Adelphi Technology, Inc. - DOE Ph 2 SBIR - Grating-Based Imaging-Scattering with Portable Neutron Generator – DOE Award No. DE-SC0019636
Final Report and Commercialization Plan - April 6, 2020 to April 5, 2023

II. ACCOMPLISHMENTS

1. What are the major goals of the project?

This project will develop a greenhouse-compatible neutron interferometry radiography system for imaging plant roots and soil systems grown or transplanted into aluminum pots.

The significance is that long-duration, extensive sampling of plant growth factors is essential for food security. The opportunity is based on recent developments in robust (battlefield) neutron sources and a new low-cost route to neutron interferometry optics.

Goal 1. Neutron Generator

The DD110.4M from Adelphi Technology Inc. is suitable for producing high intensity thermal neutrons in a compact footprint. It is the highest output neutron generator manufactured by Adelphi. Over the years, Adelphi has made great strides in improving both the output and stability of the neutron generators.

Currently, the DD110.4M is capable of 4×10^{10} n/s of sustained output with peak output of greater than 5×10^{10} n/s. The generator uses a negatively biased target which is seamlessly integrated with a polyethylene moderator to optimize the production of thermal neutrons.

Overall footprint of the DD110.4M generator head is about 15" x 30"x 30". There is an additional 19" rack that holds the power supplies and instruments as well as an industrial chiller for high power operation (greater than 5×10^9 n/s).

To obtain a small spot of fast neutrons, we intend to modify the polyethylene moderator by drilling a thru hole, which would end at the ion beam target surface. The hole diameter will be approximately the size of the neutron source spot and effectively serves as a collimator for fast neutrons, see **Fig. 1** below.

Any fast neutrons which did not travel collinearly with the hole would most likely hit the polyethylene and be scattered out of the path.

By pulsing the neutron source, a time delay occurs between fast neutron and thermal neutron arrival, which can be used to separate the fast and thermal neutron arrivals.

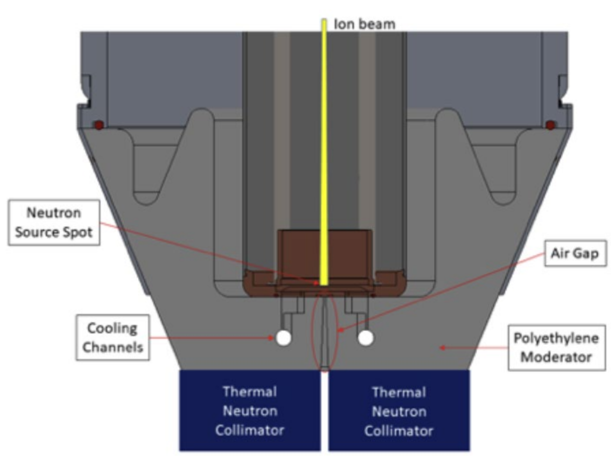

Fig. 1 Custom designed DD110.4M for fast and thermal neutron imaging.

Goal 1. Neutron Generator (continued)

A thermal neutron collimator would be placed further downstream of the polyethylene moderator to provide a small spot size of thermal neutrons. This collimator will be part of a bigger shielding system to allow generator operation without excessive radiation dose to the surrounding.

The DD110.4M has been tested in pulse mode with pulsing frequency of 10 kHz and duty cycle between 10% to 90% at 180 kV. An additional test was done to observe the neutron yield as a function of the voltage at 10% duty cycle, since this will be the proposed operating frequency and duty cycle to make best use of both the fast and thermal neutrons.

For optimal imaging with a small spot size, the highest HV acceleration should be used (225 kV). This is also the parameter that provides the highest neutron flux, up to about 4.2×10^9 n/s at 10% duty cycle. Also, at 10% duty cycle, the average output power is minimized, which would eliminate the need for a large chiller. All of the auxiliary equipment would fit inside a 19" rack.

Goal 2. Hutch, Imaging, and Interferometry Optic

In the LSU Chemistry building, a two-room hutch will be fabricated with extruded aluminum framing (8020).

The vault will be in the first room and isolated from users by steel panels, and the second room, the imaging room will have a labyrinth, interlocked entrance and sufficient floor space to contain a flight tube with 3 m from pinhole to scintillator.

The imaging room will have shielded walls, ceiling, and floor to protect workers in the lab outside of the imaging room from neutrons scattered by the optics, sample, and beam stop.

The shielding is yet to be determined but will likely range from flexible 1/8" borated polyethylene to 1" thick panels of HDPE/borated polyethylene.

The flight tube will be hollow cylinders of Li2CO3 powder held between an inner Teflon tube and an outer aluminum tube. Standard segment lengths are 30 cm long with 20 cm inner diameter opening and 5 cm wall thickness filled with Li2CO3, and mass of about 25 kg each.

The beam stop will be a large cup of lead-shielded borated polyethylene, with a 30 cm length similar to the wall thickness of the generator vault.

Fast 2.45 MeV neutron images and slow 0.025 eV neutron images are separately acquired with the gated intensifier/CCD detector.

The pulsed D+ beam with significant tail yields a prompt fast neutron pulse; the gated intensifier has a 0.5 μs switching time, hence all fast neutrons can be acquired. The fast neutron scintillator will be doped polyethylene.

The slow thermal neutron peak intensity follows about 900 μs after the D+ pulse and is essentially gone at 2000 μs; the latter time sets the pulse repetition rate. The thermal neutron scintillator is 6LiF/ZnS, 300 μm thick.

The sources sizes are 2 mm and 20 mm for fast and thermal neutrons, respectively. With a setup of 3 meter from pinhole to scintillator, L/D are 1500 and 150, respectively.

The interferometry thermal neutron optics will be fabricated by three routes: laser milling of gadolinium foils on aluminum foils, deep reactive ion etching (DRIE) of silicon wafers and infilling with Gd2O3 powder, and 3D polymer printing using stereolithography.

Goal 2. Hutch, Imaging, and Interferometry Optic (continued)

All methods will yield the slightly curved optics required to avoid shadowing where the radius of curvature is the pinhole-to-grating distance. Silicon wafers will be mounted in curved aluminum mounts; the rule of thumb is the minimum radius of curvature in millimeters is greater than the wafer thickness in microns.

The optics will be designed at Refined Imaging and printed at commercial print service bureaus (laser mill, stereolithography) and fabricated (DRIE) in-house and at regional microfabrication facilities.

The general characteristics of optics are cylindrically curved and sized for a 100 mm x 100 mm field-of-view. The silicon DRIE optics will be fabricated for both Talbot-Lau and structured-illumination. Laser-milling and 3D printing will be used to prepare structured-illumination optics. Structured-illumination optics require greater than 90% beam attenuation, hence, gadolinium features will be 20 micron along the beam path.

The Talbot-Lau uses a phase optic; a silicon feature of 37 micron will provide 90-degree phase shift. The range of optics will provide access to interferometry autocorrelation lengths ranging from about 50 nanometer to over 1 micron.

Optics will be aligned with a combination of laser transit, rulers, and feedback from interferometry images. Computerized tilt and translation stages are used to align optics. A resolution of 0.5 micron is sufficient for a linear stage in closed-loop operation. The flight tube has standard lengths of 30 centimeters, as well as some shorter lengths, to allow gaps in the flight for positioning the optics, sample, and detector.

Two interferometry data acquisition strategies will be evaluated: stepped-grating and single-shot. Stepped-grating generally yields better quality data over a larger field-of-view. Single shot has the advantage of mechanical simplicity.

The system will generally perform 2D radiography. However, the system will also be equipped with a rotation and translation stages for 3D tomography. In view of the possible rhizosphere dynamics over a long tomography experiment, the Greek golden ratio angular acquisition strategy will be used to mitigate motion effects during a tomography experiment.

Image analysis will typically involve data fusion of attenuation with scattering image sets. The procedures developed in X-ray interferometry mammography to highlight cancer will be transferred to this work to highlight rhizosphere activity.

Goal 3. Sample Handling

A growth chamber will be purchased and installed outside the imaging room.

The growth chamber and the imaging room will be connected by a sample transport system derived from 8020 (aluminum extruded strut) package motion systems.

The combination of a growth chamber and sample transport system will enable longitudinal studies of rhizosphere dynamics. The estimated time for a thermal neutron interferometry radiography data set is 3 hrs.

Hence, an automatic sample changer will be constructed to transport plants from a growth chamber to the imaging position; the conveyor belt purchase and installation is scheduled for the first quarter of Year 2.

Goal 3. Sample Handling (continued)

Instrument Operation:

A shelf in the growth chamber is loaded with plants.

The imaging hutch is secured, and the generator energized in pulsed mode.

The sample transport moves a plant into the imaging hutch.

The structured-illumination optics are moved out of the beam.

The neutron detector timing is set to acquire only fast neutrons and an exposure is taken of the attenuation image with an L/D of 1500.

Then, the optics are translated into the beam and the neutron detector timing is set to acquire only thermal neutrons. A series of images are taken as a function of optic position.

The images will have an L/D of 150, reducing the information content of the attenuation image. However, the scattering image should contain information about features with sizes near the interferometer autocorrelation length of 20 nm to 200 nm with the polymer optics and larger with the laser milled or silicon DRIE/infilled optics.

Goal 4. Soil Characterization and Phantoms:

Soil taxonomy is complicated, and the neutron attenuation properties change dramatically with moisture content. A variety of soil types will be tested at various moisture content as established by the growth chamber.

To establish detection limits of the system, phantoms simulating bare roots will be developed and placed in soil. The phantoms will be constructed from non- or slowly degradable materials with similar elemental composition and neutron scattering to authentic samples.

The aggressive timeline calls for soil imaging studies to begin in the third quarter of Year 1.

Goal 5. Application to Rhizosphere Projects

The first rhizosphere studies should start in concert with the soil/phantom studies, in third quarter of year 1. Images of authentic rhizosphere components are needed to develop and validate the rhizosphere phantoms.

Below, we describe several scientific studies designed to test the utility of fast and thermal neutron interferometry radiography. We are extremely thankful to the researchers for their willingness to expend time and effort by supplying plants, guidance, and interpreting the imaging results.

From a commercialization perspective, this Phase II project will develop “evangelists”, scientists who will promote the value of neutron imaging and urge its adoption at major agricultural research facilities.

None of the researchers mentioned below have a financial interest in either Adelphi Technology or Refined Imaging. We know of no bias that will affect their assessment of the imaging results.

Exploratory work will use flat aluminum pots, typically 10 mm x 100 mm x 100 mm and 2D imaging. 3D imaging will use cylindrical pots with various diameters up to 100 mm.

The detector system is sensitive to fast neutrons, thermal neutrons, and gamma radiation; the radiation dose to the plant will be monitored.

Goal 5. Application to Rhizosphere Projects (continued)

In the literature of neutron imaging of plant roots, there is little concern with radiation damage as the imaging sources are relatively weak compared to neutron sources used for plant mutation research.

We have a complete set of tomography and interferometry software, including our contributions to the Advanced Photon Source TomoPy/WavePy projects.

#1: High Salinity Soil: Prof. Maheshi Dassanayake, LSU Dept. of Biological Sciences

Determining plant mechanisms for surviving environmental stresses is recognized as a grand challenge in basic sciences and agriculture in a time of changing climate, diminishing freshwater resources, reduction of arable land, and a growing population.

All plants respond to stress, but most plants fall short as study systems because they fail to sustain growth at high levels of environmental stresses, see **Fig. 2**.

Salt stress is among the dominant agricultural threats, but salt stress adaptation is a complex trait and has evolved multiple times in land plants. Salt stress serves as a model environmental stress we can precisely give to plants when monitoring their gene expression.

Salt stress also has a lot of overlap with drought, heat, cold, and osmotic stresses as all these stresses elicit water-deficit stress at the molecular level. Therefore, studying genetic responses to salt stress provides insight into how plants respond to environmental stress at large.

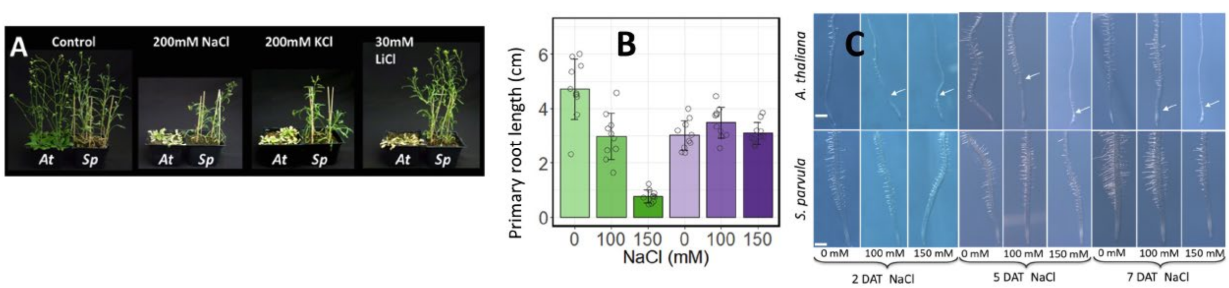

Fig. 2: The extremophyte plant, S. parvula can grow and complete its life cycle with uninterrupted root growth under salt stress.

A. Photos show survival of S. parvula (Sp) under multi-ion salt stresses grown in in soil compared to A. thaliana (At).

B. Primary root growth of 12-day-old seedlings of A. thaliana and S. parvula grown on 1/4 Murashige and Skoog media for 5 days were transferred to the same medium supplemented with indicated NaCl concentrations.
Imaged at 7 days after treatment (DAT).

C. Effect of NaCl on root hair growth in A. thaliana and S. parvula.
White arrows indicate root tip positions at the start of the treatment.
Note that the root tip positions in S. parvula under different NaCl stresses and control A. thaliana plants outgrew the frame of the image.
Scale bars are 0.5 mm. DAT (Days after treatment).

Goal 5. Application to Rhizosphere Projects (continued)

Plants that thrive in extreme environments (extremophytes) offer excellent genetic resources to study stress adaptations, and thus show great promise for studying genetic mechanisms to de-velop crops better adapted to varying and changing climates.

The emerging extremophyte models, Schrenkiella parvula exhibit many naturally-selected adaptations to abiotic stresses, including salt, drought, and cold stress. S. parvula represents the most salt-tolerant species (based on soil NaCl LD50) compared to the mustard-canola crops and is closely related to the stress-sensitive model plant, Arabidopsis thaliana.

Despite the availability of high-quality genomic resources to study salt adaptations, difficulty in observing how plant roots respond to salt in the soil is a severe bottleneck to understand how plants adapt to salt stress. Often plants are grown on artificial agar plates for a few days to assess root phenotypes in genetic studies.

In this proposed study, we plan to investigate how plant root architecture responds to salt in soil at varying salt concentrations in combination with nutrient stresses. We will use A. thaliana as a comparative species to assess the stress adapted root responses of S. parvula.

These comparative studies will benefit from the wealth of genetic studies performed on A. thaliana and provide a basis for genotype to phenotype inferences in understanding how roots sense salt, decide to grow or pause growth, and/or how resources are allocated to lateral roots and root hair development under salt stress to sustain growth.

#2: Arabidopsis Root Development: Prof. John Larkin, LSU Dept. of Biological Sciences

Plants cannot move, and plant cells are not motile. Consequently, the only way for plants to explore their environment is by differential growth. In particular, roots probe the soil for water and mineral nutrients, and can respond to nutrient limitation in quite sophisticated ways.

For example, Arabidopsis thaliana plants grown with sufficient phosphate develop long primary roots, and secondary root development occurs far from the tip of the primary root.

Plants grown with limiting phosphate arrest cell division and primary root growth, and the plant develops a highly branched root system with numerous secondary and tertiary roots, see **Fig. 3A**.

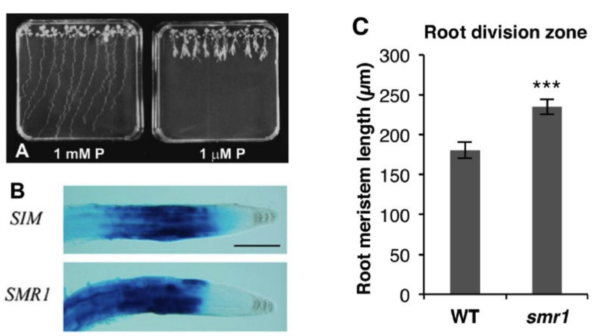

Fig. 3: Root growth and the role of SMR genes.
(A) Arabidopsis roots growth at high & low phosphate concentrations show root differences
(B) Expression of SIM and SMR1 in Arabidopsis roots, by expression of a GUS reporter gene.
(C) Root meristem size increase in smr1 mutant, compared to wild type $p < 0.001$.

Goal 5. Application to Rhizosphere Projects (continued)

Despite the complex growth responses of plant root systems to environmental conditions, root growth is generally studied on artificial substrates such as agar plates rather than in a more natural soil substrate, because soil is opaque to visible light.

The neutron imaging instrument being developed here will allow repeated imaging of developing root systems over time while growing in soil, allowing experiments that examine the evolution of the three-dimensional root architecture in response to environmental and genetic manipulation.

The Larkin lab studies the SIAMESE-RELATED (SMR) gene family. SMR genes encode cyclin-dependent kinase inhibitors that block mitotic cell division and promote cell differentiation.

Two SMRs, SIM and SMR1, are expressed in the developing root just proximal of the root meristem, where cell division occurs, see **Fig. 3B**.

When the function of either or both genes is eliminated by mutation, the dividing region of the root (i.e., the meristem) increases in length, leading to an altered growth rate of the primary root, see **Fig. 3C**. Furthermore, expression of SMR1 is increased in response to moderate drought stress, restricting cell division and growth under drought conditions.

Our goal is to understand the role that these genes play in the development of root architecture. To address this goal, we will compare root growth of wild-type Arabidopsis thaliana plants with the growth of mutant sim, smr1 and sim smr1 double mutant plants.

Plants will be grown in aluminum tubes under controlled humidity and imaged periodically. The roots will be visible from neutron attenuation (see **Fig. 4**) and the image fusion of attenuation and scattering images.

From these images, we will obtain measurements of the growth rate of primary and lateral roots, the number of lateral roots, and the angle of the lateral roots relative to the primary root.

Our ultimate goal is to apply these methods to investigate the response of various root growth mutants to abiotic stresses such as drought stress and phosphate limitation when grown in soil.

#3: Role of Symbiotic Fungi on Water Transport:
Dr. Jeff Warren and co-workers at Oak Ridge National Laboratory

Studied are the impact of symbiotic fungi on plant soil water relations to answer the following.

First, can mycorrhizal fungi facilitate water movement toward the plant roots?

Second, can fungi affect dehydration/rehydration kinetics of root tissues?

In addition, hydraulic redistribution is another topic of interest, whereby roots or fungal hyphae passively move water from wet areas of the soil to dry areas of the soil.

For example, how far into the rhizosphere does root-released water move?

With respect to this Phase II project, can water transport at the soil-fungi-root level be quantified via extended duration neutron interferometry imaging?

Fig. 4 shows the log-standing interest of the Warren group at ORNL in water transport, starting with a macroscopic scale and moving to the near-micron scale.

Goal 5. Application to Rhizosphere Projects (continued)

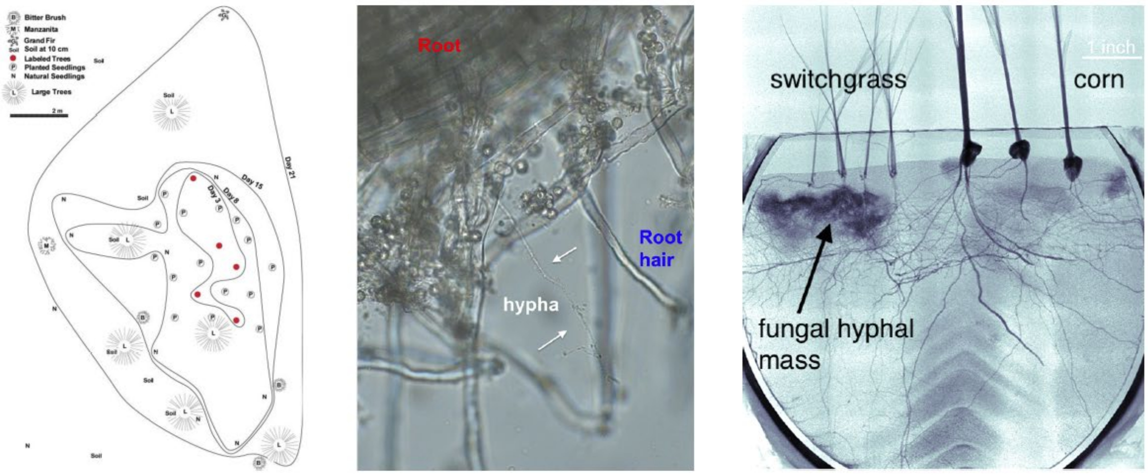

Fig. 4: (left) Water transport from D2O labeled trees to nearby seedlings.

(middle) Water transport may be aided by 3.5 µm diameter fungi hypha.

(right) Dense masses of fungi hypha associated with switchgrass roots as observed by neutron absorption imaging.

A first step is tracking root growth over time; the neutron imaging instrument offers the following two options for root size measurement:

1. Fast neutron imaging enables high resolution imaging with L/D = 1500.

2. Interferometry imaging with thermal neutrons enables sensitive edge detection with the differential phase contrast image.

Root growth studies will contribute to models correlating root structure response to environmental conditions.

Next, the effect of fungi on water transport will be studied in a compartmentalized pot with barriers constructed of single layer of 50 to 100 micron mesh.

The mesh allows roots and hyphae to grow on one side, and hyphae only on the other side.
The single layer mesh permits water transport in either direction through soil or hyphae.

A three-layer mesh creates an air gap blocking liquid water through the soil, but still permitting water transport through hyphae.

Monitoring water content of fungal hyphae will be tested with simple neutron attenuation, the scattering image, and a data fusion of scattering with attenuation.

#4: Coastal Restoration: Prof. Clint Willson, LSU Center for River Studies

The role of reactive nitrogen from land to coastal waters and the resultant impact on above- versus below-ground biomass and root structure plays a critical role in the stability of marsh soils.

Goal 5. Application to Rhizosphere Projects (continued)

Factors that impact these properties include increased nitrogen loading from agricultural runoff, sediment inputs, and sea level rise, which can increase the inundation periods and depth, introduce higher salinity water, and subject the marsh to higher tidal current and storm-related drag (shear) forces, see **Fig. 5**.

