**Phase 1: Mission Problem**

**Accelerators:** *Applied Science and Engineering to Improve the Operations of LANL Accelerator Facilities*

**Introduction**

*The Los Alamos Neutron Science Center’s (LANSCE) Drift Tube LINAC (DTL) accelerates the proton beams from 4% to 43% the speed of light using four tanks [1]. Radiation is produced from normal operations with X-rays generated by electric field between drift tubes, from unwanted radiation when the beam hits supporting structures, or arcing from newly formed cracks in the walls of the tank. An array of X-ray detectors, that can perform in situ calibration, is proposed to measure the X-ray spectrum at various points along the DTL for real time diagnostics of the condition of the DTL and the beam.*

**Background & Significance**

AP cans are currently used to monitor the beam current of the DTL. *These cans are scintillation detectors calibrated so that the integrated signals are about 1% of the production beam current. ~~The AP cans have poor sensitivity to detect X-rays, order of 100 kiloelectron-volts (keV) of energy or less, unless there is a high flux of X-rays~~. In 2018 the accelerator was having stability problems with one of the DTL tanks through arc downs. The AP cans were useless in determining where the instability was coming from, so a temporary suite of* *lutetium-yttrium oxyorthosilicate (LYSO) crystal with silicon photomultiplier (SiPM) detectors were placed next to the tank in question using X-rays to determine precisely where the problem was occurring [2]. Reference [2] demonstrated the usefulness of multiple, distributed sensors along the DTL to diagnose a specific HV problem. It was a temporary deployment used to diagnose a specific problem. This proposal aims to develop a permanent and continuously operating diagnostic that can be widely deployed along the DTL.*

How can we better emphasize significance?

I removed part about measuring the DTL gap energies…

Previously detectors have already been installed?

In addition to locating anomalous behavior such as arcing in the DTL, the LYSO detectors may have a number of other applications as a beam diagnostic. In measurements made at the DTL with various prototypes in 2022 and 2023, the integrated number of pulses in the time immediately following the RF pulses was found to be proportional to the beam current. The energy spectra in FigureXYZ have peaks when the beam is on. There were drastically more X-rays (or ionizing radiation) when a beam stop was introduced between tanks 2 and 3, indicating a capability to measure X-rays and their energies as a proxy for beam spill. The array of X-ray detectors could be used in parallel to the existing set of AP cans as real time monitor of beam loss and beam current and potentially provide additional information that may lead to a deeper understanding and more consistent running of the DTL.



Figure 1: Spectra measured in an X-ray detector prototype with 1 mA of beam current and the 40 MeV beam stop in place between tanks 2 and 3.

**Research and Development Goals**

The goal of the R&D is to build and install a permanent array of X-ray detectors along the DTL which will serve to identify and locate anomalous behavior along the beamline such as arcing or beam spill.

A small number of detectors are currently installed alongside the beamline to establish feasibility. A Phase 1 study will allow for the construction of more modules and further studies into the optimization of the shielding, mounting, and readout of detectors in order to maximize their scientific return. Measurements will be made during the startup and production phases of LANSCE operation, which will allow for the measurement of X-ray spectra during baseline operating conditions for comparison during later operation. In phase 2, a larger number of detectors would be constructed and deployed along the length of the DTL based on findings in Phase 1.

**Technical Readiness**

*The TRL is currently a 4 for this proposal. The demonstration and use of the LYSO+SiPM detectors in 2018 shows that the concept of using X-rays to determine the cause of a known problem works [2].*

Five prototype modules are currently installed(mounted?) in the DTL, as shown in Figure 1. Each prototype uses a pair of 4x4x22mm LYSO scintillating crystals each optically coupled to a SiPM and read out on custom shaper PCB, shown in Figure 2? .

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Description automatically generatedA picture containing indoor, plastic, table, electronics

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Figure 1:Prototypes of the X-ray detector, wrapped in yellow tape, mounted in the DTL near tank 2.

Figure 2: The LYSO-SiPM prototype built at UCSB (replace this pic).

