Utilizing neutron scattering techniques to measure carbon-in-soil distribution

Arun Persaud[1], Bernhard Ludewigt[1], Mauricio Ayllon Unzueta[1], William Mixter[1], Matthew Poska[1], Zachary Croft[1], Eoin Brodie[1], Cristina Castanha[1], Caitlin Hicks Pries[2], Charles Gray[3], and Craig Brown[4]

[1]Lawrence Berkeley National Laboratory
[2]Dartmouth College
[3]Adelphie Technology, Inc.
[4]Adelphi Technology, Inc.

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Abstract

Carbon distribution in soil is intricately linked to soil health. However, repeatable measurements of carbon distribution typically require destructive sampling and laboratory analyses. Soil carbon distributions in both natural and managed landscapes significantly vary due to numerous factors related to topography, mineralogy, hydrology, land use history, and vegetation. In order to accurately inventory soil C distributions and dynamics over time, we are developing a new technique that relies on neutron inelastic scattering to measure elemental distribution. This approach can be used to image a volume of approximately 50 cm × 50 cm × 30 cm (depth) with a few centimeters resolution, for example the root zone of a plant. To achieve this, we use neutrons created in a deuterium-tritium fusion reaction. The products of this reaction are an alpha particle and a neutron. Due to momentum conservation, both particles are emitted in opposite directions in the center-of-mass frame. This allows us to measure the neutron direction by detecting the alpha particle with a position sensitive detector. The neutron can then induce an inelastic scattering reaction on a carbon nucleus present in the soil, and this event produces a gamma ray with a characteristic energy for the carbon isotope. Using a gamma detector, we measure these gamma rays, which allows us to perform time-of-flight analysis between arrival times of the alpha and gamma particles. Using the information from both measurements (alpha and gamma), we can reconstruct the spatial distribution of the carbon atoms and other elements in soil. We will report on the design, potential applications, and limitations of the instrument. We will also report on initial results from laboratory experiments and progress towards future field experiments. The information, data, or work presented herein was funded by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Contract No. DE-AC02-05CH11231.

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A. Persaud B. Ludewigt M. Ayllon W. Mixter M. Poska Z. Croft E. Brodie C. Castanha C. Hicks Pries C. Gary C.Brown

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Motivation

Carbon distribution in soil is intricately linked to soil health and fertility e.g. crop yields. In addition, soil is the largest storage pool of terrestrial carbon, hence offering the potential for mitigation of climate change by carbon sequestration on a large scale.

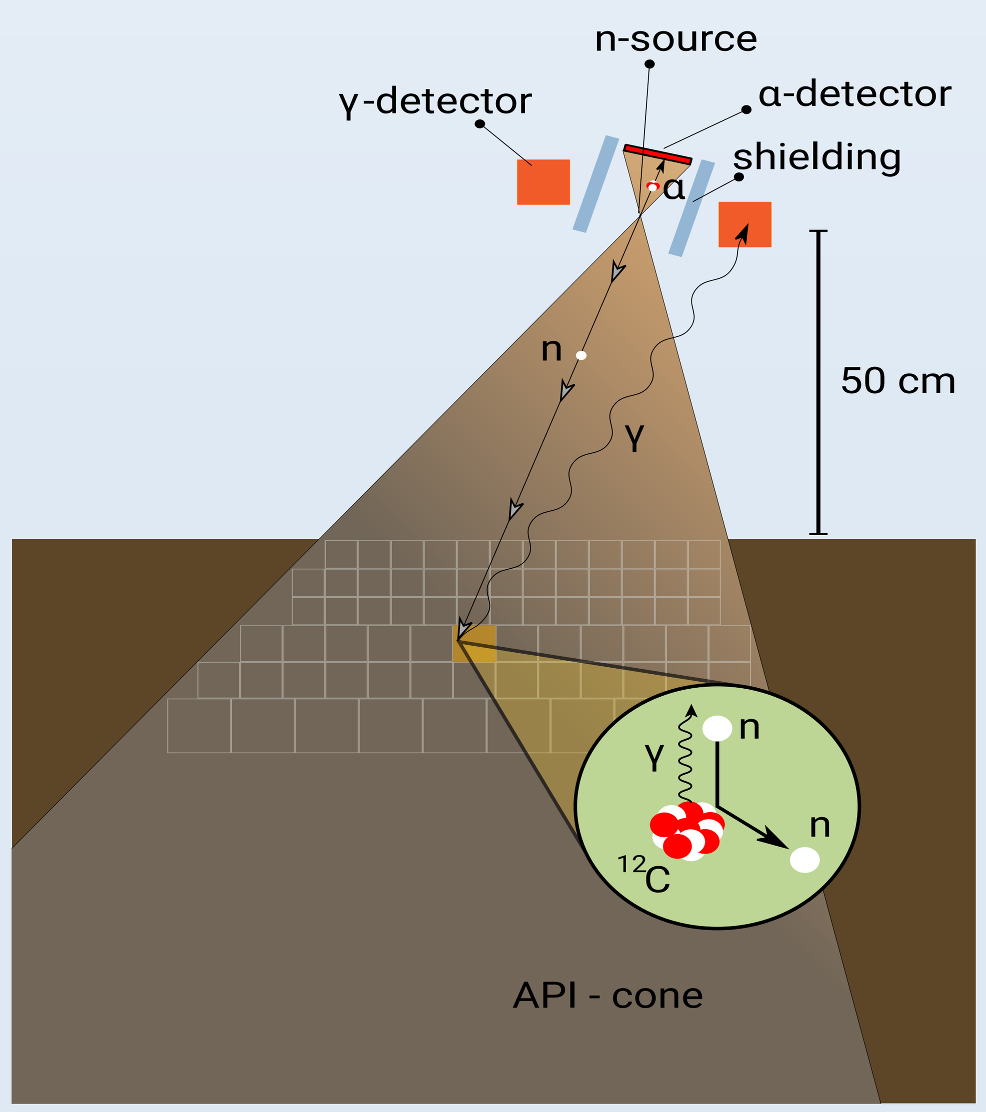
Goal: Develop a *non-destructive* method enabling in situ *repeatable* measurements for soil C and other elements.

