SAND2021-8183R

Imaging electric field with electrically neutral particles

Y.-Y. Jau[1], D.S. Hussey[2], T.R. Gentile[2], W.C. Chen[2]

[1]Sandia National Laboratories, Albuquerque, New Mexico 87123, USA

[2]National Institute of Standards and Technology (NIST), Gaithersburg, Maryland 20899, USA

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

It used to think that is impossible to determine/measure electric field inside a physically isolated volume, especially inside an electrically shielded space, because a conventional electric-field sensor can only measure electric field at the location of the sensor, and when an electric-field source is screened by conductive materials, no leakage electric field can be detected. For first time, we experimentally demonstrated that electrically neutral particles, neutrons, can be used to measure/image electric field behind a physical barrier [1]. This work enables a new measurement capability that can visualize electric-relevant properties inside a studied sample or detection target for scientific research and engineering applications.

The underlying working mechanism of this new penetrative imaging technology takes the advantage of the interaction between neutrons and an electric field while neutrons are moving through an electric field region. Neutrons carry magnetic moments (small magnetic bars) aligned to their spins. From electromagnetism in a moving frame [2], which can be described completely with the theory of special relativity, moving neutrons can see an effective magnetic field $B_{\text{eff}} = -\boldsymbol{v} \times \boldsymbol{E}/c^2$ for $|v| \ll c$, where $\boldsymbol{v}$ is the neutron velocity vector, $\boldsymbol{E}$ is the electric field vector, and c is the speed of light. Naturally, the neutron spins precess about this effective magnetic field with a precession rate that is proportional to the electric-field amplitude. For a simplified scenario, the interaction duration is l/v, where l is the path length of the electric-field region. After neutrons pass through the electric-field region, we find the total spin precession angle θ_E to be $-\gamma_n El/c^2$, where $\gamma_n = -1.83 \times 10^8$ rad s T^{-1} is the gyromagnetic ratio of the neutron. In fact, we can mathematically prove this result to still be valid even $|v| {\sim} c$. Thus, the electric field can be determined by measuring the spin precession angle. As we can see, the measured electric field is independent of neutron velocity, a nice feature that allows us to use a high-fluence, polychromatic neutron source for electric-field imaging. Mathematically, different neutron velocities, probing trajectories, polarization orientations, and analyzing directions can be employed to retrieve full vector information of electric field.

In our proof-of-concept experiment, we used the Neutron Guide 6 end station (NG6e) beam line at the U.S. National Institute of Standards and Technology (NIST) Center for Neutron Research. The experimental configuration is sketched in Fig. 1. Neutrons are spin polarized before being delivered to the electric-field sample, which is a parallel-plates capacitor with electrodes enclosed by perfluoroalkoxy (PFA) material and driven by a high-voltage source. In order to detect the very small neutron spin precession angle, we have developed a simple but sensitive neutron polarimetry scheme [3] that allows us to measure the change in spin rotation angle down to micro-radian range. The left panel in Fig. 2 illustrates the row neutron image of the electric-field sample. From the picture, one can see the electrical cables, the rectangular electrodes (dark), and the PFA body and the dielectric layer between the electrodes. By engaging the neutron polarimetry and taking images with and without the high voltage, we obtain the difference image by subtracting the "OFF" states from the "ON" state with sufficient statistics, and we find the electric-field imaging as shown in the right panel in Fig. 3. The blue-color region on the image reveals the signal of the electric field inside the dielectric layer.

For a quantitative study, we find that the contrast signal defined in Eq. (5) in Ref.[1] (the normalized difference image/signal using the intensity background) is equal to the product of the neutron polarization P_n, analyzing power A, and the spin precession angle

