Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

Recent results from Canadian Nuclear Laboratories' work on muon tomography for nuclear security and safeguards

Oleg Kamaev
(oleg.kamaev@cnl.ca)

International Workshop on Cosmic-Ray Muography

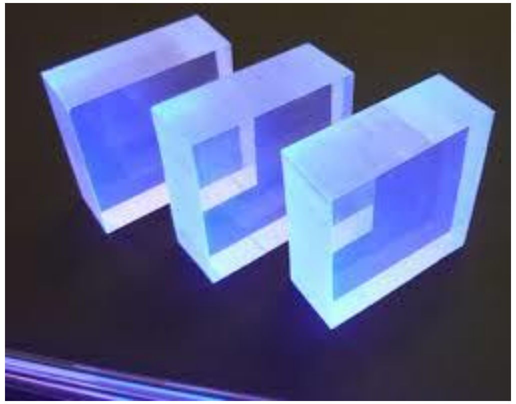
November 2021

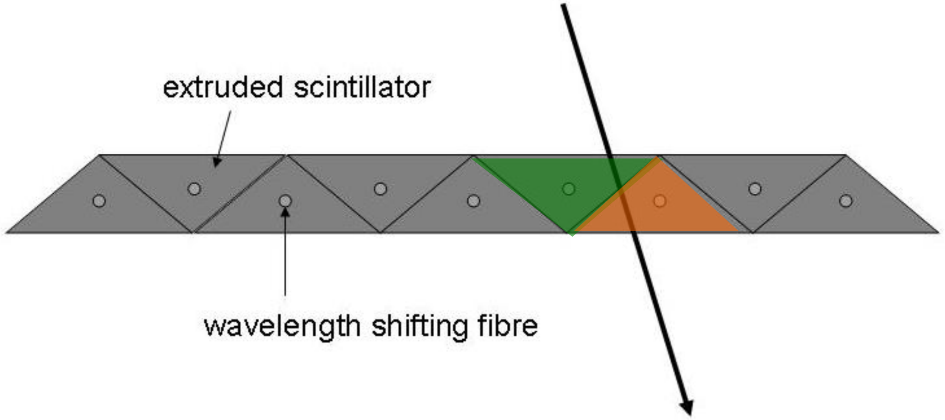
Outline

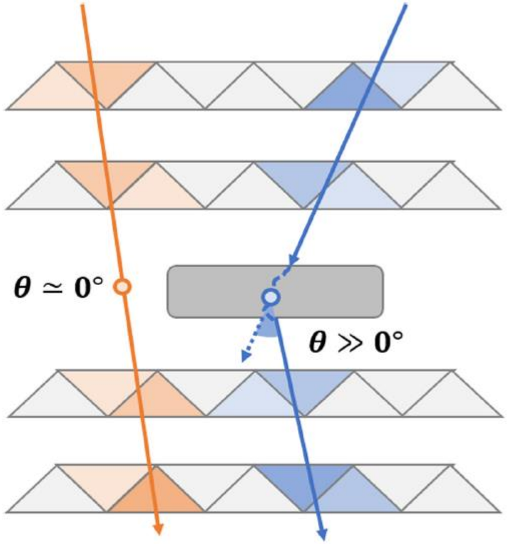
- Muon tomography detectors at CNL.
- Nonparametric algorithm for rapid dense-object detection.
- Attenuation-based muon computed tomography algorithm for imaging of large infrastructure.
- Measurements and analysis of PHWR fuel bundles in contrast with “fakes” for nuclear safeguards.

Scintillator-based muon tomography detectors at CNL

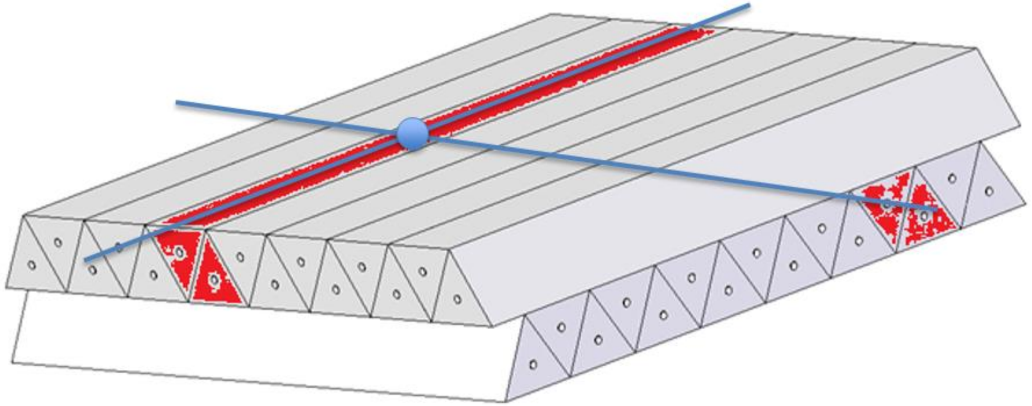
UV and blue light is produced by muon's interactions in scintillators

