WAKEFIELD BREAKDOWN TEST OF A DIAMOND-LOADED ACCELERATING STRUCTURE AT THE AWA

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Abstract

Diamond has been proposed as a dielectric material for dielectric loaded accelerating (DLA) structures. It has a very low microwave loss tangent, the highest available coefficient of thermal conductivity and high RF breakdown field. In this paper we report results from a wakefield breakdown test of (single crystal) diamond-loaded rectangular accelerating structure. The high charge beam from the AWA linac (~70 nC, σ_z = 2 - 2.5mm) was transported through a rectangular diamond - loaded resonator and induced an intense wakefield. A deep (200 um) and narrow (20 um) groove is cut on the diamond surface to enhance the field (~ε times). Electric fields at least of 0.3 GV/m were present on the diamond surface in the groove (decay time ~ 35ns). A surface analysis of the diamond was performed before and after the beam test. No breakdown-type damage was observed on scanning electron microscopy images.

INTRODUCTION

Significant progress has been made in the development and testing of high gradient dielectric accelerating structures (DLA) [1]. As various engineering challenges (breakdown, dielectric losses, efficient RF coupling) have been overcome, the technology of high gradient RF or wakefield driven dielectric loaded structures appears increasingly attractive as a viable option for high energy accelerators. Typical DLA considered in experiments is a cylindrical, dielectric tube with an axial vacuum channel inserted into a conductive sleeve or a rectangular waveguide loaded with planar dielectric pieces. In this paper we will focus on the latter structure. The dielectric constant, thickness of dielectric and the size of a vacuum gap are chosen to adjust the phase velocity of the fundamental mode at certain frequency to the beam velocity ~ c. In the application to particle acceleration, the dominant TM_{01} mode is of main interest. In this paper we report on the wakefield breakdown experiment of a small slab-symmetrical diamond-loaded standing wave structure operating at the TM_{110} – like mode at the Argonne Wakefield Accelerator facility (AWA). In the wakefield breakdown test, the ultra-high charge beam (~100nC) is transported through the structure. The wake generated by the beam is on the order of 100 MV/m (see below). Using some geometry modifications we are able to expose the diamond surface to fields ~ 300 MV/m.

There have been detailed theoretical studies and numerical simulations of DLA structures but experimental progress has only been made relatively recently [2-6]. The advantages and potential problems of using dielectric for loading an accelerating structure are discussed in the above references and are only summarized here. The advantages are: (1) Simplicity of fabrication: The device is simply a tube of dielectric surrounded by a conducting cylinder. This is a great advantage for high frequency (~30 GHz) structures compared to conventional structures where extremely tight fabrication tolerances are required. The relatively small diameter of dielectric devices also facilitates placement of quadrupole lenses around the structures. (2) Dielectrics can potentially exhibit high breakdown thresholds relative to copper, and high shunt impedance. (3) Reduced sensitivity to the single bunch beam break-up (BBU) instability: The frequency of the lowest HEM_{11} deflecting mode is almost always lower than that of the TM_{01} accelerating mode. (4) Easy parasitic mode damping [7]. Potential challenges of using dielectric materials in a high power RF environment are breakdown and thermal heating. (Problems with dielectric charging are easily mitigated by using a dielectric with small dc conductivity).

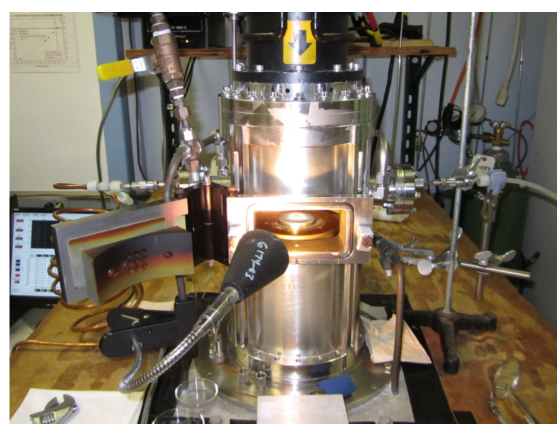

Figure 1: Dedicated reactor for CVD diamond growth.

