date, up to about 450 kW of power has been applied with the hydrogenated sample in place in the breakdown test cavity. This power level provides a surface field on the diamond of 153 MV/m. Typical envelopes of RF pulses transmitted through the diamond breakdown test cavity are shown in Figure 31, where a tangential field of >150 MV/m was applied on the CVD diamond sample. Traces in red and green are for powers incident and reflected from the test cell. There is no evidence here of breakdown. No incidence of breakdown was observed during operation with over 10^5 pulses. These experiments will continue, to improve statistics, with application of higher RF power, and with comparison of results to those with dehydrogenated samples. Unfortunately, degradation in magnicon performance prevented further experiments from being carried out. After rebuilding of the magnicon, it is expected that these experiments will be resumed.

Figure 31. Typical RF signal measured in diamond breakdown test cavity.

IIIb.8. Engineering design for Ka-band test chamber

A high-vacuum, easily demountable, test chamber was built during Phase II to facilitate tests on high-gradient Ka-band accelerator cavities and other components. Since these structures must be built to ultra-high-vacuum standards, and must be capable of withstanding high-temperature bake-out ($>450^{\circ}\text{C}$), the test chamber must allow for convenient access to the test cell for inspection, cleaning, and replacement of diamond slabs or other changes. Figures 32 and 33 show views of a test chamber that allows these requirements to be met. The chamber was also built for RF experiments at Ka-band wherein breakdown thresholds for alloys and alternative metals will be compared with copper, under nearly identical conditions. The test cell for the breakdown studies is labeled as item #1 in Figure 32 and as the densely crosshatched object towards the bottom of Figure 33. This test chamber removes the need for the test cavity itself to be vacuum tight.

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Figure 32. Top view of test chamber.

Figure 33. End view of test chamber.

The chamber has two WR-28 waveguide feeds, provision for circulating water for temperature-stabilization and thermal tuning of the cavity, and relatively simple means for removal of the surrounding vacuum enclosure—since almost all external feeds are mounted on the flange at the bottom in Figure 32. An external micrometer adjuster is seen in Figure 33 that can be used for

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mechanical tuning, as needed. Only minor modifications of this test chamber will be required to allow installation of the diamond-lined test cavity in place of the materials breakdown test cavity. A photograph of the test chamber is seen in Figure 34.

Figure 34. Photo of completed test chamber. Note hand-crank assembly that allows controlled opening for changing test structures with need to disconnect WR-28 waveguide feeds.

RF power from the 34-GHz magnicon is to be fed to the diamond test cavity at a power level of up to about 10 MW *via* the WR-28 waveguide shown in Figure 32. This power level is the limit for short pulse widths (~500 ns) that can be transported in WR-28 without breakdown. The actual pulse width required is determined by the fill-time of the cavity, as described by the following short analysis. The test cavity has a calculated unloaded quality factor $Q_o \approx 26,000$ for diamond with a loss tangent of 3×10^{-5} . Optimal coupling in the energy storage regime is determined by maximizing the filling efficiency. The efficiency η for energy transfer to the cavity is given by [13]

$$\eta = \frac{2\beta\tau_o}{t_f(1+\beta)^2} \left(1 - \exp \left(-\frac{t_f(1+\beta)}{\tau_o} \right) \right)^2,$$

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where β is the coupling coefficient, t_f is filling time (or pulse width) and $\tau_o = 2Q_o/\omega$ is the unloaded time constant for the cavity. For a filling time of 100 ns and unloaded quality factor of 25,000 the optimal coupling β is 3.4, which corresponds to a maximum efficiency of about 60%. The filling efficiency versus coupling coefficient is shown in Figure 35 for a filling time of 100 ns. The efficiency dependence vs. filling time for a coupling coefficient of 3.4 is shown in Figure 36. One can see that for $50 \text{ ns} < t_f < 140 \text{ ns}$, the efficiency is greater than 50%.

Figure 35. Cavity filling efficiency *versus* coupling coefficient for the filling time of 100 ns. The maximum efficiency is 58.9 % for a coupling coefficient of 3.4.

Figure 36. Filling efficiency for a coupling coefficient of 3.4 *versus* filling time.