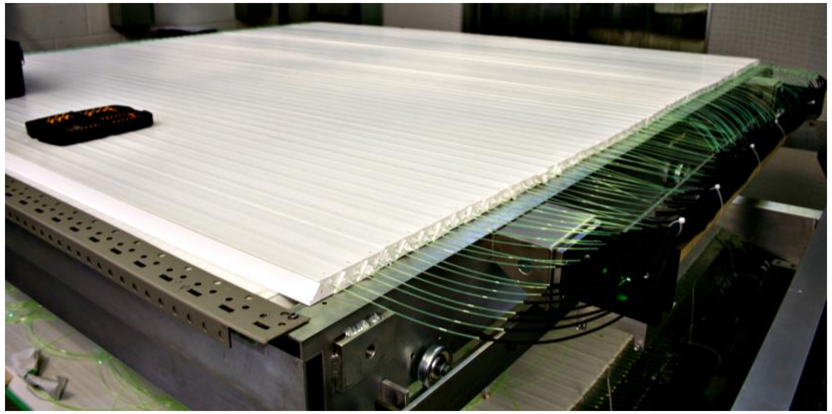






Position-sensitive super-layer

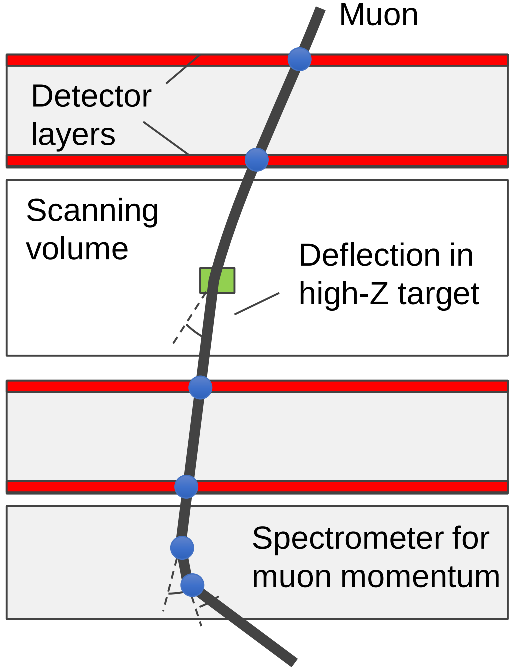


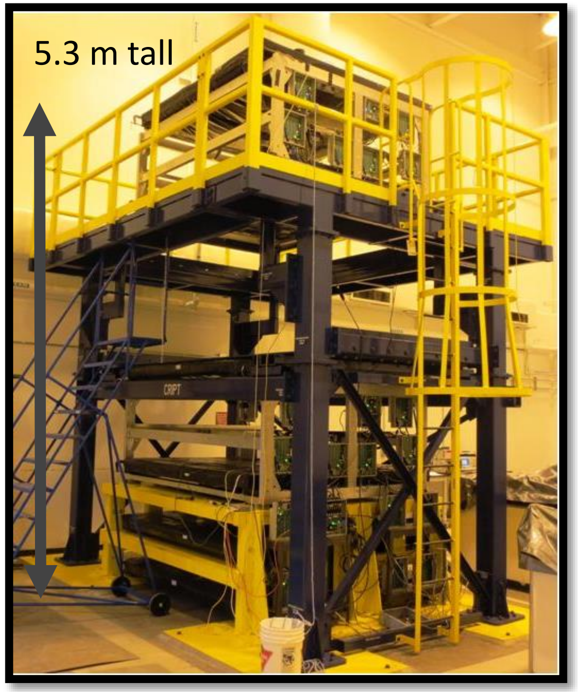


Scintillator-based muon tomography detectors at CNL

Cosmic Ray Inspection and Passive Tomography (CRIPT) detector.

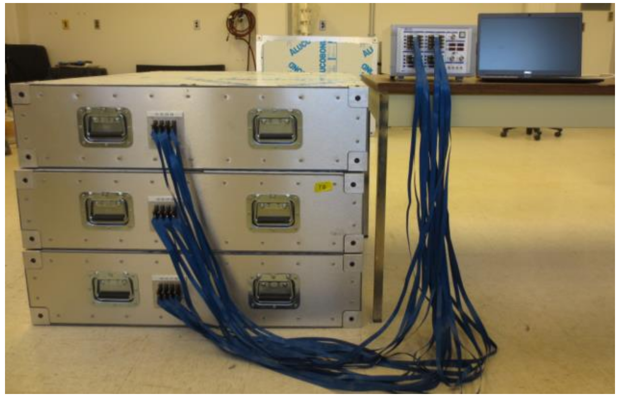
- Plastic scintillator + wavelength shifting fiber muon trackers in vertical tower with integrated momentum spectrometer.
- ~3 mm hit position resolution and ~97% muon detection efficiency.
- ~50% uncertainty in momentum estimation.

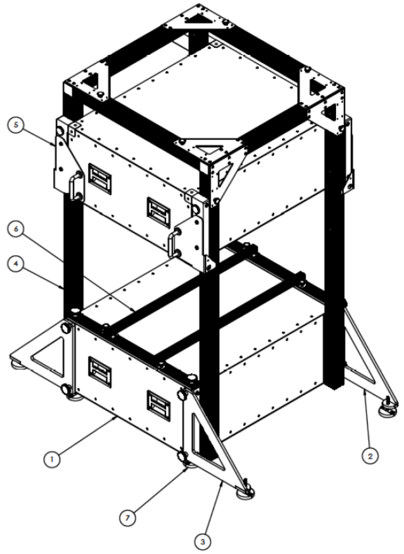




Portable muon tomography system (MuPIC).

- Hardware improvements: SiPMs and injected optical coupler.
- Data readout cards in each box are connected by high density ribbon cables to a remote Data Acquisition Unit.
- Detector enclosures can be also put inside the stand for efficient MST measurements.

