PROGRESS TOWARDS DEVELOPMENT OF A DIAMOND-BASED CYLINDRICAL DIELECTRIC ACCELERATING STRUCTURE*

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Abstract

In this report, we present our recent developments on a high gradient diamond-based cylindrical dielectric loaded accelerator (DLA). The final goal of this research is to achieve a record accelerating gradient (~ 600 MV/m) in a demonstration of the structure at high power and with accelerated beam. We discuss here a new technology for the development of cylindrical diamond-based waveguides and the design, fabrication and high power testing of a cylindrical diamond-based DLA accelerating structure. The electrical and mechanical properties of diamond make it an ideal candidate material for use in dielectric accelerators: high RF breakdown level, extremely low dielectric losses and the highest thermoconductive coefficient available. Multipacting of the CVD diamond can be suppressed by diamond surface dehydrogenation. A plasma supported Chemical Vapor Deposition (CVD) technology to produce low loss high quality cylindrical diamond layers is presented. Special attention is devoted to the numerical optimization, where the surface magnetic and electric fields are minimized relative to the accelerating gradient and within known metal surface breakdown limits.

INTRODUCTION

Progress towards development of a high gradient diamond-based cylindrical dielectric loaded accelerator (DLA) is presented [1-2]. The principal goal of this project is a development and demonstration of a new type of cylindrical Dielectric Loaded Accelerating (DLA) structure based on a diamond waveguide [2]. Our choice of CVD (Chemical Vapor Deposition) diamond as a loading material will allow demonstration of accelerating gradients as high as 0.5-1.0 GV/m as long as the diamond surface is expected to sustain a 1-2 GV/m breakdown rf field. Diamond has the lowest coefficient of thermal expansion, highest thermal conductivity and extremely low loss tangent ($<10^{-4}$) at Ka-W frequency bands. Multipacting in diamond is a strong function of surface termination and may be suppressed by diamond surface dehydrogenation [2]. Given these remarkable properties, it should come as no surprise that diamonds should find a special place in Advanced Accelerator Concepts development. Note that the CVD process technology, under intense development for the last 20 years, has matured to provide reliable and in many cases affordable high quality components.

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For the cylindrical diamond-based DLA structure, electric fields at the dielectric surface would be less than 1 GV/m for an acceleration gradient exceeding 600-700 MV/m. The proposed diamond-based accelerating structure design will provide the required fields with an electric field to accelerating gradient ratio in the 0.17-0.38 range. The diamond-loaded structure will have a shunt impedance of 150-200 MV/m, well in excess of comparable all-metal structures. In other words, the diamond-based accelerator will require smaller power per unit length for a given acceleration gradient. Our preliminary modeling of the coupling section showed that 60-80 % field ratios can be achieved to support a > 600 MV/m accelerating gradient. The feasibility of making DLA structures high gradient capable is a great advance toward the development of future high gradient accelerators, and the multi-TeV linear collider in particular.

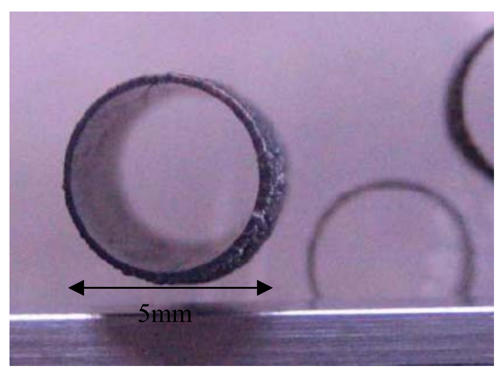

Figure 1: End view of the completed 0.5 mm wall 34 GHz diamond tube.

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 [3]. A planar diamond-based DLA structure was proposed by [4] and studied recently by Omega-P, Inc. [5]. The dielectric loading of this structure was to be made of diamond slabs fabricated using the CVD (chemical vapor deposition) technology similar to that used for RF windows and currently available only for planar geometries. Meanwhile it is known that a cylindrical structure naturally has a larger shunt impedance and a much higher efficiency than a planar structure due to its favorable geometry factor. We present here the first cylindrical 5 mm ID free standing CVD diamond loading, Fig. 1 that demonstrates feasibility of the CVD diamond-based cylindrical Ka-band DLA structure development.

DIAMOND CYLINDRICAL WAVEGUIDE FABRICATION

PECVD Diamond Tube Fabrication.

