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Review of possible applications of cosmic muon tomography

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ABSTRACT: Muon radiographic methods can be used to explore inaccessible volumes profiting of the property of muons to penetrate thick materials. An extension of the muon radiographic methods, the muon scattering tomography, was proposed for the first time in 2003 and it is based on the measurement of the multiple Coulomb scattering of muons crossing the volume under investigation. In this talk, the principles of tomographic image reconstruction are first outlined and then the experimental setup and the most adequate detectors are described. A review of the possible applications of this technique is reported, with specific reference to security in transports and monitoring of industrial processes. The technique can also be used to provide precise measurements of the properties of various materials. The experimental challenge related to this activity is discussed.

KEYWORDS: Search for radioactive and fissile materials; Gaseous detectors; Interaction of radiation with matter; Pattern recognition, cluster finding, calibration and fitting methods

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Contents

1 Introduction

The highly penetrative properties of cosmic ray muons can be used to explore inaccessible volumes. The first application of cosmic muons was obtained in 1955 by E.P. George [1] to determine the depth of rock above an underground tunnel. A spectacular application was obtained by Nobel Prize L.W. Alvarez inspecting the Chefren pyramid to search for hollow vaults [2]. More recently, volcanoes inspection was proposed and performed [3]. In all such cases, cosmic muons are treated as ordinary x-rays in usual radiography by looking at their absorption.

A completely different approach to obtain cosmic muon tomography is the muon scattering tomography (MST). The technique, proposed in 2003 [4], is based on multiple Coulomb scattering (MCS). When charged particles, as cosmic muons, cross a target volume they are deflected (and decelerated). The deviation angle, projected on a plane, has a distribution which is basically Gaussian for particles of the same momentum, with mean zero and a r.m.s. which depends on the inverse of the muon momentum p and on the material thickness X and radiation length X_0:

$$\sigma \approx \frac{13.6\,MeV}{pc}\sqrt{\frac{X}{X_0}}. \tag{1.1}$$

Measuring the deviation angles allows to reconstruct information about the radiation length (or its inverse, the linear scattering density $\lambda = 1/X_0$) of an unknown material. It must be noted that the momentum of an individual particle is in general unknown but it can be substituted by a fixed value computed from the average value $< 1/p^2 >$ of the $1/p^2$ distribution.

2 Reconstruction techniques

The MST technique requires two detectors to measure position and direction of the muon before and after it enters in the volume to be inspected.

2.1 Basic technique

The simplest reconstruction method is based on the single scattering approximation (SSA) which assumes that the scattering of any individual muon is concentrated in a single point. This point coincides with the point of closest approach (POCA) of the straight lines (in space) measured by the two detectors. A map of the material linear scattering density (LSD) can be obtained by assigning to the POCA reconstructed for the i^{th} muon a weight proportional to $\Delta\theta_i^2$ where $\Delta\theta_i$ is the measured projected scattering angle. The method is computationally very fast and it works quite well for cases with an object having a much higher LSD than the rest of the volume, but it tends to fail in presence of several scattering centers.

2.2 Tomographic technique

A more powerful but complex method is based on maximum likelihood expectation maximization (MLEM) algorithm. For a particle i with a length L_i of the crossing path inside the target volume filled by a homogeneous material of LSD λ, the average expected squared deviation can be deduced from eq. (1.1) as

$$\sigma_i^2 = \left(\frac{13.6\,MeV}{pc}\right)^2 L_i\lambda. \tag{2.1}$$

If the material is not homogeneous, the target volume can be divided in N cubic units, called voxels, where the LSD is assumed to be constant, and then in eq. (2.1) the product $L_i\lambda$ becomes $\Sigma_k L_{ik}\lambda_k$. With a data sample of M muons we have then N unknowns $\{\lambda_k; k = 1...N\}$ and M measurements $\{\Delta\theta_i^2; i = 1...M\}$.[1] Given the Gaussian probability density function

$$P_i = P(\Delta\theta_i \mid \sigma_i) = \frac{1}{\sigma_i\sqrt{2\pi}}e^{\frac{\Delta\theta_i^2}{2\sigma_i^2}} \tag{2.2}$$

with an iterative optimization algorithm applied to a maximum log-likelihood functional, the system can reach reasonably approximate values of λ_k [5–7].

A list of other algorithms, feasibility studies and other simulations is given in refs. [8–18].

