RECTANGULAR DIAMOND-LINED ACCELERATOR STRUCTURE*

Changbiao Wang,[1] V. P. Yakovlev,[1] and J. L. Hirshfield[1,2]
[1]Omega-P, Inc., 199 Whitney Avenue, New Haven CT 06511, USA
[2]Department of Physics, Yale University, New Haven, CT 06520, USA

Abstract

A millimeter-wave rectangular dielectric-lined structure is described that may have the potential to sustain an accelerating gradient beyond the limits found for metallic structures. The new structure employs artificial diamond as the dielectric, because of its high breakdown limit and low loss tangent. Interposition of vacuum gaps between the dielectric slabs and the side walls is shown to reduce Ohmic losses substantially, leading to an increase in shunt impedance and reduced susceptibility to rf breakdown on metal surfaces.

INTRODUCTION

For cm- and mm-wavelength linear accelerators with normal-conducting structures as studied by the NLC/GLC collaboration and the CLIC study group [1,2], the main limitation to achievement of high acceleration gradient is rf breakdown. Although the physics of breakdown is still unclear, it is known that the field limit is proportional to an inverse fractional root of pulse length, and will vary with structure material and surface processing [3]. Recent experiments on 30-GHz accelerating structures at the CLIC Test Facility with an rf pulse width of 16 ns showed that the maximum sustainable surface field is 260 MV/m for copper, 340 MV/m for tungsten, and 426 MV/m for molybdenum. These values correspond to average acceleration gradients of 100 MeV/m, 125 MeV/m, and 153 MeV/m [4]. Since the breakdown rate sharply increases beyond some critical field, the usable average gradient is lower than these values; e.g. ~130 MeV/m for molybdenum. Therefore, a clear objective is to increase acceleration gradient without incurring an unacceptable rate of breakdown events in the accelerating structures.

Amorphous dielectrics, such as glass, are known to exhibit high breakdown limits (~100′s of MV/m), but most have a loss tangent that is too high for high-gradient accelerator applications ($\sim 3\times 10^{-3}$). An alternative is polycrystalline artificial CVD (chemical vapor deposition) diamond [5], which shows promise for a high-gradient, dielectric-loaded accelerator (DLA) structure [6] because it has a very high breakdown field (up to 2 GV/m) [7], low loss tangent ($<10^{-4}$) [8], and the highest known thermal conductivity (2×10^{3} $\mathrm{Wm^{-1}\ K^{-1}}$) [9]. CVD diamond has already been successfully used on an industrial basis for large-diameter output windows of high power gyrotrons [10], and is produced industrially in increasing quantities. However, present CVD techniques only allow diamond to be made in planar shapes [9,10]. So slabs can be fabricated for rectangular DLA structures, but not for cylindrical structures.

In this paper, analysis of fields in rectangular diamond-lined structures is presented that shows the electric field on the conducting wall relative to the accelerating field to be significantly reduced, as compared with all-metal structures. This should help to mitigate against rf breakdown on the walls. Furthermore, the use of slab-shaped dielectric elements will facilitate application of TiN coatings to suppress multipactor discharges [11-14], if needed. Continuous narrow axial slots can be put in the centers of each wall of the structure, thus serving to suppress competing modes and to allow pumpout.

THEORETICAL ANALYSIS

In a rectangular dielectric-lined waveguide with three zones in cross section, as previously analyzed for wake field acceleration [15-17], the dielectric slabs are in direct contact with the side conducting walls, which results in increase of surface currents and high Ohmic losses in the walls. (Note that the same problem is endemic and difficult to avoid for cylindrical structures [18-19]). In contrast, the present arrangement is a symmetric five-zone structure, where gaps are left between the dielectric slabs and the side conducting walls to reduce the surface currents and wall losses; as a result, the shunt impedance of the structure can be significantly increased.

A diagram of the cross section of the five-zone DLA structure is shown in Fig. 1. Zones (I) and (III) have identical properties, characterized by $\varepsilon_1 = \varepsilon_{r1}\varepsilon_0$ and $\mu_1 = \mu_{r1}\mu_0$, where ε_0 and μ_0 are the permittivity and permeability in vacuum, while zone (II) has $\varepsilon_2 = \varepsilon_{r2}\varepsilon_0$ and $\mu_2 = \mu_{r2}\mu_0$. In this scheme, zone (III) ($-a_1 < x < a_1$) is the beam channel, zones (II) are diamond slabs, and zones (I) are gaps where rf fields decay towards the side walls.