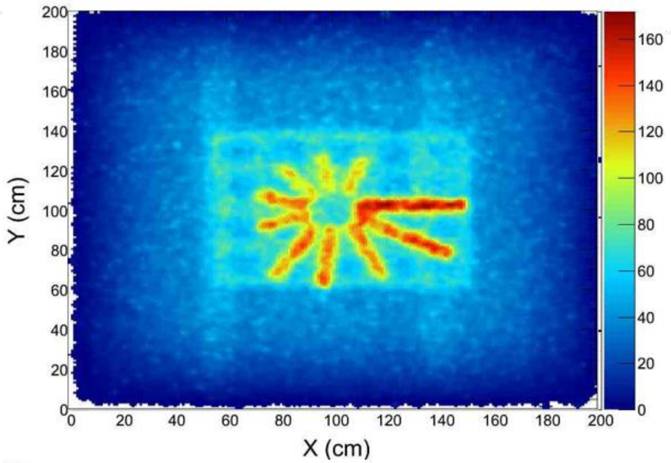




Output from muon tomography detectors

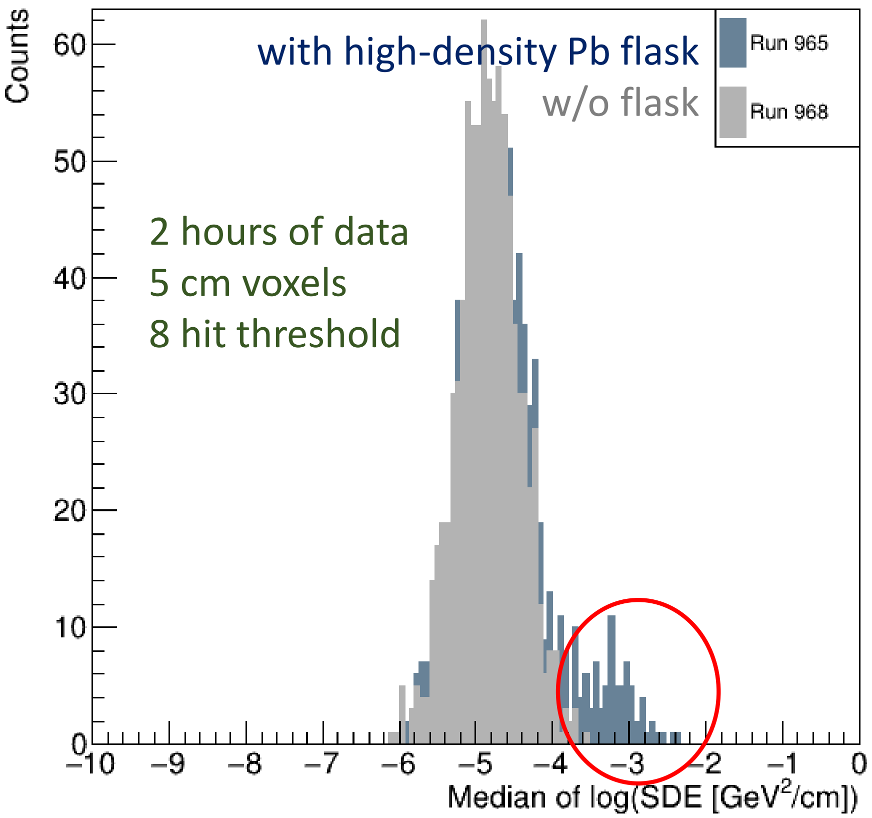
Images:

- Collect enough data in enough voxels and create an image (we get ~60 muons/s).
- Sophisticated image reconstruction algorithm *(Canada Patent 2838656, 2012)*.
- A qualitative result, rather than a quantitative.



Detection parameter:

- Evaluated with Geant4 Monte Carlo studies.
- Selected parameter: median logarithm of the scattering density estimate (SDE).
- High-density/Z material produces the tail on the right side of the distribution.



Nonparametric dense-object detection algorithm

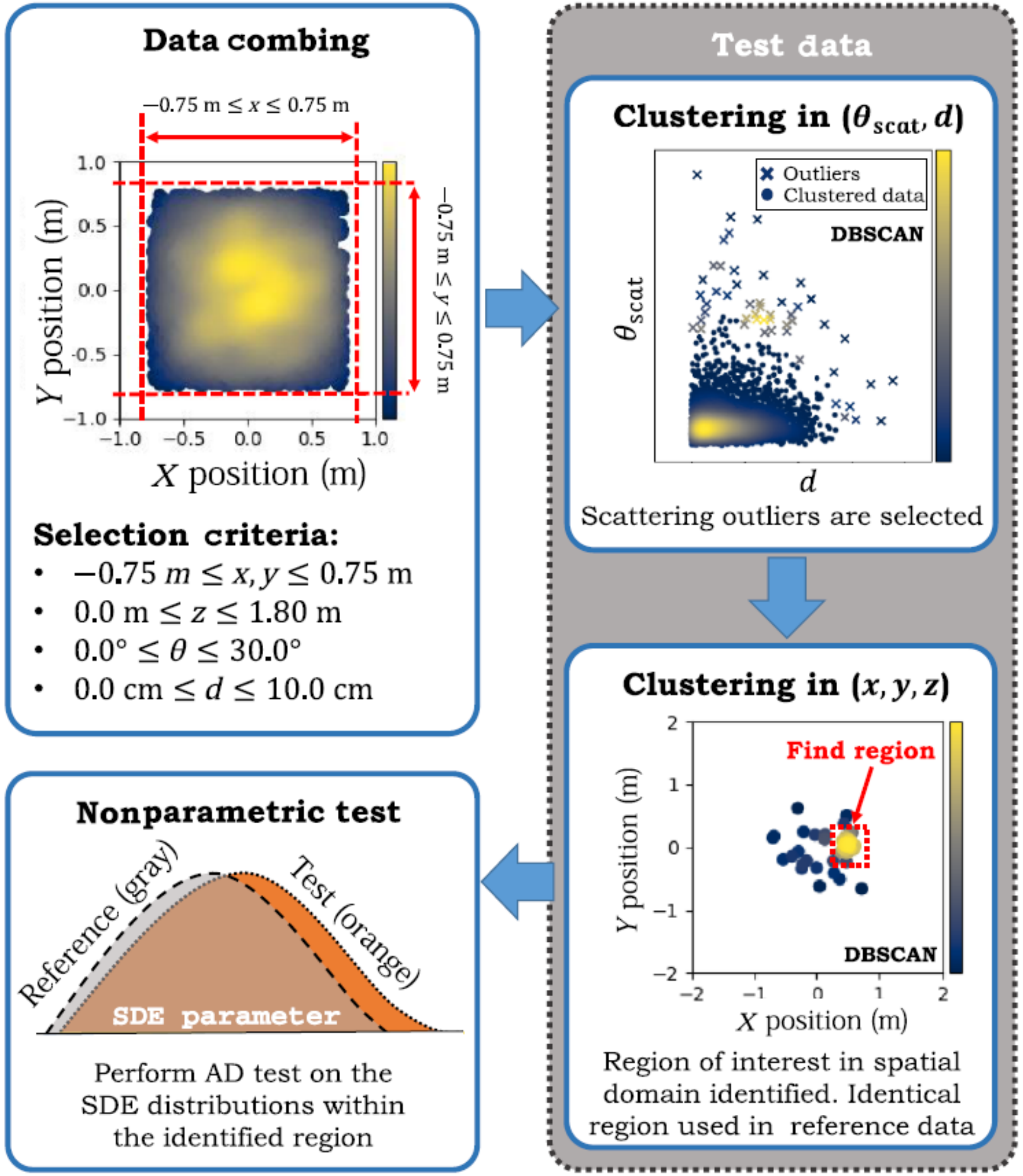
Developed generic nonparametric algorithm for rapid dense-object detection w/o need for human interpretation:

- Nonparametric tests are utilized to obtain a P-value of whether Test/Reference data are drawn from the same distribution.
- Clustering (DBSCAN) to remove low density noise and high density outliers.
- Anderson-Darling (AD) statistical test to compare Test/Reference data histograms.
- Doesn't require voxelization and imaging to identify anomalies – provides a binary yes/no result.