3 Experimental setup

3.1 The detectors

The detectors for MCS tomography must fulfil the following requirements: (i) to cover large areas (then the detectors must be reliable and cost effective); (ii) to ensure good tracking performance; (iii) to provide good angular resolution: $\Delta\theta < \mathcal{O}(10$ mrad); (iv) to produce two times bi-dimensional measurements (at least one of them should have a good angular resolution for $\Delta\theta$ measurement);

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[1] A complete treatment of the measurements should also include the muon displacement, defined as the distance between the exit point of the particle from the target volume and the trajectory of the incoming muon.

(v) to guarantee stability in time and position. In addition, if possible, the detector should provide information about the individual muon momentum.

Following these requirements, several detectors have been proposed and used to realise prototype systems for muon tomography. Among the gaseous detectors, drift chambers with different cell structure, gas electron multiplier's (GEM) and resistive plate chambers (RPC) should be mentioned. In addition, detectors based on plastic scintillators with multi-anode or silicon photomultiplier readout (MaPM or SiPM) have been considered. The scintillation-light collection can be direct or mediated by wave-length shifting (WLS) optical fibers. Fast devices as RPC or SiPM can measure with good precision the time of flight required for the muon to cross the distance between the two detectors, allowing to provide a momentum measurement at least for the low-energy particles. A list of possible detectors for muon tomography is given in refs. [19–39].

2016 JINST 11 C12072

3.2 An example

At the INFN National Laboratory of Legnaro (Padova) a demonstrator for the study of muon tomography has been assembled using two spare muon chambers produced for the CMS experiment at CERN-LHC [40] and installed in the barrel sector of the detector. Two 300 cm × 250 cm drift chambers, used to track the muons, are placed horizontally with a vertical gap of about 160 cm, as shown in figure 1. The volume enclosed by the two detectors is more than 11 m^3, one of the largest test volumes for MCS tomography of the world.

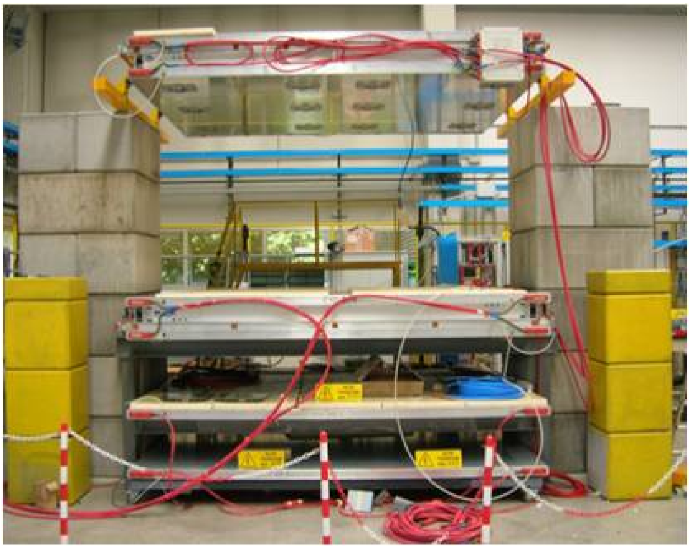

Figure 1. The muon tomography station at the INFN Legnaro Laboratories.

4 Applications

The activity based on possible applications of cosmic muons is now growing worldwide and the related literature is becoming relevant. For this reason it is difficult to produce an extensive review of all the activities on different applicative sectors, but at least the major items are considered in the following.

Several applications are based on the measurement of cosmic muon flux absorption. Namely: (*i*) geological survey (vulcanos, mines, CO_2 repositories) [41–51]; (*ii*) archaeological inspections [52, 53]; (*iii*) survey of nuclear plants [54–56]. They will not be discussed here since some of them are described elsewhere [57].

Many other possibilities are deriving from the implementation of systems based on MCS tomography.

4.1 Transport control

The first application proposed by the Los Alamos group to use the MCS tomography was addressed to detect heavy metals in containers and trucks, to contrast nuclear contraband. A portal based on drift tube technology is in operation in Freeport (Bahamas) [20]. Other portals are under construction (e.g. Catania, Italy [25, 27]). A crucial point for these controls is the capability to provide a reliable response, once a container is inserted in the portal, in a very short time, not to delay the transport chain.