CVD (Chemical Vapor Deposition) diamond is considered for demonstration of high accelerating gradients; up to 0.5-1.0 GV/m as it is expected that the diamond surface can sustain a 0.5-1.0 GV/m short pulse (~ 10ns) rf field without breaking down. Diamond has the lowest coefficient of thermal expansion, highest thermal conductivity (2×10^3 Wm^{-1} K^{-1}) and extremely low loss tangent ($<10^{-4}$) at Ka-W frequency bands. Secondary emission from the CVD diamond surface can be dramatically suppressed by diamond surface dehydrogenation [8]. CVD diamond has already been successfully used on an industrial basis for large-diameter

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output windows of high power gyrotrons, and is being produced industrially in increasing quantities. Given these remarkable properties, diamond should find numerous applications in advanced accelerator technology development. The CVD process technology is rapidly developing. Euclid Techlabs currently has a dedicated CVD diamond reactor (Fig. 1) for experimental diamond growth. The company also collaborates with several research groups on the development of cylindrical diamond structures (Fig. 2). Planar diamonds are available commercially in various grades including single crystal diamonds (Fig. 1b).

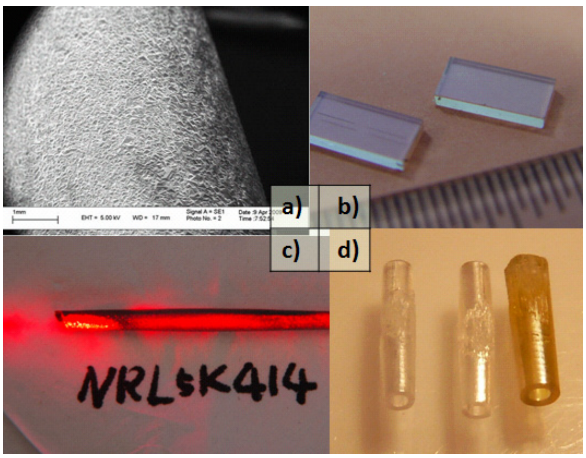

Figure 2: a) SEM image of the cylindrical diamond surface; b) single crystal CVD diamond plates for the breakdown experiment. Two collinear laser cut grooves are visible on the left piece c) long (>1") diamond tube, transparent to light; d) tubes laser cut from single crystal CVD diamonds (~400 microns inner diameter).

Euclid Techlabs had performed two wakefield experiments with diamond – loaded accelerating structures: 250 GHz structure at the Accelerator Test facility of Brookhaven National Laboratory [9] and the wakefield breakdown test of a 25 GHz structure, which is the topic of this paper, at the AWA.

EXPERIMENT DETAILS

Structure design was discussed earlier in [10]; we will briefly go over some key things. Parameters of the structure (Fig. 3, table 1) were determined via parametric simulations with constraint on the thickness of commercially available diamond plates, and the minimal gap size was determined by beam dynamics [11].

To achieve stronger fields on the surface of the diamond two small 20 and 25 micron – wide, 220 micron deep grooves were laser cut on the diamond surface transverse to the beam propagation direction. There is a large field enhancement in these grooves: the field at the entrance to the groove is higher by a factor of ~ ε (5.7) than it would be in its absence [10] – a five time field enhancement!

This happens because of the boundary conditions for the electric field at the surface of dielectric. The tangential component of the electric field should be continuous while the normal component in the vacuum region is ε times larger. For deep and narrow scratches (aspect ratio of 10 and higher) such enhancement is practically ε. As the groove becomes wider and shallower the field enhancement drops.

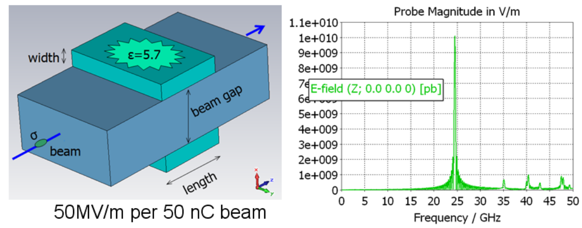

Figure 3: Left: geometry of the diamond resonator: length = 4mm, width = 1.2mm, beam gap = 4mm and overall width = 8mm. Right: spectrum of the wakefield (simulation).

Table 1: Accelerating Parameters of the Structure

Frequency	24.81 GHz
Gradient per 50 nC AWA beam	50 MV/m
Beam gap	4 mm
Diamond width (thickness)	1.2 mm
Structure width	8 mm
Diamond length	4 mm
Diamond dielectric constant	5.7; $\tan(\delta) = 10^{-4}$
Group velocity	36% c
Q, quality factor	2800
r/Q	11.4 kΩ/m

Diamond laser cutting is not a trivial procedure. Multistage cleaning was used to get rid of partial conductivity from carbon deposits. Special technology has been used that allowed removing practically all remaining carbon. SEM measurement confirmed that the laser cutting was successful as well as that target values of groove widths were achieved [11], Fig. 4, 5.

