RF Breakdown Test of Diamond-loaded Resonator for High Gradient Wakefield Accelerator Applications

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Dielectric loaded accelerating structures (DLAs) for wakefield applications is an alternative to conventional corrugated metal structures. These structures have simple geometry, scale up to THz frequencies, and feature higher breakdown threshold. Diamond had been proposed as a loading material for DLAs due to a number of its unique thermal, microwave, and electrical properties. In this paper we report results of a wakefield breakdown test of a single crystal diamond resonator. A large, 72 nC, charge beam with 2.5 mm length, 8.6 kA peak current was transmitted through a diamond-loaded parallel plate resonator, and induced a standing wave with a 70 MV/m electric field strength. One of the diamond plates had a laser cut, 20 μm wide and 200 μm deep groove. That provided an additional ~ 5 -fold field enhancement at edges of the groove resulting in electric gradient as high as 0.3 GV/m on the surface of the groove. SEM and x-ray topography analyses before and after the test did not reveal any structural damage to the diamond resonator plates. This corroborates further promotion of diamond for high gradient wakefield acceleration at high repetition rates.

After the discovery of the Higgs boson at the Large Hadron Collider (LHC), a circular particle accelerator, there is a strong scientific case to build a complimentary machine, a 31 km long International Linear Collider (ILC) [1] for precision measurements of boson's properties and further research. Proposed energy of the electron beam at the interaction point, being still varied in design, is on the order of 1 TeV with about 3 nC charge in a bunch, resulting in 3 kJ energy in a bunch. At Argonne Wakefield Accelerator (AWA) a 160 nC beam gets accelerated to 75 MeV in only 10 m length, resulting in 12 J of energy. Accelerator community knows well how to build high charge / high peak current machines. If there was a method to take the energy from the AWA beam and give it to the ILC beam, it would lead to a significant decrease in the ILC length. The wakefield acceleration is a realization of such process: high current low energy beam decelerates in a structure (corrugated metal pipe, plasma or ceramic-loaded waveguide/resonator) leaving an electromagnetic wake. Low charge high energy beam comes behind and gets accelerated by this wake. One of such examples is a proposed compact linear accelerator (CLIC) [2].

The stronger the wake the more efficient wakefield acceleration scheme works. The question now is how strong of a wake and related heat load/dissipation can a resonator support? Material breakdown

limits the practical length of the wakefield accelerator. State of the art field gradient supported in all-metal structures is 100 MV/m [2]. At AWA, gradients of more than 100 MV/m have been demonstrated in ceramic, DLA, structures. And that is why diamond based DLA structures are important for compact accelerators [3]. Diamond has 1) low microwave loss [4] – making overall energy budget better; 2) low thermal expansion [5] – making resonant frequency of the resonator more stable; 3) the highest available thermal conductivity [6] (transcended only by graphene) – making it possible to work at higher repetition rates; 4) high electrical breakdown threshold (DC breakdown field $\sim >10^9$ V/m was previously reported [7]) – making it possible to go beyond all-metal structures to gradients much higher than 100 MV/m.

This last property is a point of interest in the present study. A wakefield breakdown experiment of a small slab-symmetrical diamond-loaded standing wave structure operating at the TM₁₁₀ mode was performed at Argonne Wakefield Accelerator facility [8]. The planar diamond DLA structure has a simple geometry (Fig.1a). Parameters of the structure were determined and optimized via parametric simulations considering the thickness of diamond plates available commercially. It is a short, virtually single mode standing wave structure. Its geometry and accelerating parameters are summarized in Fig.1 and Table 1. The minimal gap size of 4 mm was determined by beam dynamics simulations; so that largest possible charge can be transported through the gap and the highest possible wakefield can be generated. An expected wakefield signal has a single mode spectrum at approximately 25 GHz. All rationale behind these optimizations was reported earlier [3].

Fig.1. (a) Planar diamond resonator geometry (metal boundary is not shown): length 4 mm; width 1.2 mm; gap for beam transmission 4 mm. (b) Spectrum of a simulated wakefield for given geometry.