4.2 Industrial applications

An application that can be classified both as transport control or industrial application regards the detection of the so-called orphan sources in scrap metal. All over the world, radioactive sources are sometimes present in scrap metal transported to foundries for steel recycling. In some cases, when the radiation source is well shielded by its heavy metal transportation cask and by the scrap metal itself, it is not detected by radiation portals, usually installed at the foundry entrance, and is melt, with serious consequences for the plant and public [58]. An European project [59] was aimed at studying and designing a portal capable to detect the heavy metal shield of the radiation source in a short ($\approx$ 5 min) exposition time. In conjunction with radiation detectors, this system will be capable to intercept every source without slowing the metal production chain. The program was successfully completed: a situation similar to the industrial case was reproduced in the Legnaro demonstrator by hiding a lead volume, corresponding to a shield cask, into a $\approx$ 1 cubic meter box of scrap metal [7]. In addition, the real situation of a full scale portal for truck inspection at a foundry was simulated. The false positive rate as a function of the exposition time, for different lead volumes is shown in figure 2. For a 2 liter volume six minutes are sufficient to avoid false alarms with 100% finding efficiency [58, 59]. To reach such a low rates of false alarms it is important to filter out noise originating from several sources as described in ref. [7].

Another industrial application concerns the study of the capability of MST for imaging of different components present in the blast furnace burden (coke, burden and reduced metal), during operation. An European project, [61] devoted to this investigation, is going to release the final results of its activity. Preliminary unpublished results based on the simulation of ideal detectors surrounding the whole furnace, have shown the potentiality of the technology to map the internal distribution of the material. Final results will be released next year. Additional use of cosmic-ray muons for monitoring blast furnaces can be found in refs. [62–64].

A study for MST application to nuclear power industry is also available [65].

2016 JINST 11 C12072

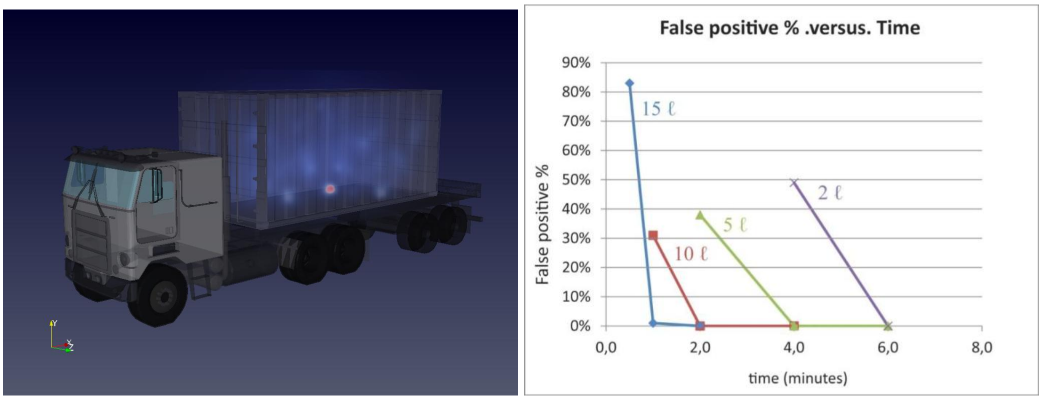

Figure 2. Simulated image of a portal for truck inspection at a foundry (left); false positive rate as a function of the exposition time, for different lead volumes (right). These figures are taken from ref. [59].

4.3 Nuclear waste/spent nuclear fuel control

A very promising field, with a lot of activities connected [18, 66–72] is related to spent nuclear fuel control and in particular the inspection of dry storage containers (DCS).[2] At present no validated methods to verify the content without opening the storage containers exist. The investigation profiting of cosmic muons may constitute a very effective method to detect or exclude the presence of spent fuel bundles. In the particular case of DCS, the approach to explore their content can profit both of the absorption/transmission of muons crossing the container, and of the MCS. Information about the position and direction of the particles entering in the container can be obtained by placing cylindrical detectors around its lateral surface. The detectors measure also position and direction of the muons that exit crossing the lateral surface of the container as sketched in figure 3.