PHYSICAL REVIEW APPLIED **14,** 064032 (2020)

Nonparametric Dense-Object Detection Algorithm for Applications of Cosmic-Ray Muon Tomography

Evan T. Rand, Oleg Kamaev,[*] Andrew Valente,[†] and Amanjot Bhullar[‡]
Canadian Nuclear Laboratories Ltd., Chalk River, Ontario K0J 1J0, Canada



Nonparametric dense-object detection algorithm

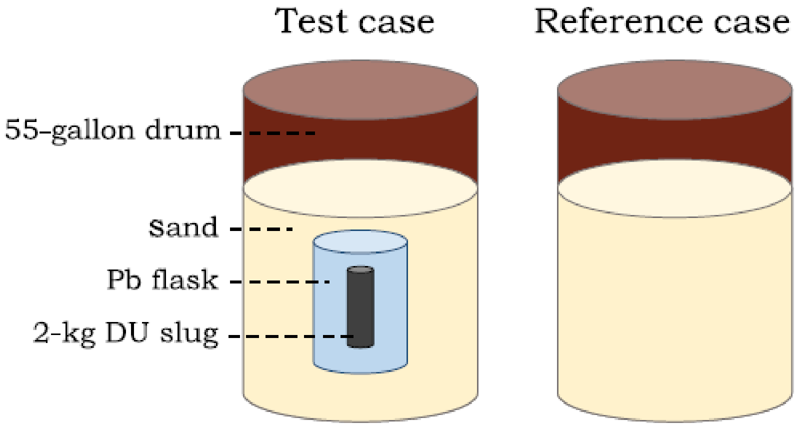
Developed generic nonparametric algorithm for rapid dense-object detection w/o need for human interpretation:

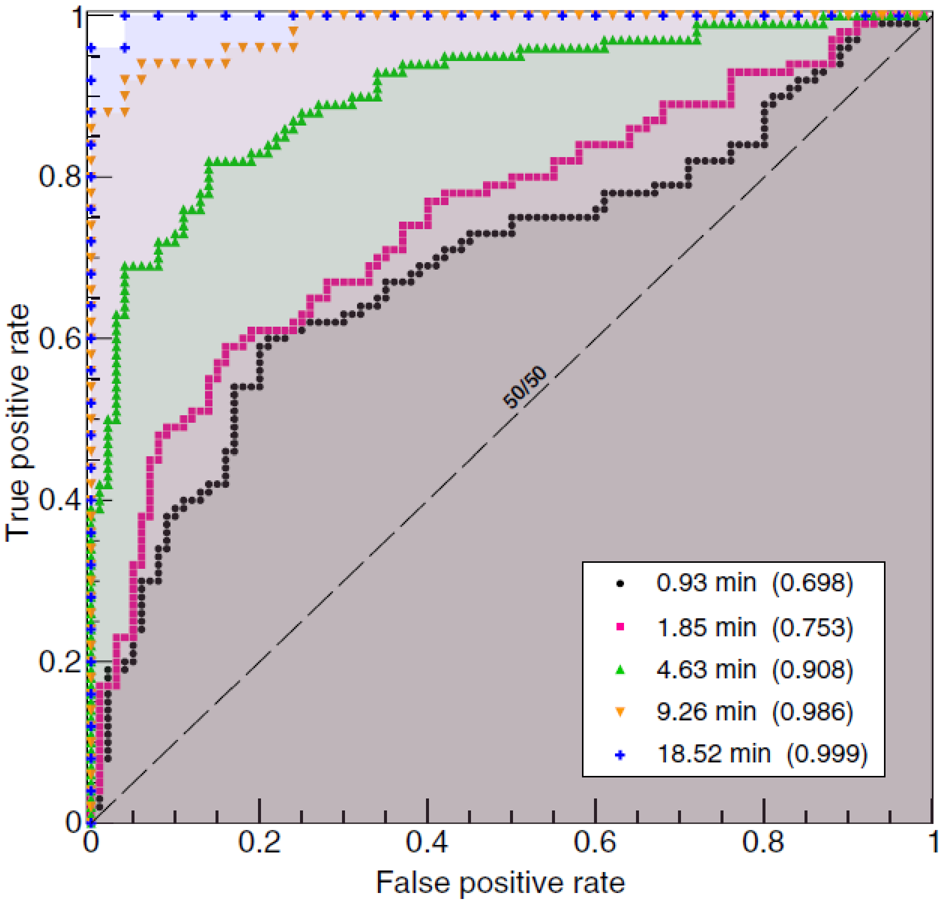
- Nonparametric tests are utilized to obtain a P-value of whether Test/Reference data are drawn from the same distribution.
- Clustering (DBSCAN) to remove low density noise and high density outliers.
- Anderson-Darling (AD) statistical test to compare Test/Reference data histograms.
- Doesn't require voxelization and imaging to identify anomalies – provides a binary yes/no result.

PHYSICAL REVIEW APPLIED **14,** 064032 (2020)

Nonparametric Dense-Object Detection Algorithm for Applications of Cosmic-Ray Muon Tomography

Evan T. Rand, Oleg Kamaev,* Andrew Valente,† and Amanjot Bhullar‡
Canadian Nuclear Laboratories Ltd., Chalk River, Ontario K0J 1J0, Canada

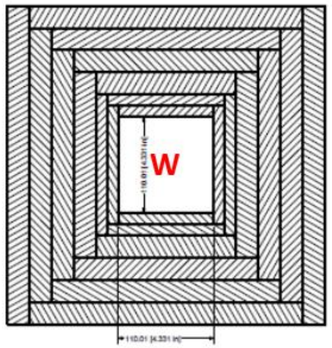


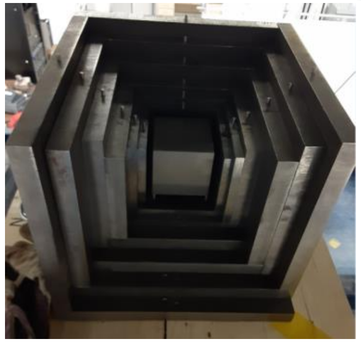


Application for Disarmament Verification

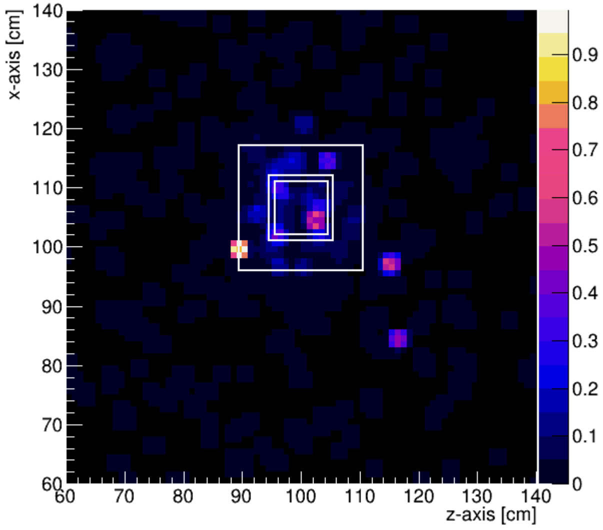
Model constructed for proof of concept experimental measurements at CNL:

