ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB164

ELECTRODELESS DIAMOND BEAM HALO MONITOR*

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Abstract

Beam halo measurement is important for novel x-ray free electron lasers which have remarkably high repetition rate and the average power. We propose diamond as a radiation hard material which can be used to measure the flux of passing particles based on a particle-induced conductivity effect. Our diamond electrodeless monitor is based on a microwave measurement of the change in the resonator coupling and eigen frequency. For measurements we put a sensitive diamond sample in a resonator that intercepts the halo. By measuring the change in RF properties of the resonator, one can infer the beam halo parameters scanning across the beam to map its transverse distribution. In recent experiments we used a Vertical Beam Test Stand (VBS), delivered DC electron beam of the 20-200 keV energy with the current up to 50 μA, to characterize several diamond samples. We have designed and fabricated a scanning diamond monitor, based on an X-band resonator, which was tested at Argonne Wakefield Accelerator (AWA) with a multi-MeV electron beam.

DIAMOND BLADE CONCEPT

Beam halo has a relatively low charge density. However, for high intensity beams, the actual number of particles in the halo is typically quite large. For this reason, the halo is associated with an uncontrolled beam loss, and must be monitored and mitigated [1]. It is difficult to use typical fluorescent screens to monitor beam halo, since the core of the beam will produce a high signal that can leave the halo signal too small to differentiate. The wire scanners allow beam profile characterization its transverse distribution [2]. Even though refractory metals such as tungsten are used for the wires, they must be replaced from time to time due to beam damage. We consider the use of diamond for a sensing material, because of its extraordinary mechanical, electrical, and thermal properties. Large bandgap, radiation hardness, high saturated carrier velocities, and low atomic number make diamond an attractive candidate for the detection of ionizing radiation and charged particles [3]. Diamond quadrant detectors have been successfully used to measure beam halo at KEK [4]. We propose an electrodeless measurement of the charged particle-induced conductivity of the diamond by means of a microwave resonator reflection measurement [5]. A diamond blade will be used to intercept electrons. The blade will be inside a critically coupled resonator, i.e., when fed microwaves at the resonant frequency, there will be no reflection from the resonator. Due to electron interactions with the diamond, the diamond will become weakly conductive. Because of that, the microwave properties of the resonator will change, and it will start to reflect power at the resonant frequency, a signal whose amplitude will be correlated to the intercepted charge from the halo. We propose a reflection-based measurement to detect beam halo (Fig. 1). A diamond blade/wire scans across the beam. The signal recorded is resonator coupling change due to particle-induced conductivity in diamond. The role of charged particles is to promote bound electrons into the conduction band across the band gap.

* This work was supported by DoE SBIR grant # DE-SC0019642.
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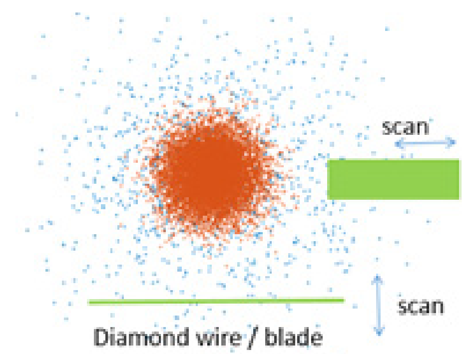

Figure 1: Diamond blade embedded in RF resonator.

Simulations for Resonator with Switchable Diamond

To simulate the response of the device to different current densities in the beam halo, we utilized a simple model of a diamond blade positioned between a 100% reflector and a variable reflector (Fig. 2).

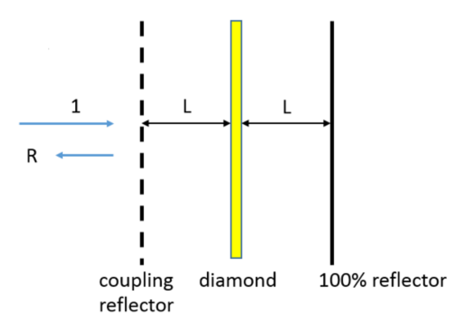

Figure 2: Simulation of resonator S_{11} for beam and no beam for the initial near to critical coupling.

We can adjust the reflectivity of the second reflector to provide critical coupling to this simple resonator. When the coupling is tuned to critical, we can demonstrate a sharp resonance (see Fig. 3). If we change the concentration of electrons in the conduction band from 0 to 10^{12} cm^{-3}, the

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coupling is significantly reduced, i.e., there is a strong reflection from the device. This reflection can be used to measure of the charge passing through the diamond blade. Following results from [3], we assume that there is no dependence on electron beam energy (between MeV and GeV) on how many electrons are promoted into conduction band when electrons pass through diamond.