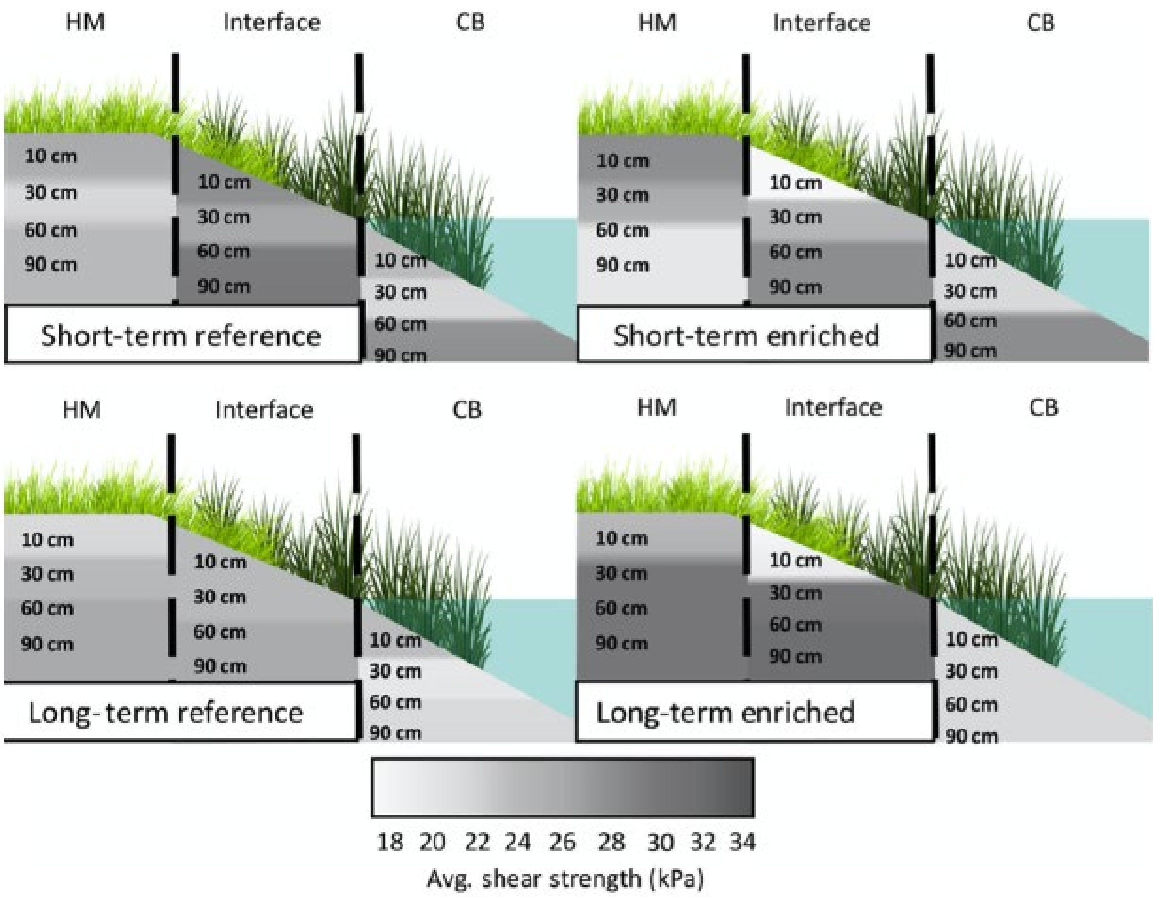

Fig. 5: Soil strength is critical to successful stabilization, where observed discontinuities in soil strength contributed to destabilization, leading to fracturing and slumping in a marsh system.

Soil strength in marshes can be enhanced by the mechanical reinforcement provided by below-ground roots and rhizomes, which is related to the diameter and density of below-ground structures and rooting depth.

Some researchers have argued that nutrient enrichment reduces below-ground biomass, increases fine organic material (OM), and increase soil decomposition rates, causing a reduction in marsh soil shear strength and increase susceptibility to erosional processes.

In contrast, in marsh systems dominated by sediment inputs, the introduction of nutrients increases the above- and below-ground productivity and enhances peat buildup.

To date, there are few studies that non-destructively characterize and measure the below-ground roots and rhizomes of marsh vegetation.

Goal 5. Application to Rhizosphere Projects (continued)

Here, we propose to combine the use of cone penetrometer method for calculating wetland shear strength with neutron imaging, allowing for the quantification of the root structure.

Above- and below-ground marsh vegetation samples will be collected from sites similar to those found in recent studies along the Louisiana coast.

On-site cone penetrometer tests will be conducted at the study sites and core samples, from the same sites, will be extruded using standard techniques, preserved and returned for neutron imaging.

#5: Plant Nutrition Technologies Inc.: https://www.plantnutritiontech.com

Plant Nutrition Technologies, Inc processes gold mine tailings to remove the gold, lead, arsenic, and then sells the detoxified mine tailings as a bio-mineral soil reconditioning products for sustainable farming.

The first large-scale experiment was at an old almond orchard in 2017, see **Fig. 6**.

Plant Nutrition Technologies wants to expand into new areas such as the canola industry in Canada.

Canadian canola is a C$15.4 billion annual business and has been impacted since 2003 by a soil-borne parasite, Plasmodiophora brassicae, causing the condition known as clubroot.

Clubroot is now estimated to cause yield losses of 10%-15% worldwide.

Fig. 6: Plant Nutrition Technologies's bio-mineral soil reconditioning product visually increased almond tree leaf foliage with just 2 treatments.
http://www.plantnutritiontech.com/current-projects.html

Researchers at the Alberta Agriculture and Forestry and the University of Alberta are testing soil additives as a treatment for canola clubroot. A first study in 2011 found that products such as wood ash and limestone were helpful, but not cost effective.

Crop rotation with 2-yr and 3-yr breaks were assessed both in greenhouse and field tests.

Goal 5. Application to Rhizosphere Projects (continued)

In 2018, the same researchers reported results for soil fumigation with sodium N-methyldithiocarbamate, tradename Vapam. This research shows the continuing interest in controlling the clubroot problem and identifies a potential advocate in Canada for bio-mineral soil recondition products, provided third party testing results are provided.

The proposed workplan is growth of canola in standard soil and soil treated with the Plant Nutrition Technologies product. The goal is collection of high-visual-impact time-lapse movies showing the enhanced root growth for the treated canola plants. The neutron interferometry systems, with the growth chamber and conveyor belt system, will be used to generate the time-lapse movies for a statistically significant number of canola plants. The results will be compressed into a visual presentation suitable for Power Point and website presentations.

Performance Schedule:

Based on time, our DOE Phase 2 SBIR project is strongly weighted towards application to rhizosphere imaging projects; basic instrument construction is only 25% of the 2-yr project.

task and milestones	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
Goal 1. Neutron Generator								
a. fast/thermal generator	■							
b. radiation shielding (vault)	■							
Goal 2. Hutch, Imaging, Interferometry Optics,								
a. hutch, flight tube, growth chamber	■							
b. scintillator and detector (Yr1 Princeton, Yr2 Lintech)	■	■			■			
c. optics fabrication (Yr1 and Yr2)	■	■			■	■		
Goal 3. Conveyor Belt (Yr2)					■			
Goal 4. Soil Characterization and Phantoms		■	■				■	
Goal 5. Application to Five+ Rhizosphere Projects			■	■	■	■	■	■

Figure 7: Milestones over the 2-year (8 quarters) project.
Rhizosphere imaging starts in Q3; that is, about 75% of project time is plant root imaging.

2. What was accomplished under these goals?

Goal 1. Neutron Generator

(a) Fast / Thermal Neutron Generator

The collimator in the original Adelphi design of the neutron generator was susceptible to high voltage breakdown. This electric breakdown problem has been resolved with a modification of the moderator of the Adelphi generator.

Installation, testing, and initiation of the Refined Imaging plant root imaging experiments at the LSU facility, which will then integrate the Refined Imaging gratings into the root imaging system, has been delayed to May 2023.

Last year 2021, test images were acquired with the camera, without grating optics, and shipped to Adelphi Technology. With zoom and email, Refined Imaging addressed questions related to focus, field-of-view, timing of the neutron pulses and camera imaging, and camera shielding.

Initial data from the LSU DD110M neutron generator, operating in pulsed-ion mode, showed prompt gamma-ray and fast neutron interference in imaging, which could be easily isolated and avoided, by using the appropriate time-delay after the deuterium ion pulse.

The ion pulse of deuterium ions strikes the neutron generator target, with deuterium embedded in the target from the prior deuterium ion pulse. The deuterium ions in the deuterium pulsed beam with the embedded deuterium in the target, yield deuterium-deuterium (DD) nuclear fusion, with the production of 2.5 MeV fast neutrons.

These 2.5 MeV fast neutrons pass through a polyethylene moderator for slowing down to thermal (0.025 eV) thermal neutrons. Next, the 0.025 eV thermal neutrons then pass through a collimator, through the radiographic imaging object, and then continue through the collimator to the neutron camera.

After installation of the Adelphi neutron source and neutron camera at LSU, the thermal neutron gratings of Refined Optics will be positioned to greatly improve the resolution and contrast of thermal neutron images, which are recorded of the roots in soil, contained within aluminum pots.

2. What was accomplished under these goals? (continued)

Goal 1. Neutron Generator (continued)

In **Fig. 8** is a plot of the total light intensity, which is recorded with the neutron camera, as a function of the time delay (gate delay) in millisecond time units, measured relative to a single neutron generator (NG) pulse.

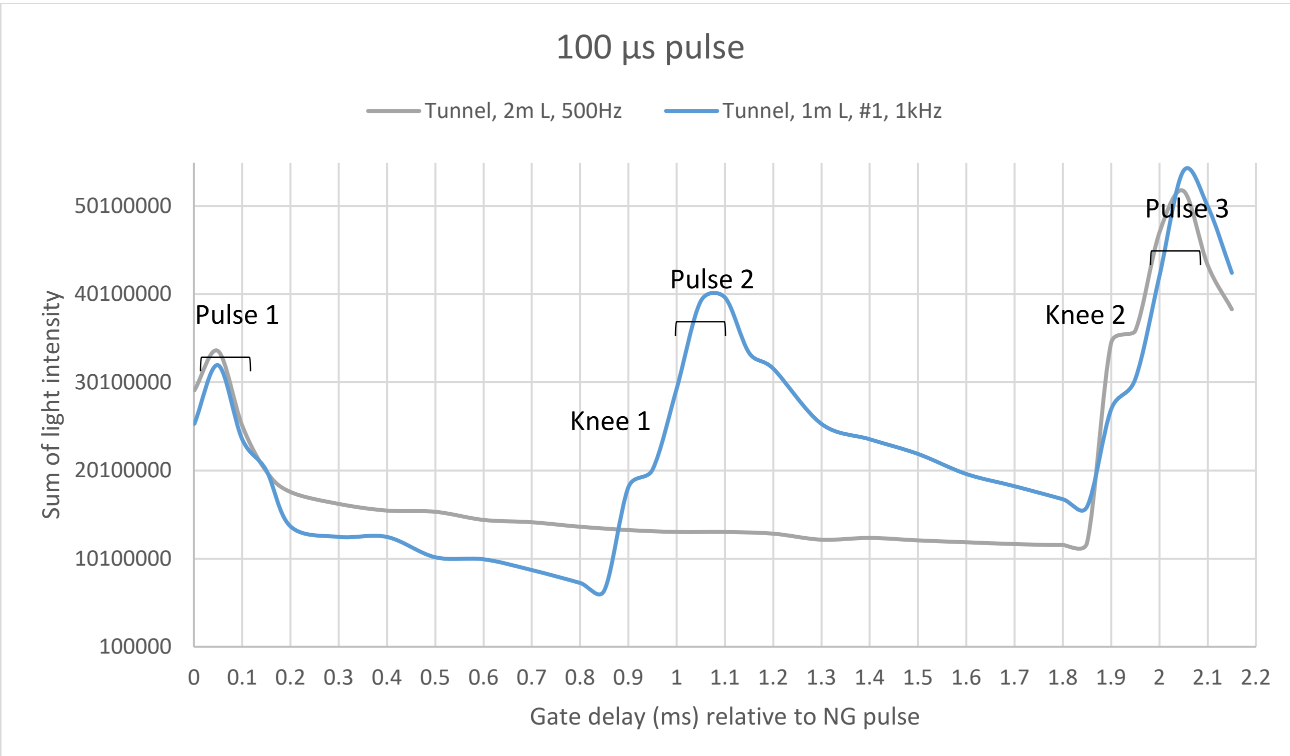

Fig. 8 Gate Delay vs. Total Light Intensity recorded by neutron camera.

The LSU neutron generator - with sub-100 us pulse capability - has been built and tested.

Data was taken at two target-scintillator distances (1 meter and 2 meter) to study the time-dependence of the output radiation (gamma-rays, fast neutrons, thermal neutrons), and any pulse accumulation effects.

The image on the next page in **Fig. 9** is a select representations of the blue plot in **Fig. 8**:
The collimator tunnel is 1 meter length and thermal neutron pulse rate is 1 kilohertz (kHz).

Each neutron pulse is 0.1 millisecond (ms) duration, and the neutron images all use a gate width of 0.1 milli-second time duration and 4 frame average. A frame represents data acquisitions for 2.5 seconds of wall clock time, where [25,000 CCD accumulations] x [0.1 ms] = 2.5 sec per frame.

The ELJEN EJ-426 scintillator is a scintillator optimized for thermal neutron imaging.

Again, the Refined Imaging gratings were not used to produce these test images.

2. What was accomplished under these goals? (continued)

Goal 1. Neutron Generator (continued)

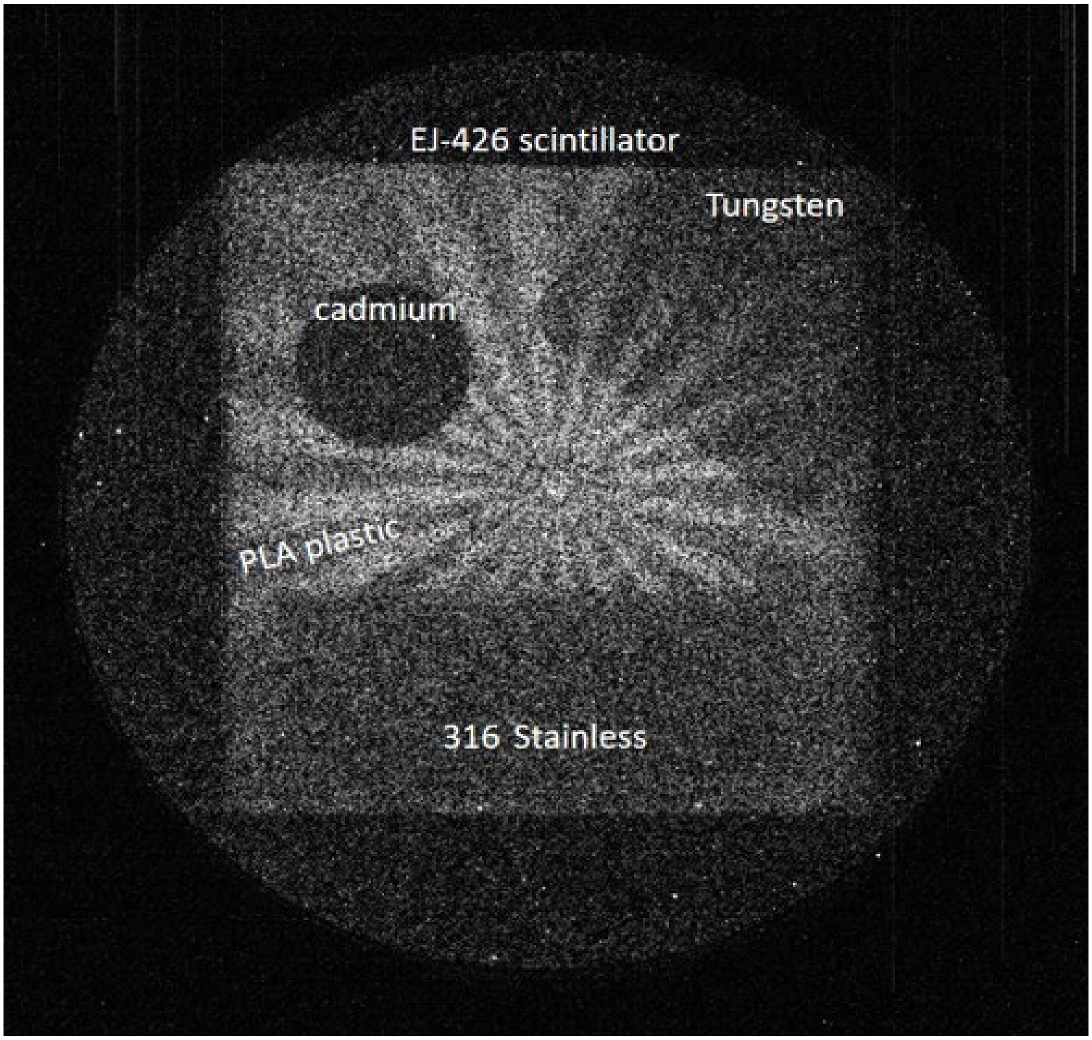

Fig. 9 In this thermal neutron image, the phantom (imaging object) used cadmium and tungsten, which were taped on top of the ELJEN EJ-426 thermal neutron scintillator. These gate delay experiments were done without using the shown 316 stainless and PLA plastic phantoms.

Total light intensity over the entire scintillator vs. time-delay is shown in the blue plot Gate Delay vs. Total Light Intensity plot in **Fig. 8**.

2. What was accomplished under these goals? (continued)

Goal 1. Neutron Generator (continued)

The image in **Fig. 10** below is a select representations of the blue plot in **Fig. 11**:
The collimator tunnel is 1 meter length and thermal neutron pulse rate is 1 kilohertz (kHz).

This **Fig. 10** image below has a much more defined at the peak of the plot in the plot of **Fig. 11** below, which is based on a 0.05 millisecond gate delay.

Each neutron pulse is 0.1 millisecond duration, and the neutron images all use a gate width of 0.1 milli-second time duration and 4 frame average.

The ELJEN EJ-426 scintillator is a scintillator optimized for thermal neutrons.

Again, the Refined Imaging gratings were not used to produce the test images.

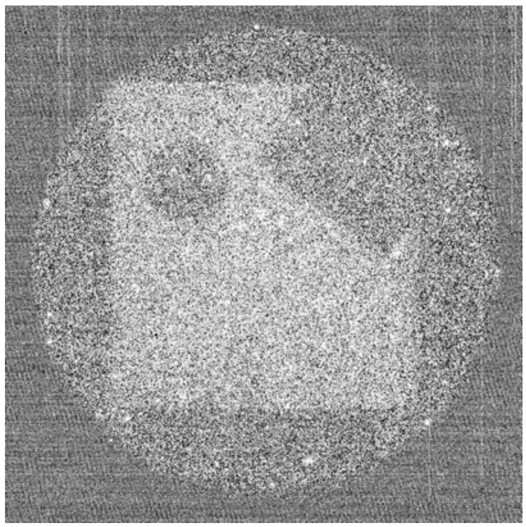

Fig. 10 Image taken with a 0.05 millisecond gate delay.

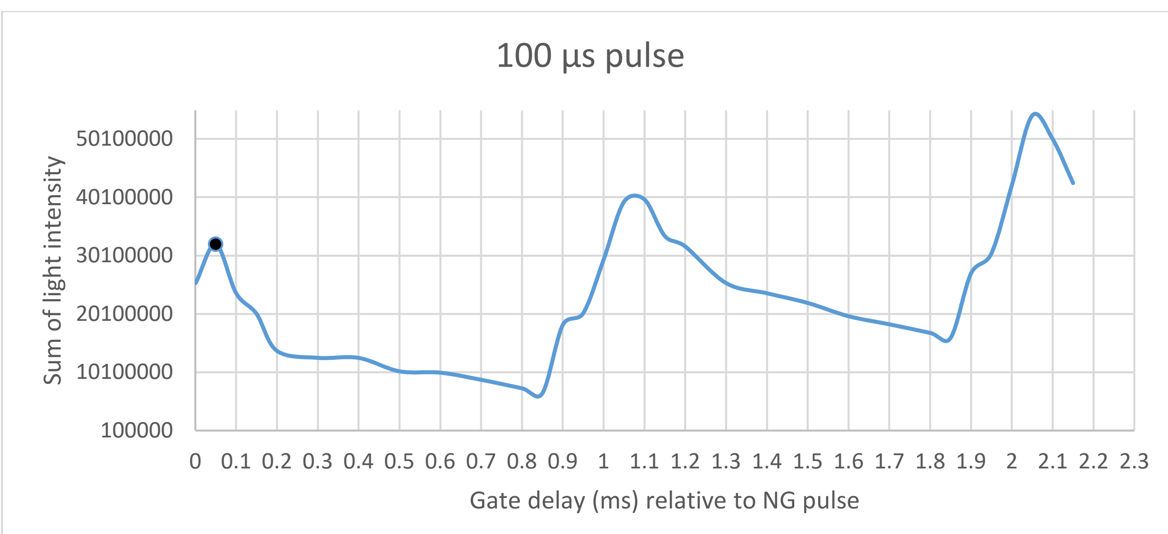

Fig. 11 Gate Delay vs. Total Light Intensity recorded by neutron camera.

2. What was accomplished under these goals? (continued)

Goal 1. Neutron Generator (continued)

The image in **Fig. 12** below is a select representations of the blue plot in **Fig. 13**:
The collimator tunnel is 1 meter length and thermal neutron pulse rate is 1 kilohertz (kHz).

This **Fig. 12** image below has a much more defined at the peak of the plot in the plot of **Fig. 13** below, which is based on a 0.40 millisecond gate delay.

Each neutron pulse is 0.1 millisecond duration, and the neutron images all use a gate width of 0.1 milli-second and 4 frame average. The ELJEN EJ-426 scintillator is a scintillator optimized for thermal neutrons. Again, the Refined Imaging gratings were not used to produce the test images.

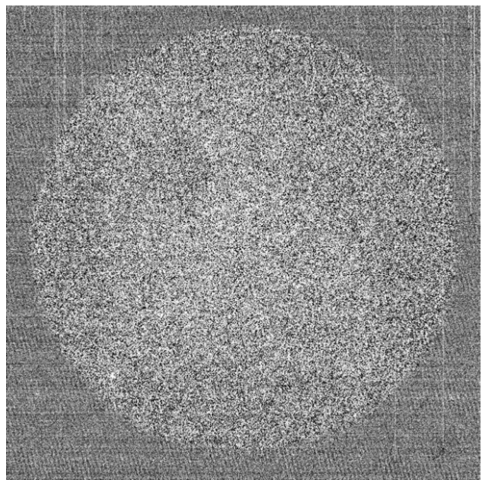

Fig. 12 Image taken with a 0.40 millisecond gate delay.

