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# DIAMOND BEAM HALO MONITOR*

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*Abstract*

Beam halo measurement is important, because novel x-ray free electron lasers like LCLS-II have very high repetition rates, and the average power in the halo can become destructive to a beamline. Diamond quad detectors were previously used for electron beam halo measurements at KEK. Diamond is the radiation hard material which can be used to measure the flux of passing particles based on a particle-induced conductivity effect. However, the quad detectors have metallic contacts for charge collection. Their performance degrades over time due to the deterioration of the contacts under electron impact. We recently demonstrated a diamond electrodeless x-ray flux monitor based on a microwave measurement of the change in the resonator coupling and eigen frequency. We propose similar measurements with a diamond put in a resonator that intercepts the halo. Without electrodes, such a device is more radiation resistant. By measuring the change in RF properties of the resonator, one can infer the beam halo parameters. In a similar manner to traditional beam halo monitors, the diamond plate can be scanned across the beam to map its transverse distribution.

## 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.

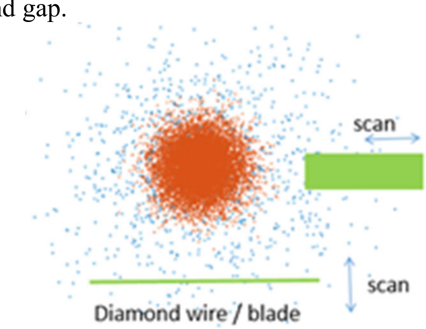


Figure 1: Diamond blade beam halo scanning.

### *Simulations for Scanning Diamond Blade Scrapper Monitor*

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).

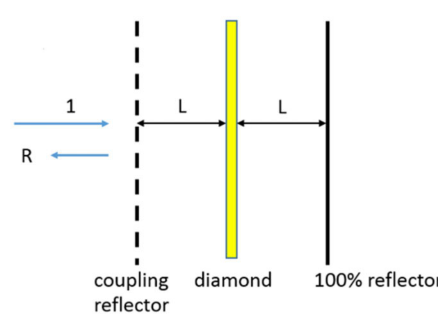


Figure 2: Simulation of resonator $S_{11}$ for beam and no beam for the initial near to critical coupling.

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 concentra-

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tion of electrons in the conduction band from 0 to $10^{12}$ cm$^{-3}$, the 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.

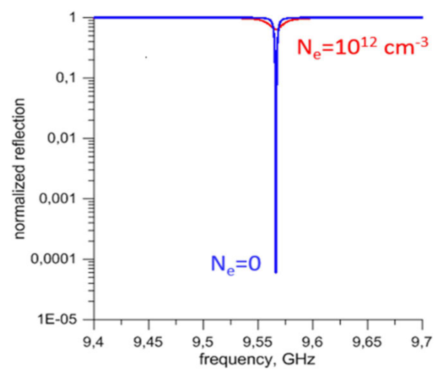



Figure 3: Simulation of resonator $S_{11}$ for beam and no beam for the initial near to critical coupling.

If we scan the effective concentration of carriers in the conduction band of the diamond, $N_e$, and plot the reflection signal as a function of time (see Fig. 4), we observe generally nonlinear response of the resonator. To measure such high concentrations with the test resonator, we first note that the quality factor of this resonator is completely dominated by the conductivity losses in the diamond blade. Therefore, the decay time of a transient measurement (Fig. 4) is fully governed by the relaxation time of the diamond's conductivity.

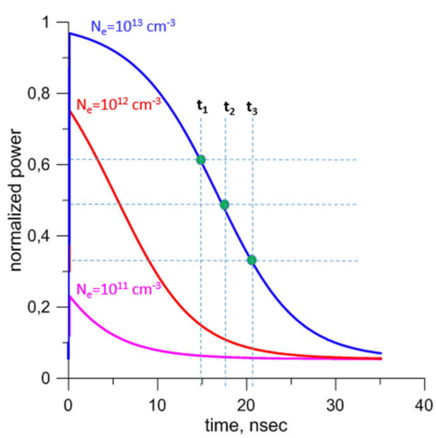



Figure 4: Time response of resonator for different carrier concentrations.

