THE DIELECTRIC WAKEFIELD ACCELERATING STRUCTURE*

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Abstract

We report here on the development of THz diamond wakefield structures produced using Chemical Vapor Deposition (CVD) technology. The diamond structures would be used in a THz generation experiment at the new FACET facility at SLAC. We consider a dielectric based accelerating structure to study of the physical limitations encountered driving > GV/m wakefields in the cylindrical and planar geometries of a dielectric loaded accelerator (DLA). In a DLA, an ultrashort drive bunch traverses the evacuated central region of the structure, creating Cherenkov wakefields in the dielectric to accelerate a witness bunch. A diamond-based DLA structure will allow a sustained accelerating gradient at FACET exceeding breakdown threshold demonstrated previously with the FFTB experiments. The electrical and mechanical properties of diamond make it an ideal candidate material for use in dielectric based structures: high breakdown voltage, extremely low dielectric losses and the highest thermoconductive coefficient available for removing waste heat from the device.

INTRODUCTION

Dielectric Loaded Accelerator structures using ceramics or other materials and excited by a high current electron beam or an external high frequency high power RF source have been under extensive study for many years [1-3,9]. Low loss microwave ceramics, fused silica, and CVD polycrystalline and single crystal diamonds [9] have been considered as materials for dielectric based accelerating structures to study of the physical limitations encountered driving > 100 MV/m at microwave [1-3,9] and > GV/m at THz frequencies in a dielectric based wakefield accelerator [4]. THz radiation has been generated recently by a short ~10 GV/m pulse within a 100 µm diameter dielectric fiber [4]. The DlA approach resolves the THz source problem by using radiated fields from short electron bunches [4].

The first measurements of the breakdown threshold in a dielectric subjected to GV/m wakefields produced by short (30–330 fs), 28.5 GeV electron bunches have been presented in [4]. Fused silica tubes of 100 µm inner diameter were exposed to beams with a range of bunch lengths, allowing surface dielectric fields up to 27 GV/m to be generated. The onset of breakdown, detected through light emission from the tube ends, is observed to occur when the peak electric field at the dielectric surface reaches 13.8 GV/m [4].

Meanwhile, diamond has the lowest coefficient of thermal expansion, highest thermal conductivity and extremely low loss tangent (<10-4) at Ka-W and THz frequency bands [5-8]. Multipacting in diamond is a strong function of surface termination and may be suppressed by diamond surface dehydrogenation [5,6,8]. A planar diamond-based DLA structure was proposed and studied recently by Omega-P, Inc., where the dielectric loading of this structure was to be made of diamond slabs fabricated using the CVD (chemical vapor deposition) technology [7].

DIAMOND BASED DLA STRUCTURES FABRICATION

Our proposed structures are based on both planar single crystal diamond elements and on cylindrical polycrystalline diamond tubes that are manufactured via a relatively simple and inexpensive chemical vapor deposition (CVD) process - plasma assisted CVD [5,6]. One can consider also the hot filament CVD process but in general it was found the structures produced in this process to be of significantly lower quality. When the diamond deposition process is completed and the tube wall thickness reaches the required waveguide dimensions, the armatures are etched away to form self-supporting diamond tubes.

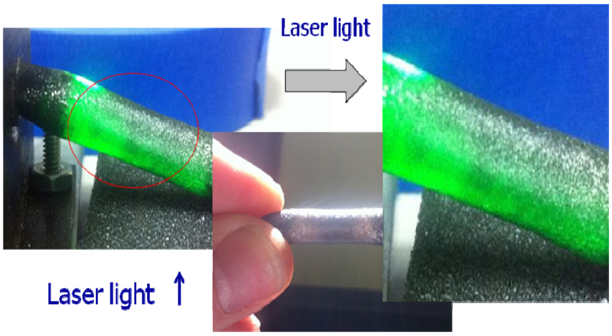


Figure 1. 35 GHz diamond tube. Tube parameters are: 5 mm inner diameter, 2.5 cm long and ~ 500 µm thick.

Diamond is deposited when atomic hydrogen recombines to molecular hydrogen on a substrate held at approximately 900^{0}C in the presence of methane. Diamond deposition can be considered the result of simultaneous deposition and etching of carbon. Consequently, the deposition rate can be slow, often less than 1 μm/hr. Microwave plasma CVD, the process that the bulk of our diamond manufacture is based on, demonstrated one to two orders of magnitude higher deposition rates providing the atomic hydrogen flux is sufficiently high. Remarkably, under high flux of atomic hydrogen the diamond quality is very good even at these high rates.

