WAKEFIELD BREAKDOWN TEST OF A DIAMOND-LOADED ACCELERATING STRUCTURE

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Abstract

Diamond has been proposed as a dielectric material for dielectric loaded accelerating (DLA) structures [1-3]. It has a very low microwave loss tangent, the highest available thermoconductive coefficient and high RF breakdown field. In this paper we report on progress towards wakefield breakdown test of diamond-loaded rectangular accelerating structure. We expect to achieve field levels exceeding 100 MV/m in the structure using the 100 nC beam at the Argonne Wakefield Accelerator Facility. Single crystal diamond plates produced by chemical vapor deposition (CVD) are used in the structure. A groove is cut on the diamond to enhance the field. Electric field will yield up to 0.5 GV/m on the diamond surface to test it for breakdown. A surface analysis of the diamond is performed before and after the beam test.

INTRODUCTION

Significant progress has been made in the development of high gradient RF driven dielectric accelerating structures (DLA) [4]. 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. The RF structure is very simple - 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 development of the experimental setup of a small standing wave structure operating at the TM_{010} mode for a wakefield experiment at the Argonne Wakefield Accelerator facility (AWA).

There have been detailed theoretical studies and numerical simulations of DLA structures but experimental progress has only been made relatively recently [5-9]. 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 [10]. 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 a small dc conductivity.)

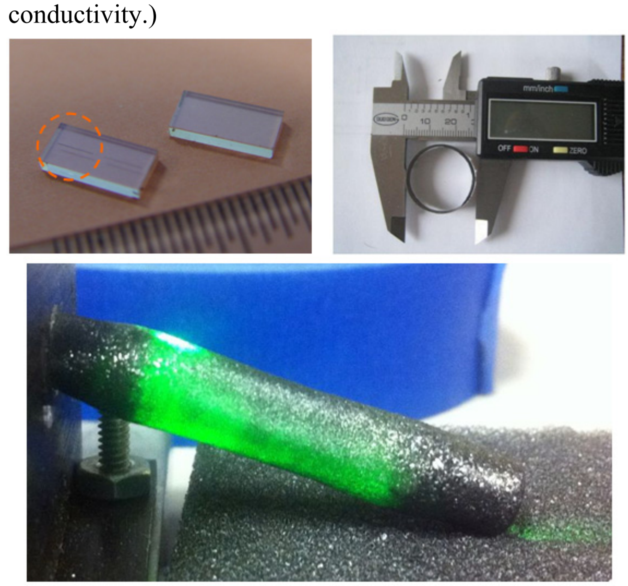

Figure 1: Examples of diamonds for use in accelerating structures. Top left: single crystal planar diamond (Element Six). Top right and bottom (CTS Inc. collaboration with EuclidTechlabs) polycrystalline cylinder diamonds. A green laser illuminates the CVD diamond in the bottom pane.

Our choice of CVD (Chemical Vapor Deposition) diamond as a loading material will allow demonstration of high accelerating gradients; up to 0.5-1.0 GV/m as long as 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 [3, 14]. CVD diamond has already been successfully used on an industrial basis for large-diameter 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 making the CVD diamond fabrication process really fast and inexpensive. Euclid Techlabs collaborates with several companies and research groups on the development of cylindrical diamond structures (Fig. 1(b,c)). Planar diamonds are available commercially in various grades including single crystal diamonds (Fig. 1(a)).

The goal of this research is to perform a first wakefield acceleration experiment using a diamond loaded structure. This experiment will test diamond for breakdown. In this paper we will report on progress [13, 14] towards the experiment at AWA.

PLANAR DIAMOND ACCELERATING STRUCTURE, FIELD ENHANCEMENT

The planar diamond loaded accelerating structure has a simple geometry (Figure 2). It is a short, virtually single mode standing wave structure. Its geometry and accelerating parameters are summarized in Table 1.

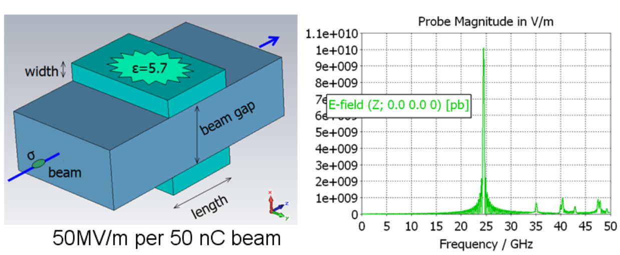

Figure 2: Planar diamond structure geometry (metal boundary is not shown) and wakefield spectrum.

Parameters of the structure were determined via parametric simulations considering the thickness of diamond plates available commercially, and the minimal gap size was determined by beam dynamics (Fig. 7) [11].

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

The wakefield spectrum is a single mode at around 25 GHz. The typical AWA beam is 50 nC and σ_z = 2.5 mm. The bunch charge can be pushed to slightly more than 100 nC, but then it may be problematic to pass such a large amount of charge through the structure. We will try to maximize the amount of charge going through the structure to achieve the highest gradient possible. The AWA beam with 50 nC charge produces a 50 MV/m gradient on axis in the structure. To achieve stronger fields on the surface of the diamond two small 20 and 25 micron – wide, 220 micron deep grooves were inscribed 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 (Fig. 3) – a field enhancement of ~ 450%. 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. We had experience with such field enhancements in the early DLA experiments when several short dielectric tubes were stacked together in DLA [12]. At the tube joints there was enhancement and dark spots were observed on copper surface after high power tests. Making a high aspect ratio groove, which does not go all the way to copper surface, allows isolating and observing the damage only on the diamond in this case.

