Nuclear Physics Detector Technology Applied to Plant Biology Research

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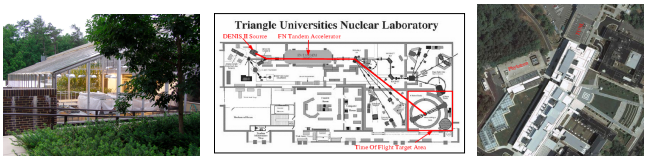
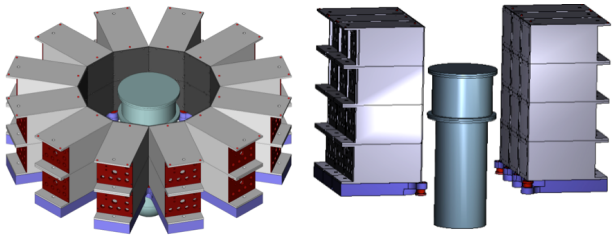
***Abstract*:**
The detection of the emissions of radioactive isotopes through radioactive decay has been used for over 80 years as a tracer method for studying natural phenomena. Carbon-11 a positron emitting radioisotope of carbon has been utilized as a $^{11}CO_2$ tracer for plant ecophysiology research. Because of its ease of incorporation into the plant via photosynthesis, the $^{11}CO_2$radiotracer is a powerful tool for use in plant biology research. Positron emission tomography (PET) imaging has been used to study carbon transport in live plants using $^{11}CO_2$. We are using nuclear physics detector technology to develop specific detectors for radiotracer imaging in plants. We are developing a high-resolution PET system to image the bio-distribution of positron emitting tracers in live plants. The positron emitting $^{11}CO_2$ tracer is used in plant biology research directed towards carbon sequestration in biomass, optimization of plant productivity and biofuel development. This PhytoPET design allows flexible arrangements of PET detectors based on individual standalone detector modules built from single 5 cm x 5 cm Hamamatsu H8500 position sensitive photomultiplier tubes (PSPMTs). Each H8500 is coupled to a LYSO:Ce scintillator array composed of 48x48 elements that are 10 mm thick arranged with a 1.0 mm pitch. An Ethernet based 12-bit flash analog-to-digital (FADC) data acquisition system (DAQ) with on-board coincident matrix definition is used to digitize the signals. The detector modules of the PhytoPET system can be re-arranged and stacked to accommodate various sized plants, plant structures and species. Radiotracer studies utilizing a PET systems for plant research are underway at the Phytotron at Duke University and uses the Triangle Universities Nuclear Laboratory (TUNL) 4-MeV Van de Graaff accelerator.



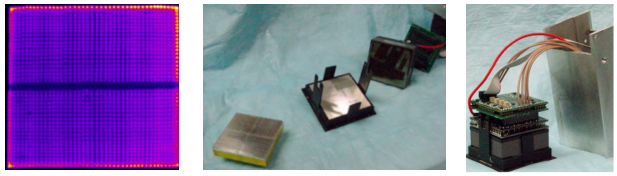
Duke University Phytotron and Triangle Universities Nuclear Laboratory (TUNL) facilities for plant studies and $^{11}CO_2$ gas production and delivery.

Objectives: Most biologically significant radioisotopes utilized in plant ecophysiological studies are positron emitters, making PET a useful imaging modality for this application. The $^{11}CO_2$ tracer is a positron emitter used in plant biology research, for instance in carbon transport studies in live plants because CO_2 gas is taken up through the natural process of photosynthesis. We are developing a new PET detector system, PhytoPET, that utilizes a novel PET system arrangement to achieve plant PET imaging. Plants present the challenge of having varying structures e.g. thin leaves, narrow stems, large canopies, and possibly bulky roots.

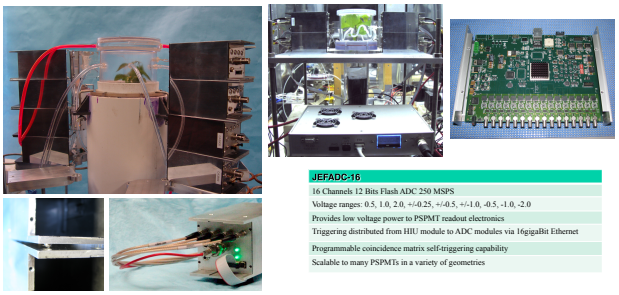
The PhytoPET design uses individual standalone detector modules based on single 5 cm x 5 cm Hamamatsu PSPMTs. Each module is self-contained and designed to allow flexible individual stacking and arranging to accommodate the several imaging geometries presented by various plant imaging scenarios. PET image reconstruction methods are under development to achieve the best result based on the geometry. We will use a variation of limited angle tomography, partial ring PET and full standard PET ring reconstruction depending on the plant under investigation.