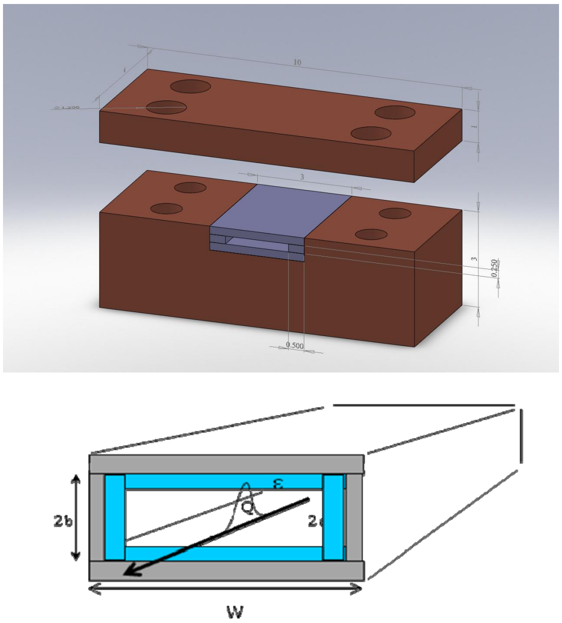


Figure 2. (a) Use of four individual diamond pieces for the (b) planar CVD diamond based structure fabrication.

A significant amount of power is required to generate atomic hydrogen. This power is then deposited on the diamond surface. The challenge for growing high quality and high rate diamond becomes the removal from the substrate of the intense heat deposited by atomic hydrogen recombination and otherwise transported from the plasma.

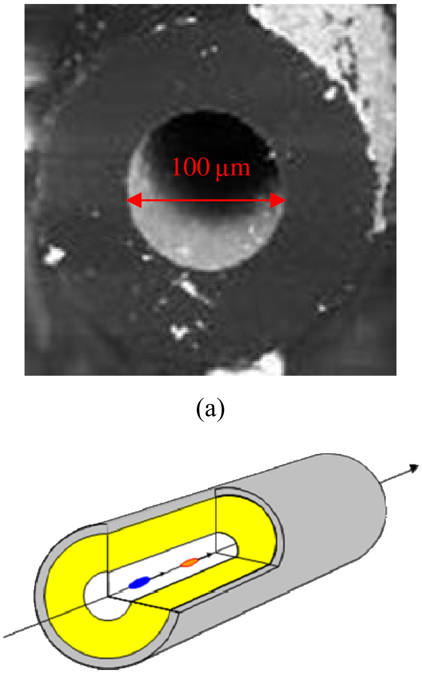
For the structures required for Ka band (35 GHz) and longer wavelength applications, the use of microwave plasma-enhanced CVD (PECVD) was determined to have a greater likelihood of success based on its larger rate of diamond deposition and the ability to control surface temperatures on the substrate during deposition [5,6,8]. With CTS, Inc., we have obtained promising results using a water cooled armature to produce a 5 mm ID free standing diamond tube. Fig.1 shows the finished free standing diamond tube. This tube represents considerable progress in diamond based accelerator development.

Rectangular cross section structures for FACET has been considered as well. Fabrication techniques have been developed based on commercially available single crystal high electronic quality diamond plates, Fig.2. Entire diamond structure is enclosed in a copper (later alumina) holder with the use of four individual diamond pieces of 100 μm to provide mechanical alignment and robust conducting boundary compared to thin layer metallic deposition.

The structure is currently being fabricated for the 2012 FACET experimental run.

The standard method of making high grade diamond relies on this idea: diamond is grown thick (usually 1.0-1.5mm thick), the substrate is removed (usually etched off) and the nucleation side is then removed (usually lapped or polished) to obtain the final thickness.

Our initial work was based on 100 μm scale tubes with fundamental frequencies in the 0.4–1.0 THz range; promising results were obtained using the plasma assisted and hot-filament CVD process to deposit a diamond layer on a cylindrical metal armature [3,5,6,8,9]. When the diamond deposition process is completed and the tube wall thickness reaches the required waveguide dimensions, the metal rods are etched out to form self-supporting diamond tubes. Fig. 3 (a) shows this type of a structure developed for the FACET beam parameters and intended for the FACET experiments.

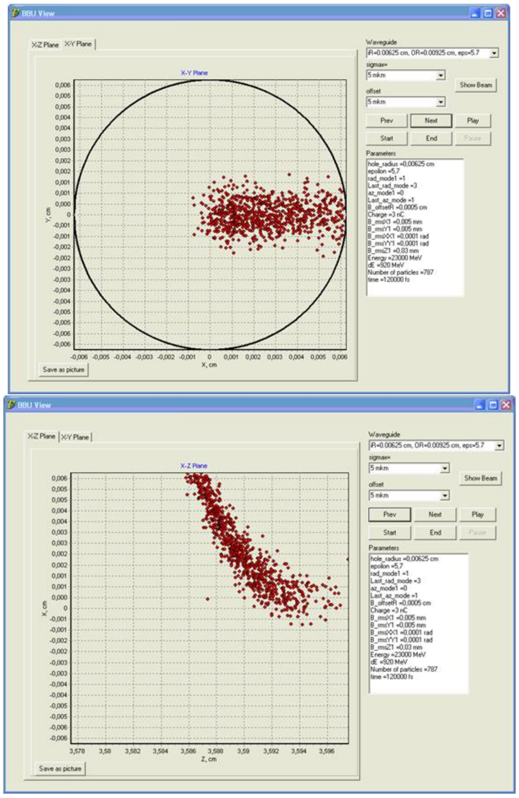


(a)

(b)

Figure 3. (a) Cylindrical hot filament diamond tube developed for (b) FACET wakefield experiment. Tube parameters: 100 μm inner diameter, 1 cm long and ~ 70 μm thick.

