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AN ELECTRODLESS DIAMOND BEAM MONITOR*

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Abstract

Being a wide-band semiconductor, diamond can be used to measure the flux of passing particles based on a particle-induced conductivity effect. We recently demonstrated a diamond electrodeless electron beam halo monitor. That monitor was based on a thin piece of diamond (blade) placed in an open high-quality microwave resonator. The blade partially intercepted the beam. By measuring the change in RF properties of the resonator, one could infer the beam parameters. At Argonne Wakefield Accelerator we have tested 1D and 2D monitors. To enhance the sensitivity of our diamond sensor, we proposed applying a bias voltage to the diamond which can sustain the avalanche of free carriers. In experiment carried out with 120 kV, ~1 μA beam we showed that the response signal for the avalanche monitor biased with up to 5 kV voltage can be up to 100 times larger in comparison with the signal of the same non-biased device.

INTODUCTION

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]. In our proposal, 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. Previously we proposed an electrodeless measurement of the charged particle-induced conductivity of the diamond by means of a microwave resonator reflection measurement [2-3]. A diamond blade is used to intercept electrons. The blade is inserted 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 becomes weakly conductive. Because of that, the microwave properties of the resonator change, and it starts to reflect power at the resonant frequency, a signal whose amplitude is correlated to the intercepted charge from the halo.

2D BEAM HALO MONITOR

The Figure 1 shows the overall view of the 2D scanning beam halo monitor (BHM) that photograph is shown in Fig. 1. 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 motor allows to move the resonator with diamond blade across beam +/- 1 inch in each X- or Y- direction. The resonator itself has the same design which was used for the 1D monitor version [3]. The resonator (f=6.7 GHz, Q~400) relates to the copper WR112 waveguide which is located inside the motorized bellow. A ceramic RF window separates ultra-high vacuum part of the monitor from air.

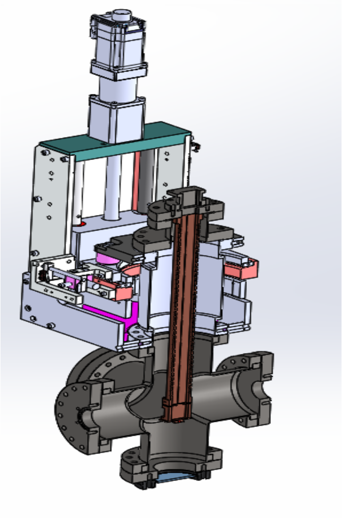

Figure 1: Engineering design of the 2D scanning beam halo monitor.

The 2D BHM monitor was tested at AWA with MeV level electron beam (Fig. 2). The preliminary results from the recent experiment with the 2D BHM at AWA demonstrate good coincidence of the beam maps plotted with the YAG screen and with our monitor (compare Fig. 3 and Fig. 4 respectively). Remarkably, the halo monitor was capable to show so small signals that were not visible for the conventional YAG screen. More accurate data processing is coming to eliminate BHM nonlinear response and to mitigate diamond blade size influence.

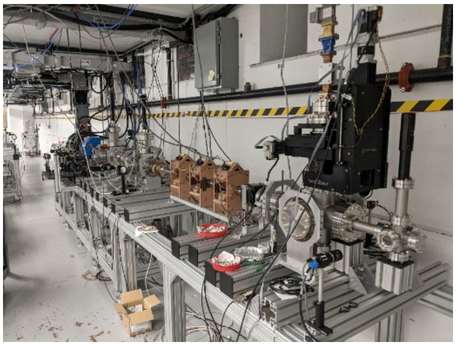

Figure 2: 2D scanning beam halo monitor at AWA beamline.

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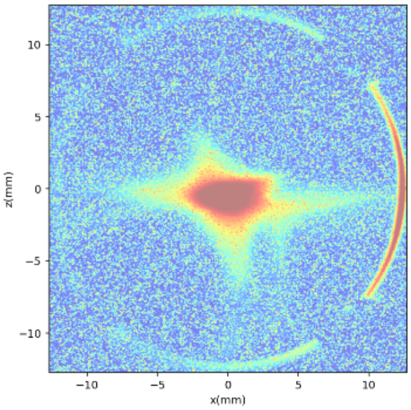

Figure 3: YAG screen image of measured beam.

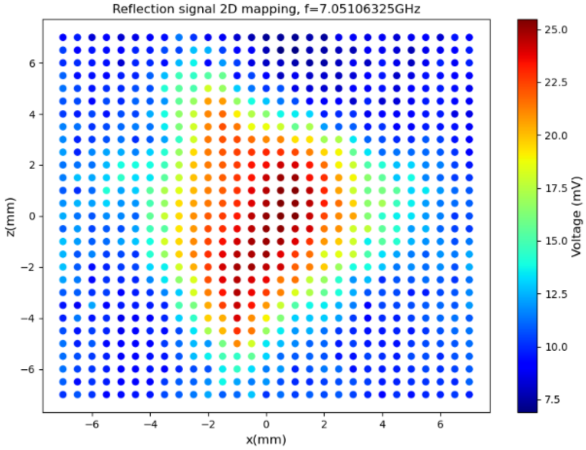

Figure 4: 2D map of beam plotted by means of the halo monitor.