The RF circuit arrangement for combining four outputs from the Yale/Omega-P 34-GHz magnicon, and for directing this power to the diamond test cell is shown in Figure 37. The figure shows the four output waveguides from the magnicon connected to a quasi-optical power combiner. When the full magnicon output is greater than what can be

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transported in WR-28 waveguide, it is a simple matter to lower the power by reducing the RF drive level to the magnicon and/or to adjust the width of the RF drive pulse.

Figure 37. RF circuit for transmitting power from the magnicon to the diamond test cell.

IIIb.9. Theory for fields in rectangular dielectric-lined accelerator structures

INTRODUCTION

Dielectric-loaded waveguides have long held appeal as accelerating structures either for supporting intense single- or multi-bunch wake field acceleration [15], or in an externally-powered accelerator [16,17]. As Gai and his coworkers indicated, the Dielectric-Loaded Accelerator (DLA) structure has its potential advantages [17]. One common objective in this area of research is to construct and test DLA structures to determine the ultimate acceleration gradient that can be achieved without incurring breakdown within the dielectric. Another common objective is to obtain high shunt impedance that is needed for high-efficient accelerators. The rf power loss in Joule heating from dielectric material and from conducting walls directly reduce the shunt impedance. Therefore, it is important to seek low loss dielectric materials with high breakdown voltage and to improve the DLA structures for reducing rf power

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loss. Diamond, for example, is probably a promising dielectric for high-gradient and high-efficiency DLA structures because of its high breakdown voltage up to 1 GV/m and low loss tangent down to 10^{-5} [20]. However, limited by the existing chemical vapor deposition (CVD) techniques, the diamond only can be made with good uniformity in a slab-like shape instead of a hollow shape [7,8], and thus the slab-like CVD diamond is more suitable for use in rectangular DLA structures than cylindrical ones.

In a rectangular dielectric-lined waveguide with three zones in cross section previously suggested for wake field acceleration [23-25], the dielectric slabs directly touch the conducting walls, which results in increase of induction current, thus leading to high Ohmic loss in the walls (Note that there is the same problem in the cylindrical structures [16,17]). Here, an alternate rectangular dielectric-lined waveguide with five zones is analyzed, where gaps are left between the dielectric slabs and conducting walls to reduce the induction current [28]. Calculations show that the power loss both in the conducting walls and dielectric slabs is reduced so that the shunt impedance is significantly improved. This Sub-Section is organized as follows. First, a three-zone version of the rectangular dielectric-loaded accelerator structure is analyzed, then the five-zone structure is followed, and finally some discussion is given.

THREE-ZONE ACCELERATION STRUCTURE

A diagram of the cross section of a symmetric three-zone version of the rectangular dielectric-loaded accelerator structure is shown in Fig. 1. Since the structure is symmetric about the y - z plane, the LSM modes ($H_x = 0$) and LSE ($E_x = 0$) modes can be divided into two types according to their axial electric field E_z : symmetric and anti-symmetric with respect to x , although this classification does not hold in an asymmetric (dielectric constant or dimension) structure.

Figure 38. Cross-section of symmetric three-zone dielectric loaded accelerator structure.

$\varepsilon_i = \varepsilon_0 \varepsilon_{ri}$ and $\mu_i = \mu_0 \mu_{ri}$ ($i = 1, 2$) are the permittivity and permeability of the dielectric.

It can be shown that the stored energy per unit length for LSM modes is given by

$$U_{LSM} = \frac{1}{4} \int_{-d}^d dy \int_{-b}^b (\varepsilon \mathbf{E} \cdot \mathbf{E}^* + \mu \mathbf{H} \cdot \mathbf{H}^*) dx = \frac{1}{2} \int_{-d}^d dy \int_{-b}^b \varepsilon \left(\frac{\omega^2 \varepsilon \mu}{k_y^2 + k_z^2} \right) E_x E_x^* dx, \quad (1)$$

and the rf power flow is given by

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$$P_{LSM} = \frac{1}{2} \iint (\mathbf{E} \times \mathbf{H}^*) \cdot \hat{\mathbf{z}} dx dy = \frac{1}{2} \frac{\omega k_z}{k_y^2 + k_z^2} \int_{-d}^d dy \int_{-b}^b \varepsilon E_x E_x^* dx, \quad (2)$$

where ω is the rf field angular frequency, k_z is the axial wave number, and $k_y = n\pi/2d$ ($n = 1, 2, 3, \dots$) is the wave number in the y-direction.