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 as the result of simultaneous deposition and etching of carbon. Consequently, the deposition rate can be slow, often less than 1µm/hr. Fig. 2 shows the 105-µm diameter diamond tube fabricated with a hot filament CVD reactor. Microwave plasma CVD demonstrated one to two orders of magnitude higher deposition rates and higher hydrogen flux. Remarkably, under high flux of atomic hydrogen the CVD can be developed with high quality even at the rates of >>1µm/hr.

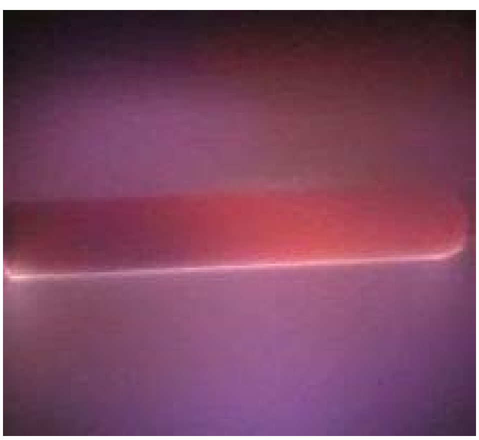

Figure 2**:** Photograph of the 5 mm ID diamond tube growing in the PECVD reactor.

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 to remove from the substrate the intense heat deposited by atomic hydrogen recombination and otherwise transported from the plasma.

Detailed heat transport analysis combined with CVD diamond expertise established viable engineering options for achieving high growth rate and high quality free standing CVD diamond tubes.

The diamond tube PECVD growing process is presented in Fig. 2. Tubes have been fabricated approximately 3 cm in length, 0.7 cm OD and 0.5 cm ID. One of the tubes was released from the substrate and is shown free standing, Fig. 1.

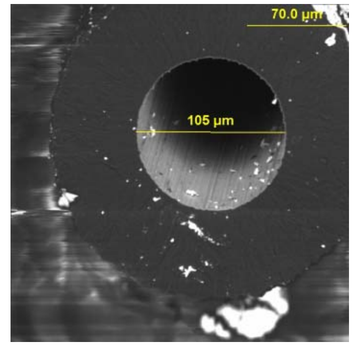

Figure 3: SEM cross-sectional surface images of a hot filament diamond tube of 105-µm diameter, 70 µm wall thickness.

The results confirmed our calculations. The tube diameters can range from 1-10 mm with the tube length up to 75 mm. This allows the development of dielectric-based accelerating structures over wide range of frequencies from 1 GHz up to 100 GHz. It is indicated with high likelihood that with further research our approach will enable production of very high quality diamond tubes suitable for particle accelerators and other microwave devices.

Loss Tangent Measurements

Minimization of losses in dielectric devices is crucial to ensure high efficiency accelerators. The loss tangent is known to be small for diamond. A concern is whether the polycrystalline CVD diamond deviates significantly in its electronic properties from natural or pressure formed artificial diamond. Recent work specifically focused on PECVD diamond materials has shown that the intrinsic lattice loss, the irreducible minimum loss mechanism leads to $\tan\delta$ values several orders of magnitude smaller than measured for polycrystalline samples [2,6].

These higher losses are caused by the electrical conductivity of non-diamond inclusions in the material. Up to frequencies ~150 GHz the loss tangent at constant temperature is found to obey a simple *1/f* scaling law. Diamond is unique among rf/microwave/mm wave dielectrics in that its loss tangent decreases with frequency. In order to quantify the losses in our diamond structures, we obtained samples of planar CVD diamond from CTS Inc. These samples were manufactured using the same reactor and procedures used to deposit the diamond tubes described previously. The results are summarized as follows: (1) 95 GHz, $\tan\delta = 4\times10^{-5}$; (2) 19.25 GHz, the dielectric constant $\varepsilon = 5.69 \pm 0.02$ (5.7 nominal for diamond) and $\tan\delta = (22\pm4)\times10^{-5}$. Using the *1/f* scaling and the results of the 95 GHz and 19.25

GHz measurements we estimate that in the Ka band, $\tan\delta \approx 11\times10^{-5}$.