PhytoPET detector concept. Two possible arrangements of the PhytoPET detector modules to image a plant in the whole plant cuvette.. Each individual module has dimensions (L x W x H) of 120 mm x 60 mm x 60 mm. Individual standalone detector modules are based on single 5 cm x 5 cm Hamamatsu PSPMTs



(Left) Flood image of LYSO:Ce array; 48x48 elements, 10 mm thick arranged with a 1.0 mm pitch. The inner 40 x40 scintillor elements are unambiguously identified. (Center+Right) Disassembled PhytoPET module showing scintillator array and PSPMT.



JEFADC-16
16 Channels 12 Bits Flash ADC 250 MSPS
Voltage ranges: 0.5, 1.0, 2.0, +/-0.25, +/-0.5, +/-1.0, -0.5, -1.0, -2.0
Provides low voltage power to PSPMT readout electronics
Triggering distributed from HIU module to ADC modules via 16gigaBit Ethernet
Programmable coincidence matrix self-triggering capability
Scalable to many PSPMTs in a variety of geometries

(Top-Left): Two stacks of PhytoPET modules positioned around a prototype whole plant $^{11}CO_2$ cuvette. (Bottom-left) Ball-detent module stacking method and rear view of PSPMT module. (Top-Right) EFADC-16: A 16 channel flash ADC PET processing system.

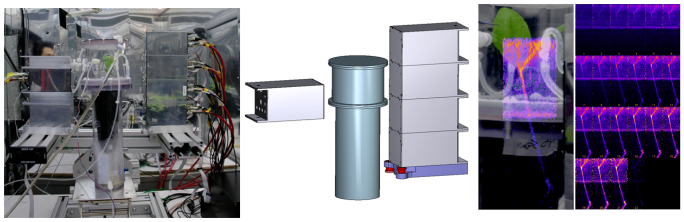
Methods: The PhytoPET design permits flexible arrangements of PET detectors based on individual standalone detector modules built from single 5 cm x 5 cm Hamamatsu H8500 PSPMTs. The Hamamatsu H8500 is a multi-anode photomultiplier tube with 64 anodes (8 x 8 matrix) and a photocathode active area of 49 x 49 mm^2. The outer dimension of the H8500 is 52 x 52 x 27.4 mm^3. The 64 anodes of the Hamamatsu H8500 flat panel PSPMT are reduced down to a 4 channel readout via a resistive network and amplification circuitry. Each H8500 is coupled to a LYSO:Ce scintillator array custom built by Proteus Inc. (Chagrin Falls, OH). The array is composed 48 x 48 elements that are 10 mm thick arranged with a 1.0 mm pitch. We intend initially to build 25 separate stackable detector modules.

Each PhytoPET detector module has an outer dimension (L x W x H) of 120 mm x 60 mm x 60 mm. The modules can be stacked to accommodate different plant shapes. Each module is constructed such that when stacked the module is locked into position by a complementary set of three detents and glued metal balls. Since blocking light to a plant impacts the plant physiology studies, it was necessary to design the detector housing to be reflective. Additionally we have constructed a set of bases which also has the set of three registering balls to support the columns. The base plates can also be interlocked by a hinge that allows the column to be positioned at a fixed angle with respect to the neighbor and the gap between the columns kept to a minimum.

The PhytoPET detector modules are served by a PET processing system composing two subsystems: (1) signal digitization and processing, and (2) time stamp collection, trigger generation and distribution. The PhytoPET detector modules are designed to be read out by an in-house FPGA based ADC system currently under development.

An on board field programmable gate array (FPGA) controls and processes the collected samples. The EFADC-16 module digitizes 16 channels simultaneously using 12-bit flash ADCs running at 256 Mega-samples/sec. A triggering/thresholding firmware algorithm was developed that provides data to a host computer over a 1000base-T Ethernet connection. The data is then analyzed using a platform independent DAQ software developed by Jefferson Lab. Up to 18 EFADC-16 units can be synchronized via fiber interface to provide a large number of simultaneous channel readouts while providing.

Results: Five PhytoPET modules have been built and equipped with the 1.0 mm pitch LYSO:Ce arrays. Each array is coupled to the PSPMT face via a 3 mm thick plastic light guide glued to the scintillator and PSPMT face with polydimethylsiloxane (PDMS). In plant imaging tests with arrangements of opposing PhytoPET modules we obtained reconstructed images using a maximum-likelihood expectation maximization (MLEM) algorithm.



(Left) Photograph (left) of five PhytoPET detector modules in an EGC arranged around an oak seedling such that one plane is defined by a single module and the other by a stack of four. (Center) Drawing to illustrate module placement with respect to the $^{11}CO_2$cuvette. (Right) Reconstructed image (right) using limited angle tomography showing uptake of $^{11}CO_2$ and co-registered with a photograph of the seedling. A montage of reconstructed images (far right) in time slices of 5 minutes in length. The translocation of ^{11}C-labeled sugars from the upper part of the plant to the roots is apparent.

Acknowledgements
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