6 Progress Toward a Solid-State Directional Dark Matter Detector

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6.1 Introduction

Next-generation Weakly Interacting Massive Particle (WIMP) dark matter (DM) detectors will soon encounter the "neutrino fog," where solar neutrino backgrounds obscure dark matter signals [86]. Diamond-based directional detectors offer a potential solution by exploiting the differing angular distributions of neutrinos and WIMPs, allowing background rejection through detailed imaging of nuclear recoil damage tracks paired with conventional diamond-based real-time event detection technology [7–9]. Building upon our contribution to MDνDM 2024 [87], we outline recent progress at the University of Maryland Quantum Technology Center (QTC) towards demonstrating the technical capabilities required for such a large-scale directional DM detector, focusing on three critical areas: experimental validation with ion-implanted damage tracks, particle track simulation, and advances in imaging methodologies, specifically the light sheet quantum diamond microscope (LS-QDM).

6.2 Experimental studies of ion-induced tracks in nitrogen-rich diamond

As a first step toward establishing the detectability of individual nuclear recoil damage tracks, we conduct experimental investigations of single-ion-induced damage tracks in mm-scale diamond samples. Precision implantation of ∼1 MeV carbon ions into nitrogen-rich Type 1b HPHT diamond chips (∼200 ppm nitrogen) was carried out at the Sandia National Laboratories ion microbeam facility [88]. Implantation was performed at a low flux to ensure production of single ion impact sites. After implantation, samples were annealed at 800°C, inducing the resulting vacancy clusters to pair with nitrogen atoms and form bright nitrogen-vacancy (NV) centers. Confocal microscopy of approximately 300 implantation sites reveal an average of 17(5) NVs per ion impact for 800 keV ion energy, compared to a background of approximately 3 NVs (Fig. 6.1).

To interpret these observations, we perform Kinetic Monte Carlo (KMC) annealing simulations using the SPPARKS software package [89], incorporating realistic vacancy diffusion, recombination, clustering, and NV formation [90]. The initial vacancy distributions are provided by SIIMPL, a binary collision approximation (BCA) code to calculate ion damage distributions in crystalline materials [91]. Preliminary simulations indicate that about 5-10% of the initial ∼300 vacancies generated per ion impact are converted into NVs, which is consistent with our experimental results. Detailed simulations incorporating local nitrogen concentrations measured with secondary ion mass spectroscopy (SIMS) are ongoing. Concurrently, we are performing T_2 electronic spin coherence measurements on the resulting NV clusters to assess their suitability towards nanoscale imaging with quantum sensing techniques such as Fourier gradient imaging [92, 93].