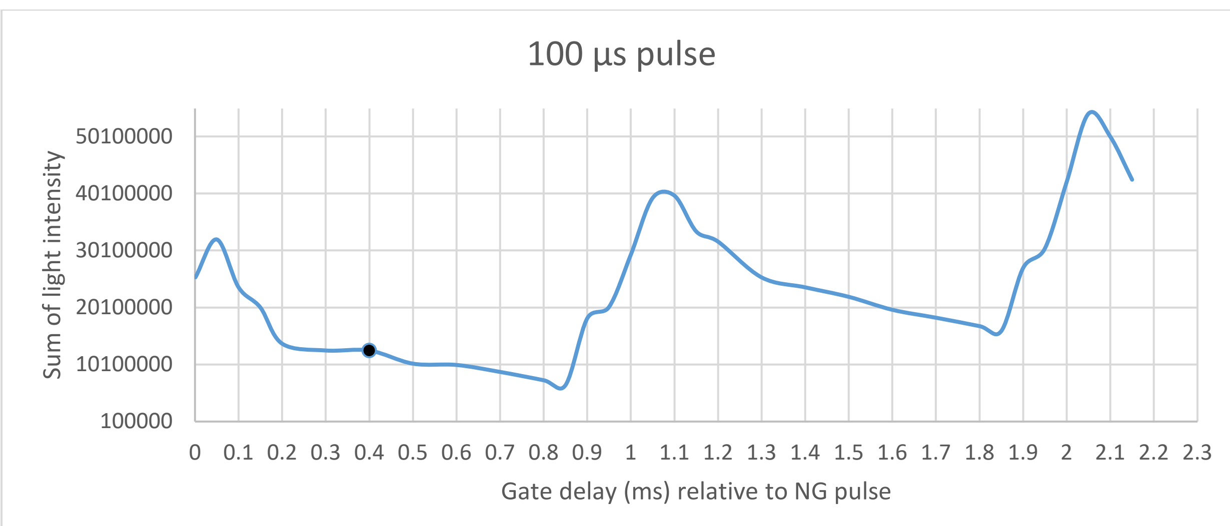

Fig. 13 Gate Delay vs. Total Light Intensity recorded by neutron camera.

2. What was accomplished under these goals? (continued)

Goal 1. Neutron Generator (continued)

The neutron image in **Fig. 10** with 0.05 millisecond delay is better than **Fig. 12** with a 0.40 millisecond delay. The apparent better resolution of **Fig. 1**0 image at 0.05 millisecond delay is due to prompt gamma, x-ray, and fast neutron emission at the peak, shown in **Fig. 11**. Sampling at 0.4 millisecond delay in **Fig. 12** eliminates the effect of this radiation on the image, which is now much weaker due to the decreased flux of thermal neutrons.

Conclusion:

We can acquire images at different neutron energies over the period of the pulsed thermal neutron source, with prompt radiation effects eliminated, using time discrimination.

A new high-density polyethylene (HDPE) generator block, without a 5 mm clear hole below the target, has been machined, and the Adelphi neutron generator has been rebuilt and is undergoing testing. The solid block design will allow for higher voltage operation of the Adelphi neutron generator, resulting in increased thermal neutron flux and decreased image integration times.

(b) Radiation Shielding (Vault)

The shielding for the neutron generator was completed in the previous 6-month reporting period, as shown in **Fig. 14** below. A hoist, shown in the picture, is used to open and move the shielding, which weighs several tons as a complete assembly.

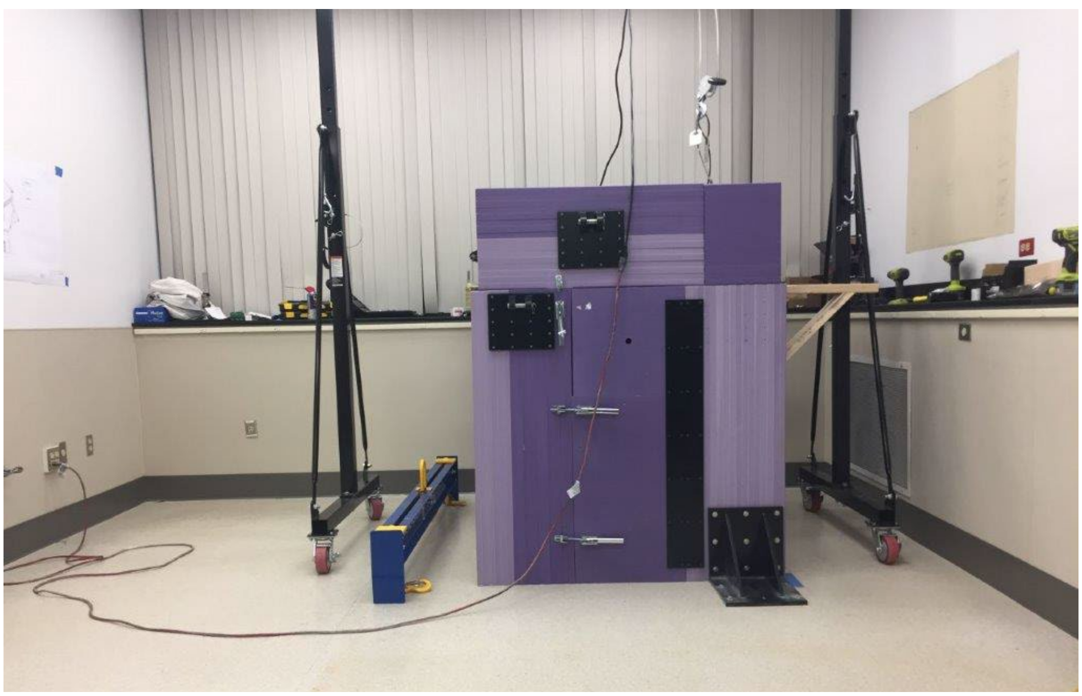

Fig. 14: Installed neutron generator shielding at LSU. Neutron generator will be enclosed within shielding with neutrons emitted through small circular aperture near middle of shielding.

2. What was accomplished under these goals?

Goal 1. Neutron Generator (continued)

The Adelphi thermal neutron source has been fabricated, tested, and packed in a crate ready for shipping to LSU, once the LSU Radiation Safety Office approves the application to allow installation and operation of the Adelphi thermal neutron source at LSU Pennington Laboratory.

At this writing, the application is nearly complete and ready for submission to the LSU Radiation Safety Office. We anticipate the next few months will see installation of the neutron generator and its approval for operation, then first images of plant roots.

LSU Radiation Safety Approval process for shipment, installation, and operation of the neutron generator is on-going as of the writing of this final report.

2. What was accomplished under these goals?

Goal 2. Hutch, Imaging, and Interferometry Optic

Instrument Construction: The pace of instrumentation construction accelerated dramatically with the arrival of Dr. Markus Bleuel, a neutron scattering expert.

Markus has 9-yrs experience with neutron scattering at NIST, serving as a beamline scientist. In May 2022, he started as an employee of Adelphi Technology, Inc. with support from a DOE STTR Phase I project (Adelphi/LSU) to develop neutron scattering and leveraging the DOE SBIR Phase II (Adelphi/Refined Imaging) instrument.

In the period of May to July 2022, Markus guided two LSU students in the construction of the SBIR Phase II optics table, programming the optics, and starting to integrate the neutron detector into the optics table software.

Markus has also contributed to the application to the LSU Radiation Safety Office for operation of the neutron generator.

The application to the LSU Radiation Safety Office for operation of the neutron generator has been challenging, with many back-and-forth questions between Adelphi and LSU.

At this writing, the application is nearly complete and ready for submission to the LSU Radiation Safety Office. We anticipate the next few months will see installation of the neutron generator and its approval for operation, then first images of plant roots.

2. What was accomplished under these goals?

Goal 2. Hutch, Imaging, and Interferometry Optic (continued)

Synergy of our DOE Phase 2 SBIR with our new DOE Phase 1 STTR on SANS

A synergistic development has emerged this reporting period with the Adelphi Technology, Inc. and LSU DOE granted STTR Phase I on **"Compact Accelerator SANS Instrument, Neutron Generator SANS Instrument" DOE STTR Contract No DE-SC0022450**.

In this synergistic development, we will use the plant root imager to evaluate several scattering instrumentation setups.

This SBIR Phase II plant root project is complementary with the new STTR Phase I SANS project.

The plant root project benefits from the technical expertise of SANS research Dr. Markus Bleuel (STTR support). Dr. Bleuel has 9-yrs experience at NIST with SANS instrumentation and is now an Adelphi employee for the STTR SANS project.

On the other hand, the STTR SANS project leverages the plant root neutron generator and neutron detector investment to add SANS optics and SANS performance with a laboratory neutron generator.

The time away from plant root imaging will not significantly impact the plant root imaging goals.

Rather, the experience gained with neutron scattering project has the potential to improve the plant root imager.

For example, a novel neutron collimator will be constructed in the scattering project; if successful, this neutron collimator could increase plant root imaging throughput by increasing the neutron flux at the plant root sample.

2. What was accomplished under these goals?

Goal 2. Hutch, Imaging, and Interferometry Optic (continued)

(a) Hutch, Flight Tube, Growth Chamber

An exclusion area hutch is under construction by Refined Imaging. The radiation calculations of Adelphi Technology indicate an exclusion distance of 2 meters from the neutron shielding surrounding the generator is sufficient. The exclusion area hutch will be fabricated from 8020 struts, screening, and will have an interlock system with the neutron generator.

The flight tubes are being fabricated by Refined Imaging. The 200 pounds of lithium carbonate has been purchased and delivered.

The flight tubes will use a cylindrical design, similar to that developed by Adelphi Technology, but with an increase in the inner bore diameter from 2.5 cm to slightly more than 10 cm to accommodate beam expansion at the sample.

A beam stop is being jointly fabricated by Adelphi Technology and Refined Imaging. We are considering a combination of borated polyethylene, lead, and lithium carbonate (thermal neutron absorption emits no gammas in lithium 6 and 7 isotopes comprising natural occurring lithium).

Simple flux calculations will be verified by Monte Carlo and lab testing with Adelphi neutron generator, which produces some gammas in addition to the main generator duty of providing pulsed thermal neutrons (via the built-in polyethylene moderator).

The old design consisted of a set of translation stages and a conveyor belt. The new design uses a 7-axis collaborative robot, which we acquired during this reporting period.

The growth chamber is no longer a customized unit, but instead a standard unit (COTS).

(b) Scintillator and Detector

We have found that the Instrument control software of choice is Python.

We have a student, an expert Python programmer, who is setting up the instrument control software in Python.

The student is presently working on the Python software for controlling the neutron camera.

2. What was accomplished under these goals?

Goal 2. Hutch, Imaging, and Interferometry Optic (continued)

(c) Optics Fabrication

In a tangential project, the Refined Imaging team, as LSU researchers, contributed to the successful first images of a Talbot-Lau neutron interferometer at the Oak Ridge National Lab, High-Flux Isotope Reactor, CG-1D beamline.

Key components of the interferometer were designed, built, and programmed at LSU. In May and June 2021 runs, the interferometer has performed, in most respects, quite well.

Issues of concern are temperature instability in the experiment hall, artifacts from the neutron beam guide upstream of the interferometer, and vibrations from equipment in an adjacent beamline.

The good results to date show the Refined Imaging team can contribute to instrument development, even while operating remotely.

Goal 3. Automated Sample Handling (Growth Chamber and Conveyor Belt)

For the conveyor belt, there has been a change of plans to switch to a collaborative robot for a recently acquired LSU X-ray instrument.

Prof. Butler, on a separate LSU contract, bought an X-ray instrument, which includes this robot. This robot is to be shared with the neutron imaging facility, which is being built under this Adelphi-LSU DOE Phase 2 SBIR.

This collaborative robot at LSU is much easier to work with than the belt and many translation stages, which was originally proposed in the Adelphi-LSU DOE Phase 2 SBIR.

In more detail, a parallel project, a collaborative robot is being installed on the WM Keck X-ray system, with initial programming being done by an LSU undergraduate.

Since the collaborative robot works well with the X-ray system, the growth chamber to imaging station system is redesigned around a collaborative robot.

As mentioned in Goal 2 (a), the tests of a collaborative robot for an adjacent X-ray system were successful. Hence, the collaborative robot purchased for the X-ray system sample will be shared with the LSU imaging facility for transport of pots from the growth chamber to the imaging station.

The switch to a robot eliminates the need for a custom designed growth chamber; a standard growth chamber will be purchased after the neutron generator is installed, operational, and passes radiation safety checks. Funds have been held in reserve so as to purchase additional radiation shielding if necessary. When the shielding is proven to be sufficient, the growth chamber will be purchased.

2. What was accomplished under these goals? (continued)

Goal 4. Soil Characteristics and Phantoms

In an effort to gain experience with plant root imaging while the neutron generator was under construction, the Refined Imaging team participated in three X-ray imaging projects. These are:

1. Maize roots in soil: Analysis of the primary and lateral roots in 3D X-ray datasets developed a skill set for segmentation of low-contrast datasets.
2. Root strength analysis: This is the X-ray version of the coastal restoration project described in the proposal on page 13, Section 2.2.5 Goal 5: Application to Rhizosphere Projects, #4: Coastal Restoration.
3. Improved root/soil contrast with X-ray interferometry: This is the X-ray version of the imaging method described in the proposal on page 2, Section 1.1.2 Method of Accomplishing Goal: Neutron Interferometry.

The X-ray interferometry project for improved contrast in plant root/soil studies was submitted to the Pacific Northwest National Lab EMS for an August 2021 call for projects and was accepted.

Project 60183 is led by Prof. Joyoni Dey, LSU Physics & Astronomy (Butler is a co-PI) and is entitled "Novel X-ray Interferometry Imaging of Plant Root Systems". The specific aims are:

1. We propose to image root structure architecture with a modulated phase grating-based interferometry system that will yield tri-modal information of attenuation images and phase image as well as small angle scattering images, simultaneously.

2. The system does not require an absorption grating and is expected to operate at low doses which will not hinder plant root growth.

3. The LSU team will test a portable (and removable) low-dose interferometry system on a PNNL CT system for plant root imaging."

One reviewer noted: "The proposed work to image the root system architecture is in alignment with the EMSL science areas and with the EMSL's mission of developing and pioneering new capabilities. The novel aspect of this project is using the modulated phase grating system to improve the image contrast and to reduce the radiation dose. The proposed work when completed successfully will be a high impact scientific contribution."

This project will provide a head-to-head competition between X-ray and neutron interferometry for plant root imaging.

Plant Root Imaging at EMSL, April to July 2022:

Prof. Butler and Dr. Ham contributed to proposal preparation of the following two X-ray imaging projects at EMSL (PNNL):

Project 60195 is led by Dr. Navid Jafari, LSU Civil Engineering (Butler is a co-PI) is entitled "Unraveling the Interplay of Wetland Root Strength and Ecogeomorphology".

Project 60183 is led by Prof. Joyoni Dey, LSU Physics & Astronomy (Butler and Ham are co-PIs) and is entitled "Novel X-ray Interferometry Imaging of Plant Root Systems".

2. What was accomplished under these goals?

Goal 4. Soil Characteristics and Phantoms (continued)

Plant Root Imaging at EMSL, April to July 2022: (continued)

Prof. Jafari's project has yielded X-ray tomography datasets for several plant root samples collected from coastal Louisiana.

The tomography datasets have been analyzed for root mass bulk, tap root length, and lateral roots between adjacent plants.

The X-ray tomography datasets have, as expected, low image contrast between live roots, dead roots, and soil structures.

Hence, conventional segmentation is not practical. Instead, a procedure has been developed to carefully normalize X-ray attenuation across multiple samples, and benchmark X-ray attenuation against root mass as measured post-tomography with careful soil washing and weighing of the root mass in vertical cross section down the cored plant root sample.

The high value of Prof. Jafari's project is the post-tomography sample analysis for ground-truthing the tomography data.

Prof. Dey's project is a high-risk/high-gain test of advanced interferometry optics. Optics fabrication is supported by NIH and NSF awards to Prof. Dey, and the EMSL facility provides a good testing instrument for recently fabricated X-ray optics.

In July 2022 four researchers from LSU---Dey, Ham, Butler, and a graduate student---visited EMSL and installed the optics into the EMSL tomography instrument and performed imaging tests over four days. Samples included maize plant roots and test objects.

The optics performance is still under analysis; preliminary results may show a very small interferometry signal, a signal which may be much improved with a higher resolution X-ray detector.

Very recently, a publication from Prof. Stampanoni's group (Paul Scherrer Institute) showed success with similar interferometry optics, though with an X-ray detector having 3-fold better spatial resolution.

2. What was accomplished under these goals? (continued)

Goal 5. Application to Five+ Rhizosphere Projects

The maize roots in soil project started with two datasets generously shared by the Danforth Plant Science center. The datasets were analyzed by an LSU undergraduate as part of her Research Experience for Undergraduates Summer 2021 project.

The analyses used manual segmentation--slow, but accurate--to compare with more automated analysis to be done later. The results were accepted for poster presentation at 2022 Emerging Researchers National Conference in STEM (Washington DC); unfortunately, the February 2022 meeting has been postponed due to COVID. The root strength analysis with X-ray tomography project was submitted to the Pacific Northwest National Lab EMS for an August 2021 call for projects and was accepted.

Project 60195 is led by Dr. Navid Jafari, LSU Civil Engineering (Butler is a co-PI) is entitled "Unraveling the Interplay of Wetland Root Strength and Ecogeomorphology".

The objectives of this exploratory research are to:

(1) Quantify the micro-scale biomass, necromass, root architecture, pore structure, and sediment density using XCT scans

(2) Measure the macro-scale field strength of root systems using cone penetrometer tests (CPTs)

(3) Develop a mechanistic understanding that captures the design functions of coastal ecogeomorphology and root structure architecture and strength that can be incorporated into future landscape models.

One reviewer commented:
"This is an outstanding proposal that is well thought through and will lead to high impact papers if successful. Mechanics of soil is rarely studied at this scale and yet it is important to do this as there is potential to find solutions to practical problems by manipulating soil and root microstructure for green engineering."

Sampling has just begun (January 2022), and samples are being sent to the X-ray lab at Pacific Northwest National Laboratory (PNNL).

The X-ray images will complement our neutron images to be acquired. We expect the neutron images to show more image contrast between fine roots and soil than do the X-ray images.

Prof. Jafari's project has yielded X-ray tomography datasets for several plant root samples collected from coastal Louisiana. The tomography datasets have been analyzed for root mass bulk, tap root length, and lateral roots between adjacent plants. The X-ray tomography datasets have, as expected, low image contrast between live roots, dead roots, and soil structures.

Hence, conventional segmentation is not practical. Instead, a procedure has been developed to carefully normalize X-ray attenuation across multiple samples, and benchmark X-ray attenuation against root mass as measured post-tomography with careful soil washing and weighing of the root mass in vertical cross section down the cored plant root sample.

The high value of Prof. Jafari's project is the post-tomography sample analysis for ground-truthing the tomography data. Prof. Jafari's project has led to an invitation to submit a PNNL EMSL Large-Scale Research project on X-ray imaging of coastal plant root samples, a project which was submitted in March 2023.

3. What opportunities for training and professional development has the project provided?

To develop proficiency with plant root image analysis, an LSU REU student is processing three X-ray tomography datasets of 10-day and 14-day maize in soil.

The datasets were supplied courtesy of Dr. Keith Duncan of the Danforth Plant Science center. The low contrast between maize brace, primary, and lateral roots versus the soil grains is very challenging for morphological segmentation.

The student is mostly using manual segmentation methods. The experience has contributed to an application to an on-line short course on the fundamentals of acquisition, visualization, and analysis of X-ray tomography data for biological and paleontological samples July 26-30, 2021, offered by the University of Texas CT Facility.

As a rising sophomore in biology, the summer REU and potentially the short course experience will make her summer 2021 REU experience most productive.

During May and June 2022, two LSU students contributed to building the 8020 and computer system for the instrument. The opportunity to touch hardware, such as 8020, and to program hardware, such as the translation stages, is a valuable opportunity for the students.

In March 2023, Dr. Kyungmin Ham worked with Prof. Maheshi Dassanayake, LSU Dept. of Biological Sciences (Project #1: High Salinity Soil) to image plant roots with X-ray interferometry in preparation for the neutron experiments. Phase contrast and dark-field scattering images were acquired of plant roots in agar demonstrating the utility of X-ray interferometry for this plant root/matrix combination.

4. How have the results been disseminated to communities of interest?

Workshop on Combined X-ray/neutron Instrumentation:
Prof. Les Butler was a co-organizer of an NSF-supported workshop on combined X-ray/neutron instrumentation. Adelphi Tech was the neutron company in a workshop tour of neutron and X-ray instrumentation.

The workshop website is: https://www.lsu.edu/science/chemistry/xn_workshop.php .

The workshop had 33 in-person participants and 45 zoom participants. A workshop report is being drafted with the intent of publication in a peer-reviewed journal.

The DOE SBIR Phase II plant root imager is a prominent prototype instrument in the workshop report. That is, the plant root imager could become the neutron-side of combined X-ray/neutron instruments where the X-ray source is either a liquid metal jet, a synchrotron, or a compact light source based on the inverse Compton effect.

Summary: Instrumentation construction is extremely active, and first plant root images should be obtained by the next reporting period. The team is gaining experience with plant root imaging as performed with X-ray instrumentation at EMSL.

The constructed instrument will be a prototype for a new generation of combined X-ray/neutron instruments.

5. What do you plan to do during the next reporting period to accomplish the goals?

The LSU Radiation Safety Office is still reviewing the application for operation of the neutron generator as of this writing, May 2023. We have requested from RSO a checklist and estimated timeline for the remaining items required for the radiation safety application. A checklist and estimated timeline will help us plan operations post-SBIR award.

With the assumption (pending the checklist) of radiation safety approval in mid-2023, the neutron generator will be shipped from Adelphi to the laboratory at the LSU PBRC C-1055. The neutron shielding is in place and the facility is ready for installation and operation of the neutron generator. The neutron detector is installed and operational. The motor systems for sample changing, interferometer, and detector are ready for final software programming using BlueSky/EPICS, the software choice recommendation from the LSU/MIT/NIST project. In summary, plant root images should be collected very soon after the neutron generator is operational.