θ_E. This allows us to quantitatively compare the measured signals and the calculated signal strengths under different experimental conditions. In this experimental study, we used two electric-field samples, short and long versions. For the long version, the electrodes are 5 cm wide and 6.35 mm thick, l = 11.4 cm, and the electrode spacing d = 400 ± 50 μm. For the short version, the electrodes are 5 cm wide and 6.35 mm thick, l = 5.7 cm, and the electrode spacing d = 500 ± 50 μm, we measured the signal contrasts from the dielectric area on the images with several driving voltages from −35 to 35 kV on the short-version sample, 36 kV on the long-version sample, and 35 kV on the short-version sample with an iron shim (neutron depolarizer) in front of the sample. The result is summarized in Fig. 3. The slope of a linear fit to the data yields 1.01 ± 0.02; hence, the results are consistent with expectations. We see zero signal contrast with the shimmed case as a proof of the need for polarized neutrons for electric field imaging. We find the minimum detectable voltage on the short-version sample is about 500 V (electric field of 10^6 V/m) using the 1172-averaged contrast images. In the future, we estimate that using multiple strategies including beam focusing [4] could provide another 2 orders of magnitude improvement, yielding a total detected neutron fluence up to the order of 10^{12} cm^{-2} in a day. For this level, we find that the minimally detectable electric-field strength for 1 cm^3 spatial resolution to be about 5×10^4 V/m (equivalent to 500 V across 1 cm distance) and 1 mm^3 spatial resolution to be about 5×10^6 V/m (equivalent to 5000 V across 1 mm distance). As we can see, trading sensitivity for higher volumetric resolution is inevitable. We believe this kind of sensitivity is sufficient for several image diagnostics applications for targets like high-voltage electronics, which usually contain capacitors with internal electric-field strengths > 10^7 V/m, dielectric materials with externally applied very high electric field, and ferroelectric materials, which usually have spontaneous electric polarization with equivalent E strength > 10^8 V/m

Before this work, visualizing electric field within an occupied diagnostic space was not feasible. In addition, owing to the great penetration capability of neutrons through metals, this neutron-based electric field imaging technology can also measure the electric field that is inside a shielded space, which cannot be achieved by any other existing sensing technology. Our work enables new diagnostic power of the structure of electric potential, electric polarization, charge distribution, and dielectric constant inside an investigated target by visualizing spatially dependent electric field from a distance.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

1. Y.-Y. Jau, D.S. Hussey, T.R. Gentile, and W.C Chen, Phys. Rev. Lett. **125**, 110801 (2020).

2. J. D. Jackson, Classical Electrodynamics (Wiley, New York, 1999).

3. Y.-Y. Jau, W. C. Chen, T. R. Gentile, and D. S. Hussey, Rev. Sci. Instrum. 91, 073303 (2020).

4. D. S. Hussey, H. Wen, H. Wu, T. R. Gentile, W. Chen, D. L. Jacobson, J. M. LaManna, and B. Khaykovich, J. Imaging Sci. 4, 50 (2018).

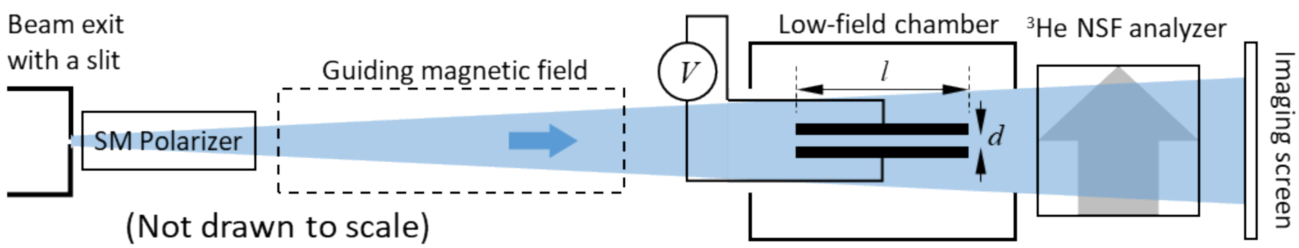

Figure 1: A schematic of the electric-field imaging experiments with polarized neutrons. The blue arrow represents the polarization of the neutron beam before arriving at the electric-field region (small gray arrows), which exists in between the two parallel electrodes driven by a voltage source. The gray big arrow denotes the analyzing direction of neutron spins at the analyzer. NSF denotes neutron spin filter

