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Progress in muon tomography

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In the last decades the interest and the research activities for applications of cosmic ray muons have grown considerably. Various groups around the world are considering these particles, that hit continuously our planet, to develop new techniques and systems. In the following the principles of muon radiography and tomography will be presented along with an overview of the present activities in this field.

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1. Introduction

The Earth is hit continuously by particles that come from the space. They are generically called *primary cosmic rays*. When they interact with the atmosphere, they undergo reactions with nuclei and produce showers that can contain a very high number of particles. These particles are generically called *secondary cosmic rays*. Most of them decay before reaching the ground, while others can survive enough to get to the Earth soil. Most of them are *muons*. In the following we will refer to these particles as *cosmic ray muons*. At the sea level about 10000 cosmic rays per minute and per square meter hit the ground. About 600 of them, in average, cross a human body every minute. The average energy is comprised between 3 and 4 GeV and the flux is maximum at the zenith (vertical) and it scales approximately with $\cos(\theta)^2$, θ being the angle with respect the vertical. For more details about cosmic rays in general see [1] and references therein. When they encounter the matter they are subject to interactions that end up in two main effects: 1) loss of energy (mainly by inelastic collisions, bremsstrahlung-radiation, production of electron-positron couples) and 2) deflection from the original trajectory (by multiple coulomb scattering) [2, 3]. In other words the muons, when crossing a given material, are deviated from a straight line path and slow down, some time to rest being consequently absorbed. The strength of these effects depends on the energy of the particle and on the thickness and the type of material that is being crossed. Given these characteristics and the fact that muons can cross large volumes, since decades they have been used to calibrate experimental apparatuses and detectors in particle and nuclear physics. Recently various groups around the world are considering its usage also for civil and commercial applications. The fact that this research field is attracting growing attention can be summarized by the distribution of the number of publications regarding *muon radiography* or *muon tomography*, in the last years, as shown in Fig. 1.

In the following, after an introduction with an historical overview, a comprehensive list of on-going activities will be presented. Conclusions and future perspectives will close this article.

2. Historical evolution

The first known application of the cosmic ray muons dates back to 1955 [4] when the thickness of rock above a underground tunnel was estimated measuring the flux of the surviving muons. A more spectacular application was performed in 1970 by nobel prize Alvarez when he tried to discover hidden rooms in the Chefren pyramid, finding none [5]. Using a similar technique various research group conducted inspections of volcanos [6, 7]. These first applications were based on the measurement of the attenuation of the cosmic rays flux. By counting the number of muons exiting the volume under inspection and assuming the composition of the crossed material, the total thickness of the material could be inferred. Clearly the number of surviving muons is related to the type and thickness of the interposed material. This technique has been reutilized and improved more recently to visualize magma dynamics in an erupting volcano [8]. Other interesting and more curious applications have also been proposed and realized such as imaging of large vessels [9], cosmic muon detection for geophysical applications [10] and observation of the moon shadow [11]. In 2002 an innovative idea was proposed by a Los Alamos research group [12]. Instead of using the absorption/transmission properties of the cosmic ray muons, the scattering angle of the