Five plant root studies were described in the 2019 proposal:

#1: High Salinity Soil: Prof. Maheshi Dassanayake, LSU Department of Biological Sciences

#2: Arabidopsis Root Development: Prof. John Larkin, LSU Department of Biological Sciences

#3: Role of Symbiotic Fungi on Water Transport: Dr. Jeff Warren, ORNL

#4: Coastal Restoration: Prof. Clint Willson, LSU Center for River Studies

#5: Plant Nutrition Technologies Inc.

Projects 1 and 4 are currently active with X-ray imaging. #1 is exploring X-ray interferometry with our LSU WM Keck instrument in a lab adjacent to the PBRC neutron imaging system. #4 has been the subject of extensive PNNL EMSL X-ray imaging for the past year, upgrading into an EMSL Large-Scale project (proposal pending).

We are very excited about #4. We helped write the PNNL EMSL Large-Scale proposal and believe that coastal sampling of plant roots by coring, particularly adjacent pairs of plants, combined with the EMSL X-ray tomography, EMSL optical tomography of washed roots (ground truth), and AI segmentation will yield high-quality snapshots of root systems.

Our neutron interferometry and plant growth chamber will be used to monitor plant root growth, especially lateral roots connecting adjacent plants. One hypothesis about coastal stabilization invokes connective lateral roots as a primary factor. The AI-assisted X-ray tomography combined with the neutron imaging as a function of plant root growth will enable hypothesis testing of this coastal stabilization process.

For commercialization, we envision a personal contact followed by demonstration strategy. We have sought funding to support a travel and sample testing process. A seed grant, $40,000, proposal was submitted to the Louisiana Board of Regents in October 2022. Unfortunately, this proposal was not funded, possibly due to the instrument not yet operational and lack of initial contacts. We plan to revise and resubmit the proposal in October 2023.

We thank the LARTA consultant for finding potential contacts in the precision agricultural sensor space. Based the LARTA search, we have 27 companies to contact once the instrument is running. In addition, we have reached out to the *Internet of Things for Precision Agriculture* (https://iot4ag.us) research center hosted by the University of Pennsylvania, Purdue University, University of California at Merced, and the University of Florida.

III. PRODUCTS:

1. Publications

There are no publications to report.

2. Intellectual Property

Adelphi has an active program to develop and commercialize a high brightness thermal neutron source based on its prior development of DD fusion generators and a unique beam shaping assembly (BSA) that is integrated into the generator to form a compact and efficient source.

This Adelphi Phase 2 STTR allowed Adelphi to submit and be issued a USPTO patent for an Adelphi neutron source with beam shaping apparatus for radiography, namely US Patent Number 10,995,365 B 11 issued March 23, 2021, under Piestrup et al., assigned Adelphi Technology, Inc., see **Fig. 15** below.

US010955365B1

(12) **United States Patent**
Piestrup et al.

(10) **Patent No.:** **US 10,955,365 B1**
(45) **Date of Patent:** **Mar. 23, 2021**

(54) **NEUTRON SOURCE WITH BEAM SHAPING APPARATUS FOR RADIOGRAPHY**

(71) Applicant: **Adelphi Technology, Inc.**, Redwood City, CA (US)

(72) Inventors: **Melvin Arthur Piestrup**, Redwood City, CA (US); **Craig Mathew Brown**, Santa Clara, CA (US); **Jay Theodore Cremer, Jr.**, Palo Alto, CA (US); **Charles Kevin Gary**, Palo Alto, CA (US); **David Lowndes Williams**, Los Altos, CA (US); **Allan Xi Chen**, Daly City, CA (US); **Glenn Emerson Jones, Jr.**, Pittsburg, CA (US); **Yao Zong Guan**, San Francisco, CA (US); **Randall Scott Urdahl**, Mountain View, CA (US); **Adam Nathaniel Amoroso**, Mountain View, CA (US)

(73) Assignee: **Adelphi Technology, Inc.**, Redwood City, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **17/032,211**

(22) Filed: **Sep. 25, 2020**

(51) **Int. Cl.**
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G01N 23/05 (2006.01)
H05H 6/00 (2006.01)
H05H 3/06 (2006.01)

(52) **U.S. Cl.**
CPC ***G01N 23/05*** (2013.01); ***H05H 3/06*** (2013.01); ***H05H 6/00*** (2013.01)

(58) **Field of Classification Search**
CPC . G01N 23/05; H05H 3/06; H05H 6/00; A61N 5/1077; A61N 5/10; G21G 4/02
See application file for complete search history.

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Primary Examiner — David P Porta
Assistant Examiner — Mamadou Faye
(74) *Attorney, Agent, or Firm* — Donald R. Boys; Central Coast Patent Agency, LLC

(57) **ABSTRACT**

A neutron generator has a neutron source generating an ion beam bombarding a Titanium target having a first diameter, the target embedded in a pre-moderator, emitting fast neutrons isotropically, a portion of the fast neutrons moderated in passing through the pre-moderator and exiting through a lowermost surface of the pre-moderator, and a plate of moderating material abutting the lowermost surface of the pre-moderator, the plate having an opening therethrough in a shape of a truncated cone with an axis aligning with direction of the ion beam, a depth, a major diameter of at the upper surface of the plate and a minor diameter at the lower surface of the plate, the opening forming a funnel through which neutrons pass. Neutrons enter the funnel and are to exit through the minor diameter of the funnel, providing a neutron beam with a spot size useful for neutron radiography.

4 Claims, 14 Drawing Sheets

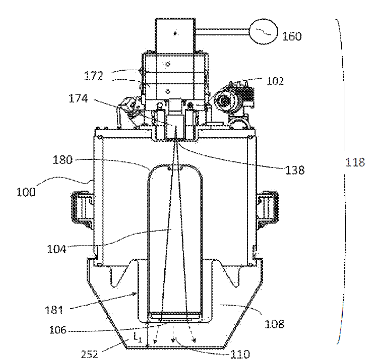

Fig. 15. Adelphi neutron source with beam shaping apparatus for radiography, namely US Patent Number 10,995,365 B 11 issued March 23, 2021, under Piestrup et al., assigned Adelphi Technology, Inc.

3. Technologies or Techniques

Adelphi has an active program to develop and commercialize a high brightness thermal neutron source based on its prior development of DD fusion generators and a unique beam shaping assembly (BSA) that is integrated into the generator to form a compact and efficient source.

Early MCNP simulations, and measurements using a prototype BSA and a Model DD110.4M neutron generator has demonstrated feasibility and expected large neutron yields.

Beam Shaping Assembly for Adelphi's High Brightness Neutron Source

The need for high yield neutron sources has grown with their known applications. Such sources are large and expensive instruments confined to reactors and LINACs at national laboratories and educational institutions. This also makes them fixed and not portable instruments and further reduces the number and location of their applications.

Inexpensive and compact, low-acceleration-voltage devices using the DD fusion reaction have been around for decades but have lacked high neutron yield.

Over several year period, we have improved our DD fusion sources by using two technologies that have increased the DD fusion generator's fast and thermal neutron yield while still decreasing the overall size and weight of the generator.

We have increased the fast neutron yield by increasing the ion beam current by using compact microwave ion sources and reduced their overall size and weight by using modern solid-state microwave sources.

To thermalize the fast neutrons, we use a solid, compact moderator with a beam shaping assembly (BSA) that is integrated into the structure of the fast neutron source thereby increasing to total available thermal neutrons in a compact instrument.

Various functions such as HV support and target cooling are shared by these substructures. These structures, such as the pre-moderator, which acts as high voltage support, and conducting channels for cooling the DD generator target, permit the close proximity of these functions, thereby increasing the neutron flux.

Fig. 16 shows cross-sectional views of a modular neutron generator consisting of two parts, a DD fusion generator close to a rectangular slab of HDPE which moderates the 2.5 MeV fast neutrons to thermal energies. A peak flux of thermal neutrons is produced with a single pass of 5 cm of HDPE.

The modular generator comprises a pre-moderator that is made of material known to moderate energy of fast neutrons to thermal energies. The pre-moderator can be a shaped, solid block of material of High-Density Polyethylene (HDPE).

The deuterium-deuterium fusion reaction generator termed "modular" has four important elements in this example: (1) a deuterium ion source, (2) an acceleration chamber, through which deuterium ions are accelerated, and (3) a titanium target that is bombarded by the deuterium ions to produce high-energy neutrons [1]. Deuterium ion source has an attached microwave source in the implementation, and microwave slug tuners.

III. Products 3. Technologies or Techniques (continued)

In operation Deuterium gas is leaked into a plasma ion chamber at an upper end of the acceleration chamber, where microwave energy ionizes the gas, creating deuterium D^+ ions. The gas is ionized by microwave energy, and Deuterium ions (D^+) are created and accelerated through an ion extraction iris into acceleration chamber, and through an electron suppression shroud which deflects back-streaming electrons from being accelerated back into the plasma source, which could damage the apparatus. Electrons are created by collisions of the D^+ ions in the deuterium gas that are being created in the acceleration chamber.

The deuterium ions are positively charged, and target is negatively charged to a level of from 120 kV to 220 kV, and the D^+ ions are strongly attracted to negatively biased titanium (Ti) target. Acceleration chamber is connected to a turbo vacuum pump that provides a modest vacuum in one embodiment of about 10^{-6} Torr, minimizing scattering of the D^+ ions as they travel from extraction iris to target. The titanium target is positioned in a cavity at the bottom of the chamber, the cavity formed in the pre-moderator material.

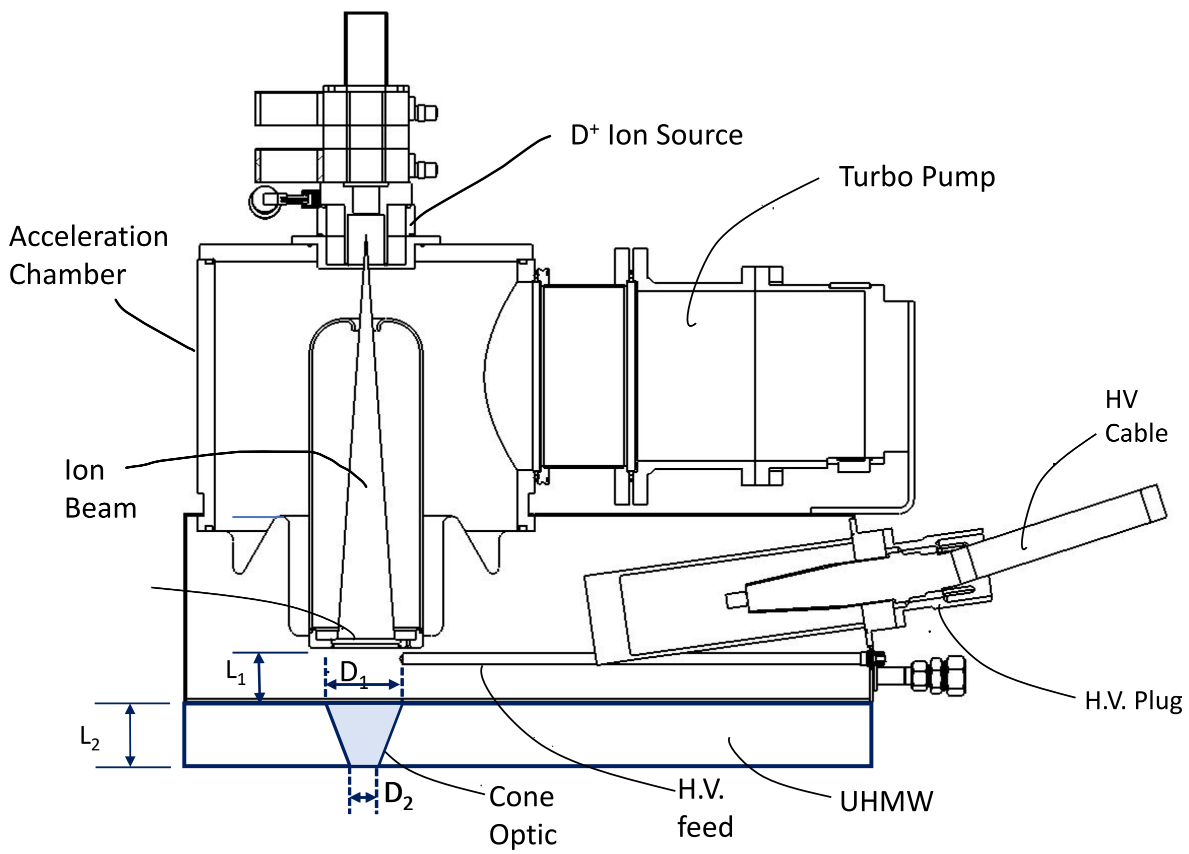

Fig. 16. Diagram of Modular Neutron Generator with a cone optic built and tested by Adelphi Technology under this DOE Phase 2 SBIR program.

III. Products 3. Technologies or Techniques (continued)

The Pre-moderator has a passage for a high voltage cable and fluid cooling channels to and from the target. Pre-moderator acts as a high-voltage insulator and as a mechanical support for the target at a high negative bias. When in operation the D^+ ions in the ion beam are attracted to the titanium target, where fast neutrons are produced in a resulting DD fusion reaction.

A major issue for fusion sources using the Deuterium-Deuterium (D-D) reaction to produce fast neutrons that must be moderated to thermal neutron energies is that fast and epithermal neutrons as well as high energy gamma emission are usually part of the moderation of the fast neutrons to thermal energies.

These fast and epithermal neutron and gamma components can accompany the thermal neutrons penetrating the absorbent material of the iris and may effectively increase the aperture size D if the extraneous radiation can penetrate the iris materials, blurring the desired image.

In large reactors, thermal neutrons have been obtained which have mixtures of thermal, epithermal, and fast neutrons along with gamma and x-rays. Applications such as neutron radiography and radiotherapy usually require the neutron energy to be confined to thermal energies without x-ray or gamma components.

Modular DD fusion generator uses a small titanium target (e.g., a 5-7 cm diameter disk of titanium backed by water-cooled copper fins) to produce fast neutrons.

Fig. 17 is a cross-sectional drawing of a modular neutron generator designed to produce maximum thermal neutrons. The target is supported directly on the pre-moderator, which is an integral part of the apparatus. The Ti target may be attached with fasteners to the pre-moderator block and may be sealed to the block with an O-ring.

The accelerator structure in embodiments of the invention is compact and includes a pre-moderator that 5 cm of High-Density Polyethylene (HDPE) to produce a first stage of thermal neutron beam emission. The “pre-moderator” in these embodiments is an integral part of each modular generator, as is taught below with reference to several figures. Other short-length attachments are added to the pre-moderator to further improve the neutron beam in beam purity, size, and shape, making the modular neutron generator a highly versatile source of neutrons.

A primary application is thermal neutron radiography, which requires a small source size, high neutron yield (n/cm^2) and high beam purity. High thermal neutron beam purity is achieved in embodiments of the invention by minimizing other neutron and photon components that may be introduced during the DD fusion process and moderation of the 2.5 MeV neutrons to thermal energies.

The filtering process is accomplished using neutron filters; both “low pass” and “high pass” filters. To maximize the resulting neutron flux and minimize the neutron source size, these filters and collimators are minimalized in length and proximity to the neutron generator. This results in a highly compact neutron source for many applications.

III. Products 3. Technologies or Techniques (continued)

Thermal neutron collection can be achieved with a conical funnel (**Fig. 17**) to both collect and channel neutrons into a small spot size D_2 with increased thermal flux at the exit D_2 of the funnel. The compact DD fusion source with a short (4-5 cm) moderator slows the fast 2.5MeV neutrons to thermal energies in a short distance from the fast neutron source (the titanium target). The neutrons are then collected by a relatively short (e.g., L_2 = 3 to 4 cm) funnel shape formed into a slab of HDPE. Both moderation and scattering continue to occur along the funnel length L.

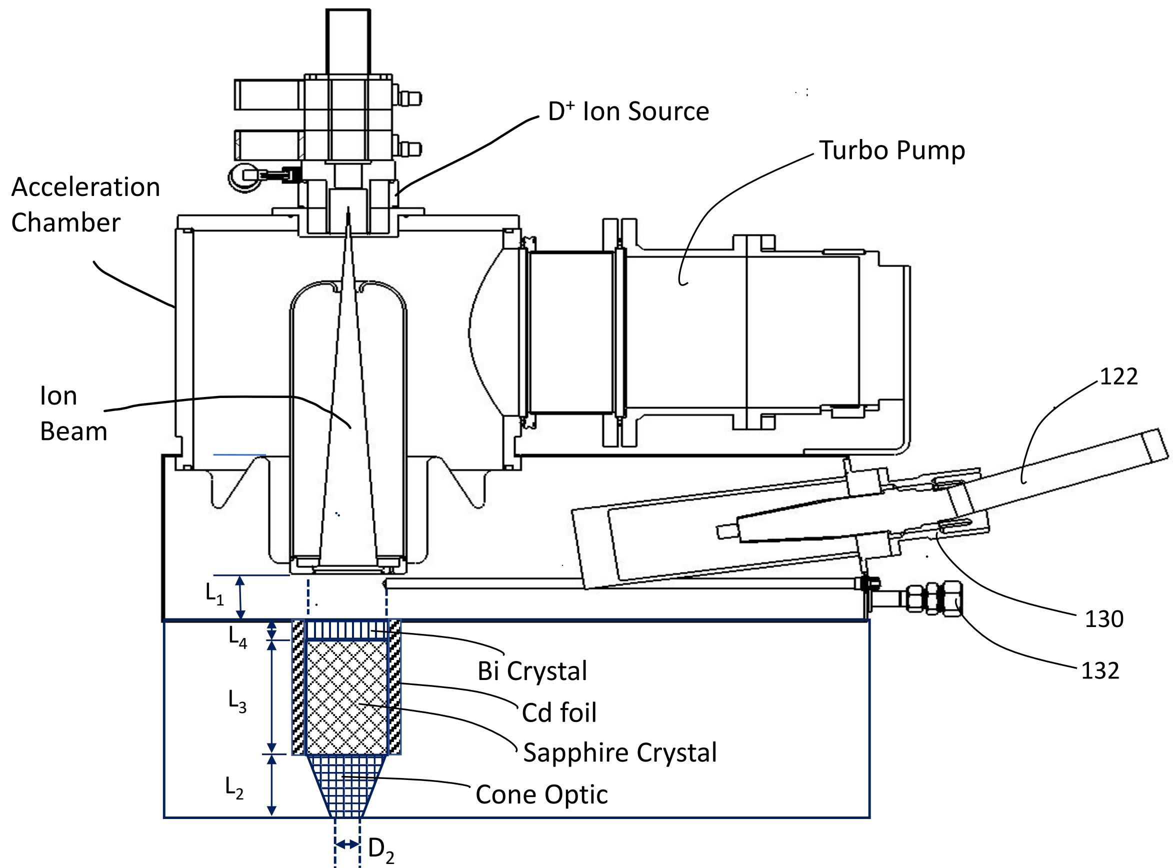

Fig. 17 Beam shaping assembly (BSA) added to filter the neutron beam.

Simulations show that this results in an increase in flux 2 to 3 times and spot sizes of 1 to 3 cm in diameter depending on the geometry of the cone and size of the fast neutron emitter (Ti target).

The compactness of the DD fusion generator, and shortness of the pre-moderator to produce and collect thermal neutrons also allow for the use of other devices in the neutron beam. These devices include short lengths of sapphire crystals and bismuth which can reduce fast neutrons and gamma emission in the neutron beam, thus cleaning up the beam and achieving a relatively pure beam of thermal neutrons.

III. Products 3. Technologies or Techniques (continued)

Fig. 18A shows the simulated thermal neutron yield (n/sec-cm^2) as a function of distance x across an axis of the convergent funnel of a simple beam shaping assembly (BSA).

A prototype of the apparatus has been built and tested. The apparatus uses a funnel collimator directly attached to a compact moderator with an input aperture of 6 cm and exit aperture of 1.5 cm.

Fig. 18B shows the measured thermal neutron yield (n/sec-cm^2) as a function of distance x across the axis of the convergent funnel of the simple BSA (HDPE Slab with funnel) and for the case of no funnel and the moderator with thickness of 9.5 cm.

In our first experiment the method of detection of the thermal neutrons is a linear array of small chips of NaCl. These chips were activated by the incoming thermal neutrons for a measured length of time. The radioactive flux was then determined by neutron spectroscopy.

The measured results are shown in **Fig. 17B**). The general shape and magnitudes are comparable with the simulated results of **Fig. 17A**.

The peak flux of **Fig. 17B** is smaller (6 x 10^6 n/sec-cm^2) than that of the simulation of **Fig. 17A**. (9 x 10^6 n/sec-cm^2). The differences are from the resolution of the detectors (measured vs simulated). The funnel BSA is indeed effective as a method of collimation.

The use of a compact fusion generator with relatively small spot sources of neutrons permits neutron filters to also be compact and close together.

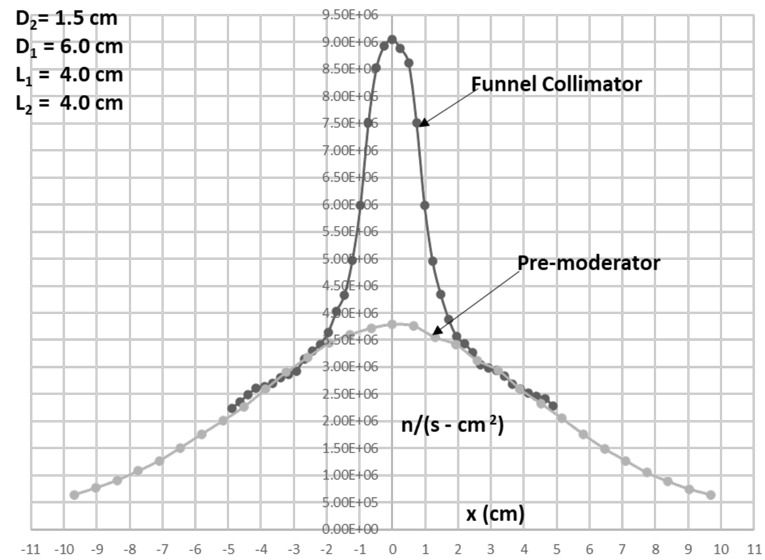

Fig. 2A Simulated (MCNP) flux across the aperture of the BSA

A. Simulated Flux across aperture of BSA

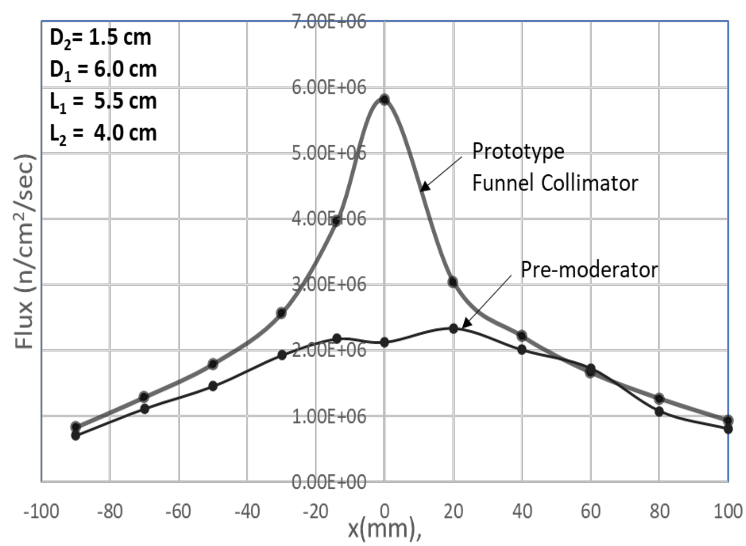

Fig. 2B The measured flux across the aperture of the BSA

B. Measured Flux across aperture of BSA

Figs. 18A (top) and **Fig. 18B (bottom).** Simulated **(A)** and Measure **(B)** neutron flux across the aperture of the Beam Shaping Aperture (BSA) compared to the case where the BSA has been removed from the pre-moderator.