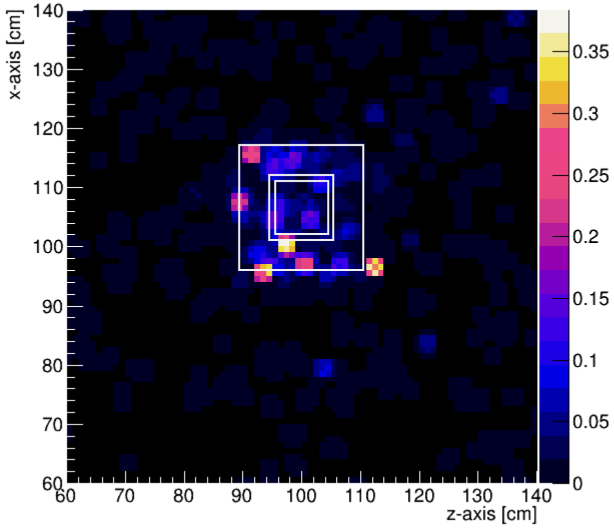
- Core: tungsten (W) cube with 9 cm side length for muon tomography measurements. W has density similar to U metal.
- Air gap between W and shielding: 1 cm thick.
- Shielding (tamper): stainless steel of variable thickness from 0.5” to 5”.



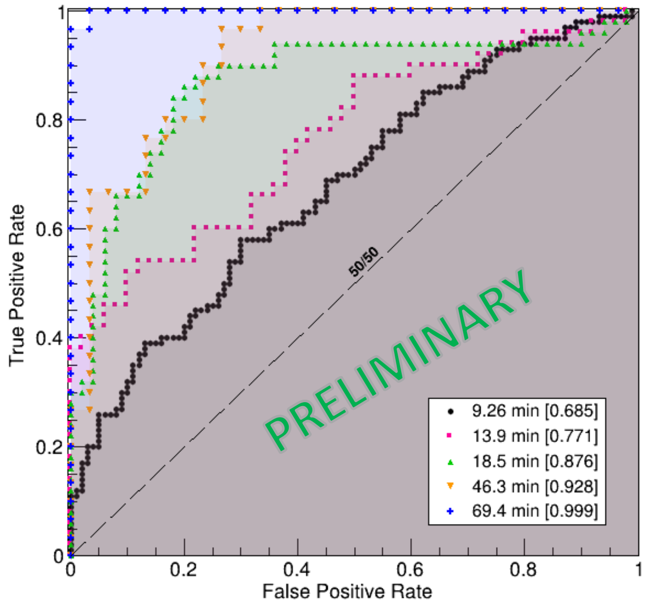


Can you observe in 70 minutes of experimental data if these setups are different? W core?



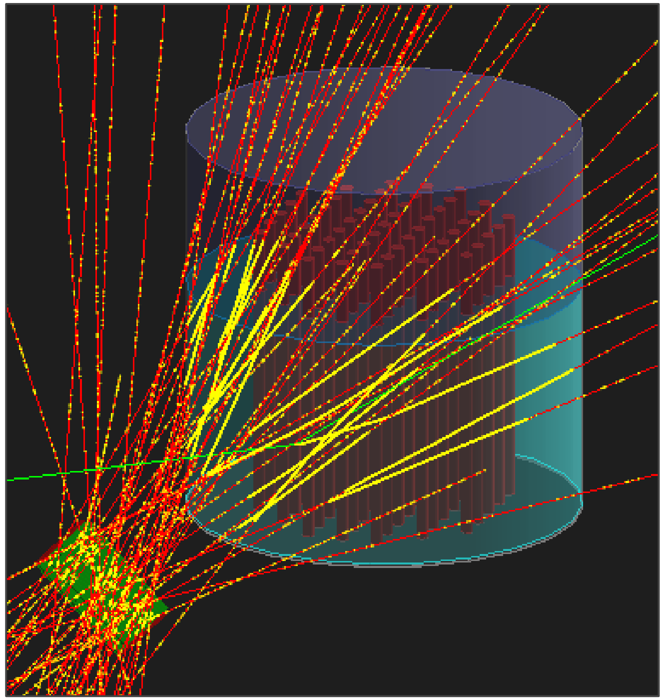


Our non-parametric detection method demonstrates ~100% success rate for 70 minutes of data with area under the curve (AUC) at 0.999.



Muon Computed Tomography (μCT)

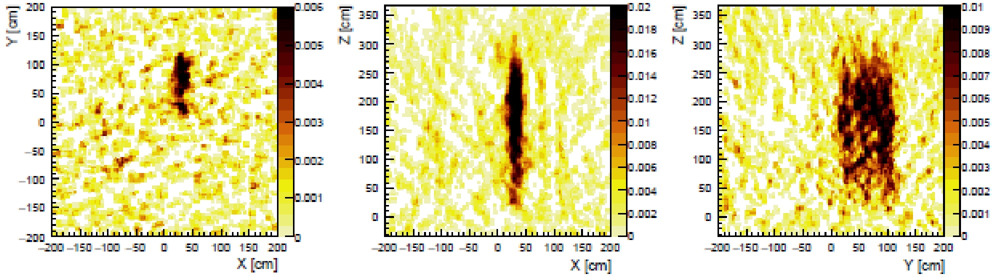
- A single-detector imaging system can provide advantages for imaging large stationary nuclear infrastructure such as a reactor or waste repository.
  - ✓ Increased angular acceptance, smaller detectors, reduced cost, easier transportation and positioning.
  - ➢ Requires higher statistics, slower.
- Computed tomography algorithms from medical physics can be adapted for use with muon flux measurements.
- Requires a single smaller detector, which rotates about the target.
- Inverted using a statistical comparison to the expected muon flux distribution.



Geant4 simulation of a portable muon detector measuring the muon flux through the ZED-2 reactor.

Identifying missing fuel rod in reactor

- Geant4 simulation studies of a simplified ZED-2 reactor core indicate that the 3D fuel rod configuration can be accurately reconstructed by this method.
- Missing rods can also be directly reconstructed if prior data for a full core is available.