BEAM BREAKUP SIMULATIONS OF A DIAMOND-BASED CYLINDRICAL DLA



Waveguide: iR=0.00625 cm, OR=0.00925 cm, eps=5.7
sigmax= 5 mkm
offset: 5 mkm

Parameters
hole_radius =0,00625 cm
epsilon =5,7
rad_mode1 =1
Last_rad_mode =3
az_mode1 =0
Last_az_mode =1
B_offsetR =0,0005 cm
Charge =3 nC
B_rmsX1 =0,005 mm
B_rmsY1 =0,005 mm
B_rmsXX1 =0,0001 rad
B_rmsYY1 =0,0001 rad
B_rmsZ1 =0,03 mm
Energy =23000 MeV
dE =920 MeV
Number of particles =787
time =120000 fs

Waveguide: iR=0.00625 cm, OR=0.00925 cm, eps=5.7
sigmax= 5 mkm
offset: 5 mkm

Parameters
hole_radius =0,00625 cm
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rad_mode1 =1
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B_rmsYY1 =0,0001 rad
B_rmsZ1 =0,03 mm
Energy =23000 MeV
dE =920 MeV
Number of particles =787
time =120000 fs

Figure 4. Beam-Breakup simulations with the Euclid Techlabs in-house code BBU-3000 for the FACET diamond structure wakefield experiment. Tube parameters: 100 μm inner diameter, 1 cm long and ~ 70 μm thick.

Beam breakup phenomena present serious limitations to the performance of dielectric structure based wakefield accelerators. We have studied here numerically BBU and its mitigation with respect to the FACET diamond based structure parameters. The numerical part of this research is based on a particle-Green's function beam breakup code (BBU-3000) [10]. The code is a flexible 2D and 3D code based on analytic Green's functions for single particle fields in axisymmetric dielectric loaded structures. BBU-3000 versions are available for both Linux and Windows operating systems. The development and features of the code have been described elsewhere [3,10].

The numerical simulations carried with this research showed acceptable BBU control for the FACET beam parameters and for the 100-200 μm ID diamond based structure. Fig. 4 shows the beam profile for the tube parameters: 100 μm inner diameter, 1 cm long and ~ 70 μm thick. One can see that at the end of the structure only 10% of the bunch has been lost.

SUMMARY

The principal goal of this paper is to present a development and fabrication of a new type of cylindrical and planar microstructures based on a diamond waveguide to be used for the ~10 GV/m range gradient demonstration with the diamond based THz dielectric accelerating structure. Our choice of CVD (Chemical Vapor Deposition) diamond as a loading material will allow us to demonstrate the highest accelerating gradients up to 10-12 GV/m in the THz frequency range. Diamond has the lowest coefficient of thermal expansion, highest thermal conductivity and extremely low loss tangent. Given these remarkable properties, it should come as no surprise that diamonds should find a special place in THz source development. Note that the CVD process technology is rapidly developing making the CVD diamond fabrication process really fast and inexpensive.

We plan the experimental demonstration of the diamond-based dielectric THz planar and cylindrical microstructures with a beam test at coming FACET facility at SLAC.

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REFERENCES

[1] W. Gai, P. Schoessow, B. Cole, R. Konecny et al. Phys. Rev. Lett. 61, 2756 (1988).
[2] W. Gai, AIP Conf. Proc.1086, Melville, New York, 2009, pp. 3-11.
[3] A.Kanareykin. Journal of Physics, Conf. Ser., 236, p.012032, (2010).
[4] M. C. Thompson et al. AIP Conf. Proc. 877, Melville, New York , 2006, pp.903-909.
[5] P. Schoessow, A. Kanareykin, and R. Gat, AIP Conf. Proc 1086, Melville, New York, 2009, pp. 398-403.
[6] A.Kanareykin, P.Schoessow, M.Conde et al. Proceedings of EPAC2006, p. 2460, 2006.
[7] C.Wang, V.P.Yakovlev and J.L.Hirshfield. Proceedings Particle Accelerator Conference PAC-2005, pp.1282-1284, 2005.
[8] P. Schoessow, A. Kanareykin, and R. Gat. AIP Conf. Proc., NY, v. 1086, pp.398-403, 2008.
[9] A.Kanareykin. AIP Conference Proceedings, v. 1299, p. 286, 2010.
[10] P.Schoessow et al. AIP Conference Proceedings, v. 1299, p. 262, 2010.