From Eqs. (1) and (2), we obtain the energy velocity β_{energy} normalized to the vacuum light speed $c = (\varepsilon_0 \mu_0)^{-1/2}$, given by $\beta_{\text{energy}} c = P_{LSM} / U_{LSM}$. Considering that the normalized phase velocity β_{phase} is defined by $\omega/k_z c$, the energy velocity can be expressed as

$$\beta_{\text{energy}} \beta_{\text{phase}} = \frac{\iint (\varepsilon_0 \mu_0) \varepsilon E_x E_x^* dx dy}{\iint (\varepsilon \mu) \varepsilon E_x E_x^* dx dy} = \frac{\sum_{i=1}^2 (\varepsilon_0 \mu_0) \iint_{(i)} \varepsilon E_x E_x^* dx dy}{\sum_{i=1}^2 (\varepsilon_i \mu_i) \iint_{(i)} \varepsilon E_x E_x^* dx dy} \leq 1. \quad (3)$$

It is seen from above that in a multi-layer dielectric-filled waveguide the product $\beta_{\text{energy}} \beta_{\text{phase}}$ is less than unity; generally speaking, it is not a constant at all, except for one-layer dielectric-filled waveguide in which $\beta_{\text{energy}} \beta_{\text{phase}} = 1/\varepsilon_r \mu_r$ holds.

It should be noted that formulas similar to Eqs. (1)-(3) for LSE modes can be obtained by replacing E_x, μ , and ε with H_x, ε , and μ .

From the wave number equation $\omega^2 \varepsilon \mu = k_x^2 + k_y^2 + k_z^2$, the group velocity defined by $\beta_{\text{group}} c \equiv d\omega/dk_z$ can be expressed as

$$\beta_{\text{group}} \beta_{\text{phase}} = \sum_{i=1}^2 \varepsilon_0 \mu_0 \left(\frac{1}{k_{ix}} \frac{\partial D}{\partial k_{ix}} \right) \bigg/ \sum_{i=1}^2 \varepsilon_i \mu_i \left(\frac{1}{k_{ix}} \frac{\partial D}{\partial k_{ix}} \right), \quad (4)$$

where $D \equiv D(k_{1x}, k_{2x}) = 0$ denotes the dispersion equation, and k_{1x} and k_{2x} are, respectively, the wave numbers in zone (I) and zone (II). It can be shown by direct calculations that the group velocity is equal to the energy velocity. This analytic result may be used for code check in numerical computations.

The electric field components of symmetric LSM modes in zone (I) for this structure can be written as

$$E_x = E_0 \frac{\sin k_{1x} x}{\sin k_{1x} a} \sin k_y (y + d), \quad (5)$$

$$E_y = E_0 \frac{k_{1x} k_y}{k_y^2 + k_z^2} \frac{\cos k_{1x} x}{\sin k_{1x} a} \cos k_y (y + d), \quad (6)$$

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and

$$E_z = -E_0 \frac{ik_{1x}k_z}{k_y^2 + k_z^2} \frac{\cos k_{1x}x}{\sin k_{1x}a} \sin k_y(y+d), \quad (7)$$

where E_x is selected to automatically satisfy the boundary conditions on conducting walls, E_0 is the amplitude, and the propagating factor $\exp i(\omega t - k_z z)$ is omitted.

The dispersion equation for the symmetric LSM modes can be obtained by use of boundary conditions imposed on εE_x and $\partial E_x / \partial x$ on dielectric surfaces, given by [9]

$$D(k_{1x}, k_{2x}) \equiv 1 - \frac{k_{2x}}{\varepsilon_2} \tan k_{2x}(b-a) \frac{\varepsilon_1}{k_{1x}} \tan(k_{1x}a) = 0. \quad (8)$$

The dispersion equations for other LSM and LSE modes may be obtained similarly [10,11], but for an external rf powered acceleration structure, more interest in LSM-s11 (symmetric) mode is taken although it is not the lowest mode. The dispersion curves are shown in Fig. 2 for a structure with parameters: $a = 3$ mm, $b = 5$ mm, $d = 4a = 12$ mm, $\mu_{r1} = \mu_{r2} = 1$, $\varepsilon_{r1} = 1$, and $\varepsilon_{r2} = 9.6$, where zone (I) is of vacuum for the beam channel.

