Snowmass2021 Letter of Intent: 3D Diamond Detectors

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The radiation levels of the High-Luminosity-LHC (HL-LHC) are expected to be a large challenge for the future detectors. By 2028 experiments must be prepared for an instantaneous luminosity of $7.5 \cdot 10^{34}$ cm^{-2} s^{-1} and charge particle fluxes of GHz/cm^2. In this environment the innermost tracking layer at a transverse distance of 30mm to the interaction point will be exposed to a total fluence of greater than $2 \cdot 10^{16}$ n_{eq}/cm^2 [1]. After the doses expected in the HL-LHC, all detector materials will be trap limited with the average drift distance a free charge carrier travels before they get trapped below 50 μm [2].

3D sensors with electrodes in the bulk of the sensor material were first proposed in 1997 [3] in order to reduce the drift distance the charge carriers must travel to reach an electrode to much less than the sensor thickness. In order to achieve this goal a series of alternating + and - electrodes perpendicular to the read out face were created in the bulk detector material. This idea is particularly beneficial in detectors with a limited distance free charge carriers travel, such as trap dominated sensor materials like heavily irradiated silicon and pCVD diamond, where the observed signal size is related to the mean free path divided by the drift distance. Under these circumstances one gains radiation tolerance (larger signals) by keeping the drift distance less than the mean free path. With the 3D geometrical structure, charge carriers drift inside the bulk parallel to the surface over a typical drift distance of 25-100 μm instead of perpendicular to the surface over a distance of 250-500 μm.

The RD42 collaboration has studied novel 3D detector designs in diamond, to extend the radiation tolerance of diamond to fluences greater than 10^{17} $hadrons/cm^2$ exceeding the HL-LHC doses. The detector design places column-like electrodes inside the detector material using 130 fs laser with a wavelength of 800 nm. After focusing to a 2 μm spot the laser has the energy density to convert diamond into an electrically resistive mixture of different carbon phases [4]. A Spatial Light Modulator (SLM) [5] was used to correct spherical aberrations during fabrication. This helped to achieve in 50 μm x 50 μm cells a high column yield of $\gtrsim$99.8%, a small column diameter of 2.6 μm and a resistivity of the columns of the order of 0.1-1 Ωcm. In this detector geometry the drift distance an electron-hole pair must travel to reach an electrode can be reduced below the mean free path of an irradiated sensor without reducing the number of electron-hole pairs created. In a detector with 25 μm x 25 μm cells the maximum drift distance for charge carriers which go into the saddle point region is 25 μm and 17.5 μm for charge carriers which avoid the saddle point.

The goal of this research project is to create a detector which is essentially immune to radiation doses at the level of 10^{17} $hadrons/cm^2$. Our initial test have shown that after 3.5×10^{15} n/cm^2 the 3D geometry with 50 μm x 50 μm cells had >3x less charge loss than a planar diamond detector after normalizing both unirradiated devices to a relative charge of 1. We note the charge in the unirradiated 3D device is twice as large as that in the planar device. So in addition to having twice the charge the 3D device also has >3x less damage due to the shorter drift distance. In order to achieve the 10^{17} hadrons/cm^2 goal we propose to complete the design of 3D diamond devices with 25 μm x 25 μm cells and test these devices after irradiation of 10^{17} hadrons/cm^2.

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