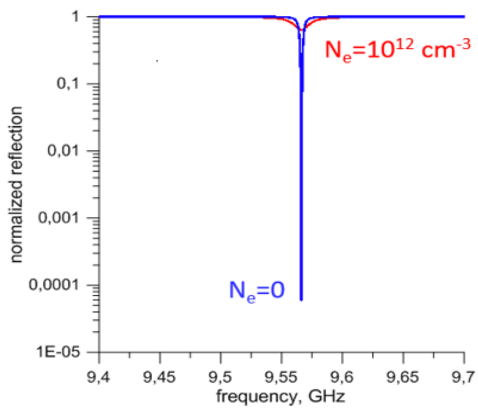

Figure 3: Simulation of resonator reflection for beam (red curve) and no beam (blue curve).

BEAM TESTS OF DIAMOND MONITORS

Tests with DC Beam

To test diamond samples we designed and fabricated resonators where diamonds could be inserted in the center to intercept maximum of beam charge (Fig. 4). We tuned each resonator to provide critical coupling (β≈1) at 6.5-7.5 GHz. The resonators had unloaded Q-factors ~1000, the loaded Q-factors varied from 30 (II-VI) to 200 (Applied Diamond). The resonators were tested at Vertical Beam Stand (VBS) at Euclid Techlabs where we operated with DC beam (up to 200 kV, up to 50 μA current).

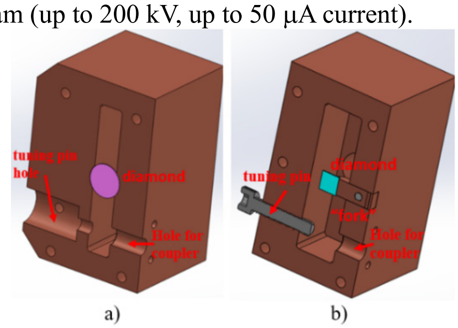

Figure 4: Test resonators: a – copper resonator to accommodate circular diamond sample of II-VI, b – copper resonator to accommodate square samples of Applied Diamond and Element6.

In experiments we could steer the electron beam with the frequency 5 Hz so that a half of time electrons flew at axis and irradiated diamond, the rest 50% of time electron beam was deflected apart not irradiating diamond at all. For the best sample, fabricated by Element6 (single crystal, high-purity diamond, 4.5 mm ×4.5 mm ×0.5 mm), we observed the substantial difference when the beam was on and when it was off.

We plotted dependencies of test resonator signal on current for different beam energies (Fig. 5). According to the figure the signal grows up with current from minimum at -38 dB to maximum, because number of free carriers increases. At 7 μA all curves tend to the saturation, The higher beam energy the higher test resonator signal. That might be caused by increase of electron penetration depth in a diamond.

We also could smoothly deflect the beam. This allowed us to explore the transverse beam profile. As a result we found out the halo for our beam (Fig. 6).

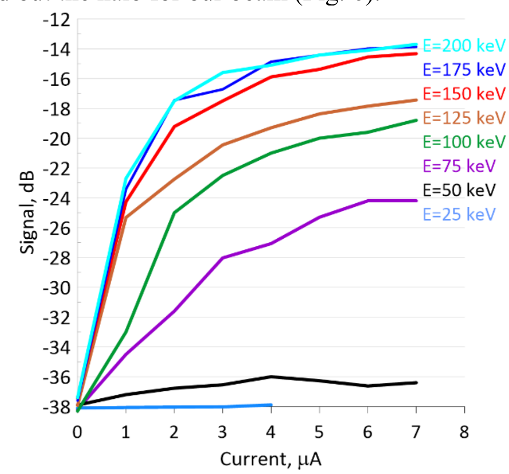

Figure 5: Experimental plot of beam monitor response amplitude vs beam current for several beam energies.

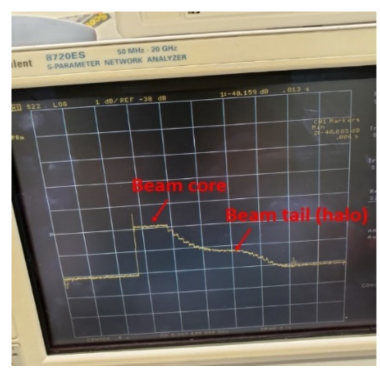

Figure 6: Measured profile of VBS electron beam.

Test with Multi MeV bunches

For experiments at Argonne Wakefield Accelerator (AWA) with multi-MeV picosecond bunches we designed a 1D scanning diamond blade halo monitor (Fig. 7). The main idea of this design was to create an ultra-high vacuum compatible device which would allow to move the diamond resonator in transverse direction by means of a bellow. The device utilized the 4.5" bellow to allow scanning range ±15 mm. The bellow was controllable by a precise motor with a controller. The blade scrapper was mounted in vacuum side at the end of WR112 waveguide. The waveguide was connected to a ceramic RF window which separated ultra-high vacuum part from air.

Figure 8 shows the current design for the monitor resonator. In the Fig. 8a one can see the field structure of the resonator tuned on resonance at 6.8 GHz when there

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are no free carriers in diamond. Reflection from the resonator is near to zero in this case (less then -30 dB). Figure 8b shows the field structure of the same resonator when beam exposure is assumed to be as strong as the concentration of free electrons and holes reaches 10^{14} cm^{-3}. In this regime reflection exceeds 50%.