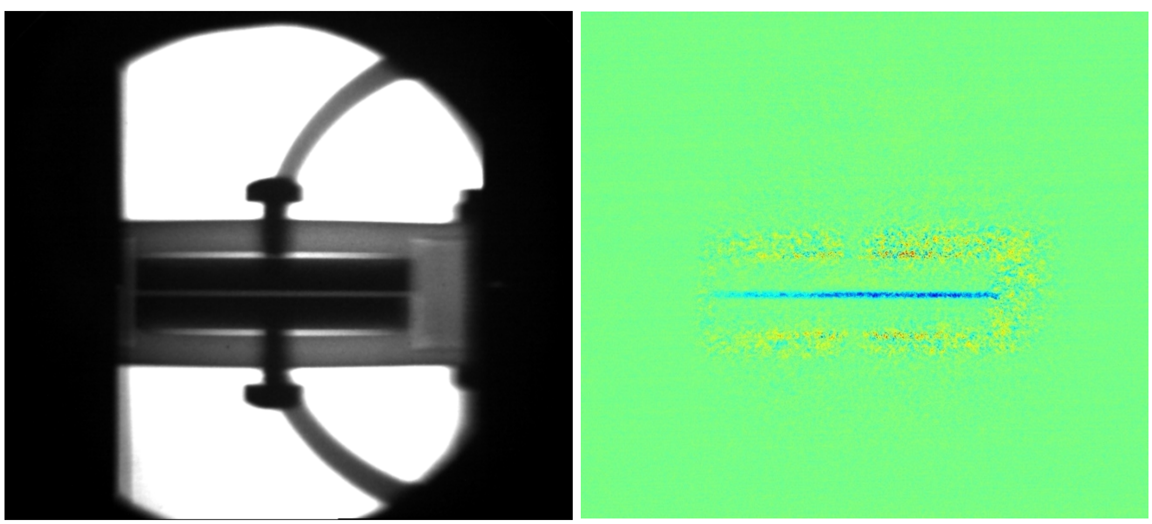

Figure 2: Left: A normal neutron transmission image of an electric-field sample. Right: Image of electric field in the dielectric layer of the sample using averaged difference images with “Jet” color scheme.

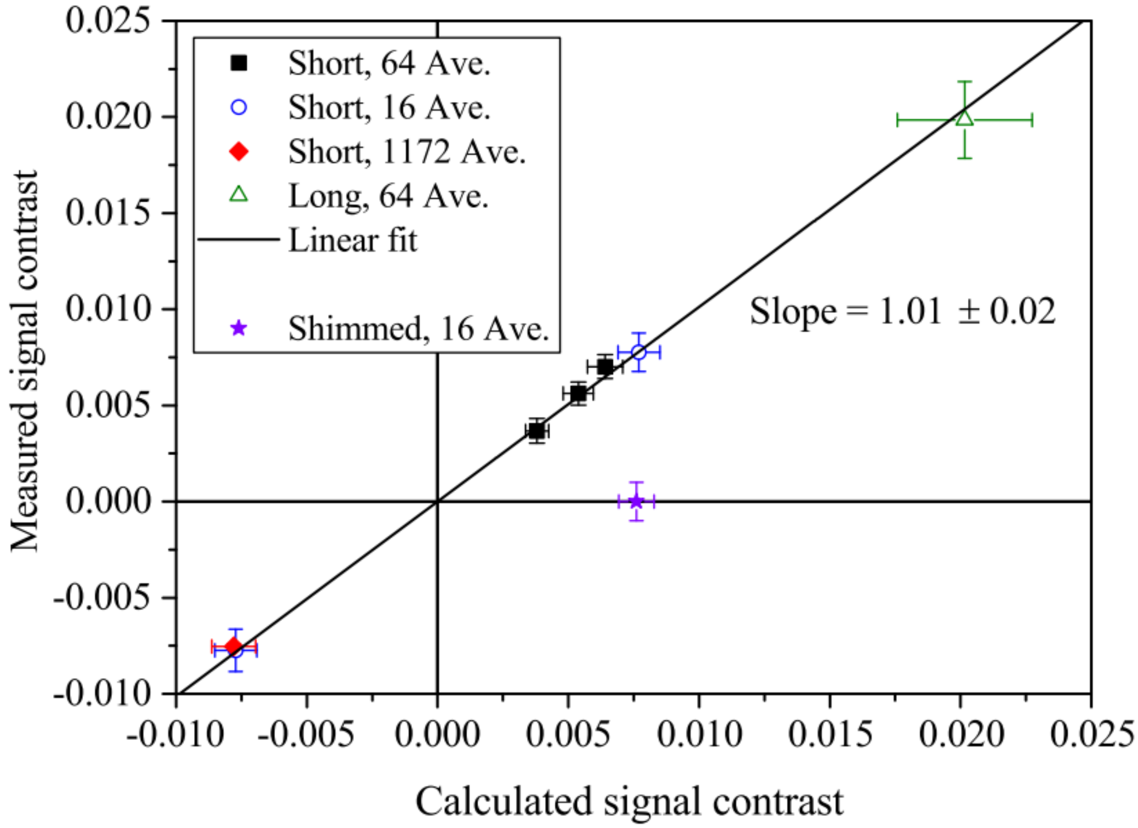

Figure 3: Measured signal contrasts vs calculated contrasts calculated “Short” and “Long” represent the data points from the short- and long-version E samples. “Shimmed” represents the data point using depolarized neutrons. The horizontal error bars are set by the machining uncertainty on the PFA membrane thickness, which is 50 μm, and the vertical error bars are limited by the imaging statistics. Also shown is a linear fit to the data, which yields a slope of 1.01±0.02.