We take a 5-ns relaxation time as a representative time for diamond. The concentration ($N_e$) evolves as $N_0 \times exp(-t/\tau)$, where $\tau$ is the relaxation time. Therefore, during relaxation, $N_e$ decreases and enters a linear region. That is why one can take several test resonator signal points, where the response is linear, for several subsequent times $t_1$, $t_2$, $t_3$. This would allow one to determine $\tau$ as well as $N_e$ at $t=0$.

## BEAM TEST OF DIAMOND SAMPLES

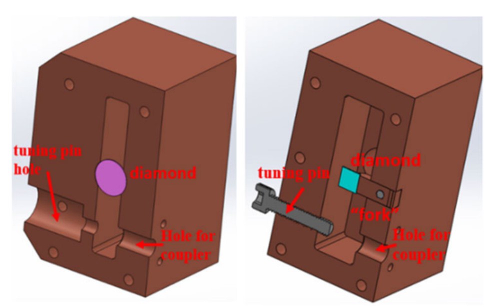
### *X-band Test Resonators*

To test diamond as sensitive elements we purchased several diamond samples for resonators to be installed in VBS (Fig. 5). The first sample (10 mm × 14 mm × 0.3 mm) was produced by Applied Diamonds Inc. (Fig. 5a). The second purchased sample (circular disk ∅8 mm, 0.5 mm thickness) was made by II-VI company and qualified as a detector grade. The third one is a square single crystal sample (4.5 mm × 4.5 mm × 0.5 mm) produced by Element6. In order to compare diamonds, we decided to carry out experiments with simplified resonators where diamonds are located in the center and catch most part of the electron beam. In all resonators samples are irradiated by particles being perpendicular to the beam. Because all the purchased diamonds have different sizes and different shapes, we produced resonators individually for each sample (Fig. 6).


a) b) c)

Figure 5: Diamond samples: a – CVD electronic grade sample from Applied Diamonds Inc., b – detector grade CVD diamond from II-VI, detector grade single crystal diamond from ElementSix.

For the smallest our diamond produced by Element6 we designed a "fork" support to hold the sample securely (Fig. 6b). 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). Figure 6 shows S11 parameter for the tuned resonator with Element6 sample (Q=100).




a) b)

Figure 6: 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.

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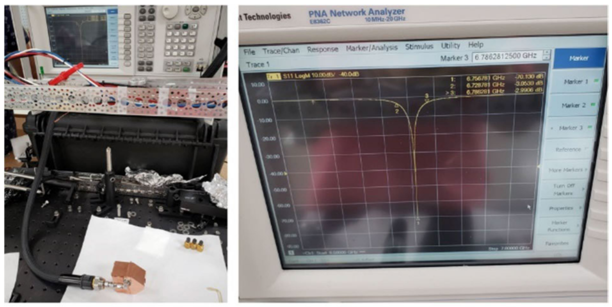
Figure 7 shows low-power measurement setup (Fig. 7a) and S11 parameter for the resonator with built-in Element6 diamond sample (Fig. 7b).



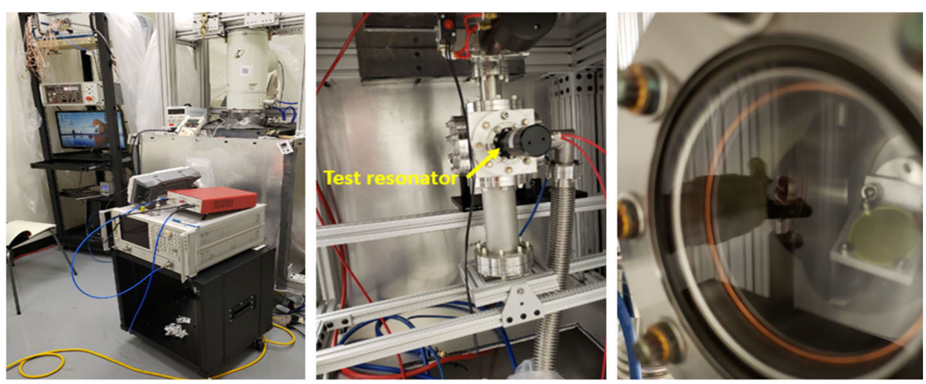
a) b)

Figure 7: Tuning of copper resonator with built-in diamond sample (Element6) before installation at VBS: a – network measurement setup, b – final curve for the tuned resonator.