Numerical Simulations of a Diamond-Based Cylindrical DLA

A DLA structure, unlike a conventional metallic one, admits the unique possibility of sustaining extremely high gradients by using a diamond-based material as the dielectric loading of the guiding structure. Field analysis for diamond-based DLA structures can be carried out analytically. The structure operates at the TM_{01} mode in the Ka band frequency range where its axial wave number corresponds to a phase velocity of *c*.

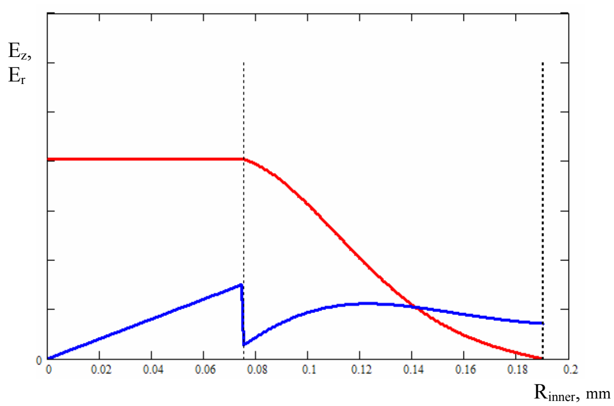

Figure 4: Longitudinal (red) and transverse (blue) electric field profiles normalized to the acceleration gradient E_{accel} for the structure parameters: (a) - ID 1.5 mm, OD 3.79 mm, thickness 1.15 mm.

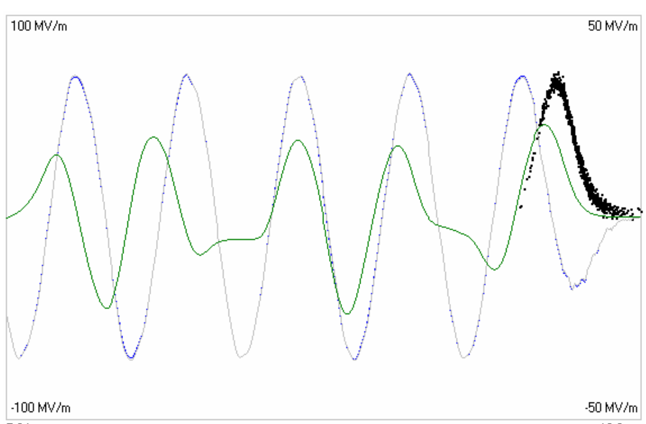

Figure 5: Wakefields (longitudinal: blue, transverse: green) and beam profile for the Ka band dielectric wakefield experiment.

The radial field profiles normalized to the accelerating gradient for the 34 GHz diamond-based structure are presented in Fig. 4. The accelerating gradient is equal to the maximum E_z field magnitude on the inner dielectric (diamond) surface. The transverse E_r /E_{accel} ratio on this surface does not exceed 0.37 at the dielectric surface and 0.17 at the metal one. The structure is assumed to have no vacuum gap between the diamond surface and the copper wall of the accelerator. Note that vacuum gaps can be naturally introduced between the dielectric loading 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.

The Ka band wakefield structure is to be tested at the Argonne Wakefield Accelerator. We assume the nominal AWA drive beam parameters (Q = 60 nC, E = 15 MeV, σ_z = 1.5 mm, σ_r = 0.05 mm, and initial transverse offset = σ_r). The magnitude of the longitudinal wakefield is ~70 MV/m, while the transverse force magnitude for the initial offset as given is ~20 MV/m as shown in Fig. 5. The bunch propagates about 13 cm through the structure before particle losses from deflection of the tail begin to occur, adequate for measurement of the signal without using external focusing to control the beam, Fig. 5.

SUMMARY

A new type of cylindrical Dielectric Loaded Accelerating (DLA) structure based on a diamond waveguide has been presented. Our choice of CVD (Chemical Vapor Deposition) diamond as a loading material is anticipated to allow demonstration of high accelerating gradients up to 1.0 GV/m. Diamond has the lowest coefficient of thermal expansion, highest thermal conductivity and extremely low loss tangent ($<10^{-4}$) at Ka-W frequency bands. Multipacting performance of the CVD diamond can be dramatically suppressed by diamond surface dehydrogenation. We have fabricated using a plasma assisted CVD reactor the first free standing diamond tubes with inner diameter of 5 mm that will enable 34 GHz dielectric-based accelerating structure development. The feasibility of making DLA structures high gradient capable is a significant advance for the development of future high gradient accelerators.

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