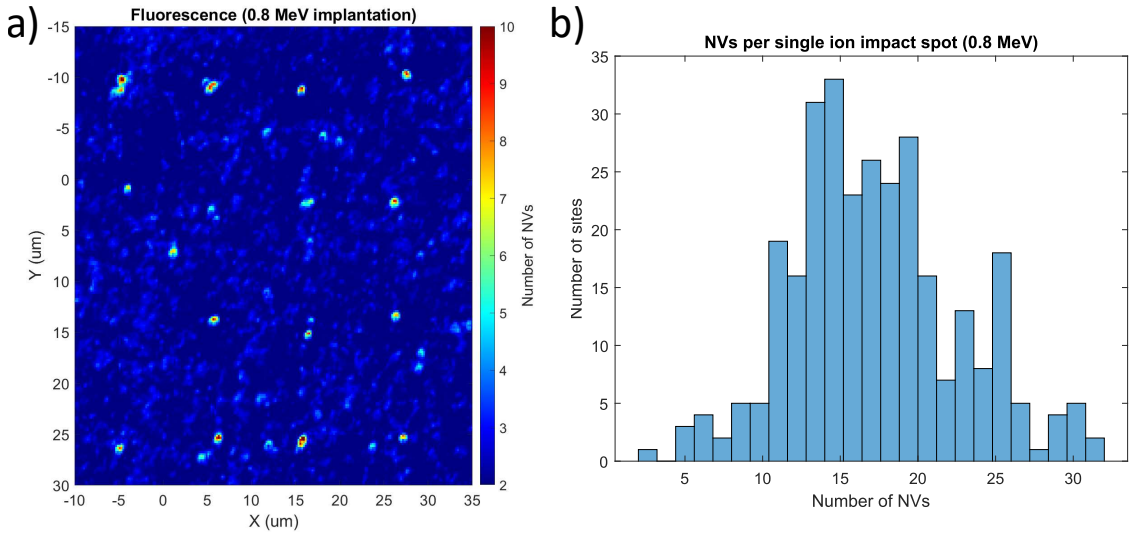


Figure 6.1: Preliminary confocal scanning results of ion-implanted mm-scale diamond samples. a) Large-scale scan of diamond surface showing a grid of single-ion impact sites from 0.8 MeV implantation with 10 μm spacing. Finer scans are subsequently performed on identified sites to deduce number of NVs produced per single-ion impact spot. b) Histogram of number of NVs produced from ∼300 sites, showing a mean of 17(5) NVs per site.

Ion implantation at lower energies (50-400 keV) is scheduled for Fall 2025 at the University of Michigan. Samples will be prepared using plasma etching procedures developed in our group to minimize pre-existing NV backgrounds and enhance signal-to-noise ratio. Implantation will also be carried out on NV-rich, quantum-grade CVD diamonds to enable track detection via our previously established quantum strain imaging methods [94].

6.3 Particle track simulations

Precise and accurate simulations are essential for understanding the damage tracks produced from neutrino and DM-induced nuclear recoils in diamond. Initial simulations used the widely popular TRIM BCA code [80], which is limited by its neglect of lattice structure effects such as channeling. Recent work employs SIIMPL [91], a lattice-aware BCA code, to more realistically model track formation including channeling effects. A fully atomistic simulation, however, requires molecular dynamics (MD). Using LAMMPS [95], we perform MD simulations of nuclear recoil events in diamond, incorporating the EDIP interatomic potential [96, 97] and the ESPNN model for electronic stopping [98]. This work extends earlier simulations by the Marks group [99]. The results agree with TRIM within a factor of two, but demand significant computational resources, limiting the maximum achievable initial recoil energy to about 10 keV.

To overcome these constraints, we have transitioned towards machine learning (ML)-driven MD, using the GPUMD package [100] with neuroevolution potentials (NEP) [101] trained on DFT data [102]. Due to GPU parallelization, this approach enables much faster

simulations with improved accuracy from DFT-informed interatomic forces. Preliminary benchmarks indicate a substantial (∼100×) speedup, which would allow simulation of higher energy recoils up to 60-80 keV (limited only by GPU memory). Work is ongoing to refine the NEP potential with newly generated close-range DFT training data, which is required to accurately model nuclear recoil damage cascades. In the future, similar ML-driven methods could be applied to model track production in other materials of interest for mineral detection of dark matter and neutrinos [16].