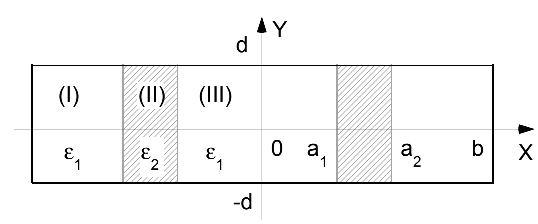

Figure 1: Cross section of five-zone dielectric-lined rectangular accelerator structure.

Field analysis for five-zone rectangular dielectric-lined accelerator (DLA) structures is similar to that for three-zone structures [17]. The operating mode for the structure in Fig. 1 is the symmetric-LSM_{11} mode, labeled LSM_{s11}, where symmetry is defined as that for E_z with respect to

*Work supported by US DoE.
[2]jay.hirshfield@yale.edu

x. The dispersion equation for LSM modes of the five-zone structure is given in Ref. 20.

As an example, Figure 2 shows the calculated shunt impedance R *vs* the beam channel half-width a_1 as calculated for a five-zone diamond-lined traveling-wave (TW) structure. The structure operates in the LSM_{s11} mode at a frequency of 34.272 GHz where its axial wave number corresponds to a phase velocity of c; the diamond has dielectric constant of 5.7 and loss tangent $\tan\delta$ of 4×10^{-5} [8]; the conductivity for the copper walls 5.56×10^{7} Ω-m. The ratio of the structure height $2d$ to the beam channel width $2a_1$ is fixed at 4, a value that leads to a favorable overvoltage factor for the accelerating field, in order to reduce energy spread. Calculations show that the maximum shunt impedance R_{max} increases with d/a_1, while the transverse forces decrease. The outer vacuum gap widths b-a_2 are selected to be 12 mm, so that rf fields decay substantially before reaching the side conducting walls at $x = \pm b$, thus greatly reducing wall losses.

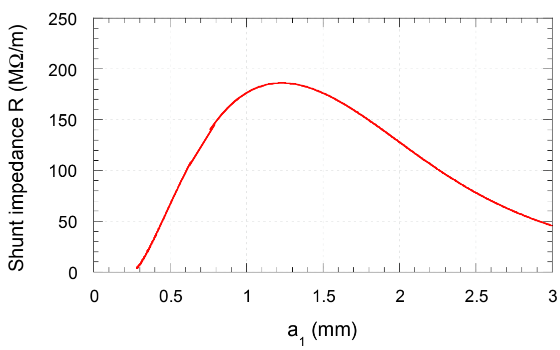

Figure 2: Shunt impedance R *vs* beam channel half-width a_1 for a five-zone diamond-lined TW structure with $\mu_{r1} = \mu_{r2} = 1$, $\varepsilon_{r1} = 1$, $\varepsilon_{r2} = 5.7$, and $d = 4a_1$.

It is seen from Fig. 2 that for $a_1 = 1.50$ mm the shunt impedance is $R = 176$ MΩ/m, and a bit higher at $a_1 = 1.20$ mm. The rf electric field profiles *vs* x for $a_1 = 1.50$ mm are shown in Fig. 3.

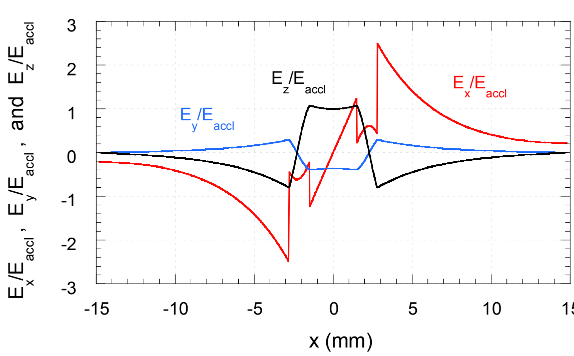

Figure 3: RF electric field profiles normalized to the acceleration gradient E_{accl}. Structure parameters: $a_1 = 1.5$ mm, a_2-$a_1 = 1.29$ mm, $b = 14.8$ mm, and $d = 6$ mm.