Figure 39. Dispersion curves for a structure with $a = 3$ mm, $b = 5$ mm, $d = 12$ mm, and relative dielectric constants $\varepsilon_{r1} = 1$ (vacuum) in zone (I) and $\varepsilon_{r2} = 9.6$ in zone (II). Light line is shown.

All modes that can compete with LSM-s11 mode at 11.424 GHz are shown. At the operating point, the group velocity $d\omega/dk_z$ for the LSM-s11 mode is $0.135c$.

The curves for symmetric LSM-smn modes are calculated from Eq. (8), and the LSM-s11 mode is set to operate synchronously with a 6-MeV beam at 11.424 GHz. The five possible

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competing modes are LSM-a11 and LSM-a12 (anti-symmetric slow waves that would be suppressed by the radiating pumping slots), LSE-s10 and LSE-s11 (fast waves that have polarizations essentially orthogonal to the operating mode), and LSM-s12 (a fast wave with $\beta_{\text{phase}} \approx 2.5$). These modes cannot be disregarded when designing the structure and the couplers, since their presence could have a deleterious effect on beam acceleration and emittance growth. But careful maintenance of symmetry should allow single-mode operation.

From $\omega^2 \epsilon_1 \mu_1 = k_{1x}^2 + k_y^2 + k_z^2$, we know that $|k_{1x}| = k_y = \pi/2d$ when the phase velocity of the LSM-s11 mode is equal to the vacuum light speed, and the overvoltage factor is $\kappa = |E_z(a, y, z)/E_z(0, y, z)| = \cosh(\pi a/2d)$. For $d/a = 4$, for example, this predicts $\kappa \approx 1.078$, as compared with $\kappa \approx 2.1$ for a typical π -mode SLAC X-band standing-wave accelerating structure. This near-factor-of-two reduction in overvoltage factor should be beneficial in minimizing unnecessarily high electric fields in the structure, with a concomitant increase in breakdown thresholds.

Suppose that the dielectric in zone (II) is dissipative with a loss tangent of $\tan \delta$ and that the loss for conducting walls can be characterized by a surface impedance of $R_s = (\omega \mu_0 / 2\sigma)^{1/2}$ with σ the conductivity. From Eqs. (5)-(7) and Eq. (1), we can obtain the normalized characteristic quantity R/Q , wall loss Q -factor Q_w , and dielectric loss Q -factor Q_d for the symmetric LSM- mn modes; with dropping the subscripts m and n , they are given by

$$\left[\frac{R_{x_0, y_0}}{Q} \right]_{LSM-s} = \frac{|E_z|_{x_0, y_0}^2}{\omega U_{LSM-s}}, \quad (9)$$

$$Q_w = \omega U_{LSM-s} \left(\frac{dP_w}{dz} \right)^{-1}, \quad \text{and} \quad Q_d = \frac{U_{LSM-s}}{2U_e^{(II)} \tan \delta}, \quad (10)$$

where

$$|E_z|_{x_0, y_0}^2 = E_0^2 \left(\frac{k_{1x} k_z}{k_y^2 + k_z^2} \right)^2 \left(\frac{\cos k_{1x} x_0}{\sin k_{1x} a} \right)^2 [\sin k_y (y_0 + d)]^2, \quad (11)$$

$$\begin{aligned} U_{LSM-s} = & \frac{1}{2} E_0^2 \epsilon_1 \left(\frac{\omega^2 \epsilon_1 \mu_1}{k_y^2 + k_z^2} \right) \frac{ad}{(\sin k_{1x} a)^2} \left(1 - \frac{\sin 2k_{1x} a}{2k_{1x} a} \right) \\ & + \frac{1}{2} E_0^2 \epsilon_1 \left(\frac{\omega^2 \epsilon_1 \mu_1}{k_y^2 + k_z^2} \right) \frac{(b-a)d}{[\cos k_{2x} (b-a)]^2} \frac{\mu_2}{\mu_1} \left[1 + \frac{\sin 2k_{2x} (b-a)}{2k_{2x} (b-a)} \right], \end{aligned} \quad (12)$$