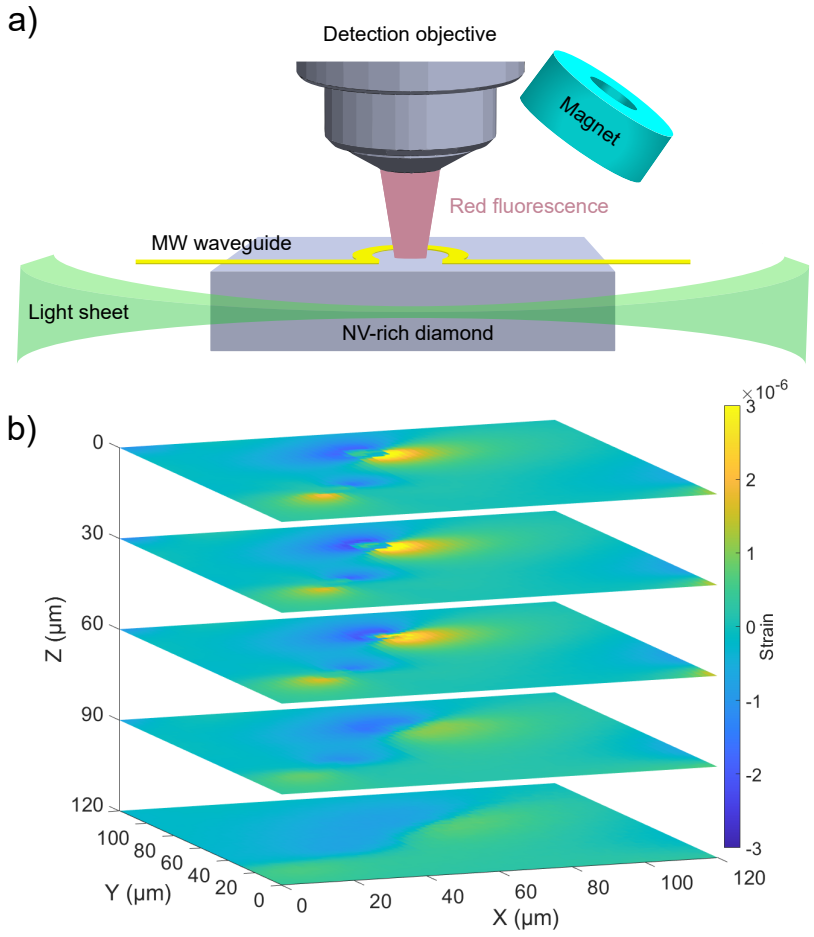


Figure 6.2: a) Schematic of light-sheet quantum diamond microscope (LS-QDM), which combines light-sheet laser excitation with conventional QDM components (magnets and microwave delivery). b) 3D widefield strain imaging of a quantum-grade diamond using the LS-QDM and the strain-CPMG protocol [94], revealing a large-scale strain feature across multiple Z-stack planes.

6.4 New imaging technique: light-sheet quantum diamond microscope

A full-scale diamond-based directional DM detector will require the capability to perform rapid, high-precision 3D strain imaging of mm-scale diamond chips. Building upon our

previous work in NV-based strain sensing [94], we are developing a light-sheet quantum diamond microscope (LS-QDM), which utilizes a sheet of light to excite a thin but wide slice of diamond, inspired by similar setups used for biological imaging [103] (Fig. 6.2a). Our current setup has a Gaussian light sheet with 9 μm thickness and $\sim$100 μm^2 field of view. Preliminary measurements with the strain-CPMG quantum interferometric protocol demonstrate the capability of the LS-QDM to perform widefield 3D-imaging of natural strain features in a mm-scale diamond chip (Fig. 6.2b). Ongoing engineering efforts focus on delivering uniform microwave fields across the entire sensing region of the diamond; and compensating for displacement of the light sheet induced by the high refractive index of diamond, which leads to systematic spatial shifts during volumetric scanning. Future LS-QDM iterations will utilize non-Gaussian beams to achieve $\sim$1 μm light sheet thicknesses, required for timely DM-induced track detection [9].

In addition, a second confocal setup is being built for development of super-resolution quantum sensing techniques such as spin-RESOLFT [104] and Fourier gradient imaging [92, 93, 105], which are required to perform detailed nanoscale NV strain imaging of the shape and orientation of a damage track once it is located with the LS-QDM. To achieve Fourier gradient imaging at depths beyond 10 μm from the diamond surface (required to resolve tracks deeply embedded in mm-scale chips), we are collaborating with the Laboratory of Physical Sciences (LPS) at UMD to design and fabricate microcoil structures capable of delivering 1–10 G/μm gradients at the required imaging depths.

6.5 Conclusion and outlook

In summary, we successfully detected $\sim$1 MeV single nuclear recoil-induced tracks in diamond via precision ion implantation and confocal NV imaging; and we developed a computational model that reproduces our data. Progress in developing ML-driven molecular dynamics simulations will enable even more accurate and precise modeling of DM and neutrino-induced tracks. Finally, our LS-QDM setup exhibits promising preliminary results towards widefield, fully 3D strain scanning of mm-scale diamond chips to enable particle track mapping. Overall, these developments illustrate substantial progress in key sectors towards diamond-based directional dark matter detection.

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