Approach

Use isotope-specific response to neutron flux to measure carbon distribution in soil:

- Neutrons excite isotopes which emit characteristic gamma rays
- Associated Particle Imaging (API) combined with time-of-flight analysis enables correlation of measured gamma ray with nucleus location in soil
- Position and timing information from API allows imaging of carbon in a region of 50 cm × 50 cm × 30 cm with a few centimeters resolution
- Measured gamma rates reflect carbon concentration
- Neutron source: Adelphi DT108-API neutron generator

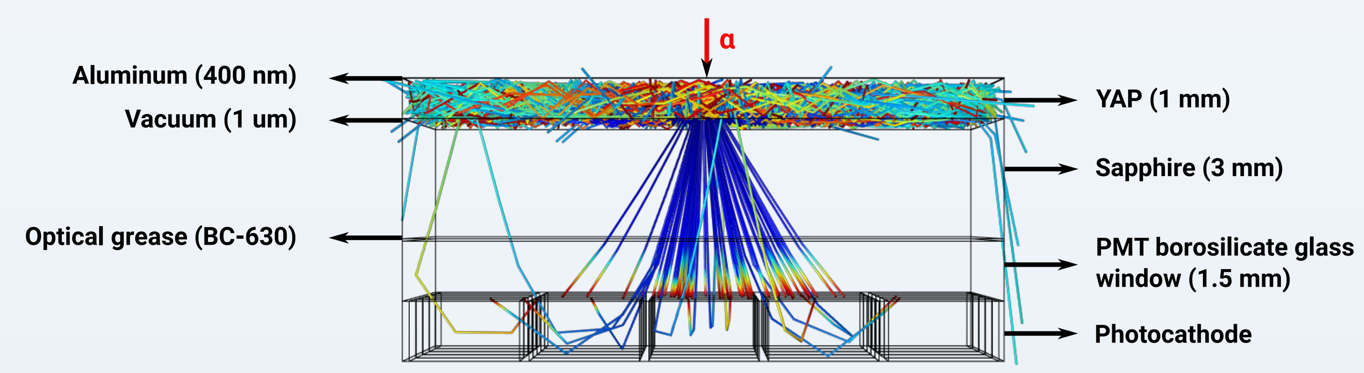
Measurement time for (0.2—1.0 ± 0.1)% C concentration:
10 min for commercial product (using multiple detectors)



Alpha Detector

The position-sensitive alpha detector allows us to calculate the 2D position of carbon nuclei in soil, and the time when the neutron was emitted.

The kinematics of the deuterium-tritium (DT) fusion reactions in the neutron generator dictate that the resulting alpha particle and neutron are emitted in opposite directions. Detecting the position of the alpha particle gives us the direction of the emitted neutron.