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$$\begin{aligned} \frac{dP_w}{dz} = E_0^2 R_s \frac{\varepsilon_1}{\mu_1} \frac{\omega^2 \varepsilon_1 \mu_1}{k_y^2 + k_z^2} \left\{ \frac{a}{(\sin k_{1x} a)^2} \frac{k_y^2}{k_y^2 + k_z^2} \left[1 - \frac{\sin(2k_{1x} a)}{2k_{1x} a} \right] \right. \\ \left. + \frac{d}{[\cos k_{2x}(b-a)]^2} \left(1 + \frac{(b-a)}{d} \frac{k_y^2}{k_y^2 + k_z^2} \left[1 + \frac{\sin 2k_{2x}(b-a)}{2k_{2x}(b-a)} \right] \right) \right\}, \quad (13) \end{aligned}$$

$$U_e^{(II)} = \frac{1}{4} E_0^2 \varepsilon_1 \frac{\omega^2 \varepsilon_1 \mu_1}{k_y^2 + k_z^2} \frac{(b-a)d}{[\cos k_{2x}(b-a)]^2} \frac{\mu_2}{\mu_1} \left\{ 1 + \left(1 - \frac{2k_{2x}^2}{\omega^2 \varepsilon_2 \mu_2} \right) \frac{\sin 2k_{2x}(b-a)}{2k_{2x}(b-a)} \right\}. \quad (14)$$

In Eq. (10), $U_e^{(II)}$ is the stored electric energy per unit length in zone (II). If the cross section of zone (I) reduces to zero, then $2U_e^{(II)}$ is equal to the total energy U_{LSM-s} in such a case, leading to $Q_d = 1/\tan \delta$.

In Figure 40, some numerical results are given from Eqs. (8)-(10) for LSM-s11 mode operating at 11.424 GHz with a normalized phase velocity of 0.9969 for acceleration of a 6-MeV electron beam. Figure 40a shows the dependence of waveguide half-width b and normalized characteristic shunt impedance R/Q (at $x_0 = y_0 = 0$) on aperture half-width a for $\mu_{r1} = \mu_{r2} = 1$, $\varepsilon_{r1} = 1$, $\varepsilon_{r2} = 9.6$, and $d = 4a$ (corresponding to a low overvoltage factor as mentioned previously). It is seen that R/Q rises as aperture width a shrinks, down to $a = 2$ mm. At $a = 3$ mm, b is 5 mm, corresponding to a 6 mm $\times$ 24 mm beam aperture, and R/Q is 6.38 k Ω /m, a value within the range of that for metallic disk-loaded structures that had been under development for NLC. Figure 40b shows the dependence of shunt impedance R , wall loss Q_w , dielectric loss Q_d , and total Q on a for the conductivity $\sigma = 5.56 \times 10^7 \Omega\text{-m}$ and dielectric loss $\tan \delta = 1 \times 10^{-4}$. The total quality factor is calculated from $1/Q = 1/Q_d + 1/Q_w$. For $a = 3$ mm, one has $Q_w = 3,560$, $Q_d = 13,219$, $Q = 2,805$, and $R = 17.9 \text{ M}\Omega/\text{m}$, a value some four times lower than that for NLC structures, severely suffering from wall loss.

The normalized characteristic shunt impedance R/Q is a structure parameter based on field distributions, having nothing to do with power dissipation, while the shunt impedance R is the ratio of the square of maximum acceleration gradient to dissipation power in unit length, a quantity that characterizes acceleration efficiency ($\propto R$). For the dielectric structure example discussed here, energy stored in the two dielectric slabs is about four times that stored in the beam channel. Clearly from Eq. (10), low-loss dielectric is required for this application.

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Figure 40. Numerical results for LSM-s11 mode operating at 11.424 GHz with a normalized phase velocity of 0.9969 in a three-zone structure. (a *at top*). Dependence of waveguide half-width b and normalized characteristic shunt impedance R/Q (at $x_0 = y_0 = 0$) on aperture half-width a . (b *at bottom*). Dependence of shunt impedance R , wall loss Q_w , dielectric loss Q_d , and total Q on a .