Nuclear Inst. and Methods in Physics Research, A 987 (2021) 164834

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

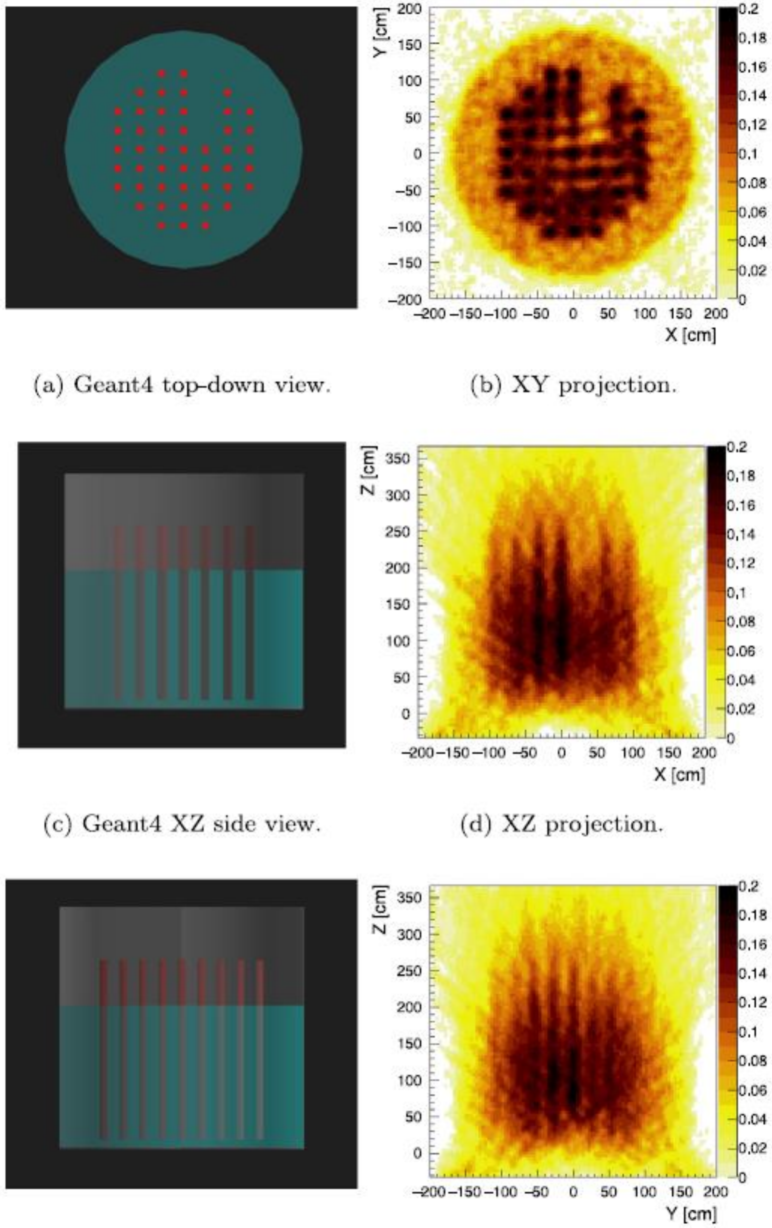
journal homepage: www.elsevier.com/locate/nima

A comparison of algebraic reconstruction techniques for a single-detector muon computed tomography system

K. Hartling*, F. Mahoney, E.T. Rand, T. Sariya, A. Valente[1]

Canadian Nuclear Laboratories, Chalk River, ON, Canada

Comparison of simulated ZED-2 geometry with plane projections of reconstructed 3D image.



(a) Geant4 top-down view. (b) XY projection.

(c) Geant4 XZ side view. (d) XZ projection.

(e) Geant4 YZ side view. (f) YZ projection.

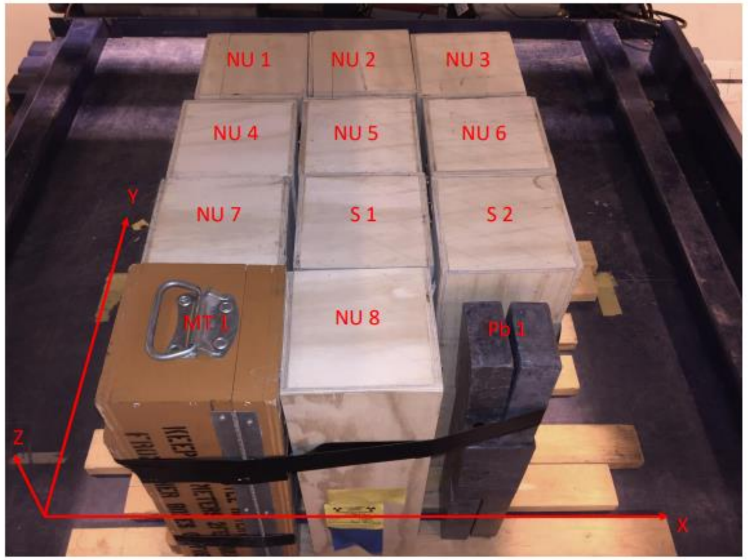
Measurements and analysis of PHWR fuel bundles in contrast with “fakes” for nuclear safeguards

- Measure scattering density of several target materials:
  - Steel, lead, air/void/zircalloy, ceramic UO_2
- Target geometry is Pressurized Heavy Water Reactor (PHWR) fuel bundles
  - Pb target is 10 cm x 10cm x 60 cm castle

Target	Material	Area [cm^2]	Length [cm]	Mass [kg]	Density [g/cm^3]	X_0 [cm]
NU 1-8	UO_2 + Zr	78.5	50.0	22.5	5.73	0.74
S 1	Steel + Zr	78.5	50.0	18.1	4.61	1.76
S 2	Steel + Zr	28.3	50.0	12.8	9.04	1.76
MT 1	Zr + Air	78.5	50.0	~ 2.1	1.43	1.57
Pb	Pb	100.0	60.0	68.0	11.3	0.56