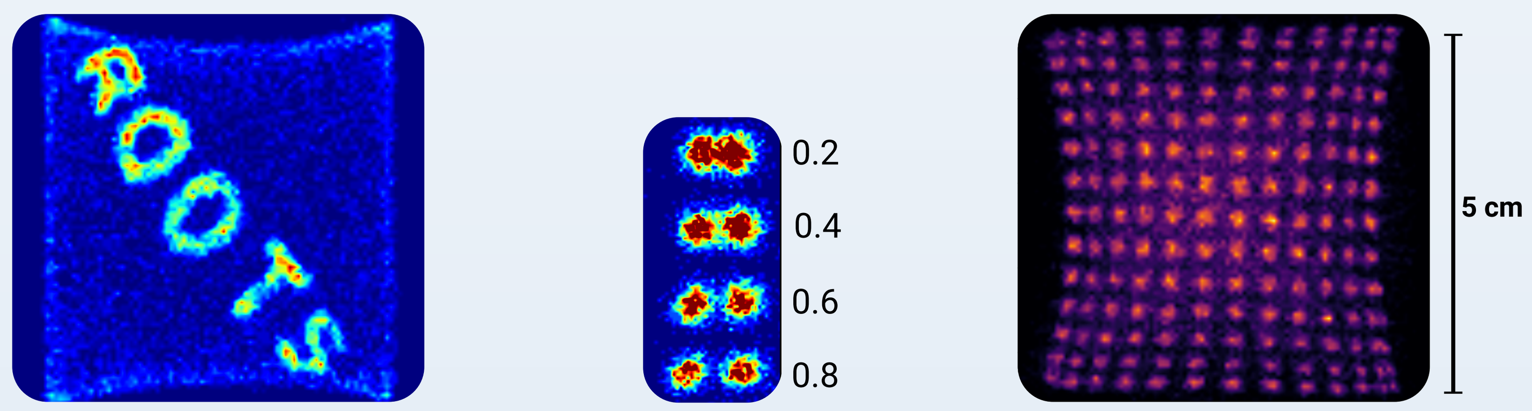


Image of the word "ROOTS" obtained from alpha particles going through a mask and into a position-sensitive detector.

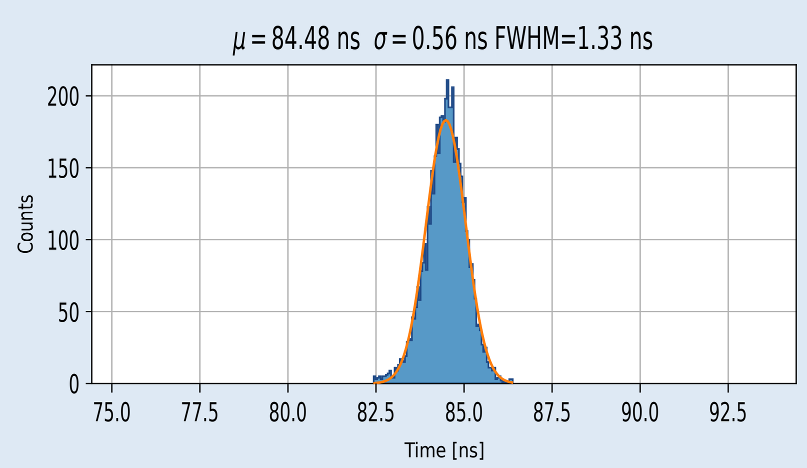
Minimum detectable distance [mm]

"Flood Field" image with the position-sensitive alpha detector showing overall uniformity.