The feasibility of using the tagged gammas from LYSO for in-situ self-calibration has been demonstrated with the currently installed modules. In Figure 3? is the x-ray spectrum from tagged LYSO gammas as measured in one of the SiPM modules ex-situ at UCSB and in-situ mounted in the DTL. A scale factor of 1.63 leads to good matching between the spectra. The correction factor arises from differences in effective bias voltage and temperature.

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Figure 4: Tagged LYSO gamma spectra measured at UCSB and in-situ at LANL. (Do we have anything with RF on? With LYSO instead of LaBr?)

A prototype of a digitizer to read out the signals for the shaper board has also been developed and tested at UCSB. The digitizer samples the shaper board signals with an ADC which is written to an SRAM read out by a RasberryPi. The digitizer can be run at 20, 40, or 50 MHz with a memory depth of 65536, allowing for over 3 ms of sampling to capture the entire 1 ms RF window and beyond. The trigger logic is configurable, to accept an external trigger (on the RF gate or Low Beam Emittance Gate), OR triggers, or and AND trigger to measure LYSO coincidences and perform self-calibration. Pulse finding and custom data compression are integrated into the software. *It is designed to collect data automatically, with simple network communication between the individual modules.*

*The use of commodity scintillators, SiPMs, and a simple readout system makes each detector tank inexpensive so that they can be widely deployed.*

**Research Approach: Approach, Methods, Technical Challenges**

*Reference [2] showed the importance of using an array of X-ray detectors to find where a DTL tank is not behaving as expected*. Background measurements done in 2022 provided the necessary information that an in-situ calibration of X-ray detectors along the DTL is plausible. These studies also demonstrated that the detector is capable of measuring changes in the beam, such as the beam current or a large spill generated by the 40 MeV beam stop between tanks 2 and 3. Figure 5? shows the distribution of the time of pulses in a detector in various beam conditions, the number of events after the RF window increasing with the beam current and drastically with the introduction of the beam stop. *The next step is to demonstrate the prototype detector is capable of measuring* more subtle *changes in the beam and DTL configuration as a function of time.*



Figure 5: Time of pulses measured relative to the LBEG with different beam conditions.

In Phase 1, another iteration of a small number of detector modules will be constructed and installed based on the experience with the set of five detector modules which is currently installed and will be in place for the 2023 run cycle. Once installed, these new prototypes will be tested to prove they are capable of measuring changes in X-ray spectra corresponding to more subtle changes in operating conditions. *Time plots comparing the observed X-ray spectrum and rate with various operation knobs, e.g. amplitude and phase set point for the DTL tanks, steering and bending magnetic set points, etc., power, and AP measurements will be used to demonstrate the X-ray detectors can observe changes in the quality of the beam transport. X-ray distributions around known periods of time when problems occurred will also demonstrate the effectiveness of using these X-ray detectors to troubleshoot the system.*

Shielding is one of the main areas to improve in the next iteration of these detectors. In the current version, shown in Figure 6, each detector is contained within a ½” thick steel box made from industrial grade steel tube and plates with collimating holes to allow X-rays to reach the LYSO crystals from the desired part of the DTL. This much steel should reduce X-rays by 99% (85%??) at 100 (300 keV). *Additionally, several layers of 0.6 mm Pb tape have been wrapped around the LYSO crystals and near the gaps created at the intersection of the steel plate and tube to improve the hermicity of the enclosure.* In the next iteration, a custom-order Pb-polymer case would lead to better hermiticity, more shielding, and more consistent results.

The development of the next iteration of prototypes would also include a more consistent approach for mounting detectors near the DTL and continued development of the front-end and readout electronics to improve energy resolution and data limitations.