Table 1. Parameters of the wakefield resonator structure

Frequency	24.81 GHz
Beam gap	4 mm
Diamond width (thickness)	1.2 mm
Structure width	8 mm
Diamond length	4 mm
Diamond dielectric constant	5.7
Loss tangent $\tan(\delta)$	10^{-4}
Q factor	2800
r/Q	11.4 k Ω /m

The AWA beam [8] at standard conditions would produce 50 to 100 MV/m on-axis gradient in the structure. To achieve stronger fields on the diamond surface, a high aspect ratio groove on the diamond surface was cut transverse to the beam propagation direction to additionally enhance electric field by a factor close to the permittivity of the material. This must happen because of the boundary conditions for the electric field at the surface of dielectric. The tangential component of the electric field should be continuous at the dielectric – vacuum interface while the normal component in the vacuum region is ϵ times larger. For a deep and narrow scratch/groove (aspect ratio of 10 and higher) such enhancement is close to the value of the dielectric constant. As the groove becomes wider and shallower the field enhancement drops. In our particular geometry we obtained field enhancement of ~ 4.5 in simulations. Making a high aspect ratio groove allows isolating the high field region thus making it easier to search for the damage on the diamond surface after the experiment.

Single crystal CVD diamond plates were purchased from Element 6. The 20 microns wide and 200 microns deep grooves were cut by a commercial laser system. Multistage cleaning was used to get rid of any conductive carbon deposits. Resulting resonator plates are shown in Fig.2a. The copper holder (Fig.2b) of diamond structure was specifically designed and built to avoid any field enhancements everywhere else except the groove on the diamond, in particular in the corner regions of diamond/copper interfaces.

In the experiment, an ultra-high charge beam 70 nC, 2.5 mm long was transported through the structure (peak current ~ 8.6 kA). The wake generated by the beam had electric field strength of about 70 MV/m and duration of 35 ns. Due to local field enhancement surface of the grove was subjected to an electric field gradient of more than 0.3 GV/m.

Fig.2. (a) Single crystal CVD diamond plates for the breakdown experiment. Two collinear laser cut grooves are visible on the left piece; (b) Upper half of the diamond resonator assembly put into the vacuum.

To investigate produced damage, we used scanning electron microscopy (SEM) to analyze the diamond surface topography before and after the experiment. Besides the presence of some lint the surface did not undergo noticeable changes. Fig.3a shows a typical comparison of a location around the groove before and after the breakdown test. Use of SEM is a standard approach to look at topographical damage by-products accompanying significant field emission currents and intense x-ray pulse generation seen in real time in RF experiments. Fig.3b demonstrates a breakdown damage of a copper surface at gradients ≤ 100 MV/m in one of our recent experiments [9].

Fig.3. (a) Diamond. Typical SEM images of the groove before (top) and after (bottom); (b) Copper. Typical damage of the copper surface in a breakdown experiments.

Since the plates were high optical quality CVD single crystals, x-ray topography [10] was chosen to assess internal damage. White-beam x-ray topography in Laue (transmission) geometry was performed at 1BM (bending magnet) beamline of the Advanced Photon Source. In this method, a crystal under investigation is exposed to a polychromatic (white) x-ray beam while several Laue reflections are registered simultaneously using an x-ray film placed behind the sample (the direct transmitted beam is blocked by a beam stopper). Each reflection represents a diffraction image (topograph) of the entire crystal (or its large portion). Diamond plates were enclosed in thick kapton to improve stability of the sample in the intense white x-ray beam.

The obtained white-beam x-ray topographs corresponding to several hkl Laue reflections are presented in Fig.4. By comparing the exposed and the unexposed (to 300 MV/m gradient) plates, we intended to reveal an internal structural damage. As seen from Fig.4, such a method presents some limitations in assessment of damage in the crystal lattice due to the high dislocation density in the CVD diamond. Nevertheless, we do see an enhanced damage (black halos) around the grooves. The damage is directional, and it propagates and grows from the center of the plate toward its edges. At the moment, we can only speculate that this damage originated from the laser cutting procedure being accumulated due to long time exposure to the laser beam to achieve the very high aspect ratio of the grooves. It is also unlikely that the damage originated from electron beam scraping: in the experiment the electron beam was not localized, while the revealed damage is localized around the grooves.

Fig.4. Three white-beam x-ray topographs obtained from several Laue reflections: (a) the resonator plate without the groove (i.e. unexposed to 300 MV/m); (b) the resonator plate with the groove.

In conclusion, we did not observe any evidence of catastrophic breakdown in diamond loaded resonator by RF electric field of more than 0.3 GV/m on surface. Breakdown event (if happens) would be visible on the RF trace from the probe as in case with copper (Fig.3b). This corroborates the use of diamond for high gradient wakefield acceleration in excess of 300 MV/m.

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