III. Products 3. Technologies or Techniques (continued)

The modular generator combines multiple functions that were separate functions in the prior art. These integrated functions include both neutron production and neutron energy band selection. This method shortens the overall length of the device and ensures higher fluxes.

The expected thermal flux from the BSA is shown in **Fig. 18A** where the flux density is plotted as a function of lateral dimension in cm at D_2 (exit aperture0. In the example of **Fig. 18A**, the spot size is roughly 1.5 cm at diameter (D_1).

Without the funnel the diameter of the source size would be a disc 6 cm in diameter and expanding as is shown also in the plot (**Fig. 18A**).

The use of the moderator in direct or near contact with Titanium target is to produce a maximum thermal neutron flux at the top aperture D_1 of the funnel.

Adding a funnel of modest length (L_2 = 4 cm in this example) directly on to the pre-moderator permits a maximum number of neutrons and higher thermal neutron flux to be collected and a smaller source size to be obtained.

The close stacking of the pre-moderator and the BSA (Funnel in HDPE slab) permits a maximum number of thermal neutrons to be obtained with a small source size.

Fig. 18A clearly illustrates the beneficial effect of the slab with the funnel.

A prototype of the apparatus has been built and tested is shown in **Fig. 17** with a funnel collimator as shown in the two figures, as described above. The dimensions of the prototype funnel collimator are D_1 = 6 cm and D_2 = 1.5 cm with L_1 = 5.5 cm and L_2 = 4 cm. These dimensions may be different in other embodiments.

The method of detection of the thermal neutron is a linear array of small chips of NaCl. These chips were activated by the in-coming thermal neutrons for a measured length of time. The neutron flux was then determined by neutron spectrographic means. The results are shown in **Fig. 18B**.

The general shape and magnitudes are comparable with the simulated results of **Fig. 18A**.

The peak flux of **Fig. 18B** is smaller (6 x 10^6 n/sec-cm^2) than that of the simulation of **Fig. 18A**. (9 x 10^6 n/sec-cm^2).

The differences are from the resolution of the detectors (measured vs simulated). However, in both case L_2 = 5.5 cm and the comparison between **Fig. 18A** and **Fig. 18B** shows that the HDPE funnel BSA is indeed effective as a method of collimation. To improve the resolution, different parameters for D_1 and D_2 are selected, and different distances from the BSA aperture D_2 to the knife edge are tried, L.

All other parameters for the generator, knife edge and detector array are the same. Larger apertures D_2 = 5 cm, and D_1 = 8 cm. The distance to the knife edge L = 2 cm.

Flux as a function of distance x across an axis of the convergent funnel of a simple beam shaping assembly (BSA) is shown in **Fig. 18A**.

The maximum thermal flux is a healthy 3.4 x 10^6 n/cm^2-sec, but the resolution is 6-mm. Increasing the distance L to 100 cm, as shown in **Fig. 18B**, sub-mm resolution is achieved.

Throughout these simulations, HDPE is used in both the moderator and in the BSA, the thickness of the Moderator is L1 = 4 cm, and the thickness of the BSA is L2 = 4 cm.

III. Products 3. Technologies or Techniques (continued)

Plotting the resolution as a function of L, the resolution continues to improve. We can achieve the desired resolutions of 1 mm for L = 20 to 50 cm.

However, with increasing distance L, the available neutron flux for imaging decreases resulting in an increase in measurement time for the collection of neutrons. This may be estimated with a simple assumption that each diode of the array needs around 250 neutrons for a measurement.

Plotting the measurement time as a function of L, we achieve measurement times in the order of seconds. With L = 20 to 50 cm, the detection of the knife edge image with 1-mm resolution can take place within 1 to 3 seconds, a time more than adequate for achieving a high-quality image.

The resolution may further be improved by attenuating the fast neutrons by means of a low pass filter, in which thermal neutrons are transmitted, while fast neutrons are attenuated. Fast neutrons need to be attenuated or the detector's sensitivity to the fast neutrons needs to be suppressed.

Because tungsten target is on the plastic (HDPE) pre-moderator, fast neutrons coming from the target immediately enter the pre-moderator and can be moderated to thermal or epithermal energies.

A short Beam Shaping Assembly (BSA) is provided below the Ti target and the pre-moderator, where some of the thermal neutrons may be collected and directed to a small aperture at the end of the BSA. A short, L_5, iris is placed just below the BSA. The material of the iris may be made of lead and B_4C.

In its simplest embodiment, the BSA is an inverted cone as shown in **Fig. 15** and **Fig. 16**. The HDPE of the BSA acts as a reflector and collimator of the thermal neutrons. Without the BSA the diameter of the source size at the pre-moderator would be a disc 6 cm in diameter and expanding. The idea behind the use of the pre-moderator in direct or near contact with Titanium target is to produce a maximum thermal neutron flux.

Adding a BSA of modest thickness (L_2 = 4 cm in this example) directly on to the pre-moderator permits a maximum number of neutrons and higher thermal neutron flux to be collected and a smaller source size to be obtained. The close stacking of the pre-moderator and the BSA permits a maximum number of thermal neutrons to be obtained with a small source size D_2.

In the filter version, the thermal neutron collection can be achieved with a conical funnel to both collect and channel neutrons into a small spot size with increased thermal flux at the exit of the cone of the funnel.

The compact DD fusion source with a short thermal moderator (such as HDPE, or UHMW plastics with a high concentration of hydrogen atoms) quickly scatters the fast 2.5 MeV neutrons to thermal energies in a short distance ($L_1 + L_2 + L_3 + L_4$) from the fast neutron source (the titanium target). The neutrons are then collected by a relatively short (e.g., L_2 = 3 to 4 cm) funnel in the slab of HDPE. Both moderation and scattering continue to occur along the cone length L.

Simulations show that this results in an increase in flux 2 to 3 times and spot sizes of 1 to 3 cm in diameter depending on the geometry of the cone and size of the fast neutron emitter (Ti target). Additions of short spatial and energy filters improve the image by improving the brightness of the neutron source and limiting the effects of spurious radiation of fast neutrons, gamma emission.

III. Products 3. Technologies or Techniques (continued)

The compactness of the DD fusion generator and the moderation process to produce and collect thermal neutrons also allows for the use of other devices in the beam including short lengths of sapphire and bismuth crystals, which can reduce the fast neutrons and gamma emission in the neutron beam, thus cleaning up the beam and achieving a relatively pure beam of thermal neutrons.

The use of a compact fusion generator with relatively small spot sources of neutrons permits these neutron filters to also be compact and close together. This results in a useful source of neutrons that can be used in many laboratories and field locations, unlike the fixed, large, and expensive reactor sources.

III. Products

4. Other Products

There are no products to report.

IV. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS:

Participant 1

(1) Name: Dr. Jay Theodore Cremer, Jr.

(2) Project Role: Adelphi Technology, Principal Investigator

(3) Nearest person month worked in Phase 2: 5.08

(4) Contribution to Project:

As Adelphi PI, Dr. Cremer will work closely with LSU Profs. Butler and Ham and Refined Imaging personnel to develop a prototype neutron imaging laboratory at LSU as a prototype of a greenhouse-compatible neutron interferometry radiography system for imaging plant roots and soil systems grown or transplanted into aluminum pots in greenhouse settings.

Coordinating with Refined Imaging and LSU personnel, Dr. Cremer will perform experimental testing of plant roots in soil at the LSU laboratory, where is installed the Adelphi neutron source for testing plants in aluminum pots provided by LSU and other university and government agricultural researchers.

Dr. Cremer will provide technical support in the design, analysis, and testing of radiographic imaging experiments at the LSU facility in collaboration with LSU and Refined Imaging personnel.

Dr. Cremer will lead the commercialization of the compact and deployable Adelphi neutron imaging instrument for rhizosphere imaging at academic and government agricultural R&D facilities.

(5) Funding Support: None

(6) Collaborated with individual in foreign country: No

(7) Country(ies) of foreign collaborator: None

(8) Travelled to foreign country: No

(9) If traveled to foreign country(ies), duration of stay: Not Applicable

IV. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS: (cont.)

Participant 2

(1) Name: Dr. Charles K. Gary

(2) Project Role: Adelphi Technology, Senior Scientist (Key)

(3) Nearest person month worked in Phase 2: 0.92

(4) Contribution to Project:

As Adelphi Technology CEO and business official, Dr. Gary, will assist Dr. Cremer in the administrative and commercialization aspects of this Phase 2 program to develop working prototype of the Adelphi neutron instrument deployed for imaging the rhizosphere at agricultural laboratories,

Dr. Gary will assist Dr. Cremer in reviewing and overseeing technical aspects of the project.

(5) Funding Support: None

(6) Collaborated with individual in foreign country: No

(7) Country(ies) of foreign collaborator: None

(8) Travelled to foreign country: No

(9) If traveled to foreign country(ies), duration of stay: Not Applicable

Participant 3

(1) Name: Dr. Allan Chen

(2) Project Role: Adelphi Technology, Senior Scientist (Key)

(3) Nearest person month worked in Phase 2: 2.03

(4) Contribution to Project:

Dr. Chen will direct design, fabrication, and testing of Adelphi DD110M thermal neutron source, modified to become a deployable neutron imaging for greenhouse-based R&D on the rhizosphere.

Dr. Chen will assist Dr. Cremer in the installation and follow-up of Adelphi neutron imaging instrument at the LSU laboratory, where testing of plant roots in soil will follow. Dr. Chen will perform Monte Carlo simulations to improve imaging instrument design and function, and he will perform Monte Carlo simulations of LSU experiments and analyze results.

(5) Funding Support: None

(6) Collaborated with individual in foreign country: None

(7) Country(ies) of foreign collaborator: No

(8) Travelled to foreign country: No

(9) If traveled to foreign country(ies), duration of stay: Not Applicable

IV. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS: (continued)

Participant 4

(1) Name: Dr. Craig Brown

(2) Project Role: Adelphi Technology, Staff Scientist (Key)

(3) Nearest person month worked in Phase 2: 0.51

(4) Contribution to Project:

Dr. Brown will perform Monte Carlo simulations and analysis to modify the Adelphi DD110M neutron source into a greenhouse deployable neutron imaging instrument for imaging roots of potted plants.

Dr. Brown will assist Dr. Cremer and Dr. Chen on Monte Carlo simulations and analysis in designing plant imaging experiments at the LSU laboratory and analyzing results.

(5) Funding Support: None

(6) Collaborated with individual in foreign country: No

(7) Country(ies) of foreign collaborator: None

(8) Travelled to foreign country: No

(9) If traveled to foreign country(ies), duration of stay: Not Applicable

Participant 5

(1) Name: Adelphi Engineer

(2) Project Role: Adelphi Technology, Engineer

(3) Nearest person month worked in Phase 2: 9.18

(4) Contribution to Project:

In Year 1, Adelphi engineer assembles & tests the neutron generator at Adelphi, and then installs & tests Adelphi generator at LSU. In Year 2 Adelphi engineer services & upgrades generator at LSU.

(5) Funding Support: None

(6) Collaborated with individual in foreign country: No

(7) Country(ies) of foreign collaborator: None

(8) Travelled to foreign country: No

(9) If traveled to foreign country(ies), duration of stay: Not Applicable

IV. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS: (continued)

Participant 6

(1) Name: Dr. Les Butler

(2) Project Role: Co-Investigator, Refined Imaging, co-founder/Chief Scientist, LSU Professor

(3) Nearest person month worked in Phase 2: 3.3 months

(4) Contribution to Project:

Prof. Butler is world renowned for his research in interferometry. Dr. Butler has built two interferometers at LSU and is currently the PI of an LSU project to build a neutron interferometer at the ORNL HFIR. Butler will dedicate a minimum of 6 hours per week for 2 years; total $30,000.

(5) Funding Support: None

(6) Collaborated with individual in foreign country: No

(7) Country(ies) of foreign collaborator: None

(8) Travelled to foreign country: No

(9) If traveled to foreign country(ies), duration of stay: Not Applicable

Participant 7

(1) Name: Mr. Charles Hartman

(2) Project Role: Co-Investigator, Refined Imaging, co-founder, and Manager

(3) Nearest person month worked in Phase 2: 4.8 months

(4) Contribution to Project:

Hartman's degree in nuclear science and his work at the LSU CAMD synchrotron, where he is clean room certified and trained to use the beamline will ensure the scientific project goals are achieved. As neutron images of plant root/soil systems become available, Hartman will use these results for business development at agricultural trade shows, soliciting additional scientific studies with the goal of first sales. Hartman will dedicate a minimum of 12 hours per week for 2 years; a total of $60,000.

(5) Funding Support: None

(6) Collaborated with individual in foreign country: No

(7) Country(ies) of foreign collaborator: None

(8) Travelled to foreign country: No

(9) If traveled to foreign country(ies), duration of stay: Not Applicable

IV. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS: (continued)

<u>Participant 8</u>

(1) Name: Dr. Kyungmin Ham

(2) Project Role: Co-Investigator, Refined Imaging, co-founder, and Scientist

(3) Nearest person month worked in Phase 2: 3.1 months

(4) Contribution to Project:

Dr. Ham is a beam-line expert at the LSU CAMD synchrotron and will direct the quality assurance program. Ham will dedicate a minimum of 6 hours per week for 2 years; a total of $30,000.

(5) Funding Support: None

(6) Collaborated with individual in foreign country: No

(7) Country(ies) of foreign collaborator: None

(8) Travelled to foreign country: No

(9) If traveled to foreign country(ies), duration of stay: Not Applicable

<u>Participant 9</u>

(1) Name: Dr. Michael Vincent – **Left Project in June 2022**

(2) Project Role: Co-Investigator, Refined Imaging, Scientist

(3) Nearest person month worked in Phase 2: 3.5 months

(4) Contribution to Project:

Dr. Vincent was a full-time employee for Refined Imaging and was the head of the micro-fabrication process. Dr. Vincent has experience at the LSU CAMD synchrotron microfabrication, the Tulane University microfabrication, and (January 2020), the Georgia Tech microfabrication facilities. His task on this project includes grating fabrication. Vincent dedicates 6 hours per week for 2 years, ending June 2022; total $30,000.

(5) Funding Support: None

(6) Collaborated with individual in foreign country: No

(7) Country(ies) of foreign collaborator: None

(8) Travelled to foreign country: No

(9) If traveled to foreign country(ies), duration of stay: Not Applicable

IV. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS: (continued)

Participant 10

(1) Name: Dr. Wieslaw Stryjewski

(2) Project Role: Refined Imaging, Software Programmer

(3) Nearest person month worked in Phase 2: 0 months

(4) Contribution to Project:

No contribution to the Project

(5) Funding Support: None

(6) Collaborated with individual in foreign country: No

(7) Country(ies) of foreign collaborator: None

(8) Travelled to foreign country: No

(9) If traveled to foreign country(ies), duration of stay: Not Applicable

Participant 11

(1) Name: Mr. Don Patterson

(2) Project Role: Refined Imaging, Electronics Engineer

(3) Nearest person month worked in Phase 2: 0 months

(4) Contribution to Project:

No contribution to the Project

(5) Funding Support: None

(6) Collaborated with individual in foreign country: No

(7) Country(ies) of foreign collaborator: None

(8) Travelled to foreign country: No

(9) If traveled to foreign country(ies), duration of stay: Not Applicable

IV. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS: (continued)

Participant 12

(1) Name: Refined Imaging Operator

(2) Project Role: Refined Imaging, Operator

(3) Nearest person month worked in Phase 2: 0 months

(4) Contribution to Project:

The operator was not hired.

(5) Funding Support: None

(6) Collaborated with individual in foreign country: No

(7) Country(ies) of foreign collaborator: None

(8) Travelled to foreign country: No

(9) If traveled to foreign country(ies), duration of stay: Not Applicable

Partners Detail

There are no partners to report.

Other Collaborators Detail

There are no other collaborators to report.

V. Impact

1. What is the impact on the development of the principal discipline(s) of the project?

This project will develop a greenhouse-compatible neutron interferometry radiography system for imaging plant roots and soil systems grown or transplanted into aluminum pots.

The significance is that long-duration, extensive sampling of plant growth factors is essential for food security. The opportunity is based on recent developments in robust (battlefield) neutron sources and a new low-cost route to neutron interferometry optics. The technical approach recognizes the reduced flux of a portable neutron source relative to a reactor source and therefore uses interferometry to regain imaging performance.

Food security in a high population planet requires constant attention to the maintenance of our intensive agriculture system. Fungal and microbial attack of plant roots is a documented problem with severe consequences.

For example, Project #5 of our Phase 2 project, in collaboration with Plant Nutrition Technologies Inc., describes a major problem in the canola fields. Plants are also crucial for stabilization of coastal environments.

In another example, Project #4 of our Phase 2, explores the root structures of plants protecting the Louisiana coast. The proposed portable neutron imaging system offers botanists and agricultural scientists an effective research tool for in situ, long duration studies of plants in a greenhouse environment.

2. What is the impact on other disciplines?

The markets for radiography and tomography, which use fast and thermal neutrons, X-rays, gammas and competing modalities for non-destructive imaging, analysis, and testing, include the following two market areas:

(1) Agriculture – Our neutron imaging system can be applied to imaging and diagnosing plant disease and used plant development R&D resulting in improvement of crop yields, conducted in greenhouse and small lab settings, addressing customer needs for imaging of in-situ plants roots in soil or above-ground portions of the plant in green houses and R&D agricultural fields.

A rugged, portable neutron generator, combined with advanced neutron interferometry imaging, could measure of sugarcane fiber and sugar content directly in the sugar cane field of agricultural research stations and laboratories, directed to aviation biofuel production from sugar cane.

(2) Industry – Our neutron-based imaging system could be applied to non-destructive imaging/testing/analysis in manufacturing, defense, construction, buildings, vehicles and aircraft, transportation infrastructure (bridges, roads, and rails).

3. What is the impact on the development of human resources?

The Adelphi Technology DOE Phase 2 SBIR in collaboration of Refined Imaging, Inc. of Baton Rouge, Louisiana, and the Prof. Les Butler Group in the Department of Chemistry at Louisiana State University (LSU) in Baton Rouge, together provide post-graduate and undergraduate training in a broad-based program of agricultural sciences, physics and chemistry, and engineering disciplines, directed to developing advanced technology and instrumentation with a potentially strong impact on the US agricultural and industrial sectors.

V. Impact (continued)

4. What is impact on physical, institutional, information resources that form infrastructure?

Successful plant growth depends upon an efficient and robust root system. The plant root is part of a larger system of water and microbial flows in the soil system. While much effort has been exerted to develop an imaging system for water, microbes, and roots, the problem is challenging, and no widely accepted imaging method currently exists.

The optical solutions use a highly modified soil system.

X-ray imaging methods are insensitive to the soft tissues in the presence of sand.

Thermal neutron imaging has been often tested, but found inadequate, due to limited access and low image resolution. This project will develop a new strategy for neutron imaging of plant/soil systems. The project will allow long duration experiments in greenhouse environments and increase the image information content to the micron scale.

A rugged, portable neutron imaging system, deployable for in-the-field agricultural sensor for sugarcane breeding could advance the biofuels industry, especially if marginal lands can be used for developed new strains of sugar cane, whose identification would be aided by our proposed neutron instrument for nondestructive imaging of plants.

Furthermore, our proposed, compact, and deployable, neutron-based imaging system could provide better imaging and testing of industrial parts produced by additive manufacturing.

5. What is the impact on technology transfer?

Our neutron imaging instrument could make a strong contribution to non-destructive imaging, testing, and analysis in the industrial and agricultural sectors of the US economy, as well as to US space and defense.

6. What is the impact on society beyond science and technology?

Neutron-based instruments are powerful materials science probes, providing unique information about the structure of matter and the way in which structures vibrate.

Our proposed instrument expands the use of neutrons to uniquely probe many important new materials, which can be exploited to extend existing and develop new science and technology, important to the US economy, security, and well-being.

The pursuit of life, liberty, and happiness, the advancement of quality of life, the advancement of knowledge of life and the universe, as well as the safety and security of the peoples of the USA and worldwide nations, are dependent on science and technology, and the benevolent and proper applications of science and technology to all aspects of society.

Furthermore, this dependence on technology is rapidly increasing, and we are challenged to create a desirable future in this fast-paced and changing world.

Development of scientific and engineering instrumentation in industry, medicine, academia, government, exploration of earth and beyond, defense, and homeland security is one important endeavor for US and worldwide nations to achieve a desirable present and future their citizens.

7. Foreign Spending None

VI. CHANGES/PROBLEMS:

1. Changes in approach and reasons for change   None

In the reporting period, two significant changes in approach have been made:
(1) Synergy with DOE STTR
(2) Synergy with LSU/MIT nuclear reactor project. Both changes are having a strong, positive impact on the plant root imaging project.

(1) Synergy with DOE STTR: The DOE plant root and the DOE small angle neutron scattering (SANS) projects are sharing, for a time, the same laboratory space and equipment. The principal SANS researcher, Dr. Markus Bleuel, has been an energetic worker building up the plant root imager in preparation for some preliminary SANS experiments. Through his efforts, the base imaging equipment is now in position and ready to acquire plant root imagers with the imminent installation of the neutron generator.