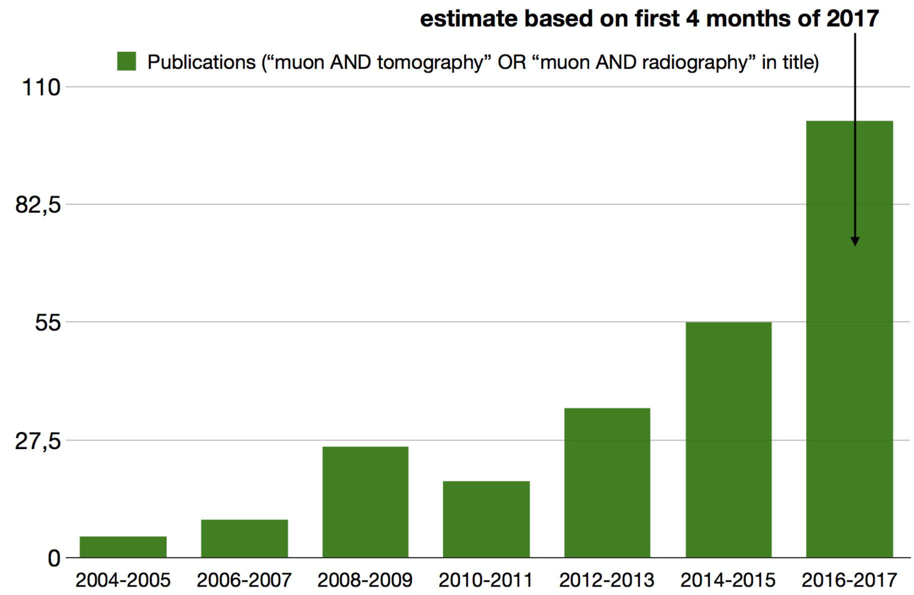

Figure 1: Number of publications regarding *muon radiography* or *muon tomography* in the last years.

surviving muons could be used to infer the properties of the crossed material. This novel technique opened up new scenarios and indeed more and more groups around the world investigated the possibility to apply such method for civil applications. A description of these new activities will be provided in the following.

3. Basics of the technology

As previously reported, given a region of space to be inspected, the overall muon incoming flux will be diminished when exiting the material and the angular distribution modified. Details of the volume crossed by the cosmic rays can be inferred by measuring both effects. The first applications in order of time, as reported above, were based on the "absorption/transmission" in a way very similar to common x-ray radiography. Indeed this technique is usually referred to as *muon radiography*. On the other hand the new method proposed by the Los Alamos group [12, 13] rely on the "scattering/deviation" effect to obtain a tomographic image of the volume under inspection. This technique is thus usually referred to as *muon tomography*. The basic idea is relatively simple. When crossing materials the cosmic ray muons undergo the well-known interaction called multiple coulomb scattering [14, 15]. Due to this interaction, the direction of any charged particle travelling in matter is modified. The angular difference between the particle direction entering and exiting a given material depends on the thickness as well as on the nature and on the density of the material. Thus the measurement of the angular deflection of a sample of cosmic muons allows, by means of a complex data analysis and image reconstruction software, to determine the distribution of the density inside the sample. In other words this technique can discriminate different materials inside the volume under inspection.

It is worthwhile noticing that to perform a muon radiography a single detector, or more precisely a single set of detectors, placed at one side of the object to be inspected, is sufficient, while for muon tomography two sets of detectors are needed, placed at two opposite sides of the volume under inspection.

3.1 Details of muon tomography

As previously reported, muon tomography is based on multiple coulomb scattering of cosmic ray muons crossing the volume to be inspected. When a charged particle crosses a material, its trajectory is deflected from the direction of incidence. The distribution of the scattering angle ($\delta\theta$) projected on a plane containing the incident particle trajectory is approximately Gaussian with zero mean value and variance related to the properties of the homogeneous crossed volume by the following approximate formula [14, 15]:

$$\sigma^2 \approx \frac{(13.6\ \mathrm{MeV/c})^2}{\beta^2\ \mathrm{p}^2} \frac{\mathrm{L}}{X_0} \tag{3.1}$$

where L is the thickness of the crossed material, X_0 is its radiation length, p is the particle momentum and β its velocity. Measuring the deflection of many particles, it is therefore possible to infer the quantity

$$\lambda = \frac{1}{\mathrm{X}_0} = \rho \cdot Z \left[\frac{(Z+1)\log 287/\sqrt{Z}}{A \cdot 716.4\ \mathrm{g/cm}^2} \right] \tag{3.2}$$

which can be referred to as *scattering density*. As can be seen from (3.2), this quantity is strongly related to the mass density and atomic number of the crossed material. The projections of the scattering angle on two orthogonal planes are statistically independent.

An additional measured quantity is the displacement (δx), defined as the difference of the impact point of the muon on the exit detector and the impact point expected in the absence of any scattering. For a given scattering angle, the displacement is proportional to the distance of the scattering object from the exit detector, therefore it gives information on the vertical position of the object. The use of the displacement improves the space resolution of the tomographic image.