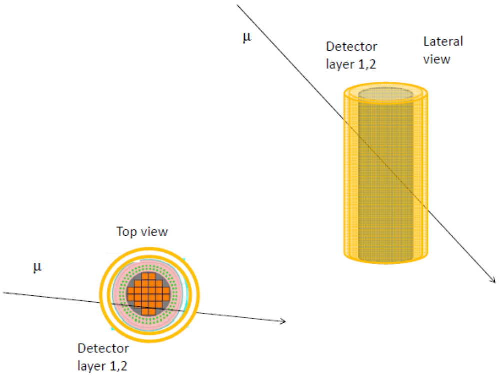

Figure 3. Muon Tomography Station sketch (not in scale). Top and lateral view.

Simulation results about the detection of a missing bar in a CASTOR®[3] container are shown in figure 4. On the left there is the reconstructed CASTOR® density average along vertical axis, obtained using absorbed muons information. The right image shows the same simulated data

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[2] There are several types of DCS, in general 5 m high cylinders of different diameters and different materials [60].

[3] http://www.gns.de/language=en/24429/castor.

analysed using muons passing through the container. The missing bar is clearly visible with both techniques.[4]

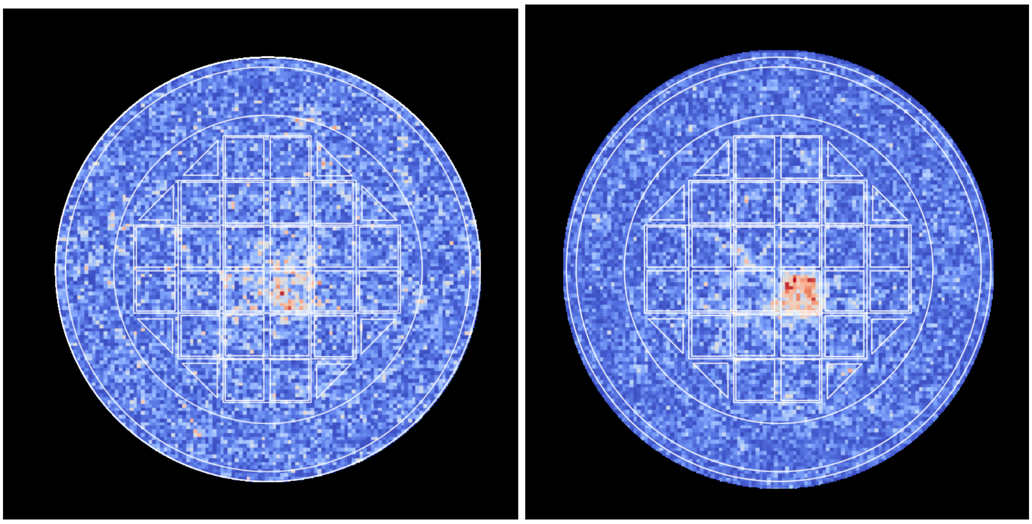

Figure 4. Top view of the reconstructed castor density, averaged along vertical axis, in a simulated castor container with one missing bar, obtained using absorbed muons information (left). The density obtained using muons passing through the container (right). Both panels correspond to one hour of data taking of cosmic muons.

4.4 LSD precision measurements

To make precision measurements with MCS tomography that is to determine LSD (or the ratio $R = \lambda/\rho$, where ρ is the mass density) of a material with a small uncertainty is not a trivial task. Among several difficulties to provide quantitative measurements it must be mentioned that the choice of the parameter $< 1/p^2 >$ in absence of momentum measurement implies a careful calibration. In addition, when crossing thick materials, the muon spectrum is modified by the absorption of low energy muons with the consequent appearance of non-linearity effects in the LSD evaluation [73].

Despite the difficulties, it has been demonstrated that MST can be used to measure the properties of various materials [74] extracted from an experimental blast furnace during activities related to the above mentioned Mu-Blast project [61]. The measurements produced at the Legnaro Laboratory include light materials (coke) and iron oxides with increasing degrees of reduction. By adopting experimental procedures for calibration, noise reduction, background subtraction and by controlling the MLEM algorithm convergence, an absolute precision of 10% on the measurements of R has been achieved. In figure 5 a good correspondence of measured R with the values calculated on the basis of the chemical composition of each material is shown. The precision expected by considering the sources of systematic uncertainties is between 7 and 10%, while the measures show a deviation of 3.1% with an r.m.s. of 4.8%.

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[4] This results have been obtained in collaboration with P. Checchia, A. Rigoni Garola, S. Vanini and G. Zumerle, from INFN and P. Peerani from JRC-ITU.