(2) Synergy with LSU/MIT nuclear reactor project: LSU researchers hosted an NSF-supported workshop in June 2022 on the subject of combined X-ray/neutron instrumentation. One outcome is a project to add X-ray interferometry to the MIT neutron imaging beamline. MIT has requested that the instrumentation software be based upon the open-source BlueSky/EPICS. The plant root/SANS team has recently developed proficiency with BlueSky/EPICS software for the LSU/MIT project and is transferring this expertise to the DOE plant root/SANS instrumentation.

2. Actual or anticipated problems or delays and actions or plans to resolve them

One delay has been a slow, but deliberate and thorough, review of the radiation source application submitted by Les Butler and colleagues to the LSU Radiation Safety Office.

We note with pleasure that the director of RSO is a 2022 winner of the William A. McAdams Outstanding Service Award. This award is presented annually by the American Board of Health Physics (ABHP) to honor a certified health physicist who has made significant contributions toward professionalism in health physics and to the certification process.
https://www.aahp-abhp.org/abhp/awards/mcadams/2022

Thus, we are extremely confident that our application is in good hands. However, the application has taken significantly more time than originally anticipated.

The LSU Radiation Safety Office approved the application (verbally) in February 2023. Then, the site of the neutron generator installation, the business incubator space at the LSU Pennington Biomedical Research Center (PBRC) began its own review of the radiation safety application. PBRC contracted with an out-of-state radiation expert, and this yielded another three rounds of questions and answers from February 2023 to April 2023. Then, PRBC sent the application package back to LSU Radiation Safety Office for a review of the Q&A with the out-of-state radiation expert. The duration and detail of the radiation safety application, starting from June 2022 to now, May 2023, was not anticipated.

Update – July 5, 2023: LSU Radiation Safety Office and PRBC decided in late June 2023 to approve shipment and installation of Adelphi Technology DD110M thermal neutron source, to be done in July 2023.

VI. CHANGES/PROBLEMS:

2. Actual or anticipated problems or delays and actions or plans to resolve them (continued)

We recall that preliminary groundwork for the radiation safety application was started before the SBIR Phase II project was initiated by a personal visit in spring, 2019 by Dr. Ted Cremer with the LSU Radiation Safety Office. Cremer and RSO discussed neutron shielding and tritium monitoring. The director of RSO has Y-12 experience. There was no indication at this 2019 that the application process would be so lengthy as to impact the SBIR Phase II project.

In the spirit of lemons to lemonade, we have started an Overleaf document which may turn into a peer reviewed publication and includes a member of the LSU Radiation Safety Office as a co-author. The document has appendices giving the various stages of the application and is currently 54 pages long.

Synergy of our DOE Phase 2 SBIR with our new DOE Phase 1 STTR on SANS

A synergistic development has emerged this reporting period with the Adelphi Technology, Inc. and LSU DOE granted STTR Phase I on **"Compact Accelerator SANS Instrument, Neutron Generator SANS Instrument" DOE STTR Contract No DE-SC0022450**.

In this synergistic development, we will use the plant root imager to evaluate several scattering instrumentation setups.

This SBIR Phase II plant root project is complementary with the new STTR Phase I SANS project.

The plant root project benefits from the technical expertise of SANS research Dr. Markus Bleuel (STTR support). Dr. Bleuel has 9-yrs experience at NIST with SANS instrumentation and is now an Adelphi employee for the STTR SANS project.

On the other hand, the STTR SANS project leverages the plant root neutron generator and neutron detector investment to add SANS optics and SANS performance with a laboratory neutron generator.

The time away from plant root imaging will not significantly impact the plant root imaging goals.

Rather, the experience gained with neutron scattering project has the potential to improve the plant root imager.

For example, a novel neutron collimator will be constructed in the scattering project; if successful, this neutron collimator could increase plant root imaging throughput by increasing the neutron flux at the plant root sample.

3. Changes that have a significant impact on expenditures None

4. Significant changes in use or care of human subjects, vertebrate animals, and/or Biohazards

Not Applicable

5. Change of primary performance site location from that originally proposed None

6. Carryover amount None

VII. DEMOGRAPHIC INFORMATION

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VIII. SPECIAL REPORTING REQUIREMENTS

None

COMERCIALIZATION PLAN

Adelphi Technology, Inc. estimates cumulative sales revenues of $ 60,500,000 and cumulative licensing revenues of $ 0.00 during the first 10 years of commercialization.

Executive Summary

Company Information

Adelphi Technology, Inc. (https://www.adelphitech.com/), a California corporation based in Redwood City, CA, manufactures neutron generators, both as stand-alone devices, and as neutron source components in larger systems.

Our DOE Phase 2 proposal is to modify the Adelphi DD110M thermal source into a thermal/fast neutron imaging system. One mode of this system is a thermal neutron interferometric-based imaging, via the addition of low-cost, three-dimensional (3D) printed optics. The first application is plant root/soil imaging and analysis system for rhizosphere imaging of undisturbed plant roots in soil in greenhouse settings and agricultural laboratories.

The Redwood City, CA based Adelphi subcontractor is Refined Imaging, LLC, (https://refinedimagingllc.com/), affiliated with Louisiana State University - both in Baton Rouge. Refined Imaging is a startup company, which develops and manufactures grating-based interferometric optics for advanced X-ray and neutron imaging, has secured three SBIR Phase I projects in its first year of operation, with expertise in high-aspect-ratio microfabrication, an essential technology for fabrication of the X-ray and neutron optics.

Markets for Proposed Adelphi Compact, Neutron Imaging Instrument, Using Interferometric Gratings

The markets for radiography and tomography, which use fast and thermal neutrons, X-rays, gammas and competing modalities for non-destructive imaging, analysis, and testing, include the following two market areas:

(1) Agriculture - plant disease and plant development R&D resulting in improvement of crop yields, conducted in greenhouse and small lab settings, addressing customer needs for imaging of in-situ plants roots in soil.

(2) Industry - Non-destructive imaging/testing/analysis in manufacturing, defense, construction, buildings, vehicles and aircraft, transportation infrastructure (bridges, roads, and rails).

1.0 Market Opportunity

Agriculture provides for mankind's needs for food, fiber and energy, in which presently farm-lands dominate 38% of the global land surface1 and almost 30% of global net primary production is appropriated for human use. The demand for agricultural commodities is projected to increase from 70 % to 100 % by 2050, see Zabel et al. (2019).

The Food and Agriculture Organization of the United Nations **[1]** estimates that 20 to 40 percent of global crop production is lost to pests. "Each year, plant diseases cost the global economy around $220 billion, and invasive insects around US$70 billion." Food losses due to crop infections from pathogens such as bacteria, viruses and fungi have been persistent issues in agriculture for centuries across the globe. A single kind of bacterium, Xylella fastidiosa, is estimated to cost $104 million per year in wine losses in California. In order to minimize the disease induced damage in crops during growth, harvest and postharvest processing, as well as to maximize productivity and ensure agricultural sustainability, advanced disease detection and prevention in crops are imperative.

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1.0 Market Opportunity (continued)

The rhizosphere or soil region, which surrounds the root systems of plants, contains root secretions (e.g., proteins and sugars), discarded plant cells and material that are in complex symbiosis with bacteria and other microorganisms.

The rhizosphere profoundly influences plant growth and reproduction, such as nutrient cycling and disease suppression, and provides space to produce allelochemicals, needed to control neighboring related and unrelated plants. Plant-soil feedback loops and other external physical factors determine the success or failure of plant survival and reproduction, see 2017 Report DOE/SC-0189, see Adams et al. (2017).

Thermal neutron imaging is a very useful modality for imaging plant-root interfaces, as neutrons are readily scattered by the light elements of hydrogen and its isotope deuterium; and provides contrast with heavier elements, such as carbon, nitrogen, and oxygen. Thermal and especially fast neutrons are highly penetrating and, unlike X-rays, do not cause radiation damage to sensitive biological samples.

Thermal neutron radiography and tomography are used to study (1) root system architecture, and (2) water dynamics in the roots and the surrounding rhizosphere in situ using deuterium oxide as a contrast agent. Thermal neutron radiography currently has a spatial resolution of about 50 µm, and a temporal resolution of 1 second.

[1] Food and Agricultural Organization of the United Nations. (2019). New standards to curb the global spread of plant pests and diseases. http://www.fao.org/news/story/en/item/1187738/icode/

Improvements in thermal neutron imaging detector and optics could increase spatial resolution to less than 10 µm and enable cellular imaging. High impact R&D by many users in fundamental physics, magnetism, material science, engineering, plant physiology, food science, archeology and paleontology, was performed at the thermal neutron imaging facilities, which include Helmholtz-Zentrum Berlin (HZB), see Kardjilov et al. (2011), UC Davis McClellan Nuclear Radiation Center, see Tumlinson et al. (2007) and Kaestner et a. (2016).

Neutron tomography, using a fission nuclear reactor source of thermal neutrons, permits the monitoring of plant health and the detection of root pathological changes over a period of 4–6 years by quantitatively measuring root water content in situ, where Sim et al. (2018) reported neutron tomography was the most appropriate method for studying the epidemiology of root-rot and rust because it can detect significant accumulations of inorganic elements of iron, aluminum, silicon, and magnesium ions and water of root in the soil, all of which interact with the fungi, mycorrhiza, and yeast inoculation in the rhizosphere. Also, small neutron sources, other than fission reactor type, provide a diverse array of applications in area of prostate cancer treatment, petroleum exploration, detection of explosive material, and inspection of aeronautics and astronautics components.

Imaging of in-situ roots in potted plants to study disease and growth, could be much improved by a compact Adelphi neutron source with Refined Imaging interferometric gratings to enhance resolution and contrast.

Traditional subtractive manufacturing, and evolving additive manufacturing are other market opportunities for the Adelphi neutron imaging system, which is integrated with the Refined Imaging grating optics. Additive manufacturing is used for rapid tooling for creating molds for final products, and has been adopted by companies like Boeing and General Electric, serving as integral parts of their product fabrication process, see https://phys.org/news/2017-12-additive.html, and use of X-rays by Kio et al. (2018).

The Neutron Microscope project at PSI is high-resolution neutron imaging instrument for producing 5-micron image resolution, with 10-minute exposure times of 27 mm sized objects, see Trtik et al. (2015, 2019).

The Adelphi-Refined Imaging instrument is neutron interferometric imaging and scattering that can be applied as a nondestructive testing modality for detection and imaging of defects in additive manufactured parts. For example, several innovative, non-destructive neutron imaging methods are used to observe crack formation in fatigued steel objects. Neutron-based Talbot-Lau and far field interferometry is used in assessing additively manufactured parts, see Brooks et al. (2017a,b, 2018a,b), Grunsweig et al. (2008), and Endrizzi & Olivo (2014).

1.1 Market Need

1.1.a Customer Need to be addressed.

Nondestructive imaging and testing of plants and soil has important implications in agriculture and the US and world food supply. Non-destructive imaging and testing in plant laboratories and plant field stations can play an important role in better understanding the rhizosphere and exploiting the experimental R&D field studies to improving US and world crop yield and prevention of plant diseases, see Li et al. (2014).

The use of medicinal plants, both in allopathic and herbal medicine, is expected to rise globally, due to the increasing number of elderly people and consumer preference for natural and eco-friendly products. Hence, increasing use of natural medications has renewed interest in extraction of medicinal compounds from roots, creating a very strong demand for phytotherapeutic roots.

1.1.b How the customer's need is currently addressed.

Plant disease identification methods currently used in agriculture are categorized as direct and indirect.

Direct methods of plant disease are laboratory-based techniques, which include polymerase chain reaction (PCR), immunofluorescence (IF), fluorescence *in-situ* hybridization (FISH), enzyme-linked immunosorbent assay (ELISA), flow cytometry (FCM) and gas chromatography-mass spectrometry (GC-MS), and biosensors. The biosensors are based on highly selective bio-recognition elements, such as enzyme, antibody, DNA/RNA, and bacteriophage.

Indirect methods include plant phenotyping, currently a preferred method of quantitative analysis of plants, which include remote-sensing technologies (UAVs, fixed wing gliders, satellites), 3D imaging techniques, thermography, fluorescence imaging and hyperspectral techniques, see Fang & Ramasamy (2015) and Chawade et al. (2019).

Relatively few direct investigations have attempted to study in situ the undisturbed rhizosphere as an entire entity. Existing techniques are laborious, require substantial root and soil disturbance, and do not allow for the dynamic study of living roots over time. Radiation based, non-destructive imaging modalities such as X-ray radiography, X-ray Computed Tomography (CT), and Neutron Radiography are overcoming these limitations.

The rhizosphere concept was introduced a 100 years ago by the German biologist Lorenz Hiltner (1904), who first proposed the area around the roots is a region of high microbial activity. Despite a large amount of work and research on the biology and biochemistry of the rhizosphere, very little is known about the detailed mechanisms that take place in the soil. Although most plant biodiversity research focuses on what is visible above ground, researchers have demonstrated a clear link between 'above-ground' and 'below-ground' diversity, see Morrissey et al. (2004).

An enormous microbe diversity with tens of thousands of microbe species is found associated with plant roots, which results in a complex plant-associated microbial community, referred to as the second genome of the plant, is crucial for plant health, see Berendsen et al. (2012). The rhizosphere is the zone of soil influenced by a plant root, so that the rhizosphere is critical for plant health and nutrient acquisition, in which below ground resources must pass through this dynamic zone, prior to their capture by plant roots. Radiation based, non-destructive imaging modalities have provided undisturbed, rapid visualizations of the soil and root environment with micron to mm spatial resolutions.

Helliwell et al. (2017) monitored the temporal changes to intact rhizosphere pore structures, during the emergence of a developing root system in different soils. They used high resolution X-ray Computed Tomography (CT) to quantify the impact of root development on soil structural change, at scales relevant to individual micro-pores and aggregates (μm). Their results indicate the structural zone of influence of a root can be more localized than previously reported (μm scale rather than mm scale), where growing roots can significantly alter the immediate, surrounding soil physical environment, via reducing root-soil contact and increasing porosity at the root-soil interface.

Several root phenotyping platforms are available from such vendors as Rhizotubes and Growscreen-rhizo, as well as the semi-automatic platform RADIX, and the automatic RhizoChamber-Monitor, see Wu et al. (2018).

1.1.b How the customer's need is currently addressed. (continued)

The RhizoChamber-Monitor is a robotic platform enabling characterization of root growth. This device combines a cultivation system with an imaging system into an integrated unit, including a shading system, where the platform is shaded. Root growth is monitored day & night, and the device allows control of shoot and root temperatures independently.

The Rhizotubes platform, Jeudy et al. (2016), provides high through-put phenotyping of plant shoots and roots under various abiotic and biotic conditions. This device allows easy visualization or extraction of roots and measurement of root traits in responses to plant root stresses, including interactions with soil microorganisms,

A Web-of-Science search of "neutron radiography and (root or soil or rhizosphere)" finds 104 hits from 2008 to now. Improved neutron imaging of rhizosphere will address this large need in soil science research, as indicated in the 2017 Report DOE/SC-0189, see Adams et al. (2017). The neutron reactor experimental hall is a harsh environment for plants. This problem is often heard from speakers and poster presenters and its mitigation is described in beamtime requests. An instrument, which operates in the greenhouse or field, would yield more realistic results. Currently 250 minor research reactors worldwide provide radiography/tomography, neutron activation analysis, radioisotope production, material testing, other neutron-based research, and training students. Another 33 major research reactor and spallation neutron facilities worldwide are for cold and thermal neutron research, see Farhi et al. (2015).

Our proposed instrument will be the first to integrate grating-based interferometry with a portable neutron generator, as demonstrated by successful experiments in August 2018, resulting in decreased cost and improved performance, where our first estimate of 3D printed neutron masks is \$10/cm^2. This is 30-fold less than the going cost of mask produced with silicon microfabrication technology.

1.1.c What are shortcomings of the current approach to meeting customer needs

Established methods such as PCR, FISH, ELISA, IF, FCM and GC-MS are available and widely used for plant disease detection. However, these diagnostics are relatively difficult to operate, require expert technicians, and are time consuming for data analysis. Furthermore, most of these methods cannot provide real-time detection, which makes them less suitable for on-field testing and early warning systems. Imaging techniques such as thermography and fluorescence imaging, have been used on-field for disease detection, but are susceptive to parameter change of the environment, and lack of specificity of each type of disease.

1.1.d The degree of pain or urgency for solution to customer needs

Direct yield losses, which are caused by pathogens, animals, and weeds, are together responsible for losses ranging between 20% and 40% of global agricultural productivity.

Crop losses due to pests and pathogens are direct, as well as indirect. However, the phrase, "losses between 20% and 40%", does not adequately indicate (1) the actual costs of crop losses to farmers, consumers, and public health, and (2) the actual crop loss impacts on politics and society, as well as the environment, see Savary et al. (2012).

Very little is known of the physiology of the diseased plant, and what is happening in farmers' fields, with respect to diseases, pests, and crop management. Importantly, specifically designed crop loss experiments are needed to quantify risks, or to parameterize and test models.

The supply of medicinal plants has remained limited by their soil conditions, which are affected by soil-borne pathogens. Consequently, eco-friendly soil management techniques are needed to conserve and continually produce such rare plant species, such as Astragalus, Dioscorea, Glycyrrhiza, Harpagophytums, Panax ginseng, Rauvolfia, and Valeriana, see Sim et al. (2018).

A very strong consumer demand exists for medicinal products, derived from the phytotherapeutic roots of rare plant species. The roots of these plants have unique pharmacological effects, which include immunomodulatory, anti-inflammatory, and antioxidant effects, and provide a source of valuable natural medicines, used to treat hypertension, cardiovascular disease, insomnia, and HIV, Sim et al. (2018).

1.1.d The degree of pain or urgency for solution to customer needs (continued)

Recent advances in plant–microbe interactions show plants can shape their rhizosphere microbiome, as evidenced by different plant species hosting specific microbial communities, when grown on the same soil. Evidence shows upon pathogen or insect attack, plants recruit protective microorganisms, and enhance microbial activity to suppress pathogens in the rhizosphere.

A comprehensive understanding of mechanisms, which govern selection and activity of microbial communities by plant roots, will provide new opportunities to increase crop production. McNear (2013) in "The Rhizosphere – Roots, Soil and Everything in Between" states the following:

"Soil is one of the last great scientific frontiers, Science (2004), and the rhizosphere is the most active portion of that frontier in which biogeochemical processes influence a host of landscape and global scale processes. A better understanding of these processes is critical for maintaining the health of the planet and feeding the organisms that live on it, Morrissey et al. (2004).

There is a small but concerted effort under way to harness the root system of plants in an attempt to increase yield potentials of staple food crops in order to meet the projected doubling in global food demand in the next 50 years, Zhang et al. (2010) and Gewin (2010).

These efforts are being done in the face of a changing global climate and increasing global population which will inevitably require more productively grown food, feed and fiber on less optimal (and often infertile) lands; a condition already encountered in many developing countries (Tilman, et al, 2002). Meeting the global challenges of climate change and population growth with a better understanding and control of rhizosphere processes will be one of the most important science frontiers of the next decade, requiring a diverse, interdisciplinary trained workforce."

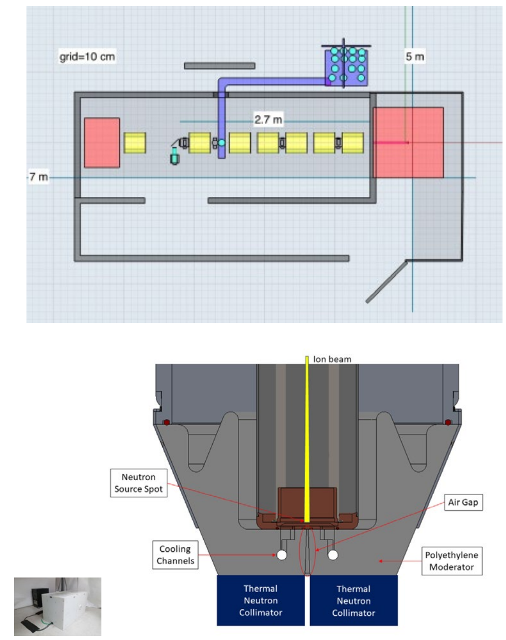

Fig. 1 Adelphi neutron instrument for imaging rhizosphere, industrial imaging & NDT. (top) Hutch design top view. (bottom) Adelphi DD110M thermal neutron source and drawing of modified design for rhizosphere imaging.

1.1.e Proposed neutron imaging system

Our proposed Phase 2 neutron imaging system, which can be placed in a small laboratory or deployed in the field, is expected to be in high demand by customers in the agricultural R&D and testing of plant roots in soil and well as plant stems and leaves, as well as the industrial non-destructive imaging and testing sectors. Our thermal and fast neutron imaging systems are expected to have far superior spatial and temporal resolutions than the current neutron radiography/tomography setups in research reactor facilities.

1.2 Product / Technology

1.2.a Description of our SBIR product

Our product is a thermal neutron radiography and tomography system to provide spatial resolution of less than 10 microns with temporal resolutions, much shorter than 1 second, as shown in **Fig. 1**.

Our product would be used for plant and soil imaging and is comprised of one or more grating optics from Refined Imaging, combined with the Adelphi pulsed thermal neutron source (20 µs pulses up to 100% duty cycle) and a thermal and fast neutron imaging camera. Neutron cameras are COTS in the price range of 5 k$ to 120 k$.

1.2.b Features of our Phase 2 technology and how they translate into a value proposition.

The Adelphi DD110M thermal neutron source (winner of the R&D 100 award in 2015), produces a high flux of thermal (0.025 eV) neutrons, 10^7 n/cm^2/s. The relatively inexpensive (230 k$) Adelphi DD110M thermal neutron source generator, with attached fast/thermal neutron shielding, is compact and relatively maintenance, and can be wheeled around to different experiments or facilities.

The Adelphi DD110M thermal neutron source can be continuous or pulsed with 50 microsecond or longer pulses up to 100% duty factor. Under development is a high-yield, 10^{13} n/s fast neutron generator, using the deuterium-tritium reaction and multiple ion beams, which has a built-in moderator with 10^9 to 10^{10} n/cm^2/s thermal neutron fluxes.

Co-founders of Refined Imaging, Drs. Kyungmin Ham and Les Butler, have built two X-ray interferometry/tomography systems at LSU and a neutron interferometry system at ORNL HFIR CG-1D. With the Refined Imaging expertise, an operational system was designed and successfully tested only 35 days notification of CG-1D beamtime. A NIH-supplied 3D printed mask for proof-of-concept experiment, provided good initial success. Refined Imaging is now optimizing the mask period, mask material, surface finish, and curvature.