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Figure 6. Detector modules in steel capsules being tested at UCSB

The second phase will use the results of Phase 1 to design an optimized array of detectors. *A new structure will, most likely, have to be designed to accommodate the array of X-ray detectors around the tank*. *The new array will be installed, and analysis will be performed on measurements taken with and without beam. Phase 2, having more detectors in place, can also investigate effectiveness of determining the spatial coordinates of where the X-rays were generated from within the tank by knowing exactly where the beam is hitting the collector/absorber during phase scans. ~~It will also answer the question if secondary radiation from the beam loading could be used for field characterization or only serves as background to the signal.~~*

## Expected results

A successful Phase 1 will demonstrate that these X-ray detectors are able to *see a change in rate/spectrum as the beam goes through the tuning process, e.g. beam hitting different absorbers/collectors along the DTL and the voltage and phase of the DTL changes while searching for the optimal tune,* and also able to detect arcs and other faults that may occur. *A successful Phase 1 will prove to AOT management the capabilities of these X-ray detectors to use as a diagnostic of the DTL and beam conditions. The system could be used in the proposed machine learning controls of the accelerator, as it will provide fast and localized information about what is going on with the DTL and beam.*

## Qualifications of PI and Team

The team has a mix of senior, mid and early career scientists and engineers. The talents include accelerator physics, experimental detector research, computer simulation and RF engineering. The work can only be done at LANL because we need to demonstrate the detectors will characterize and monitor the LANCE DTL.

***Remington T. Thornton (AOT-AE, PI)*** is the lead on the accelerator solenoid test stand for the SCORPIUS accelerator project. He also works with the LANSCE operations physics team for the machine startup and contributes to troubleshooting complications with the beam delivery. Dr. Thornton is well known for his expertise with modeling of particle systems and development of detector systems. He was one of the key scientists in the development and analysis of the CAPTAIN-Mills detector in the Lujan center. In addition to managing the project and team, he will provide the simulations of particle interactions.

***Janardan Upadhyay (AOT-AE, co-PI)*** is part of the LANSCE operations physics team where he is the teams foremost expert on electromagnetic modeling of radiofrequency cavities. He has designed cavities in CST microwave studio for various LDRD’s and is currently building the new simulation for the fields in the current and planned harmonic buncher in the proton storage ring at LANSCE. Dr. Upadhyay will be developing the electromagnetic field models for the DTL in this study.

***Charles Taylor (AOT-AE, Co-Investigator)*** is the machine expert for the PSR and the team leader for the operation physics team. He is familiar with all tuning procedures, especially for optimizing the tune for the drift tube LINAC (DTL), and excellent at trouble-shooting operation problems. Dr. Taylor has over 20 years’ experience with detector systems. He will be involved in beam developments and provide guidance on the integration with operation.

***John Lyles*** ***(AOT-RFE, Co-Investigator)*** of the AOT-RFE group is the primary SME for RF engineering for both the LANSCE LINAC and PSR. He developed and installed an improved proton buncher system in the PSR in 1998. He has four decades of experience with high power radio frequency technologies with 29 years at LANSCE. He directs the RF measurements of the magnetic materials and will lead in the construction of a new inductive insert system.

***Patrick Freeman (UCSB)*** postdoctoral research associate at UCSB. He developed and tested the 2022 prototype and improvements. Funded by a University of California grant.

***David Stuart (UCSB)***professor at UCSB. Funded by a University of California grant.

## Budget Request Justification

The Phase 1 funding would be used to develop detector modules with more standardized and hermetic shielding, and then to build, install, and operate a number of these detectors, ideally at least two per DTL tank. *The cost of parts and assembly of each tank is targeted to be about $6k in the first round, with procurement around 1.5 months. For two modules per tank, we estimate the M&S budget will be around 50k. The remaining will pay for labor at LANL for installation of modules, data analysis, simulations, and design of* mounts*.*

Mission Agility: Mission Alignment and Impact, and Transition Plan

*A successful first phase will show the AOT division and LANSCE operations the usefulness of such an X-ray detector system in monitoring the DTL and beam conditions. Better monitoring of the DTL will extend the life of the DTL until a replace*ment *occurs under the proposed LANSCE Accelerator Modernization Project (LAMP). The X-ray system may be incorporated into the LAMP upgrade as a similar, if not exact, system will be needed for the same reasons LANSCE currently needs the system. Other accelerators, e.g. Brookhaven National Laboratory, are interested in a similar system. If AOT division and LANSCE operations agree to install such a system, procurement and installation will be done by the diagnostic and integrated software teams at LANSCE.*