AVALANCHE BEAM MONITOR

If one induced free carriers in diamond and forced its to drift in DC electric field, these particles due to collisions could create new secondary particles. This scenario is considered as an avalanche that can involve much higher concentration of the particles in comparison with the non-biased case. Biased diamond detectors exist and show ~10 times sensitivity enhancement. Applying of a bias voltage makes sense for electrodeless detectors as well.

For this purpose, we designed an avalanche Diamond Beam Monitor (ADBM) at 8.5 GHz. It was based on an open resonator consisted of two copper plates (Fig. 5). The existing diamond sample (single crystal CVD 4.5 mm×4.5 mm×0.5 mm) from Element6 must be installed between these copper plates to be at a bias voltage (up to 10 kV). The copper plates maintain the RF resonator itself, and simultaneously sustain the applied DC bias. To get a high Q-factor like a conventional closed resonator has, we proposed an RF design based on a ring-like choke, which should prevent RF power leakage out of the resonator. The diamond blade faces the electron beam. The SMA coupler is aimed to provide the necessary coupling β to equal 1 when the resonator is not exposed by the beam. The field structure at resonant frequency 8.52 GHz is shown in Fig. 6. The S_{11} parameters for the non-exposed resonator and for the resonator exposed by the beam carrying 10^{14} cm^{-3} electron concentration (with avalanche taken into account) in the diamond are shown in Fig. 7. One can see that the given electron concentration causes strong decoupling of the resonator.

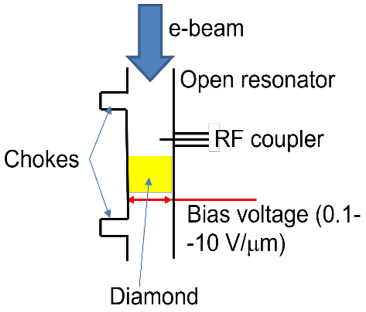

Figure 5: Avalanche diamond beam monitor.

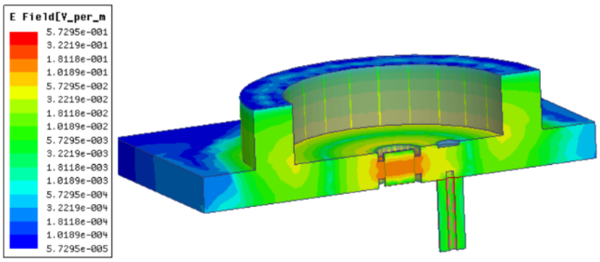

Figure 6: E-field structure at resonant frequency when no beam (logarithmic scale).

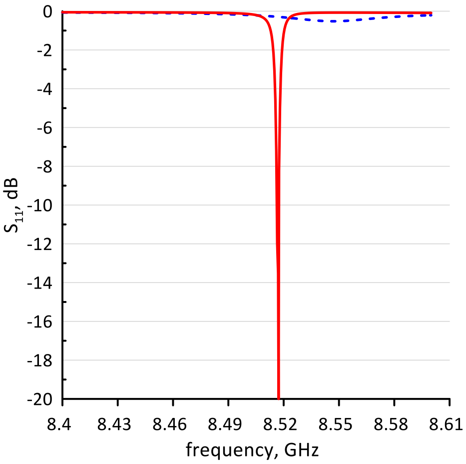

Figure 7: S_{11} parameter when no beam (solid red) and with beam exposure (dashed blue).

We decided to carry out experiment at Vertical Beam Stand (VBS) at Euclid Techlabs LLC. Before to install the ADBM we carried out low-power measurements of the resonator (Fig. 8). We tuned the resonator so that resonator's response without beam exposure at the resonant frequency was as low as -47 dB (Fig. 9). The measured Q-factor was as high as 800.

For the first test at VBS we used 120 kV beam with about 1 µA -5 µA current. The current was intendedly modulated with the frequency 5 Hz so that during 100 ms our resonator was exposed by the beam and was not during the rest

100 ms. We could observe signal increase when we applied the bias voltage. Unfortunately, we could not apply voltage higher than 0.7 kV because for higher bias voltage we again observed permanent discharges so that the discharge threshold dropped almost two times in presence of the beam.