It is seen in Fig. 3 that all field components decrease exponentially in the vacuum gaps ($a_2 < |x| < b$). The axial field E_z on the axis is defined as the acceleration gradient E_{accl}. On the dielectric surface $x = a_2$, E_x reaches its maximum value of $2.5E_{accl}$. If the dielectric breakdown limit is indeed 2 GV/m [7], the maximum acceleration gradient would be 800 MeV/m, if dielectric breakdown is the ultimate limitation. The maximum surface electric field on the conducting walls is at the joint between the top and bottom conducting walls $|y| = d$ and the dielectric surface $|x| = a_1$, giving a relatively low E_{surf}/E_{accl} ratio of 0.4; from this the maximum acceleration gradient would be 750-1000 MeV/m, if breakdown at the conducting wall is the ultimate limitation [21]. In either case, maximum acceleration gradient values well in excess of those for all-metal structures can be anticipated.

Table 1 shows characteristics for a diamond-lined accelerating structure (DLA) operating in the traveling-wave mode with parameters described above and, for comparison, those of a CLIC main-linac accelerating-structure design HDS (Hybrid Damped Structure) [22].

Table 1: Characteristics of DLA and the CLIC structure HDS, in traveling-wave modes

	DLA (34.272 GHz)	**DLA** (30.0 GHz)	**HDS** (30.0 GHz)
R (MΩ/m)	176	160	99
$E_{diel\text{-}surf}/E_{accl}$	2.5	2.4	-
$E_{metal\text{-}surf}/E_{accl}$	0.4	0.35	2.2

Since HDS is designed for 30 GHz, rather than 34.272 GHz, values for DLA are shown in Table 1 for 30.0 GHz as well. It is seen that the ratio of maximum surface field to accelerating field at the metal wall $E_{metal\text{-}surf}/E_{accl}$ is only 0.35 for a 30-GHz DLA, much smaller than the value 2.2 for HDS. This bodes well for DLA in helping to avoid breakdown at the metal walls. It is important to note, however, that the DLA structure is not free of electric-field enhancement, since the maximum value of $E_{diel-surf}/E_{accl}$ is 2.4-2.5, as shown in Fig. 3. However, the field enhancement occurs 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 160-176 MΩ/m for DLA, as compared to 99 MΩ/m for HDS, a further favorable attribute for DLA.

To determine the CVD diamond breakdown limit under accelerator-relevant conditions, a cavity DLA structure has been designed. Table 2 shows the parameters for this cavity, based on the TW structure described above. The cavity, with a length of six wavelengths ($L = 5.25$ cm), operates in the $LSM_{s1,1,12}$ mode at a frequency of 34.272 GHz. The acceleration gradient E_{accl} for the cavity structure is defined as the maximum of a co-traveling component of E_z on the axis, namely half of the standing wave amplitude. For example, E_{accl} is 183 MV/m for an injected power level of 20 MW, while the maximum axial field E_z on the axis is 366 MV/m. In this case, maximum electric fields are 144 MV/m and 913 MV/m on the conducting walls and dielectric surfaces, respectively.

0-7803-8859-3/05/$20.00

Table 2: Parameters for example of a cavity structure

frequency for the LSM_{s11} mode	34.272 GHz
cavity height $2d$	12.0 mm
cavity width $2b$	29.6 mm
cavity length L	52.5 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}
wall quality factor Q_w	74,000
dielectric quality factor Q_d	100,000
overall quality factor Q	43,000
characteristic shunt impedance R/Q	108 Ω
shunt impedance R	4.6 MΩ

It should be pointed out that, since $H_z = 0$ (i.e., no surface currents flow along x) at the centers of the top and bottom conducting walls ($x = 0$, $y = \pm d$), that thin slots along z may be cut along the centers of these walls to allow continuous pumpout into a surrounding vacuum plenum without affecting the operating mode. Anti-symmetric modes can be shown to have $H_z \neq 0$ at this point, so that these slots should also serve to help suppress undesired modes. Slots may also be cut at centers of the side walls ($x = \pm b$, $y = 0$) since walls currents here are small, thus providing further mode suppression and pumpout access. Such slots also allow application of a moderate dc electric field along the dielectric, as another means of suppressing multipactor, should such suppression be required.