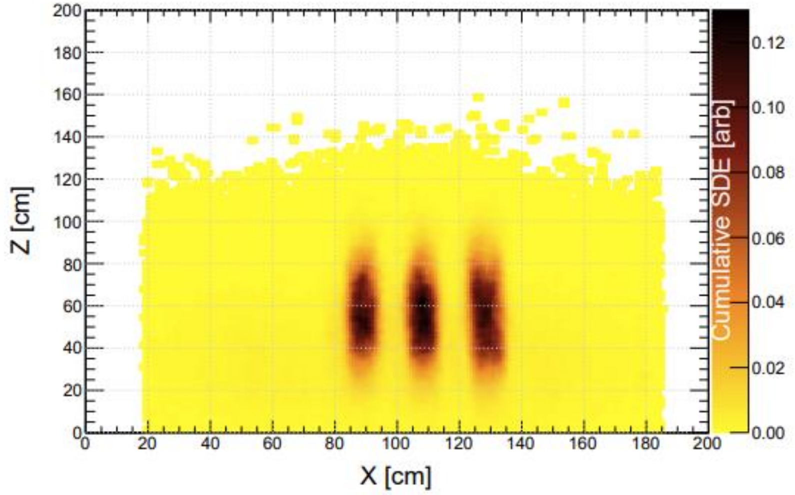
- Targets placed in wooden boxes and stood upright (see figure)
- Data acquired over a ~44 h period
- Approximately 6.4M events recorded

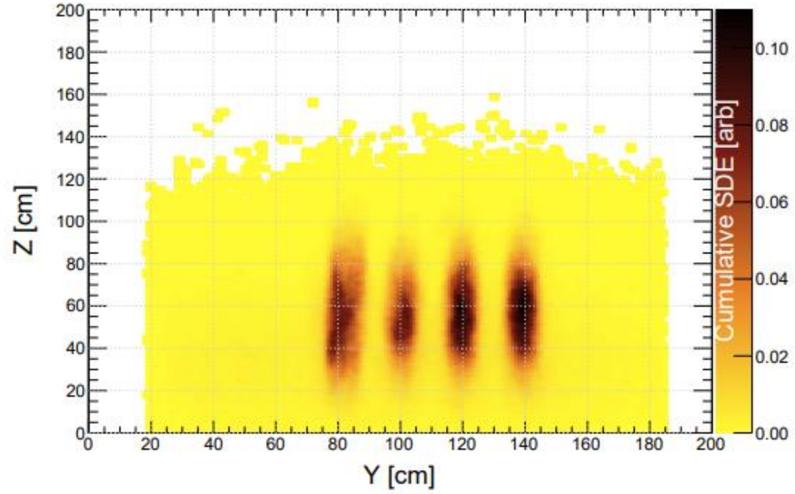
37 element PHWR fuel bundle (cross sectional view)



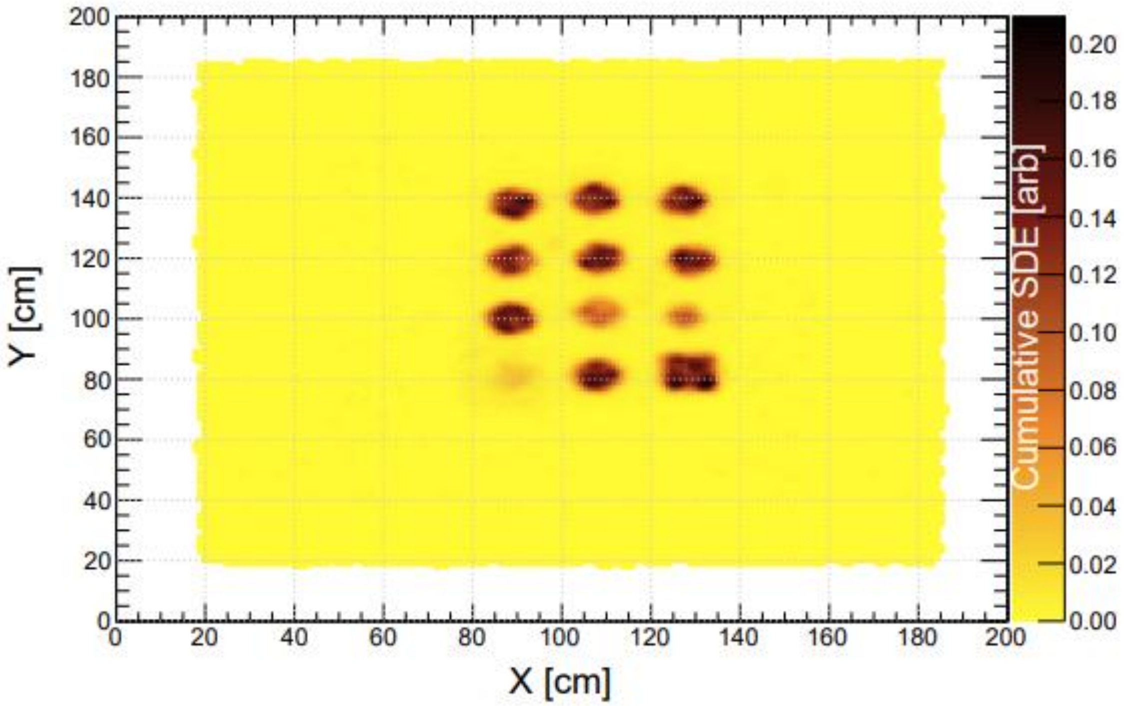
Targets placed in CRIPT imaging volume with coordinate system overlaid. Z-axis is vertical.

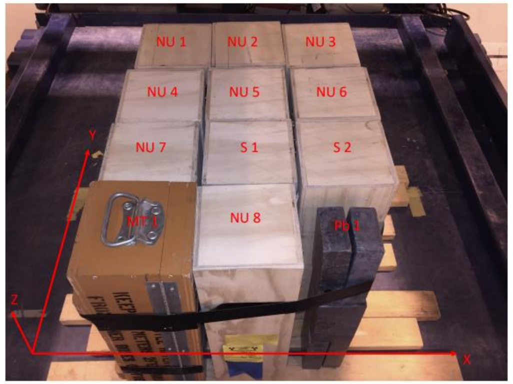
Reconstructed images





- Overall dimensions, relative intensities are well represented in images.
- Geometrical differences are very obvious.
- Real PHWR bundles distinct from weighted and unweighted “fakes”.