### *Tests with DC Gun*

For high-power tests we decided to use Vertical Beam Test Stand (VBS) at EuclidTechlabs. The VBS is a DC gun of an electronic microscope delivering 20-200 keV electron beam with current up to 0-50 μA. In VBS the electron beam is accelerated toward the floor, with the compressed air lines for the pneumatic gate valve, focusing solenoid, and finally lead-enclosed experimental beamline following the electron gun. A solenoid provided the ability to focus the electron beam. The data acquisition system was controlled by a PC running LabVIEW. Figure 8 shows the experimental setup (Fig. 8a), the installed tube included a resonator with a sample to be tested (Fig. 8b), and the removable YAG screen upstream the test resonator (Fig. 8c). The YAG screen was mounted on a pneumatic actuator at a 45-degree angle with respect to the beam. In experiments with diamond resonators we could steer the electron beam with frequency 5 Hz so that a half of time electrons fly at axis and irradiate diamond, the rest 50% of time electron beam is strongly deflected not irradiating diamond at all. We tuned beam focus with the condenser lens to get maximum current at YAG screen. Then YAG screen was led out of the tube to measure resonator response by the steered beam.

Figure 9 shows typical oscillogram of the resonator signal with inserted Element6 diamond when the current was as low as 7 μA and beam energy was about higher limit of 200 keV. One can see that RF signal is modulated by the incoming electron beam with the frequency 5 Hz. Even with this small current the measured signal was pretty recordable. No beam signal was as low as -38 dB. The higher beam current generated the stronger response signal. The highest recorded signal for 7 μA current and 200 keV voltage was as high as -13 dB.




a) b) c)

Figure 8: VBS test stand with installed test resonator: a – overall view, b – test resonator in vacuum chamber installed in the bottom, c – view through quartz window to YAG-screen.

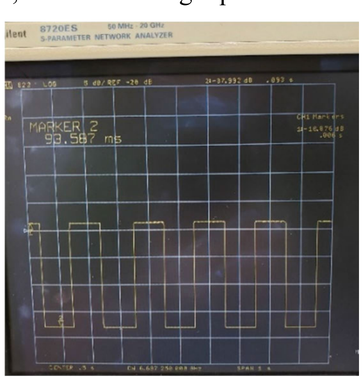



Figure 9: Monitor time response for 5 Hz steered beam.

Because the resonator with Applied Diamond sample showed less signal in comparison with Element6 diamond resonator we kept going to measure the resonator with Element6 diamond. We plotted dependence of test resonator signal on current for different beam energies (Fig. 10). 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. This effect is limited by diamond thickness. That can explain why near 200 keV beam energy test resonator signal stops to increase, the curves for 175 keV and 200 keV are almost coincident.

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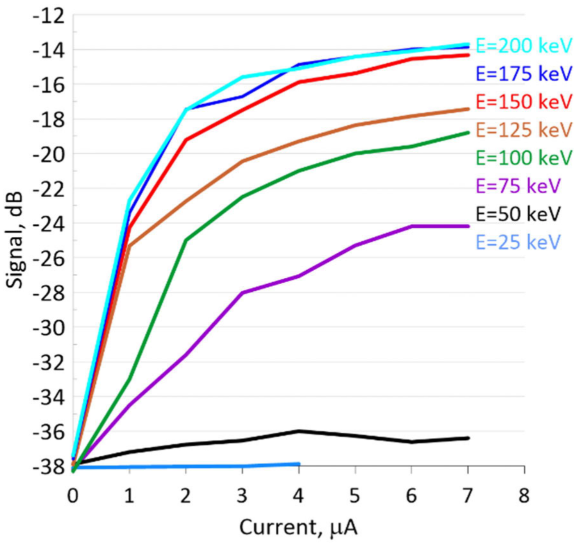


Figure 10: Experimental plot of beam monitor response amplitude vs beam current for several beam energies.