An additional favorable feature of the rectangular DLA structure is revealed by analysis that shows that transverse forces in the beam channel can behave like a magnetic quadrupole, focusing in one transverse direction while de-focusing in the other [15]. However, the sign of each component of transverse force reverses as the particle phase is shifted through the location where the axial force is a maximum. Therefore, a sequence of accelerator sections can be arranged to behave something like a FODO channel, if the rf phases in successive sections are adjusted with respect to the bunch entry phase, so as to present equal but alternating phase differences in adjacent sections, thereby providing transverse stability.

CONCLUSIONS

A five-zone rectangular dielectric-loaded waveguide structure has been analyzed, showing several attributes that could allow operation at acceleration gradient levels without rf breakdown that exceed those for all-metal structures. When artificial CVD diamond slabs are chosen as the dielectric, with its reported high breakdown limit of 2 GV/m [7], and low loss tangent $\tan\delta$ of 4×10^{-5} [8], it has been shown that electric fields at the metal walls do not exceed 40% of the accelerating field. Electric fields at the dielectric surface would be equal to 2 GV/m for an acceleration gradient of 800 MeV/m. The diamond-lined structure can have a shunt impedance 60-75% higher than comparable all-metal structures, thus producing a corresponding reduction in the required rf power/length to provide a given acceleration gradient.

Realization of an accelerator structure with the attributes described here will require experimental tests to establish rf breakdown limits for CVD diamond. For such experiments, a test cavity has been designed and described that would impose surface and volume fields on the diamond slabs up to 913 MV/m, and surface fields on the conductor of up to 144 MV/m, using up to 20 MW of rf power, as available from the Omega-P/Yale 34-GHz magnicon amplifier [23]. Finally, it deserves mention that the results presented here are for idealized rectangular geometry, with no attempt to moderate field enhancements. Before a test structure is fabricated, further design analysis will be conducted to add roundings and tapers that should serve to reduce field enhancements below values cited in this paper.

REFERENCES

[1] International Linear Collider, Technical Review Committee, Second Report 2003, SLAC-R-606.
[2] CLIC Study-Team, CERN Report 2000-008, 2000.
[3] S. Döbert, SLAC-PUB-10690, Sept. 2004.
[4] W. Wuensch, *et al*., in *Proc. PAC*03, pp. 495-497.
[5] *Handbook of Industrial Diamonds and Diamond Films*, edited by M. A. Prelas, *et al*., (NY-HK, Marcel Dekker, 1998).
[6] M. E. Hill, *et al*., SLAC-PUB-8666.
[7] National Materials Advisory Board, NMAB-445, (National Academy Press, 1990), p. 79.
[8] A. Vikharev, private communications.
[9] P. W. May, *Phil. Trans. R. Soc. Lond. A* **358**, 473-495 (2000).
[10] ITER Technology R&D Progress Report, *TAC-16_Progress Report-R&D*, Ch. 3.12 EC, June 2000.
[11] R. A. Kishek, *et al*., *Phys. Plasmas* **5**, 2120 (1998).
[12] M. Neubauer, *et al*., SLAC-PUB-7209.
[13] P. Yla-Oijala*, TESLA Report, TESLA 97-21* (1997).
[14] R. L. Geng, et al., Proc. EPAC02, pp. 2238-2240.
[15] L. Xiao, *et al*., *Phys. Rev. E* **65**, 016505 (2001).
[16] C. Jing, *et al*., *Phys. Rev. E* **68**, 016502 (2003).
[17] S. Y. Park, *et al*., in *AAC*: *Tenth Workshop*, AIP Conf. Proc. **647** (AIP, New York, 2002), p. 527.
[18] W. Gai, *et al*., in *Proc. PAC*97, (IEEE, Piscataway, 1998), pp. 636-638.
[19] T-B. Zhang, *et al*., *Phys. Rev. E* **54**, 1918 (1996).
[20] C. Wang, *et al*., in *AAC*, AIP Conf. Proc. **737** (AIP, New York, 2004), pp. 871-879.
[21] H. H. Braun, *et al*., *Phys.Rev.Lett.* **90**, 224801 (2003).
[22] A. Grudiev and W. Wuensch, in *Poster of LINAC2004*, THP72, private communications.
[23] O.A. Nezhevenko, et al., *IEEE Trans. Plasma Sci.* **32**, 994 (2004).