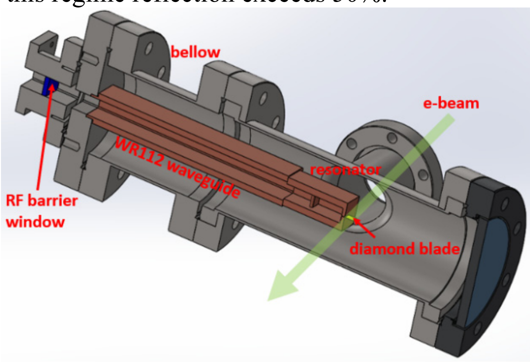

Figure 7: Engineering design of scanning diamond blade scraper halo monitor based on motorized bellow for tests at AWA.

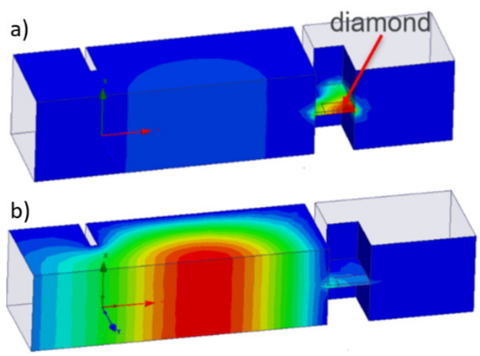

Figure 8: Field structure at resonant frequency 6.8 GHz: a – diamond not exposed by beam (N_e=0), b – diamond exposed by beam (N_e=10^{14} cm^{-3}).

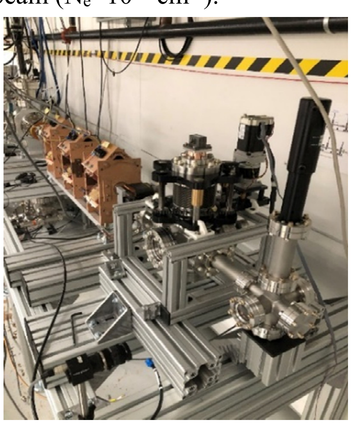

Figure 9: Beam halo monitor installed at AWA beamline.

The monitor installed at AWA is shown in the Fig. 9. In order to calibrate our beam halo monitor, we began the experiment with measurements of signals when electron bunches as well as diamond blade were lined up at the same axis inside the metallic pipe. Figure 10 shows typical oscillograms related to this case. Bunch arrival time corresponded to 2 µs. At this time reflection grew up and relaxed during several microseconds. For bunch charges larger than 200 pC monitor signals saturated.

Then we scanned resonator transversely. This allowed to plot maximum of the monitor response as a function of the monitor position for different bunch charges (Fig. 11). This figure shows that the monitor can reliably detect particles moving ~1 cm far from a bunch core in transverse direction if bunch charge exceeds 1 pC.

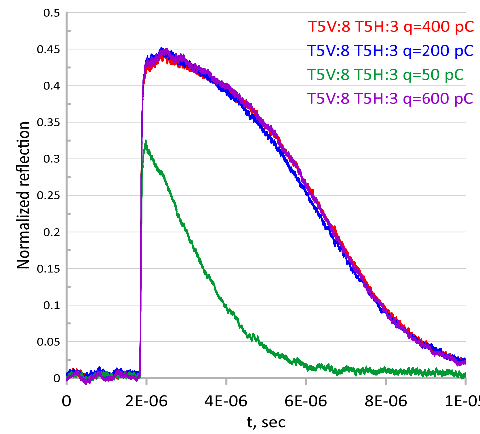

Figure 10: Beam halo monitor response vs time when exposed by bunch coming exactly at diamond blade.

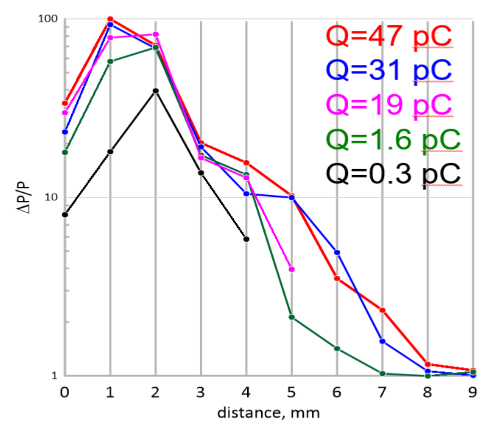

Figure 11: Beam halo monitor response vs transverse shift of diamond blade.

CONCLUSION

We proposed diamond as a radiation hard material which can be used to measure the concentration of passing particles based on a particle-induced conductivity effect. In first experiments we used a Vertical Beam Test Stand, delivered DC electron beam of the 20-200 keV energy with the current up to 50 µA. The experiment showed that detector grade single crystal diamond only can provide high detector sensitivity. We have also designed and fabricated a scanning diamond X-band resonator, which was tested at AWA. In the experiment at AWA we studied sensitivity and of our monitor using multi-MeV, picosecond electron bunches. The obtained results show that the monitor can reliably detect particles flying ~1 cm far from a 1 pC – 600 pC bunch core in transverse direction.

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