Charge Collection in the MERIT Diamond Detectors

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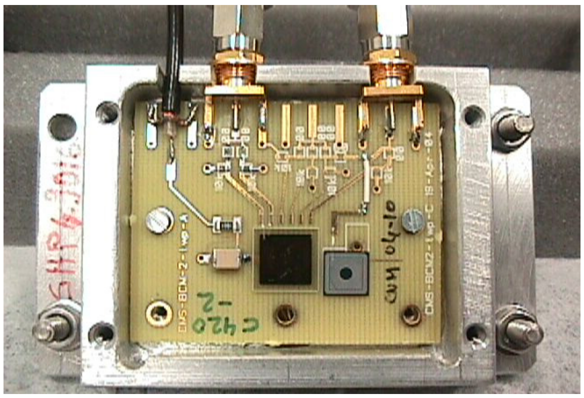
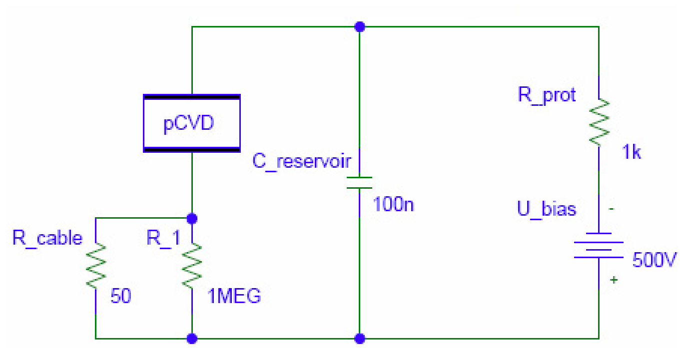
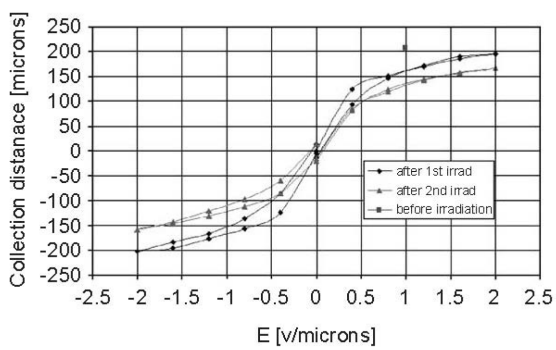
The polycrystalline diamond detectors used in the MERIT experiment have been described in [1, 2]. Each detector was 7.5×7.5 mm^2 in area, 0.5 mm thick, and mounted on a circuit board as shown in the photograph below. The circuit diagram is also shown below.





The efficiency of charge collection as a function of the bias voltage is illustrated below (from [2]). The MERIT detectors used a bias field of 1 V/μm, *i.e.*, 500 V.[1]



The capacitance of the diamond detector itself was about 6 pf, small compared to the 100-nf capacitance of the reservoir.

The charging time constant of the detector was $\tau = R_{\rm prot} C_{\rm reservoir} = 10^3 \cdot 10^{-7} = 10^{-4}$ s $= 100$ μs.

When operated at a bias of 500 V, the maximum signal charge that could be delivered in a time small compared to τ was $Q = V C_{\rm reservoir} = 500 \cdot 10^{-7} = 5 \times 10^{-5}$ C $\approx 3 \times 10^{14}$ electrons.

A minimum-ionizing particle normally incident on the detector generates about 18,000 electron-hole pairs. Hence, it took roughly $3 \times 10^{14} / 2 \times 10^4 = 1.5 \times 10^{10}$ minimum ionizing particles to fully drain the charge on the detector in a time small compared to τ.

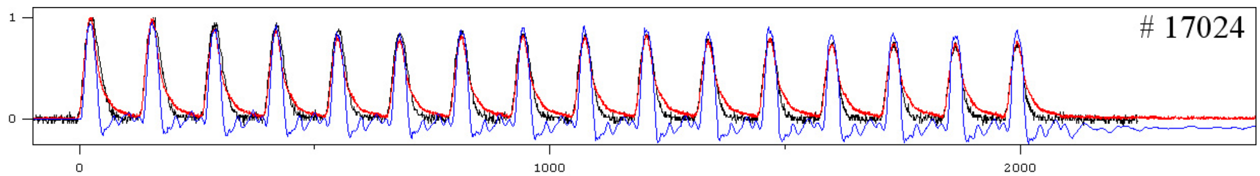
[1] In case the detector is exposed to a steady rate of ionizing particles, such that a steady current I is developed, then the voltage drop across the detector would be $\Delta V = 500 - I(R_{\rm prot} + R_{\rm cable}) = 500 - 1050I$. The figure above indicates a 30% loss of efficiency (for an "unirradiated" detector) if ΔV falls to half nominal, *i.e.*, to 250 V. In this case the average detector current would be about 250 mA.