Gamma Detector

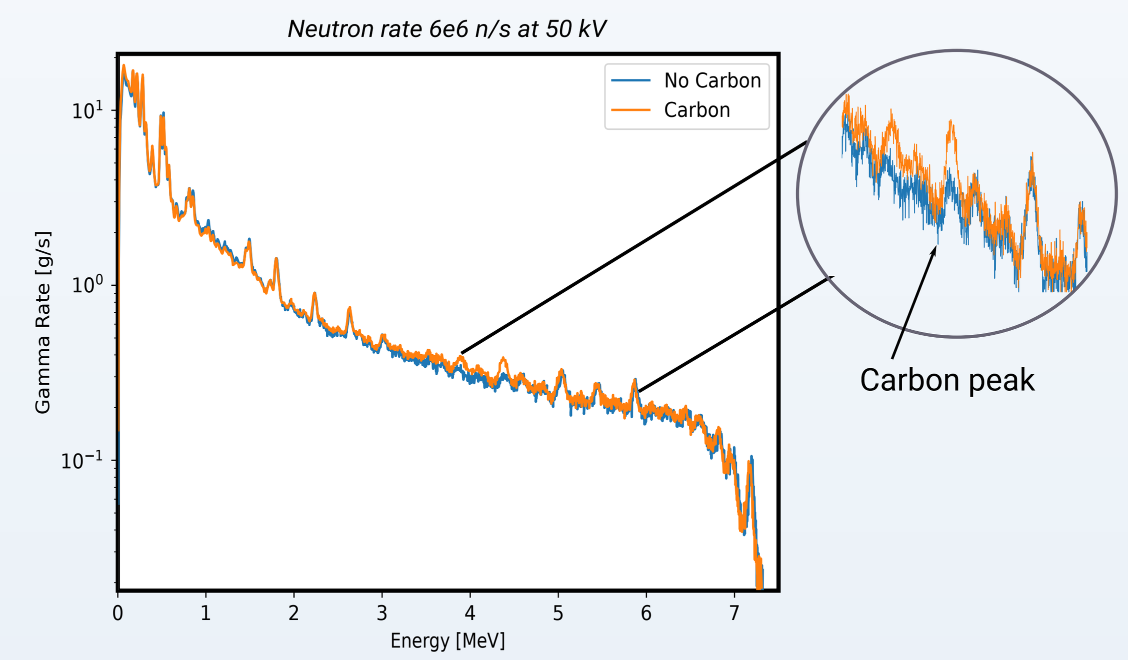
The gamma detectors (LaBr, NaI) allow us to detect gamma rays emitted from carbon and other isotopes, providing information on the energy and time.

Time-of-flight measured between the alpha detector and the gamma detector is domintated by the neutron travel time and therefore identifies the depth in the soil where the gamma was emitted. The gamma energy is used to identify the isotope.



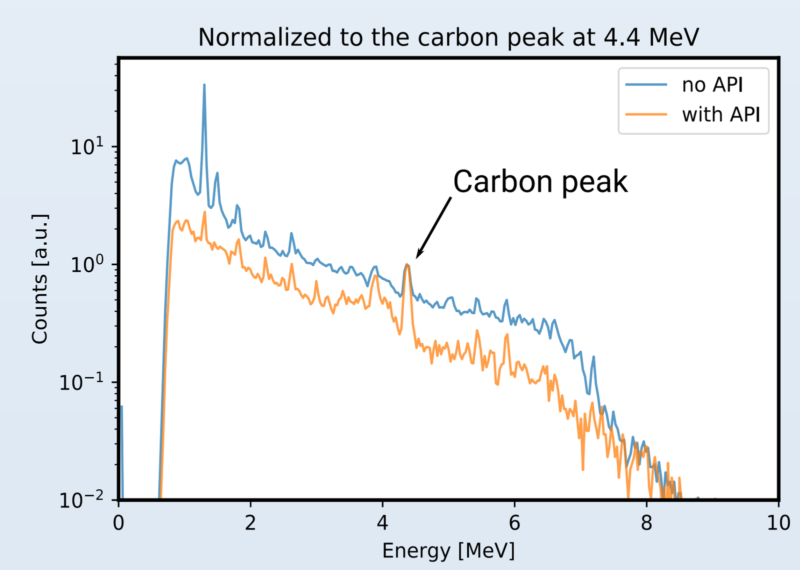
Non-API Carbon Spectrum

Carbon-12 emits 4.4 MeV gamma rays when excited by high-energy neutrons. The plot below shows a gamma-ray spectrum for a graphite block exposed to 14 MeV neutrons in our lab setting.



API Carbon Spectrum

When using the alpha-detector timing, the unwanted gamma-ray background is reduced, which allows us to both isolate the gamma rays from carbon, and obtain depth resolution.



Outlook

The complete system integration including the lateral position resolution is ongoing together with further optimization to improve detector parameters such as arrival time and gamma-ray energy resolution. Soil measurements will start in 2019 and field experiments are planned towards the end of 2019.

We are looking for feedback from soil scientists and other potential users and are interested in other use cases for this instrument (e.g. co-variance between C and other elements).

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Contact information: Arun Persaud - apersaud@lbl.gov
Mauricio Ayllon - mayllonu@lbl.gov