FIVE-ZONE ACCELERATION STRUCTURE

As we have seen in the above example, the total quality factor is reduced mainly by wall loss. This means of reducing wall losses relies on the fact that, for the three-zone structure, losses on the side walls ($x = \pm b$) greatly exceed losses on the top and bottom walls ($y = \pm d$). So it might be conjectured that, if the side walls are moved outwards by interposing an outer vacuum

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gap on either side of the dielectric, then wall losses would diminish. This can be understood physically from the fact that k_{1x} in the outer region has the same (imaginary) value as in the inner beam channel. Thus fields will decay exponentially away from the dielectric towards the outer side walls and, if the outer gap is wide enough, fields at the outer walls should be such as to reduce wall losses to the point where $Q_w \gg Q_d$, yet without necessarily increasing the overvoltage factor in the beam channel. This conjecture has been tested, by analyzing a symmetric five-zone dielectric waveguide with vacuum gaps in the zones $a_2 \leq |x| \leq b$, as shown in Figure 41.

Figure 41. Symmetric five-zone dielectric-lined accelerator structure.

In general, as in the way for calculating fields in a structure with any number of zones, we can obtain the dispersion equation for symmetric LSM modes in the five-zone structure

$$D(k_{1x}, k_{2x}) \equiv 1 - \frac{k_{1x}}{\epsilon_1} \tan k_{1x} (b - a_2) \frac{\epsilon_2}{k_{2x}} \tan k_{2x} (a_2 - a_1) - \frac{k_{2x}}{\epsilon_2} \tan k_{2x} (a_2 - a_1) \frac{\epsilon_1}{k_{1x}} \tan(k_{1x} a_1) - \tan k_{1x} (b - a_2) \tan(k_{1x} a_1) = 0. \quad (15)$$

It is seen from above that the three-zone structure is just a particular case of the five-zone structure when setting $a_1 = a$ and $a_2 = b$.

Figure 42 shows some numerical results for the LSM-s11 mode operating at 11.424 GHz with a normalized phase velocity of 0.9969 in the five-zone structure with parameters: $\mu_{r1} = \mu_{r2} = 1$, $\epsilon_{r1} = 1$, $\epsilon_{r2} = 9.6$, $d = 4a_1$, $\sigma = 5.56 \times 10^7 \Omega\text{-m}$, and $\tan \delta = 1 \times 10^{-4}$, the same as those in Fig. 40 for comparison with the three-zone structure discussed previously. The vacuum gap width $b - a_2$ is kept at 12 mm, to make rf fields decay enough before reaching conducting walls and consequently to reduce wall loss. It is seen that when $a_1 = 3$ mm, $b = 18.5$ mm and $R/Q = 2.2$ k Ω /m (Fig. 42a), and $Q_w = 63,000$, $Q_d = 24,000$, $Q = 17,000$, and $R = 38.5$ M Ω /m (Fig. 42b). As expected, the wall loss is greatly decreased and the shunt impedance is more than doubled, although R/Q is lower, which may result in a lower acceleration gradient. The acceleration gradient could be improved by increasing flowing power that is much less than the dissipation power in NLC.

It also can be understood from the field plots in Figure 43 how the wall loss is reduced by the introduction of vacuum gaps. It is seen that all the field components are decreased

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exponentially in the vacuum gaps ($a_2 < |x| < b$). H_y is reduced from 218 A/m to 84 A/m, which generates induction current at side walls $|x| = b$, while H_z is reduced from 54 kA/m to 20.7 kA/m, which generates induction current at $|x| = b$, and also is the only component for wall current at $|y| = d$ since $H_x = 0$ for LSM modes.

As mentioned previously, low loss dielectric is required for this application. To show its importance, some numerical calculations were done based on the Fig. 5-case by only changing $\tan\delta$. As shown in Fig. 7, at $a_1 = 3$ mm, R is 60.5 M Ω /m for $\tan\delta = 5 \times 10^{-5}$, and 78.3 M Ω /m for $\tan\delta = 3 \times 10^{-5}$, compared to 38.5 M Ω /m for $\tan\delta = 10^{-4}$. Table 1 tabulates the parameters for the case with $\tan\delta = 5 \times 10^{-5}$.