The diamond data from many MERIT beam pulses suggest that perhaps 10% of the charge on the detector was drained away, which would require about 1.5×10^9 particles to have passed through the detector during the pulse.

MARS simulations of the MERIT experiment [3] suggest that the particle flux through the diamond detectors at 10° to the beam was about 5×10^{-5} per primary proton. In this case, it would take about $1.5 \times 10^9 / 5 \times 10^{-5} = 3 \times 10^{13}$ protons to cause a 10% drainage of the charge, and a consequent "sag" of the signal by the end of the pulse.

Since the highest number of protons per pulse during the MERIT experiment was 3×10^{13}, some "sag" of the diamond detector signals was to be expected.

For example, the last pulse of the experiment, no. 17024, had $2.9 \times 10^1 3$ protons over 16 bunches. Normalized signals from this shot are shown below (from [4]): blue = beam current transformer, red = diamond detector L20, black = scintillating fiber.



While the diamond detector appears to "sag", so do also the fiber signal, and the peak height of the beam-current-transformer pulses.

In, addition, the baseline of the beam-current-transformer signal appears to "sag". If we correct for this effect, the beam-current-transformer data suggest that all 16 bunches of this pulse had roughly the same number of protons. Then, we would interpret the diamond detector and the scintillating fiber as having "sagged" in almost identical manners. The difficulty with this interpretation is that we have no understanding of how/why the scintillating fiber signal would have "sagged" this way.

A Appendix: Test in a NSLS X-Ray Beam

T. Tsang has recently tested one of the MERIT diamond detectors in the X15A x-ray beam line at the BNL National Synchrotron Radiation Light Source [5]. This beam has a nominal x-ray energy of 19 keV, and the beam power on the detector was nominally 4 W, *i.e.*, nominally 1.3×10^{15} x-rays/s.

The diamond detector is 0.5-mm thick, with a density of 3.52 g/cm^3 (Table 4.3 of [1]), and so presented 0.176 g/cm^2 to the beam. According to Fig. 27.16 of [6] the absorption length in carbon for 19-keV x-rays is 2 g/cm^2, so about $0.09 \times 1.3 \times 10^{15} = 1.1 \times 10^{14}$ x-rays/s were absorbed by the detector. Since it takes 13 eV to generate one electron-hole pair, each absorbed x-ray generated about 1,460 electrons. The current in the detector should then be 1.6×10^{17} e/s ($\approx$ 10 mA). T. Tsang reported the average current in the detector as 20 mA.

A steady current of 20 mA implies a drop of about 10 V in the detector bias voltage, and a loss of efficiency of only 1-2%, according to the figure on the preceding page. Hence, the 4-Watt x-ray beam would not cause the diamond detector to "sag" significantly when operated at 500 V.

References

[1] I. Efthymiopoulos, A. Fabich and M. Palm, *Development of a Particle Flux Detection System for the MERIT High-Intensity Target Experiment at CERN*, CERN AB-Note-2008-xxx ATB (2008),
http://www.hep.princeton.edu/~mcdonald/mumu/target/Palm/MPalm_AB_note.pdf

[2] L. Fernandez-Hernando *et al.*, *Development of a CVD diamond Beam Condition Monitor for CMS at the Large Hadron Collider*, Nucl. Instr. and Meth. **A552** 183, (2005),
http://puhep1.princeton.edu/~mcdonald/examples/detectors/fernandez-hernando_nim_a552_183_05.pdf

[3] S. Striganov, *Particle flux simulations* (June 11, 2008),
http://www.hep.princeton.edu/~mcdonald/mumu/target/Striganov/flux-evo061108.pdf

[4] T. Tsang, *Comparisons of Scintillating Fiber, Diamond Particle Detector and Beam Current Transformer* (Nov. 11, 2009),
http://www.hep.princeton.edu/~mcdonald/mumu/target/Tsang/tsang_110909.pdf

[5] T. Tsang, *Response of diamond particle detector using x-ray injection @ NSLS-X15A* (Feb. 9, 2010),
http://www.hep.princeton.edu/~mcdonald/mumu/target/Tsang/tsang_021710.pdf

[6] Particle Data Group, *Passage of particles through matter*,
http://pdg.lbl.gov/2009/reviews/rpp2009-rev-passage-particles-matter.pdf