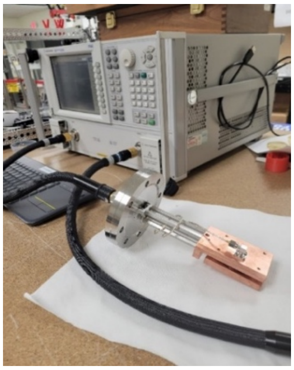

Figure 8: Measurement of S_{11} parameter.

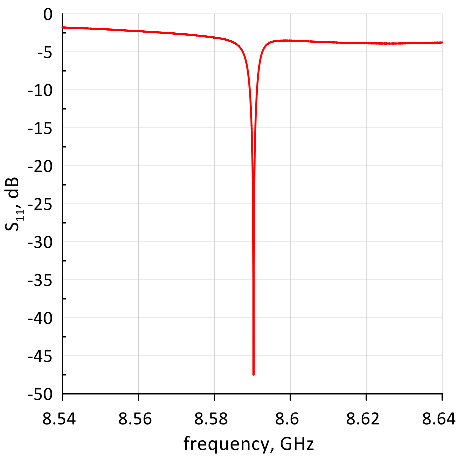

Figure 9: S_{11} parameter for ADBM resonator vs. frequency.

To overcome the mentioned discharges, the second experiment was carried out with AC voltage supply. That power supply could produce the sinewave signal at frequency 100 Hz. Remarkably, all breakdowns disappeared in this AC regime. This allowed to assume that breakdowns were caused by partial charging of the diamond surface. Typical oscillograms are plotted in Fig. 10. The blue curve corresponds to the non-biased case and plays a role of the reference. When we applied the bias like it is shown with the red curve in the Fig. 10 we could observe ripples at the top of the curve. These ripples exactly corresponded to the bias voltage pulse shape. The green curve (about 3 kV bias) describes near to saturation case with the largest avalanche effect.

In the Fig. 11, we tried to summarize results of measurements for different bias voltages ant two beam energies, 100 keV and 115 keV. We plotted maximum of signals only. One can see that at voltages less than 400 V the avalanche effect is weak. Then response signal grows up very fast. At voltage higher than 1 kV the response signal tends to saturation. Remarkably, the enhancement of the signal with respect to the non-biased case reaches more than 100 times. This result inspired us to develop an avalanche 2D BHM.

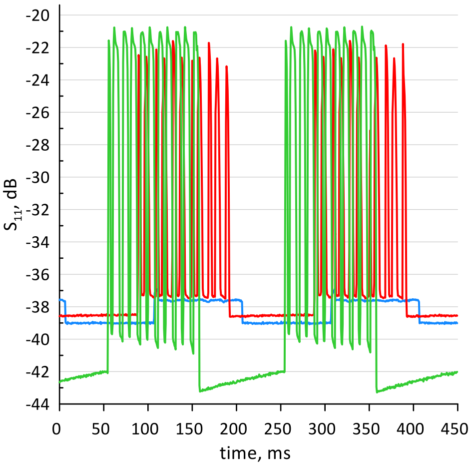

Figure 10: Typical measured oscillograms for 4 µA 115 keV beam: no bias voltage (blue curve), 1.2 kV bias voltage (red), and 2 kV bias voltage (green).

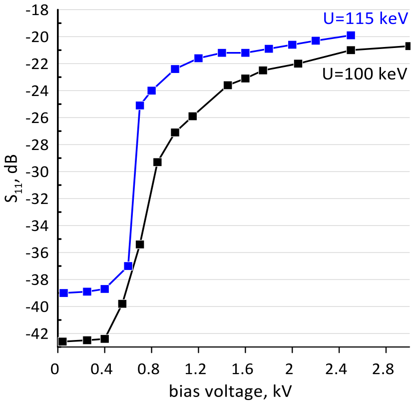

Figure 11: Beam monitor response signal vs. applied bias voltage.

CONCLUSION

In the experiment with the ADBM biased with ~3 kV AC voltage we have shown that the sensitivity of the diamond detector based on RF technology could be increased by factor ~100 times in comparison with the non-biased device. We plan to design and test at AWA a new modification for the 2D BHM in order to allow bias voltage at diamond.

REFERENCES

[1] S. Liu *et al.*, “In Vacuum Diamond Sensor Scanner for Beam Halo Measurements in the Beamline at the KEK Accelerator Test Facility,” *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 832, pp. 231-242, 2016. `doi:10.1016/j.nima.2016.06.122`

[2] S. V. Kuzikov *et. al.*, “Diamond Beam Halo Monitor”, in *Proc. IBIC’20*, Santos, Brazil, Sep. 2020, pp. 197-201. doi:10.18429/JACoW-IBIC2020-WEPP38.

[3] S. V. Kuzikov *et al.*, “Electrodeless Diamond Beam Halo Monitor”, in *Proc. IPAC’21*, Campinas, Brazil, May 2021, pp. 2990-2993. `doi:10.18429/JACoW-IPAC2021-WEPAB164`