Figure 42. Numerical results for LSM-s11 mode operating at 11.424 GHz with a normalized phase velocity of 0.9969 in a five-zone structure. (a at top). Dependence of waveguide half-width b and normalized characteristic shunt impedance R/Q (at $x_0 = y_0 = 0$) on aperture half-width a_1 . (b at bottom). Dependence of shunt impedance R , wall loss Q_w , dielectric loss Q_d , and total Q on a_1 .

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Figure 43. RF field profiles when the parameters from Fig. 42 are set to be: $a_1 = 3$ mm, $a_2 = 6.5$ mm, $b = 18.5$ mm, and $d = 12$ mm. The profiles are plotted at the y - and z -values that make them maximum while 300 MW input power is assumed. (a). Electric field components E_x and E_z vs x ; the axial acceleration field at center is 19.3 MV/m. (b). Magnetic field components H_y and H_z vs x . It is seen that all the field components are decreased outwards walls.

Figure 44. Dependence of shunt impedance R on beam channel half-width a_1 for a different value of $\tan\delta$. It is seen that R at $a_1 = 3$ mm is increased to either 60.5 MΩ/m or 78.3 MΩ/m, from 38.5 MΩ/m, when $\tan\delta$ is decreased to 5×10^{-5} or 3×10^{-5} from 10^{-4} . Evidently, these lower $\tan\delta$ values are not unrealistic for alumina [3,13].

DIELECTRIC-LINED HIGH-GRADIENT ACCELERATOR STRUCTURE**TABLE 1.** Parameters for a five-zone DLA Structure.

operating frequency at LSM-s11 mode	11.424 GHz
phase velocity v_{phase}	$0.996915 c$
waveguide height $2d$	24.0 mm
waveguide width $2b$	37.0 mm
beam aperture width $2a_1$	6.0 mm
width of dielectric slabs $a_2 - a_1$	3.5 mm
relative dielectric constant	9.6
group velocity v_{group}	$0.418 c$
loss tangent $\tan\delta$	5×10^{-5}
overvoltage factor κ	1.078
wall quality factor Q_w	63,499
dielectric quality factor Q_d	48,112
overall quality factor Q	27,372
characteristic shunt impedance R/Q	2.21 k Ω /m
shunt impedance R	60.5 M Ω /m
power attenuation length $\Lambda = Qv_{\text{group}}/\omega$	47.8 m

DISCUSSION

There are some favorable attributes of rectangular DLA structures operating in the LSM-s11 mode, compared to cylindrical ones. First, a conventional input/output coupler cell can be employed, which does not contain dielectric elements. Secondly, planar one-piece dielectric slabs are free of any internal joints and/or gaps where breakdown could originate, with direct access before assembly for precision planar grinding and polishing of open faces, and ease of application of uniform films of TiN [28] or other materials [29] to suppress multipactoring [30]. Thirdly, open slots along the top and bottom of the structure may be used to suppress all anti-symmetric higher-order modes, and to facilitate high-speed pumping all along the structure.

This analysis shows, as far as electrodynamic properties are concerned, that DLA structures can probably be competitive with disk-loaded metallic structures. But to achieve genuine competitive status will evidently require use of alumina with a $\tan\delta$ of 5×10^{-5} or less at 11.4 GHz. A second crucial issue is the rf breakdown limit which, for off-the-shelf alumina, may not exceed 31 MV/m [31]. However, it is not clear whether this figure is due to surface multipactor or to volume breakdown; the former can be suppressed using a low secondary-emission thin film coating such as TiN, while the latter can probably be increased with improved fabrication of the alumina. In addition, search for new dielectric materials keeps going on; as mentioned previously, diamond is a potential promising material since it has some of the most extreme physical properties of any material [21].

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Relevant Publications

- “Rectangular Dielectric-loaded Structures for Achieving High Acceleration Gradients,” Changbiao Wang, V.P. Yakovlev, T.C. Marshall, M.A. LaPointe, and J.L. Hirshfield, 12th Advanced Accelerator Concepts Workshop (AAC2006), Grand Geneva Resort, July 10-15, 2006 July 10-15, 2006, *see* <http://www.hep.anl.gov/aac06/>.
- “Theory for Wakefields in a Multizone Dielectric lined Waveguide”, C.Wang and J.L. Hirshfield, *Phys. Rev. ST Accel. and Beam* **9**, 031301 (2006). <http://prst-ab.aps.org/abstract/PRSTAB/v9/i3/e031301>
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