Title: Advanced Charged Particle Radiography for SNM Detection

Author(s): Konstantin Borozdin, Christopher Morris, Kiwhan Chung, Andy Fraser, Gary Hogan, Fesseha Mariam, Alexander Saunders

Intended for: 2010 Symposium on Radiation Measurements and Applications, University of Michigan, Ann Arbor, USA, May 24-28, 2010
Advanced Charged Particle Radiography for SNM Detection
Konstantin Borozdin, Christopher Morris, Kiwhan Chung, Andy Fraser, Gary Hogan, Fesseha Mariam, Alexander Saunders
Physics Division, Los Alamos National Laboratory

As a technique for special nuclear materials (SNM) detection, X-ray radiography has severe limitations due to a limited range of X-rays penetration and significant noise for higher energy photons. The attractive alternative is provided by another type of radiography that uses high-energy charged particles as a probe. This technique is selective to high-Z materials, both SNM and shielding materials. The physical basis for charged particle radiography is well established. High-energy charged particles are more penetrating than X-ray and gamma-ray photons, allowing the inspection of a variety of objects, from people and suitcases to trucks, sea containers, airplanes, and ships. In contrast to photons, charged particles interact with matter in several different ways, and provide signal not only by attenuation, but also by multiple scattering and energy loss.

Conventional radiography takes advantage of the absorption of penetrating radiation. For X-ray radiography, the areal density of the object seen in a pixel of the image is determined by the absorption or scattering of the incident beam:

\[ N = N_0 e^{-L/L_0}, \]

where \( L \) is the path length (areal density) through an object, and \( L_0 \) is the mean free path for scattering or absorption. The precision of radiographic measurements is limited by the Poisson counting statistics of the transmitted flux, \( \Delta L/L_0 = 1/\sqrt{N} \). The maximum mean free path for photons in high-Z elements occurs at a few MeV. The mean free path is approximately 25 g/cm² for all materials at this energy. This corresponds to less than 2 cm of lead. Penetrating objects of tens of \( L_0 \) requires very large incident doses.

For charged particles we can go beyond the absorption signal and use the multiple Coulomb scattering. The trajectory of a charge particle through any material is the result of the convolution of many small deflections due to Coulomb scattering from the charge of the atomic nuclei in the medium. The many small interactions add up to yield an angular deviation that follows a Gaussian distribution to a good approximation:

\[ \frac{dN}{d\theta} = \frac{1}{\sqrt{2\pi\theta_0^3}} e^{-\left(\frac{\theta^2}{2\theta_0^2}\right)} \]

The width of the distribution is related to the scattering material: \( \theta_0 = \frac{14}{p\beta} \sqrt{\frac{L}{X}} \), where \( p \) is the particle momentum, \( \beta \) is the velocity divided by the velocity of light, and \( X \) is the radiation length. Here we have dropped logarithmic terms that are on the order of 10%. The net angular and position deflection of the trajectory are very sensitive to the charge \( (Z) \) of the atomic nuclei. High-energy charged particles are more strongly affected by materials that make good gamma-ray shielding and by SNM than by the most commonly used materials such as water, paper, aluminum, and steel. In a layer 10 cm thick, a 3 GeV muon will scatter with a mean angle of 2.3 mrad in water \( (X = 36 \text{ cm}) \), 11 mrad in iron \( (X = 1.76 \text{ cm}) \), and 20 mrad in tungsten \( (X = 0.56 \text{ cm}) \). If the muon scattering angle in an object can be measured, and its momentum is known, then the path length, \( \Delta l \), can be determined to a precision of \( \Delta l/l = 1/\sqrt{N} \), where \( N \), the number of transmitted muons, is very nearly equal to the number incident. Thus, each transmitted muon provides information about the thickness of the object.
Another signal is provided by the energy loss of charged particles in different materials. For mono-energetic particles, energy loss is the integral of the Bethe-Bloch formula along the particle track, and depends mainly on the electron density. The probability density function for energy loss is described by a narrowly peaked Landau-Vavilov distribution, therefore each single particle provides a precise measurement of the amount of material it traversed, to a precision of \( \approx 5\% \). Monte Carlo simulations support the simple estimate of density resolution of \( \frac{\Delta \rho}{\rho} = \frac{0.05}{\sqrt{N}} \) for energy loss radiography. Only a few particles are enough to measure material parameters with high accuracy, providing for a high-quality radiography with extremely low dose. Even a single-projection energy-loss-only radiography would be qualitatively superior to existing technologies based on attenuation of high-energy photons (X-ray radiography, CAARS). We can however further improve the performance by using multiple projections for 3d tomographic imaging and/or by incorporating signals from the multiple Coulomb scattering and nuclear attenuation of the beam. In our previous work we demonstrated how to use the multiple scattering of cosmic-ray charged particles for the nuclear threat detection and 3d localization. High quality of the reconstructed images we obtain with muon tomography demonstrate the power of charged particles as advanced radiographic probe. Here we discuss how we can go beyond that previous work in three ways: 1) using particle accelerator as a source, we overcome limitations of the technique related to the limited flux of the cosmic rays; 2) measuring energy loss signal, we tap into the superior source of information for enhanced discrimination of different materials; 3) combining three different sources of information, we improve reliability of the threat detection and reduce number of false positives (this advantage is similar to the advantages of using multispectral imaging for detection and identification of the threats).

Position resolution of energy loss radiography is limited by the stochastic uncertainty in the particle tracks due to the Coulomb multiple scattering of charged particles in the object. We have seen however that for a variety of objects under consideration this uncertainty is of the order of centimeters. For applications we consider cm-scale resolution is sufficient. Using the estimate above, \( 1\% \) resolution at cm scale requires incident fluxes of 25 particles/cm\(^2\), or doses less than 1 microrem. This can be compared with \( \sim 10 \) microrem per scan from currently deployed backscatter X-ray systems. Per cent resolution can be achieved by measuring incoming and outgoing trajectories for each particle together with its initial and final energy. Both incoming trajectory and source energy can be known for an accelerator produced beam, so only outgoing trajectory and energy need to be measured to calculate energy lost in the object. Earlier attempts to use the energy loss information by ranging out of protons in a detector, were limited by both multiple scattering and narrow range of density and thickness variations that can be measured with ranging techniques. The single particle tracking extends the range of densities and thicknesses by several orders of magnitude as required by the applications.

Charged particle radiography can be used in many scenarios where X-ray radiography is inefficient or impossible. We discuss capabilities and limitations of charged particle radiography for several potential applications, where SNM materials or other threats have to be detected.