In the experiment we manage to transport 72nC through the structure, which corresponded to at least 300 MV/m on the surface of the groove. The bunch length measurement was not available, so for this estimate we used maximum value of 2.5mm. Shorter bunch length yields higher gradient.

In the experiment we planned to have an RF probe [11], this is standard equipment in wakefield experiment. RF signal from the probe provides the spectrum information and we could monitor the breakdown events by the shape of the RF pulse. However the probe failed during the experiment. We used alumina spacers for the center pin of the probe to prevent it from shorting. Possibly spacers got shifted and changed the impedance of the antenna. Interestingly enough, when the structure was disassembled after the test, alumina spacers looked visible damaged (blackened). We plan to reengineer the pickup probe for the future experiment.

SEM ANALYSIS: BEFORE AND AFTER

We used scanning electron microscopy to analyze the condition of the diamond surface before and after the experiment. Besides the presence of lint the surface did not undergo noticeable changes.

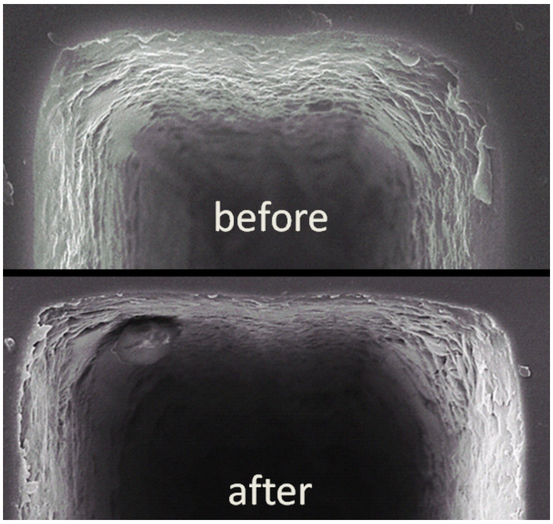

Figure 4: SEM measurement of another location along the groove: top – before, bottom – after.

In the SEM measurement we were able to determine, that the artifacts seen on the "after" pictures, are not permanent surface features. If we stayed long enough zoomed on the object with the SEM electron beam it would charge up and fly away. The origin of these surface contaminants is not clear; but we could see some contaminants on the images "before" as well.

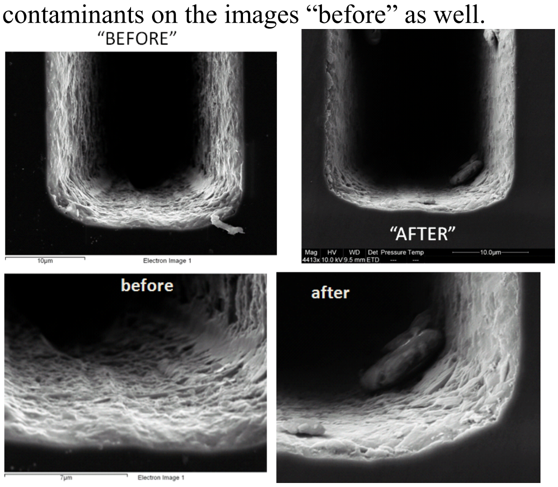

Figure 5: SEM measurement of the groove: right – before, left – after the test; lint is visible. Top: edge of the groove, Bottom: zoom on the surface.

In the future we will try to eliminate a possibility of introducing extra lint on the diamond surface. SEM measurement typically requires conducting surface. Since diamond is not conductive it will charge up during the SEM measurement distorting the image. For the SEM measurement prior to the test we had to coat the sample with few nanometers of gold. After that the sample had to be cleaned again. SEM imaging was performed at Argonne, while cleaning was done at Naval Research Laboratory. It is possible, that during these operations diamond surface picked up some lint.

For the next run we will perform an SEM scan on an uncoated diamond and then immediately install it in the AWA experiment chamber. SEM of the non-conductive sample can be in principle performed, but the image resolution will be sacrificed.

Figures 4 and 5 show some characteristic comparisons of the diamond surface in couple locations of the groove before and after.

SUMMARY AND PLANS

In the post-experiment analysis we did not see evidence of catastrophic breakdown due to RF. There was also no indication of damage from the AWA beam scraping the diamond in microscopic and photoluminescence analysis. We plan to repeat the measurement with repaired RF probe. Breakdown event (if happens) would be visible on the RF trace from the probe. In the follow up test we will change the sample handling procedure to eliminate the possibility of introducing lint.

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