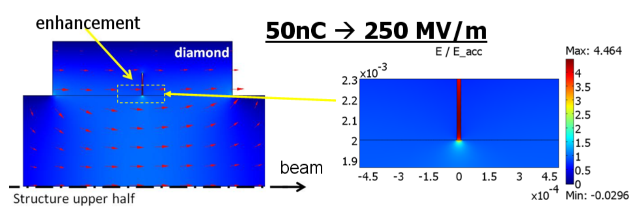

Figure 3: Field enhancement on the diamond's groove, finite element method simulation.

We performed an SEM measurement of the diamond surface before the high power test. The sample images are shown in Figure 4.

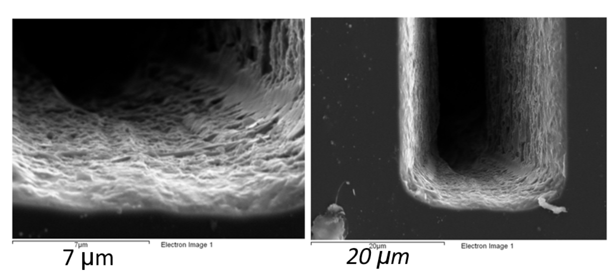

Figure 4: SEM image of the groove recorded prior to the high power experiment.

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 confirms that the laser cutting was successful as well as that target values of groove widths were achieved.

SEM measurements will be repeated after the high power wakefield experiment. We will try to determine and characterize the level of damage of the diamond in the groove location.

PLANNED EXPERIMENT AT THE AWA

The copper holder of diamond structure was specifically designed (Fig. 5) and built to avoid field enhancements everywhere else except the groove on the diamond, in particular in the corner regions of diamond – copper interfaces.

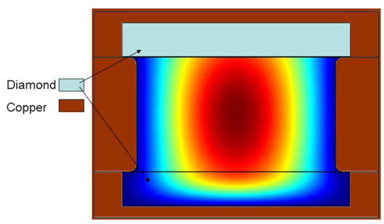

Figure 5: Diamond holder design and simulation. No field enhancement present.

There is also an RF probe (Fig. 6) that samples the wakefield as beam passes through the structure. The Figure shows the bottom half of the structure. A symmetrical upper half piece goes on top of the structure to form a small diamond resonator with a cut-off rectangular waveguide through which the beam is to travel.

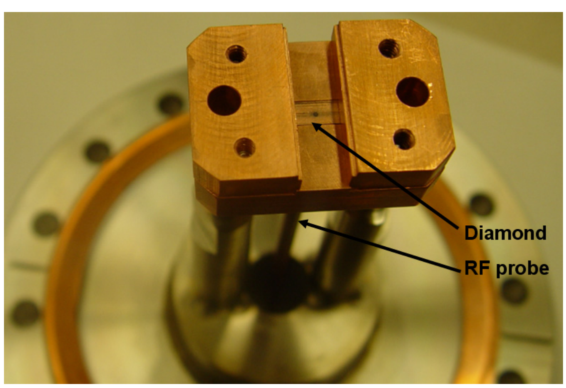

Figure 6: Bottom half of the diamond structure holder assembled on a 6 inch flange.

The holder is mounted on a six inch flange along with the vacuum RF probe. The whole assembly will go into a large cross with view ports. There will be a retractable YAG screen in front of the structure for beam alignment.

Beam delivery was simulated. Figure 7 shows beam transverse envelope as a function of the coordinate along the beamline with the cathode located at z = 0 inside the electron gun. Results of a parametric study of envelope dependence on solenoid strength are shown.

Currently the structure is fully assembled (vacuum cross with the diamond holder, RF probe and YAG screen) and awaiting installation. Originally it was planned to present the first beam experiment results at this conference, but unfortunately due to the AWA expansion activities the experiment had to be rescheduled.

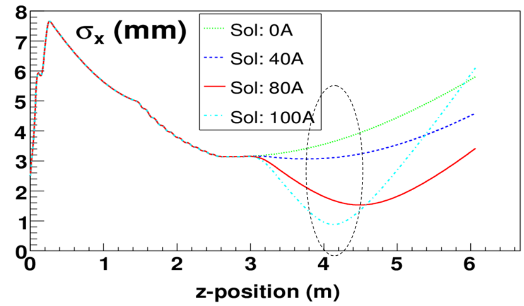

Figure 7: Beam envelope simulations for structure positioning.

SUMMARY

We designed a planar diamond-based structure for a wakefield experiment at Argonne Wakefield Accelerator Facility. In this experiment the surface of the diamond will be exposed to an EM field of a few hundred MV/m strength due to enhancement in a purposely produced groove. SEM measurement of diamond surface was carried out to record its condition prior to the high power test. After the wakefield experiment we plan to repeat SEM measurements to determine the effects of extremely high EM fields on diamond.

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