## DESIGN OF HALO MONITOR FOR TEST IN AWA

We have been designing the scanning diamond blade scrapper halo monitor to be tested at Argonne Wakefield Accelerator (AWA) with multi-MeV electron beam (Fig. 11). The main idea behind this design is to create an ultra-high vacuum compatible device which would allow to investigate all physical properties and to proceed to the final beam halo monitor fabrication. Figure 12 shows the current design for the monitor resonator. In Fig. 13 one can see $S_{11}$ parameter for the designed monitor. The device utilizes the 4.5" bellow to allow 1D scanning range ±15 mm. The bellow is controllable by a precise motor with a controller. The blade scrapper is mounted in vacuum side at the end of WR112 waveguide. The waveguide is connected to a ceramic RF window which separates ultra-high vacuum part from air.

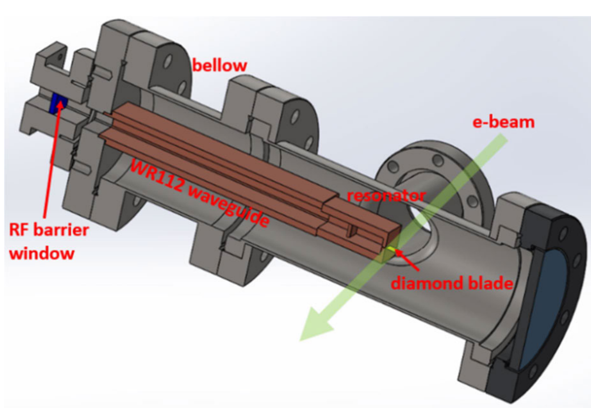


Figure 11: Engineering design of scanning diamond blade scraper halo monitor based on motorized bellow for tests at AWA.

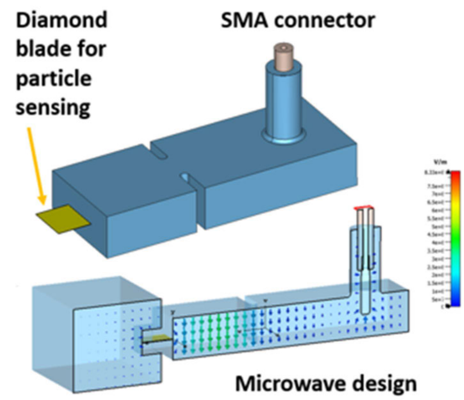


Figure 12: RF design of a diamond blade halo detector resonator with RF connector.

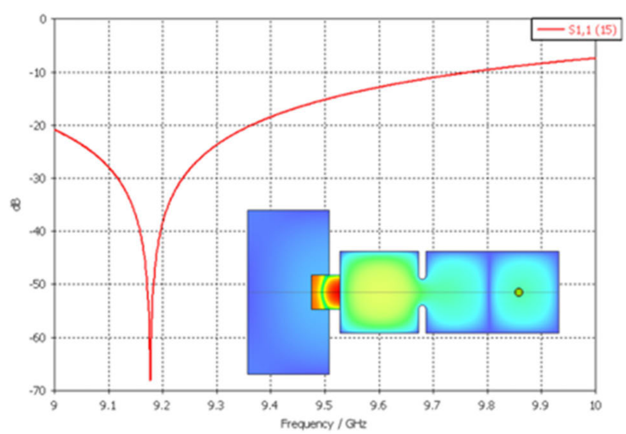


Figure 13: Reflection simulation and field distribution in the resonator.

## CONCLUSION

We proposed diamond blade concept and developed engineering design for halo scanning measurements. The carried out VBS tests allowed to select the best diamond sample for beam halo tests with multi-MeV beam at AWA. We plan to complete design of the remotely steering monitor prototype and fabricate it by November. The AWA tests are planned by end of this year.

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