**References**

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| [1] | S. Kurennoy, *Modeling Beam Dynamics in the LANSCE DTL with CST Particle Studio,* AOT-AE: 15-006 (TN), 2015. |
| [2] | M. S. Barrueta, J. T. M. Lysle, J. E. Zane, G. O. Bolme (retired), Pinsky and R. Z, "X-RAY Detector Array for Spatial and temporal Diagnostic at the LANSCE LINAC," in *NAPAC*, Lansing, MI, 2019. |
| [3] | G. O. Bolme, G. P. Boicourt, K. F. Johnson, R. A. Lohsen, O. R. Sander and L. S. Walling, "Measurement of RF Accelerator Cavity Field Levels at High Power from X-Ray Emissions," in *Proceedings of the Linear Accelerator Conference*, Albuquerque, New Mexico, 1990. |

**FY23 MFR Phase 1: FINAL FEEDBACK for project 20230421MFR**

**Project: 20230421MFR**

Project title: External Monitoring of the LANSCE Drift Tube LINAC using X-rays

Principal investigator: Remington Thornton

**Overall Summary**

 This proposal aims to employ an array LYSO detectors to measure x-ray spectrum at various points along the LANSCE drift tube linac (DTL) to monitor tank conditions during startup and operation of the beam. These detectors would aim to provide an early warning system to monitor the DTL and extend component lifetime by using them to measure the accelerating gradient. The current competition is the Activation Protection (AP) cans that are scintillation detectors with poor sensitivity to detect x-rays < 100keV of energy. As demonstrated in the past, the proposed LYSO sensors were previously deployed next to one tank to pinpoint the location of the instability. Following this demonstration, this proposal aims to develop a permanent and continuously operating diagnostic along the DTL.

Challenge: Monitoring x-ray output from the DTL tanks as a measure of degradation in the system, e.g., cracks can be inferred from increasing x-ray detection. Previously demonstrated LYSO sensors to pinpoint problem.

Proposal: Phase 1: Install two x-ray detectors on each DTL tank to demonstrate the capability of an early warning system by measuring the change in the x-ray spectrum during startup and production. What changes in spectrum would represent a ‘failing’ system? Would there just be more flux of x-ray on the detectors? Is there a difference between each DTL tank such that proving it on all 4 is necessary? Would it make more sense to first focus the technique on 1 tank to prove out the capability? What is different about this installation than what was done in 2018 with the temporary installation of these sensors next to one of the tanks? Are there particular challenges with permanent installation and an array that must be understood?

Phase 2: Determine optimal array configuration to measure the accelerating gradient for each DTL. It appears that these sensors have already been shown to be able to measure problems in a tank. Measuring the accelerating gradient is a new challenge**. The risk could be lowered if the focus of the first phase was to deploy these already-demonstrated sensors onto one tank and measure accelerating gradient. Then, if successful, optimize the array configuration and then apply to more tanks?**

**Questions:**

* The use of these detectors for lifetime prediction is not clear. Are they used in a controls configuration where a beam might be changed to reduce x-ray scattering?
* Not being an expert in the area, I don’t understand the benefits of measuring the accelerating gradient. Is this something that we currently don’t do and would create great benefit? Is this done already and this technique would be better by some metric?

**Criteria Assessment**

**Technical Vitality:**

Pros: TRL is appropriate given previous experience with sensors.

Cons: Unclear how this work advances the demonstration of these sensors on these tanks in 2018. Compare efficiencies or other metrics compared to Ge detectors.

**Mission Agility (Mission Alignment and Impact; Transition Plan):**

Pros: Extending beam time through extending lifetimes of different components of our aging accelerators is obviously mission critical.

Cons: The impact of extending the lifetimes of the DTL tubes is not articulated. How often do they fail, for example? How do they fail? How challenging is it to get something like this deployed and installed in the future?

**Workforce Development:**

Pros: Some mix of early, mid and late career staff. Appreciate collaboration with university.

Cons:  FTE required seems low considering workload.

**Research Approach:**

Pros: Low risk considering the 2018 demonstration previously accomplished. Research approach was well-laid out and methodical. The hypotheses were clearly stated.

Cons: Details are lacking in the approach. What are the challenges for install? Few references make it difficult to judge team’s expertise.