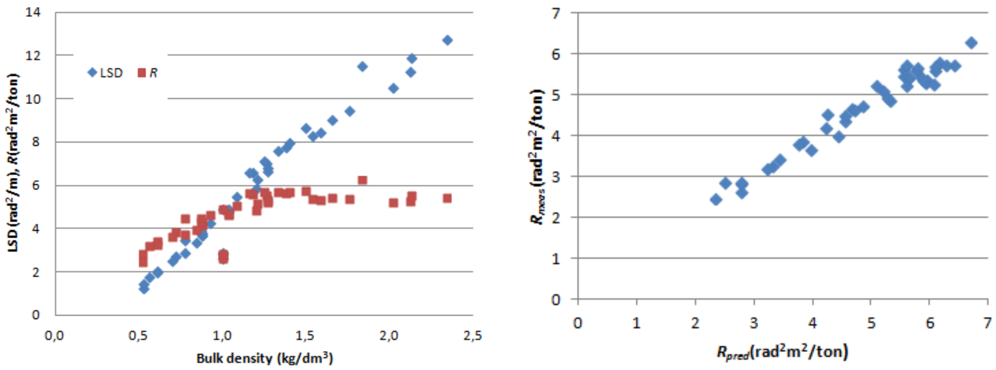

Figure 5. LSD and R as a function of the effective bulk density for several samples (left panel). R as a function of the predicted value, R_{pred}, for the same samples (right panel). This figure is taken from [74].

4.5 Monitoring of building stability

An interesting application of cosmic muons, although not involving tomographic or radiographic technologies, is related to stability monitoring in civil engineering. Tracking detectors sensitive to cosmic muons, may be devoted to the static monitoring of buildings, in particular of the ones, as historical buildings, with severe conservation constraints and deformation phenomena with long scale time evolution (months or years). A specific measurement system has been designed to monitor the wooden vault of “Palazzo della Loggia" in Brescia [75]: a target fiber scintillator detector with SiPM readout is fixed at the roof whose deformation should be monitored, and a muon telescope, based on the same technology, is located in the fixed part of the building as shown in figure 6. Cosmic muons traversing both detectors monitor continuously the displacement of the target detector relative to the muon telescope. From simulation, the expected precision in the described conditions should be of the order of a few millimeters with an observation time of a couple of weeks. The precision should be sufficient to follow seasonal deformation and, more so, to detect general deformation trends.

5 Final remarks

The use of cosmic muons for applicative purposes provides a large group of possibilities and the field is evolving so quickly with new ideas and new proposals to require a dedicated event to illustrate the status all items. Any related activity constitutes an important technological transfer from high energy physics and particle-detector sectors to the civil society. It has to be pointed out that there are several technological, computational and analysis challenges that should increase the interest of high energy physicists to participate. In this field, resources arrive mainly from funding subjects alternative with respect to “standard" research agencies: this requires an effort to prepare and submit appropriate proposals for projects, and to involve potential partners out of research/academic network with additional benefits for the dissemination of HEP competence.

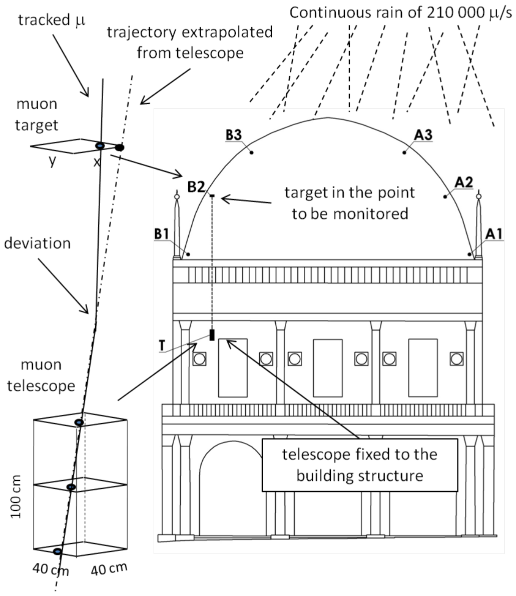

Figure 6. Schematic view of “Palazzo della Loggia" and of the detector system. The muon telescope is fixed to a structural element of the building while the muon target is located on the points to be monitored (courtesy of A. Zenoni).

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