The strong success of Refined Imaging in their X-ray and neutron interferometry experiments provides a very optimistic expectation of the success of Adelphi neutron interferometry system for imaging plant roots in soil, as well as in nondestructive imaging and testing in the manufacturing and aerospace sectors.

1.2.c. Customer interviews verified advantages of our technology to fulfill critical needs

Via discussions with the agricultural research facility at LSU as well as with other Louisiana agricultural facilities, we have found a strong need for automated imaging and detection beyond the current state of the art of visual inspection that could be fulfilled by neutron-based imaging. Also, the neutron interrogation of plant roots in soil can indicate, via gamma emission from inelastic fast neutron scatter and thermal neutron capture, the soil moisture and salinity, C, N, and P content, and toxic metal content.

1.2.d. Describe pricing and method to validate customer's willingness to pay

Based on the prior sales of the Adelphi Technology fast and thermal neutron sources worldwide for a wide variety of applications in neutron science and technology R&D, as and nondestructive testing and imaging, and given the low additional cost of the grating optics of Refined Imaging, we expect a selling pricing of about 250 k$ for Adelphi instruments, is affordable to university and government agricultural R&D facilities, as well as to the wide variety of industries, universities, and government labs engaged in non-destructive imaging, testing, and analysis.

1.3 Industry Overview

1.3.a. Industrial Setting for Proposed Adelphi Technology – Refined Imaging Product

Our Phase 2 instrument for neutron-based imaging will address the markets of agricultural research and development and agricultural testing of plants and provide a unique solution to imaging and analyzing roots in soil in undisturbed plants in greenhouse and laboratory settings. Also, our neutron imaging instrument will address the non-destructive imaging and testing markets in industry, academia, and government for detecting and identifying defects in structural components, manufactured parts, and in additive manufacturing.

As compared to neutron research reactors and spallation sources, our neutron instrument will easily fit into the small to medium sized laboratory rooms. Also, our compact instrument is designed to be deployed at agricultural customer sites, such as greenhouses and laboratories, and to fabrication and testing facilities in the industrial sector.

Our expected customer base has a need for specialized neutron instruments, which can perform (1) thermal neutron radiography using gratings for improved resolution and contrast, via absorption, scattering, interferometric, and phase contrast imaging, (2) fast neutron radiography, (3) spatial mapping of sample composition, via associated particle imaging with fast 14 MeV neutron interrogation, (4) trace isotope identification in samples, via measured gamma emission by inelastic fast neutron scattering and thermal neutron capture, (5) thermal neutron diffraction, small angle scattering, and reflectometry, diffraction, and phase contrast radiography.

1.3.b. Adelphi Technology Business Model

The Adelphi business model is a company comprised of highly educated and skilled scientists and engineers, who interact directly with highly trained scientists and engineers in industrial, government, or academic laboratories.

To manufacture the proposed neutron radiographic instrument for rhizosphere imaging and testing, as well as industrial imaging and testing, requires highly educated and experienced personnel to interact with customers. We will strive to meet our customer needs, via the design, assembly, testing, and installation of the customer-specified neutron instrument for their laboratory environment.

1.3.c. Sales and Marketing to Customers - Channels to be used to reach targeted customers

To promote sales, Adelphi has a comprehensive website, and our personnel attend scientific and industrial meetings to present talks and posters on our products and R&D. As a marketing tool, Adelphi publishes results in peer-reviewed journals and other publications with collaborating customers at the industrial, government, or academic laboratories to promote our business and capabilities.

1.3.d. Our immediate customers – actual and potential customers

Our immediate existing customer is the agriculture department of LSU and nearby State of Louisiana agricultural testing center. Our immediate potential customers are the agriculture departments and schools within the United States. Nearby to Adelphi are potential customers and collaborators, the University of California at Davis, University of California at Berkeley, and Stanford University. Potential future customers are agricultural departments and schools and agriculture R&D and testing facilities worldwide, as well as worldwide non-destructive imaging and testing customers in manufacturing, aerospace, and infrastructure.

1.4 Market

The potential market for the Adelphi neutron imaging instrument includes agricultural testing and nondestructive imaging and testing as shown in **Table 1**. Our proposed imaging instrument is directed primarily toward the agricultural testing market, and specifically to imaging plant roots in soil of undisturbed plants; i.e., imaging the rhizosphere in an undisturbed manner with a compact neutron source deployable to green houses and agricultural labs.

Secondarily, our proposed neutron imaging instrument can be applied to non-destructive imaging and testing in general, and specifically in additive manufacturing and infrastructure inspection.

One big motive for our product is crop loss due to diseases, estimated to be about 30-50%. Cultivated plants are often more susceptible to diseases than their wild relatives. Plant roots play a large role in understanding crop losses.

Important environmental factors that may affect development of plant diseases are temperature, relative humidity, soil moisture, soil pH, soil type, and soil fertility. Each pathogen has an optimum temperature for growth. Raising or lowering the levels of certain nutrients also influences the development of some infectious diseases.

Root-based crops of widely used in the world, including cassava, sweet potato, beet, carrot, rutabaga, turnip, parsnip, radish, yam and horseradish. Spices from roots include sassafras, angelica, sarsaparilla and licorice.

Herbal products are increasing in popularity and are now used by approximately 20% of the population. Herbal products are complex mixtures of organic chemicals that may come from any raw or processed part of a plant, including leaves, stems, flowers, roots, and seeds. Nearly 1 in 5 adults in the US report taking an herbal supplement.

Four countries, South Korea, China, Canada, and USA, account for 99% of world total ginseng production of 79,769 tons, worth 2.1 billion USD, see Baeg & So (2013).

The global herbal medicine market size is expected to reach more than USD 129 billion by 2023, according to the latest research report from Market Research Future, see MRFR (2018).

1.4 Market (continued)

The MRFR (2018) report states the global herbal medicine market is expected to exhibit a strong 5.88% CAGR over the forecast period from 2018 to 2023. Leading companies in the global herbal medicine market, include Arkopharma, Beovita, Schaper & Brummer, Venus Pharma GmbH, Arizona Natural Products, Dasherb, ZeinPharma Germany GmbH, Hishimo Pharmaceuticals, and Bayer AG.

By medicinal plant type, MRFR (2018) states the global herbal medicine market is segmented into Marrubium vulgare, Cinnamomum spp., Vaccinium macrocarpon, Echinacea, Camellia sinensis, Curcuma longa, Actaea racemosa, Aloe vera, Zingiber officinale, Cocos nucifera, and others. Marrubium vulgare (white horehound), is likely to dominate the global herbal medicine market over the forecast period with a CAGR of 6.45%.

By form, the market is segmented into capsules and tablets, powders, extracts, syrups, and others. Extracts account for the largest market share in 2017 and are likely to remain dominant over the forecast period, MRFR (2018).

By source, the global herbal medicine market is segmented into leaves, roots and barks, fruits, whole plants, and others. The leaves segment is likely to lead the global herbal medicine market over the forecast period, MRFR (2018).

Technavio (2018) forecast the global agricultural testing market to grow at a CAGR of over 6% during 2018-2022. The global initiatives to improve agricultural output is one of the major trends with growing population and increased the need for food safety and security. This will accelerate demand for agriculture testing services to improve the agriculture industry, which includes soil, water, plant, and seed testing in the form of services and instruments.

Wiseguyreports.Com (2018) estimates the global Agricultural Testing Market at $961.69 million in 2017 and is projected to reach $1797.98 million by 2026, at a CAGR of 7.2%. Stringent safety and quality regulations for agricultural commodities, technological advancements in the testing industry and increase in outbreaks of foodborne illnesses are some key factors fueling the market growth.

By geography, North America dominated the global market. Exponential growth in the agricultural testing in the emerging countries such as Brazil and India drive the global agricultural testing market growth. Technological advancements in the developing economies, which include Japan and China, drives the global market growth.

Type	2016	2017	2022	CAGR% 2017-2022
Nondestructive Testing Equipment	9,720	10,550	15,860	8.5
Nondestructive Testing Services	6,110	6,700	10,550	9.5
Total NDT Market	15,830	17,250	26,410	8.9

Radiographic NDT Equipment Based on Technology	2016	2017	2022	CAGR% 2017-2022
Film radiography	420	450	655	7.8
Real time radiography	385	415	620	8.4
Computed tomography	370	405	625	9.1
Digital radiography	350	385	600	9.3
Other types of radiography	235	245	360	8.0
Total	1,760	1,900	2,860	8.5

Region	2016	2017	2022	CAGR% 2017-2022
North America	3,135	3,392	5,085	8.4
Europe	2,805	3,041	4,550	8.4
Asia Pacific	2,385	2,602	4,005	9.0
Rest of World	1,395	1,520	2,220	7.9
Total	9,720	10,550	15,860	8.5

Table 1 Worldwide markets from BCC Research (2017). (top) NDT Equipment and Services (middle) Radiographic equipment based on technology. (bottom) Radiographic equipment sales by region.

Costs associated with the operation of agricultural testing is a major obstruction in the global market.

Some of the key players in Agricultural Testing Market are R J Hill Laboratories Ltd, ZUV Nord Group, Intertek Group Plc, and Agilent Technologies, bioMerieux S.A, ALS Limited, 3M Company, Eurofins Scientific, BioControl Systems Inc, Apal Agricultural Laboratory, Exova, Bureau Veritas S.A, Biolumix , Charm Sciences Inc, SCS Global Services, ALS Limited, Neogen Corporation and Idexx Laboratories.

1.4 Market (continued)

Mordor Intelligence (2017) predicts the agricultural testing market is posed to grow at a CAGR of 5.8% during 2017-2022, reaching a market value of USD 6980.4 million by 2022. Testing of various samples involving water, soil, seed, etc., determines quality and contaminant content, and other characteristics, such as acidity or pH level, which then aids in analyzing the appropriate input requirements and resources to be supplemented for optimal plant growth.

Mordor Intelligence (2017) further states the agricultural testing can act as a boon for the commercialized agriculture sector and farming community, globally. The increasing demand from agriculture dominated developing nations like India, China and Brazil and further technological advancements are expected to provide future growth opportunities for the industry. Soil testing has a major market share, followed by water testing. By application, the market is based on contaminants and quality assurance, where the contaminants market is expected to grow at a 6.1% CAGR, as it covers testing for chemical residues, pathogens, toxins, etc.

The agricultural testing market is dominated by North America, followed by Europe. Given the high growth, industrialized agriculture sector, the US forms the largest market for agricultural testing, both regionally and globally, which is followed by Canada. Due to increased awareness about the benefits of testing, India and China are going to emerge as the highest growth countries in Asia-Pacific. The market growth in South America will be driven by Brazil and Argentina. Major agricultural testing companies include Eurofins Scientific, R J Hill Laboratories Ltd., Agilent Technologies, Inc., SCS Global Services, Bureau Veritas S.A., ALS Limited, see Mordor Intelligence (2017).

In addition to agricultural testing services our proposed Phase 2 instrument, using the Adelphi neutron source with the Refined imaging grating optics for improved radiographic resolution and contrast, can be combined with one of many different types of neutron imaging cameras to provide non-destructive imaging services and non-destructive analysis via characteristic gamma emission from inelastic fast neutron inelastic scatter and thermal neutron capture.

Non-destructive Testing (NDT) is a technique used to help assure safety and reliability through detection of any flaws or defects in the product or industrial components. For instance, radiography, ultra-sonics, and other advanced imaging techniques can be used to monitor the condition of industrial assets throughout the project life cycle.

BCC Research (2017) reports the total NDT market was worth more than $15.8 billion in 2016, increasing to nearly $17.3 billion in 2017, and further increasing to over $26.4 billion, with an expected Compound Annual Growth Rate (CAGR) of 8.9% from 2017 to 2022.

For specific markets, BCC Research (2017) reports the radiography market is expected to be worth 2.86 billion USD by 2022 from 1.9 billion USD in 2017, at 8.5% CAGR from 2017 to 2022. Currently, the radiographic NDT technologies market is comprised of a non-destructive testing technique, computed tomography (CT). This CT market is expected to be worth $625 million by 2022 from $405 million in 2017, at 9.1% CAGR from 2017 to 2022.

Hurdles to overcome in entering (1) the agricultural testing market, and (2) the industrial non-destructive imaging and testing, is resistance of customers to neutron sources and instrument cost. We will show the customers the safety, reliability, effectiveness, compactness and versatility of our Phase 2 neutron imaging instrument, which can be deployed in greenhouses and industrial settings. As to instrument cost, we will show the ability of our instrument to detect and image in real time, features of customer interest that are beyond the ability of competing instruments.

1.5 Commercialization Strategy

1.5.a. Overall Strategy to bring our product to market

Adelphi is comprised of highly educated and skilled scientists and engineers, who interact directly with highly trained scientists and engineers in industrial, government, or academic laboratories.

Adelphi meets customer needs, via the design, assembly, testing, and installation of the customer-specified neutron instrument for their laboratory or experimental field station. This meeting of customer needs will especially apply to Adelphi sales, installation, and follow-on of neutron imaging systems in agricultural laboratories and greenhouses, as well as non-agricultural customers in need of non-destructive imaging, detection, and analysis.

The marketing of our products is done primarily through the Adelphi website, publication of results in peer-reviewed journals, and attendance and presentation of products and research results at conferences. Adelphi attends scientific meetings, with booth and print advertising, to promote Adelphi products and target customers.

Also, Adelphi marketing efforts are done via internet searches, identifies, and then contacts potential customers, whose research program appears to be a match for an Adelphi product.

The word of mouth from prior and existing Adelphi customers, as a result of Adelphi providing excellent products and service, provides a very important channel to reach and attract potential new customers.

1.5.b. Product Sales, Leasing, and Licensing

Adelphi Technology will focus on product sales, and Adelphi does not expect to license the Phase 2 nondestructive testing and imaging instrument. Initially, Adelphi does not expect to be leasing our instrument, unless there is a strong customer demand for leasing or leasing with option to buy, with tax break for the customer.

1.5.c. IP and Trade Secret Strategy

Adelphi will pursue patents on important inventions, which can increase the value of our company. For less important developments Adelphi will maintain trade secrets.

1.6 Impact of our product

1.6.a. Societal Impacts of our product

The societal impact of the Adelphi Phase 2 neutron imaging instrument is to provided valuable knowledge by neutron imaging and non-destructive testing, whose results may significantly contribute to increasing crop yields, thereby impacting and benefiting communities and societies economically, and contributing to community stability.

1.6.b. Educational Impacts of our product

The societal impact of our Phase 2 product will contribute to our understanding of the rhizosphere and new knowledge to improve crop yields and fight plant pathogens.

1.6.c. Scientific Impacts of our product

There are strong market opportunities for thermal neutron imaging in agriculture, as well as in additive manufacturing, in which thermal neutron imaging is superior to X-ray imaging in many applications. Unfortunately, neutron sources have, until recently, lacked the performance to acquire useful images.

Now, with robust, high-performance sources combined with advanced optical systems, high-quality image sets can be acquired. Currently, as an example, the newly cast blades of jet turbines used in commercial aviation, are inspected with film-based neutron imaging at low-power reactors in Canada and North Carolina. The imaging goal is detection of blocked cooling passages inside the blade.

1.6.d. Overall Significance of our product

The overall impact of the Adelphi neutron imaging instrument with the Refined imaging grating to improve contrast and resolution, is bettering people's lives, via improved crop yields and effective reduction of plant pathogens.

2.0 Company/Team

Adelphi Technology, Inc. is recognized globally as a leading manufacturer of high-power neutron sources, extended-lifetime neutron generators, and novel radiation detectors, having received the following 3 R&D 100 awards:

(1) In 2012, an R&D 100 award for their development of "High Output Neutron Generators, DD100 Series." The DD100 series includes the models DD-108 and DD-109.

(2) In 2013, R&D 100 award: "High Flux Fast Neutron Source" Model DD-109X (Beam Instruments)".

(3) In 2015, an R&D 100 award for "Model DD110M Hybrid Neutron Generator".

Called the "Oscars of Innovation", the R&D 100 Awards recognize and celebrate the top 100 technology products of the year. These neutron generators are used primarily in mining, chemical analysis and homeland security applications.

Based on core technology originally developed at Lawrence Berkeley National Laboratory, and further developed by Adelphi, these generators provide many times greater neutron output than other technologies and have a greater lifetime and much greater output than competing technologies.

The Adelphi Technology subcontractor for this Phase 2 project is Refined Imaging, LLC, affiliated with Louisiana State University, both in Baton Rouge, Louisiana. Refined Imaging is a startup company, which develops and manufactures grating-based interferometric optics for advanced X-ray and neutron imaging. Refined imaging has secured three SBIR Phase I projects in its first year of operation, whose personnel consists of experts in high-aspect-ratio microfabrication, an essential technology for fabrication of the X-ray and neutron optics.

The Refined Imaging team has X-ray and neutron tomography experts with decades of experience in synchrotron, laboratory, reactor, and spallation sources. The team includes a member of the Laser Interferometer Gravitational-Wave Observatory group. This expertise has yielded a patent for a hardware/software solution to improve performance of gratings with support structures.

Adelphi's current revenue is almost entirely from sales of neutron generators; however, the company has a history of successful research projects, including those that developed the generators. Adelphi has moved into larger facilities to manufacture neutron generators and neutron and x-ray optics.

Adelphi's revenue history for the past three years is given in Table **2**. This table shows projected revenue for the period of the SBIR and the fifth year of the project (2025). No investment funding was received over this time. Adelphi's fiscal year is the same as the calendar year.

Table 2 Adelphi's revenue history and projected revenue.

Year	Commercial Revenue	SBIR Revenue	Total Revenue
2018	$3,565,136	$698,741	$4,263,877
2019	$3,964,026	$1,339,957	$5,303,983
2020	$1,686,360	$2,504,782	$4,191,142
2022*	$4,000,000	$1,000,000	$5,000,000
2026*	$6,539,000	$0	$6,539,000

*Projected revenue.

2.0 Company/Team (continued)

Adelphi Technology, Inc. is a California based C-corporation, founded as a research service corporation in 1986 by Dr. Melvin Piestrup, as a spin-off of the Prof. Richard Pantell group at Stanford University, where Dr. Piestrup received his PhD and worked as a research scientist for many years in the area of advanced electron physics, specifically free electron lasers and novel X-ray sources, such as transition, channeling, and parametric radiation. The acronym (Ad el phi), which stands for advanced electron physics, became the company name, Adelphi Technology.

Adelphi Technology, Inc. manufactures neutron generators, which have applications in security, medicine, industrial inspection and materials analysis. With a mature neutron generator technology and commercial sales of 15 generators in 2017-2018, Adelphi has developed neutron generator technology over the last decade. Adelphi continues to improve the generator's yield and to reduce the size, weight and power (SWaP) of the generators.

Adelphi has benefitted from US government funding including the DARPA Intense COmpact Neutron Source (ICONS) Phase I (Contract # HR0011-15-C-0069) and Phase II (Contract # HR0011-17-C-0020) programs which have enabled us to implement new technologies to radically reduce the SWaP of the generator.

Development of an integrated cold-moderator will enable Adelphi to produce a laboratory-based instrument, which could be used for materials analysis, requiring cold neutrons. Such cold neutron sources today are present only at beamlines and reactors. A neutron-generator-based approach could both enable a whole new cold neutron source and instrument product line for Adelphi, and revolutionize the cold neutron source landscape, potentially bringing cold neutron R&D into the mainstream and small to large laboratory settings.

Adelphi's current management team consists of Dr. Melvin Piestrup, the founder and President, and Charles Gary, Chief Executive Officer. Dr. Piestrup has 40 years of experience in radiation science, over 100 publications and 10 patents. Dr. Gary, with a PhD in Electrical Engineering and MBA, leads Adelphi's production effort and operations. Dr. Cremer is Adelphi Technology's chief scientist, and he leads the effort of developing new Adelphi products.

Dr. David Williams, with PhD in Physics and an MBA, is a registered Chartered Engineer, and Project Management Professional (PMP), and Certified Scrum Master (CSM) and has qualified as a lead auditor for ISO9001:2008, with has over 25 years' experience in optics, microwaves, nuclear physics, instrumentation, computing, and electronics. Dr. Williams was previously at Intel Capital and Intel Corporation.

Dr. Cremer is the Phase 2 Principal investigator, and Adelphi chief scientist for over 18 years, and author of Elsevier books (half of 4th Elsevier book) on neutron & X-ray optics, 45 refereed papers with 4 issued patents, has a diverse experimental and theoretical background in applied physics, biophysics, chemistry, and engineering. He has postdoctoral training in biophysics and biochemistry at UCSF and a co-inventor of the issued US patent on an ozone-based instrument for sterilization of medical equipment, and photo-resist removal, has had extensive wet bench chemistry, including applied microbiology, as well physicochemical hydrodynamics in biotechnology.

Assisting Dr. Cremer is Dr. Brown, who is an experienced scientist with a multidisciplinary background encompassing chemistry, physics, mathematics, and computer modeling, and over 20 years of experience in radiation detection and measurement of heavy ions, light ions, neutrons, electrons, photons; detector development; and radiation transport. Cr. Brown is skilled in every aspect of experimental design and setup, vacuum systems, cryogenics, signal processing, data acquisition, and data analysis.

Dr. Allan Chen obtained his UC Berkeley PhD, under Prof. Ka Ngo at the LBNL neutron and ion source lab, the original source of the present Adelphi neutron generators. He has a strong background in experimental physics, engineering, computer simulations, and Monte Carlo applied to designing optimized thermal and fast neutron sources. Assisting Dr. Cremer in this Phase 2 project, Dr. Chen will oversee the modification of the Adelphi DD110M for thermal and fast neutron imaging of the rhizosphere and industrial NDT.

2.0 Company/Team (continued)

Prof. Les Butler of Refined Imaging and LSU and his team will design, fabricate, and test the grating optics, which will enhance resolution and contrast in the Adelphi neutron imaging instrument. Furthermore, Prof. Butler will oversee the design and fabrication of the Refined Imaging hutch in which will be placed the neutron imaging instrument. Prof. Butler, assisted by Dr. Cremer, will recruit agricultural researchers to collaborate on rhizosphere imaging experiments. As a result of successful experiments and publications in peer-reviewed journals, Adelphi expects to have sales of the Adelphi neutron imaging instrument in the first year following the end of Phase 2.

PI Dr. Cremer will lead marketing/sales of the Adelphi neutron imaging instrument in phase 2 and beyond.