Material discrimination

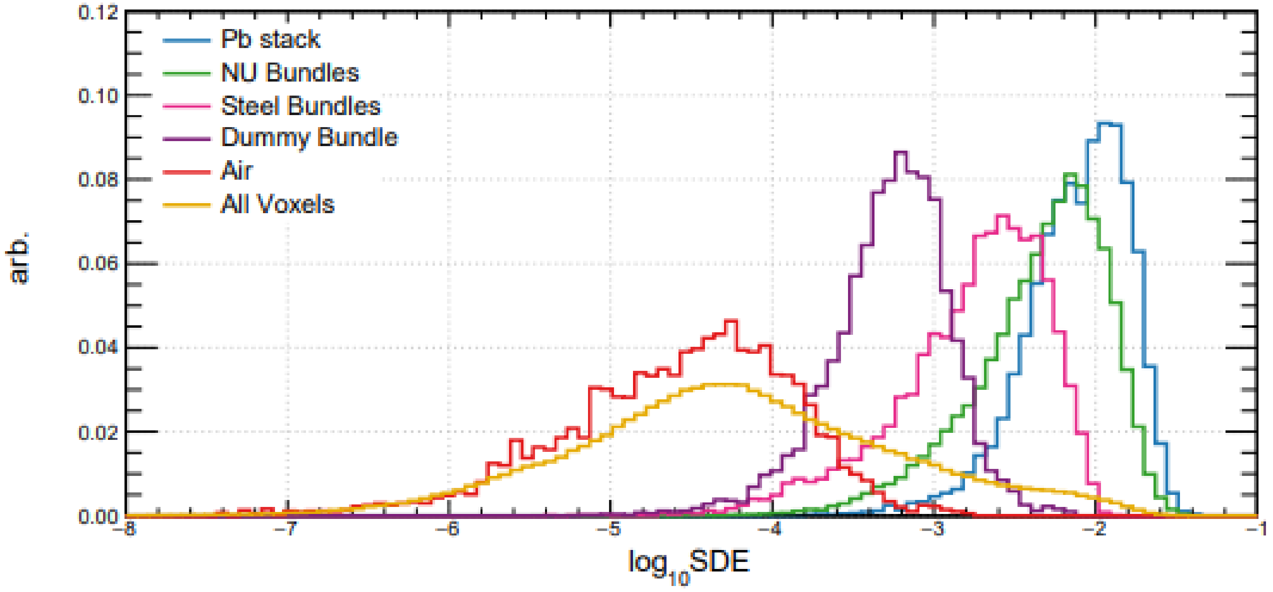
- Scattering density distributions (SDE) constructed by fiducializing volumes containing each material.
- Receiver Operator Characteristic (ROC) curves constructed by comparing fractions below/above moving threshold between two materials.
- Pb and UO_2 are quantitatively distinct.
- UO_2 and "fake" bundles are also distinct.
- Discrimination achieved well inside of IAEA guidelines (~1 month).

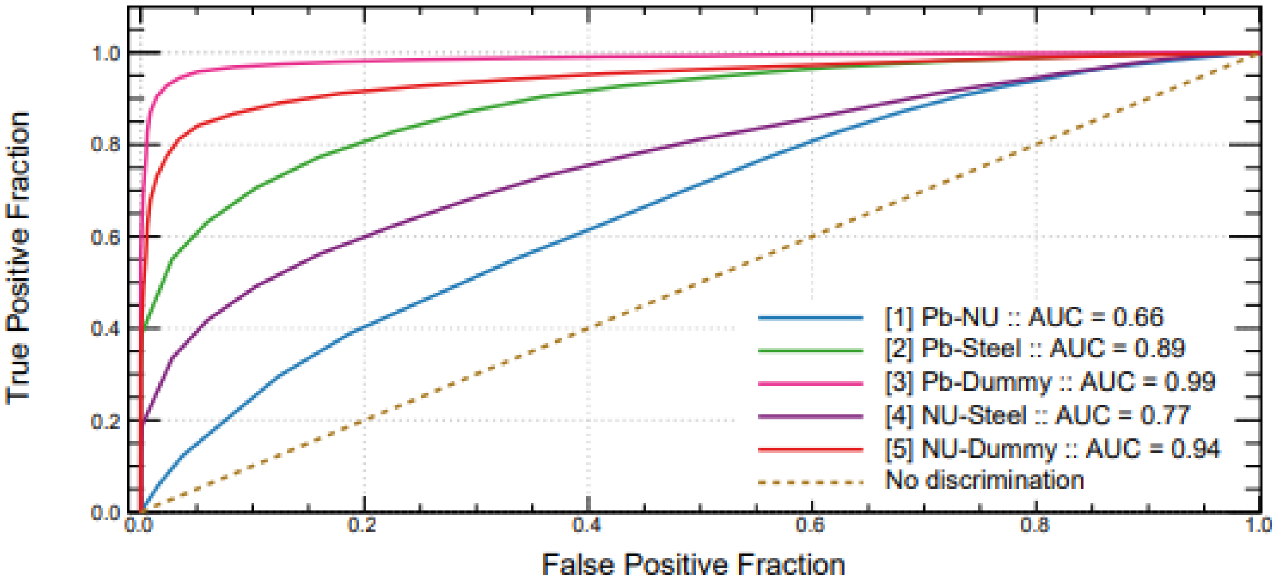
An analysis of pressurized heavy water reactor fuel for nuclear safeguards applications using muon scattering tomography

A. Erlandson[1], V.N.P. Anghel[1], D. Godin[1], C. Jewett[1] and M. Thompson[1]

Published 22 February 2021 • © Canadian 2021 Crown copyright

Journal of Instrumentation, Volume 16, February 2021





Summary

Canadian Nuclear Laboratories (CNL) has considerable experience in the development of muon radiography techniques with a focus on potential applications for nuclear security and safeguards.

Currently there are two scintillator-based muon tomography systems at CNL:

- ➢ Stationary CRIPT detector with unique ability to measure muon momenta.
- ➢ A compact portable system designed for field use.

Recent advances at CNL in detection systems and data analysis techniques for muon radiography include:

- A clustering-based algorithm that uses a nonparametric statistical test to provide a single output – a simple ‘yes’ or ‘no’ – to confirm the presence of nuclear material. This new algorithm has the potential for many important applications in nuclear safeguards, including the security of nuclear facilities and nuclear materials controls (e.g., nuclear treaty verification efforts).
- A novel attenuation-based muon computed tomography algorithm to enable imaging of large nuclear infrastructure using measurements from a single muon tracking module.
- First experimental analysis of PHWR fuel bundles in contrast with “fake” bundles in a safeguards context.

Acknowledgements

The following scientists, technologists and students at CNL contributed to the work presented:

V.N.P. Anghel, G. Bentoumi, A. Dunn, A. Erlandson, D. Godin, G. Harrisson, K. Hartling, C. Jewett, L. Li, D. Pérez Loureiro, E.T. Rand, M. Thompson