Adelphi's location in Silicon Valley makes it easy to collaborate for the commercial production of thermal and fast neutron sources, as well as neutron instrumentation.

In addition to a functional structure with individuals in charge of marketing, production, administration, etc., Adelphi also employs a matrix structure. For each new design or research project, Adelphi assigns a principal investigator to lead that effort, who then draws from administrative, scientific and engineering resources as necessary.

Adelphi plans to form an advisory committee of experts from agricultural science and non-destructive imaging and testing (NDT) to ensure the smooth implementation of this DOE Phase II project and Phase III commercialization. We envision these experts as collaborators and co-authors on peer-reviewed publications on the Adelphi neutron imaging instrument applied to the rhizosphere R&D and non-destructive imaging and testing.

Our plan is to keep the advisory committee informed of our progress, via email communication, on a regular basis (probably every 6 months) and to use video conferencing to engage the group in discussions, which identify potential impediments and opportunities. The advisory committee also has a "word of mouth" advertising role helping to recruit early adopters of our technology.

3.0 Competition/Intellectual Property (IP)

Currently, the Adelphi neutron source and imaging instrument competition is as follows:

(1) Worldwide reactor & spallation neutron sources - 250 facilities, Farhi et al. (2015), Vogel (2013), Lehmann (2017)

(2) Companies, including Phoenix, Starfire, Sodern, Thermo Fisher Scientific, VNIIA, Gradel (NSD Fusion)

The Adelphi neutron imaging instrument will use Adelphi neutron sources, unlike the Adelphi neutron imaging instrument will compact and deployable into the field, while providing larger neutron fluxes at a lower price, while also allowing customization of the Adelphi sources for customer needs. The current Adelphi competition are the reactor and spallation neutron facilities, and large, immobile private company imaging facilities, such Phoenix.

Emerging Competition from R&D that could compete or replace the Adelphi neutron source for non-destructive imaging such as X-ray radiography, X-ray CT, and Neutron Radiography are non-invasive methods in imaging the rhizosphere, in which potential competitors include X-Ray Industries/X-R-I Testing, Phoenix Inspection Systems, and Starfire Industries. These companies could improve their products for rhizosphere imaging.

Biosensors for plant disease detection and the advent of nanotechnology have resulted in the advancement of highly sensitive biosensors due to modern nanofabrication techniques. The specificity of the biosensors is greatly enhanced by using enzymes, antibodies, DNA and bacteriophage, as the specific recognition element, and thus be significant competition to our product. However, Adelphi Technology has established a Bowling Green, Kentucky subsidiary, Adelphi Technology, LLC, which is partnering with the Dobrokhotov Group Applied Physics Laboratory at Western Kentucky University in Bowling Green to develop very compact gas sensors.

3.0 Competition/Intellectual Property (IP) (continued)

These very compact gas sensors can fit in a cell phone and are capable of rapid detection (within seconds or less) of parts per million to parts per trillion of characteristic and complex gas emissions from rhizosphere, soil, and plants. Using Adelphi gas sensors, identification of organic and inorganic gases emitted from the rhizosphere (roots and adjoining soil), soil, or, plant stem and leaves, can potentially identify disease or abnormal conditions of plant or soil.

As a result, Adelphi Technology, Inc. in cooperation with Refined Imaging, LLC, can not only produce a neutron-based, compact rhizosphere imaging system for agricultural research green houses, medium-sized laboratory rooms. In addition, the Adelphi, LLC gas sensor can detect and analyze complex gas mixtures, emitted from plants and soils, and identify gas components, ranging from parts per million to parts per trillion within a few seconds or less.

Regarding intellectual landscape and Adelphi freedom of operation, Adelphi completely owns the patent on which is based the Adelphi neutron source technology. Furthermore, Adelphi has been selling these patent-protected neutron generators worldwide for the past 10 years.

3.1 Adelphi Legal counsel and frequency of legal counsel

Adelphi's IP strategy depends strongly on patents and know-how. Adelphi retains the services of a leading patent lawyer, Joseph Smith, with more than 30 years of experience in patent law and intellectual property. He has helped Adelphi with over a dozen patent applications and works closely with Adelphi's scientific personnel.

3.2 Adelphi Corporate IP history (patents, trademarks, copyrights)

Adelphi Technologies' 11 existing patents cover a range of neutron optics and generators in addition to several x-ray technologies. Since 2000, Adelphi has obtained 6 issued USPTO patents:

(1) Compound refractive lens for x-rays - U.S. Patent 6,269,145, 7/31/2001.

(2) Methods of imaging, focusing and conditioning neutrons - U.S. Patent 6,765,197, 7/20/2004.

(3) Fabrication of unit lenses for compound refractive lenses - U.S. Patent 6,674,583, 1/6/2004.

(4) X-ray and neutron imaging - U.S. Patent 6,992,313, 1/31/2006.

(5) X-ray tomography and laminography - U.S. Patent 7,177,389, 2/13/2007.

(6) Neutron source for neutron capture therapy - U.S. Patent 9,636,524 B2 5/02/2017.

3.3 Description of Adelphi strategy to protect IP going forward with rational and timeline

Adelphi will pursue patent protection of new technology as this technology evolves. Trade secrets are documented, stored in a secure location, protected by confidentiality agreements and non-disclosure agreements.

4.0 Adelphi Finance and Revenue Model

4.1. Estimate of Adelphi Funding Needed

In the 2-year Phase 2, from 2nd quarter of 2020 to 2nd quarter 2022, the major technical and business milestones, are demonstration of working prototype of Adelphi Technology neutron imaging instrument, using the grating optics of Refined Imaging. In sales of the imaging system, starting in 2nd quarter of 2022 Adelphi will receive 50% upfront of the imaging instrument selling price, and 25% half-way through project, and 25% upon delivery.

Table 3 presents Adelphi technical & sales milestones, and sources of funding from present, via Phase 2 funding.

Table 3 Adelphi Technology Milestone and Funding

Milestone	Time frame	Financing Approach	Funding anticipated
Prototype fabrication	Q2 2020 – Q2 2021	DOE Phase II	$750K
Prototype testing and redesign	Q2 2021 – Q2 2022	DOE Phase II	$750K
Sales of Imaging systems	Starting Q2 2022	Customer funds 50% upfront, 25% half-way, 25% on delivery.	0

4.2. Evidence of Support

4.2.1. Validation of Adelphi path to necessary funds - contacts, leads, relationships, and agreements

Adelphi Technology sells and manufactures fast and thermal neutron sources. Refined Imaging is developing an inexpensive 3D printing process for neutron optical gratings. We expect the direct sales of the Adelphi neutron imaging instrument, based on the Refined Imaging neutron grating optics, to provide necessary funds to go forward after Phase 2 funding. The Phase 2 funding will allow development of a customer-ready neutron imaging instrument.

A customer-paid neutron camera and high purity germanium gamma detector (HpGe) or triple mode detector (gammas and fast neutrons and thermal neutrons) for measurement of the characteristic gamma energy spectrum, which is produced by fast and thermal neutron interrogation of samples (greenhouse plants & roots and industrial objects), will be integrated by Adelphi into the final delivered neutron instrument to the customer.

4.2.2. List of Letters of Support for Adelphi and Refined Imaging

Letters of support are attached at the end of this document and uploaded into Grants.gov.

4.3. Method of Adelphi Revenue Generation

The initial revenue stream will come from sales of neutron imaging instruments, starting 2026. Breakeven with the neutron imaging instrument is expected to occur by the end of 2027.

In the development of these neutron imaging instruments, Adelphi will perform internal R&D during this Phase 2 and afterward in Phase 3, driven by prospective and actual customer demand.

No licensing or royalty is assumed. Adelphi will manufacture and sell the neutron imaging instrument.

The potential customers include university, industrial, and government agricultural R&D facilities, as well as industrial and government non-destructive imaging and testing facilities.

The cost of unit instruments is expected to remain approximately constant in price over the next 12 years, due to the offset between assumed increased cost of living index and more synergies and intelligence in fabrication.

One or two Adelphi engineers will be added to support fabrication, testing, installation, and maintenance.

4.3. Method of Adelphi Revenue Generation (continued)

One marketing channel used by Adelphi is the low cost of joint journal publications with collaborating academic, industrial and government laboratory personnel with installed Adelphi products. Almost 100% of potential customers and purchasing authorities will be exposed to such publications. Importantly, in its marketing and sales approach, Adelphi will attend key agricultural testing and non-destructive imaging and testing conferences, where Adelphi will interview potential individual agricultural lab distributors at these conferences to increase lead generation. Adelphi has two scientist/engineers, who are also talented salespeople, when selling to the academic and research facilities.

The annual cost of Adelphi marketing, via peer-reviewed publications and attendance at scientific and technical meeting will be initially about 3 k$. Marketing budgets from other Adelphi products and government R&D contracts will add to this 3 k$ marketing budget assigned the proposed Adelphi neutron imaging instrument.

The sales cost to sell each proposed neutron imaging instrument is expected to be about 3 k$. The selling price of the proposed Adelphi high flux thermal neutron source, the Refined Imaging optic, and the neutron camera is expected to be about 250 k$. As a percentage of selling price of a single Adelphi neutron imaging instrument, direct cost of materials is 30%, direct cost of labor is 30%, and indirect costs (G&A) adds 40% to the labor costs.

The consulting and after-sales service, and neutron imaging instrument upgrade, is assumed to be about 10% of the 250 K$ selling price of a single instrument.

In **table 4** are Adelphi annual pro forma income statements for 3 years post Phase 2. The potential customers include agricultural research centers and laboratories.

Adelphi Technology and Refined Imaging are working towards the goal of establishing a neutron R&D user center at Louisiana State University in Baton Rouge to serve the State of Louisiana and the southwest region.

This Refined Imaging neutron user facility would not only allow scientists and engineers to perform experiments on installed fast and thermal neutron beam lines, but in addition, would allow deployment of compact neutron instruments to customer agricultural facilities, as well as industrial, academic, and government facilities.

The Refined Imaging neutron user facility would form an industrial incubator at Louisiana State University (LSU), with Adelphi Technology and Refined Imaging as the first 2 industrial members. Adelphi Technology would provide neutron sources and partner with neutron camera companies, while Refined Imaging would produce neutron optics needed to improve the contrast, resolution, and performance of the thermal and fast neutron-based instruments for imaging and non-destructive testing and analysis.

Adelphi Technology and Refined Imaging, in cooperation with LSU, have submitted a DOE Phase 1 STTR in Oct. 2019, which involves initial R&D to develop a compact cold neutron source to be applied to neutron small angle scattering, diffraction, reflectometry, radiography/tomography, and refractive imaging (cold neutron microscopy. This technology will be applied to imaging sugarcane, an important source of biofuel.

Pro Forma Income Statement - Manufacturing example					
	Adelphi Technology, Inc. For years 2024 to 2026				
1 Market	**Phase II (2019)**	**Phase II (2020)**	**2024**	**2025**	**2026**
Served Available Market size	$ 250,000,000	$ 255,000,000	$ 260,100,000	$ 265,302,000	$ 270,608,040
Market Growth Rate	10%	10%	10%	10%	10%
2 Production Revenue (Sales - Product)					
Units expected to be sold			1	2	4
$ avg selling price of total product			$ 250,000	$ 250,000	$ 250,000
New product sales	$ -	$ -	$ 250,000	$ 500,000	$ 1,000,000
Consulting or aftersale services	$ -	$ -	$ 25,000	$ 50,000	$ 100,000
Total Production sales (Revenue)	$0	$0	$275,000	$550,000	$1,100,000
% market share - total market	0%	0%	1%	2%	4%
SBIR/STTR Contract R&D	$ 750,000	$ 750,000			
Total revenue	$ 750,000	$ 750,000	$ 275,000	$ 550,000	$ 1,100,000
3 Cost of Goods Sold (COGS)					
Material			$ 75,000	$ 150,000	$ 300,000
Manufacturing			$ 75,000	$ 150,000	$ 300,000
Licensing & Royalties					
Total COGS new product	$0	$0	$150,000	$300,000	$600,000
COGS (per unit)	NA	NA	$ 150,000	$ 150,000	$ 150,000
COGS consulting or after sale service			$ 2,500	$ 5,000	$ 10,000
Total COGS	$ -	$ -	$ 152,500	$ 305,000	$ 610,000
4 Gross Margin					
Total GM$	$ 750,000	$ 750,000	$ 122,500	$ 245,000	$ 490,000
Total Gross Margin %	100%	100%	45%	45%	45%
5 Operating Expenses					
SBIR Expenses (Direct and Indirect)	$ 700,935	$ 700,935			
Sales			$ 3,000	$ 6,000	$ 12,000
Marketing			$ 3,000	$ 3,000	$ 3,000
Administrative (G&A)			$ 30,000	$ 60,000	$ 120,000
Legal			$ 1,000	$ 2,000	$ 4,000
Facilities			$ 1,000	$ 2,000	$ 4,000
Total Selling General and Administrative	$0	$0	$38,000	$73,000	$143,000
Internal R&D			$ 50,000	$ 50,000	$ 50,000
Total Operating Expenses	$ 700,935	$ 700,935	$ 88,000	$ 123,000	$ 193,000
6 Operating Profit (EBIT)	$ 49,065	$ 49,065	$ 34,500	$ 122,000	$ 297,000
EBIT Margin % (Operating Margin %)	6.5%	6.5%	12.5%	22.2%	27.0%
7 Income before tax (EBT)	$ 49,065	$ 49,065	$ 34,500	$ 122,000	$ 297,000
Tax rate	35.0%	35.0%	35.0%	35.0%	35.0%
Taxes	$17,173	$17,173	$12,075	$42,700	$103,950
Net income	$ 31,893	$ 31,893	$ 22,425	$ 79,300	$ 193,050
Net income as %/sales	4.3%	4.3%	8.2%	14.4%	17.6%
8 Cash Proxy					
(Add back depreciation)	$ -	$ -			
9 EBITDA	$ 49,065	$ 49,065	$ 34,500	$ 122,000	$ 297,000
+ Matching Grants					
- Capital Expenditures					
- Loan Payments					
+ Investments (Paid in Capital)					
Net Addition (Subtraction) from Cash	$49,065	$49,065	$34,500	$122,000	$297,000
Year-End Cash Proxy	$ 49,065	$ 98,131	$ 132,631	$ 254,631	$ 551,631

Table 4 Neutron imaging instrument annual *pro forma* income statements for 3 years post Phase II

4.4. Model for Projecting Revenue

The initial revenue stream will come from sales of the neutron imaging instrument, starting by 2025. Breakeven is expected to occur by 2026.

To determine the niche market size Adelphi would serve with its neutron imaging instruments for (1) agricultural testing (specifically rhizosphere imaging and analysis) and (2) non-agricultural - nondestructive imaging and testing in manufacturing and infrastructure, our model for market size will consider only the existing large university, government, and large industrial laboratories and facilities with large R&D operating budgets in (1) agriculture departments and (2) industrial, civil, aerospace, mechanical engineering departments.

The Wikipedia "List of Agricultural Universities and Colleges" worldwide includes 76 US, 22 Canada, 75 India, 58 Japan, 29 China/Taiwan, 26 Thailand/Vietnam, 3 South Korea, 19 Australia/New Zealand, 25 Brazil, 30 UK, 25 Germany/France, 8 Holland/Belgium, 17 Portugal/Spain, 28 Russia, thus totaling 441 agriculture departments.

We estimate a 230 million USD market for the agricultural sector, based on the 2018 USDA ARS budget, which among the many USDA budget items, includes the following 2 budget items:

(a) Crop protection - 167 M$ USD – Understand pest and disease transmission mechanisms, identify and apply new technologies that increase understanding of virulence factors and host defense mechanisms.

(b) Product Quality/Value Added - 65 M$ USD –

(1) Improve efficiency, reduce cost to convert agricultural products into biobased products, biofuels;

(2) develop new and improved products for domestic and foreign markets

(3) provide higher quality, healthy foods that satisfy consumer needs in United States and abroad

Potential customers for our neutron imaging source include the top 100 worldwide engineering schools given by CEOworld (2019) magazine, as well as the above 441 listed agricultural universities and colleges.

For 2018 – 2024, Wiseguyreports.Com (2018) estimates the global Agricultural Testing Market has a 7.2% CAGR, while Technavio (2018) reports 6% CAGR and Mordor Intelligence (2017) reports a 5.8% CAGR. The above 230 million USD budget for the USDA is assumed the present 2019 market size of the agricultural testing market.

360ResearchReports (2019) reports the worldwide market (non-agricultural) for neutron generators for nondestructive imaging and testing (NDT) has a 13.2 % CAGR over the next 5 years, reaching 50 million USD in 2024, from 24 million USD in 2019. See IAEA (2012) about neutron generators. The 2019 NDT market for the Adelphi neutron imaging instrument is estimated to be 20 million USD.

From above **USDA Budget Summary (2018)**, the market for the Adelphi neutron imaging instrument is 230 million USD in the US agricultural sector, where a more conservative 6% CAGR from **Technavio (2018)**.

The 230 M$ agricultural testing market with 6% CAGR, comprises 92% of the 250 M$ combined market for 2019, and the 20 M$ NDT market with 13.2% CAGR, comprised 8% of the combined 250 M$ market for 2019, result in a 250 M$ worldwide market for the Adelphi neutron imaging instrument within a weighted average 6.6 % CAGR.

See **Table 5** with the DOE Investment Multiplier, which involves estimating the anticipated revenues for the 10 years post market entry in 2024. The investment multiple is assumed to be 1.2.

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DOE STTR Phase I and II Funding to Adelphi Technology: Years 0 - 2

Neutron Imaging Instrument		PH I	PHII - Year 1	PHII - Year 2
		0	1	2
($ in1000s)	Year	2018	2019	2020
SBIR Funding		$225	$750	$750
	Discount Rate		15.0%	15.0%
	Discount factor		0.93	0.80
Net Present Value (NPV)		$225	$696	$600

Market size PHII - Year 1 ($000)	$20,000
Market growth rate	2.0%
First year of commercial sales:	2021

Ten Year Revenue Projection: Years 6 - 15

		6	7	8	9	10	11	12	13	14	15
($ in1000s)	Year	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
	Market Size	$ 22,082	$22,523	$22,974	$23,433	$23,902	$24,380	$24,867	$25,365	$25,872	$26,390
	Market growth rate	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
	Market Share	5.7%	5.7%	11.0%	12.0%	13.0%	14.0%	16.0%	18.0%	21.0%	24.0%
Gross Revenues mfg/licensee		$1,259	$1,273	$2,527	$2,812	$3,107	$3,413	$3,979	$4,566	$5,433	$6,333
	Royalty rate	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Gross Revenues Licensing		$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
	Operating Margin	27%	27%	27%	27%	27%	27%	27%	27%	27%	27%
Operating Profits		$340	$344	$682	$759	$839	$922	$1,074	$1,233	$1,467	$1,710
	Discount Rate	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%
	Discount factor	0.44	0.38	0.33	0.28	0.24	0.21	0.18	0.16	0.13	0.12
Net Present Value (NPV)		$150	$130	$223	$214	$204	$193	$193	$191	$196	$197

Project NPV and Investment Multiple

Cumulative NPV 10yr Profits:	$1,891
Cumulative NPV SBIR funding	$1,521
Project NPV	$ 370
DOE Investment Multiple	1.2

Table 5 Calculation of *DOE Investment Multiplier* for neutron imaging instrument. Calculation estimates anticipated revenues for 10 years post market entry.

During the first 10 years of commercialization after the DOE Phase 2 grant:
Estimated for the Adelphi neutron imaging instrument Adelphi are:
(1) Cumulative sales revenues of $ 60,500,000.
(2) Cumulative licensing revenues of $ 0.00

Adelphi total revenue is 2026 is estimated to be 6.5 M$ (see table 2).
The proposed Phase 2 neutron imaging instrument would contribute 2.5 M$.

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Letters of Support

Plant Nutrition Technologies Inc.

PLANT NUTRITION TECHNOLOGIES, INC.

268 ROCKY POINT ROAD OROVILLE CALIFORNIA 95966 530-589-9134 OFFICE 408-476-1935 PRESIDENT

13 October 2019

Ted Cremer
Adelphi Technology
Re: Plant Root Imaging Technology

Dear Ted,

Your proposed project involving mobile radiography imaging of plant root systems would dovetail very well with our current work in plant root growth and nutrient support.

We are currently working on the following projects which would benefit substantially from the availability of this type of technology. The use of our bio-mineral products in replacing chemical fertilizer has demonstrated an increase in root growth and function, however it is difficult to gather accurate data on the root growth progress without intensive labor and time involved. Your proposed technology would increase our ability to image plant root growth and health in a much more timely and accurate fashion.

Phylloxera in vineyards; Root mites and root health could be imaged quickly and more frequently as our nutrient program is applied.

Red Blotch in vineyards; Bacterial infection of the plant is reduced and even eradicated with the support of the root growth and health. Imaging of the roots would dramatically increase our ability to adjust nutrient parameters in the fertilizer program for the eradication of this disease.

Citrus greening in citrus groves; Bacterial infection of the trees is directly affected by the health and growth of the root system. Imaging can once again increase our ability to adjust parameters of nutrient programs to increase the immune system of the tree and eliminate the infection altogether.

Club Root in Canola fields; As above, imaging of the root systems would give us a great advantage in the eradication of this devastating root disease by giving us faster more accurate data to use in our program of root health and growth stimulation by application of the proper 100% natural nutrients.

We look forward to seeing the results of your work and helping to commercialize it into the agricultural industries of the US and Canada as well as the global agricultural markets.

Sincerely,
Dennis Amoroso President
Plant Nutrition Technologies, Inc.

Letters of Support

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December 6, 2019

Les Butler, Professor
Department of Chemistry
Louisiana State University

Ted Cremer, Chief Scientist
Adelphi Technology, Inc.

Dear Les and Ted,

Your proposed DOE SBIR Phase II project to develop and evaluate a neutron interferometry imaging system optimized for plant root/soil interactions is important and timely. I am happy to participate as described in the workplan in your proposal.

My background with neutron attenuation imaging at the Oak Ridge National Lab, High-Flux Isotope Reactor, CG-1D beamline will enable me to assess your neutron imaging results. I am curious about scientific throughput for a low-flux neutron source when coupled to a growth chamber with automatic sample transport. Certainly, I wish for time-lapse studies on my systems, an experiment which is difficult to accomplish at CG-1D due to limited beamtime.

I look forward to first results from your imaging system and the chance to compare with similar work done at CG-1D.

Sincerely,

Jeffrey M Warren, Ph.D., Research Staff Scientist, Climate Change Science Institute