To perform a muon tomography of a large volume, two muon detectors need to be placed at two opposite sides, for example as sketched in Fig. 2. The full volume can be divided in elements, namely *voxels*, small enough to allow considering the material distribution homogeneous. The unknown quantity that has to be calculated is thus the scattering density λ_i of each voxel i.

When a muon crosses the volume, the muon in Fig. 2 for instance, the incoming and outgoing trajectories are measured. The true path is approximated with the broken line from entry point to the exit point through the Point of Closest Approach (PoCA).

Within this approximation, the voxels traversed by the muon can be identified. The total scattering angle of the muon will be determined by the scattering density of all the voxels crossed by that muon. By the measurement of many muons crossing the inspected volume in different positions and at different angles, the scattering density of each individual voxel can be disentangled, as long as the individual voxel has been crossed by a sufficient number of muons.

More formally, the total variance of the scattering of the i-th muon through N voxels can be written as a function of the voxel scattering density and path length L_{ij} of the i-th muon inside the

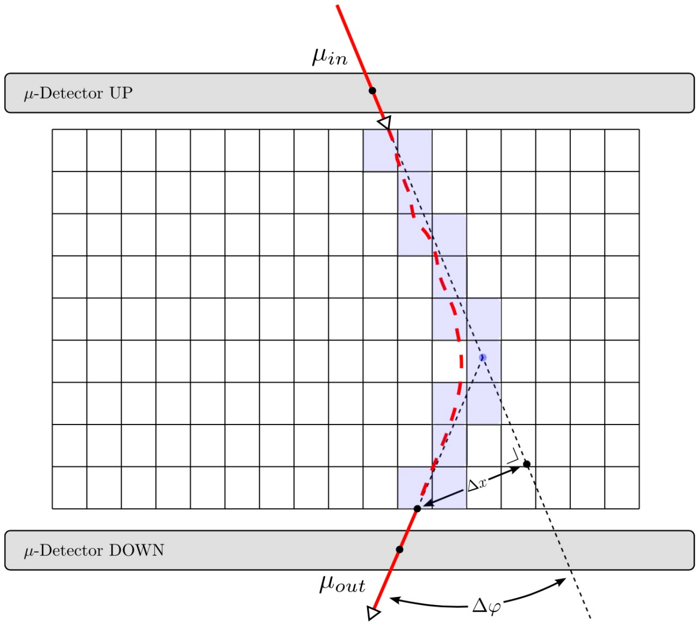

Figure 2: Hypothetic path of a muon inside the inspected volume. Muon is supposed to cross grey voxels.

j-th voxel:

$$\sigma_i^2 = \frac{(13.6\,\mathrm{MeV/c})^2}{\mathrm{p}^2} \sum_{j=1}^{\mathrm{N}} \mathrm{L_{ij}} \lambda_j \tag{3.3}$$

Since the measurement of the muon momentum, in general, is impossible or very difficult, and the muon momentum spectrum is very broad, the previous equation is averaged over the muon momentum spectrum and the p value is substituted by an "effective" momentum value $\mathrm{p_{eff}}$. This approximation leads to a degree of noise of the reconstructed image.

To build a useful 3D map, the contribution of the largest possible set of muons must be collected, covering different positions and trajectory angles in the reconstructed volume. From (3.3) with the fixed $\mathrm{p_{eff}}$ value of the momentum, one can write the likelihood of the occurrence of the scattering angles measured in the sample of M muons as a function of the scattering density profile in the N voxels ($\underline{\lambda} = \lambda_1, \lambda_2, ..., \lambda_{\mathrm{N}}$):

$$\mathrm{P}(\underline{\lambda}) = \prod_{i=1}^{\mathrm{M}} \frac{1}{\sigma_i(\underline{\lambda})\sqrt{2\pi}} \exp\left(-\frac{\delta\theta_i^2}{2\sigma_i^2(\underline{\lambda})}\right). \tag{3.4}$$

Thus is possible to build the density profile $\underline{\lambda}$ in the volume by minimizing the logarithmic likelihood:

$$\ln \mathrm{P}(\underline{\lambda}) = \sum_{i=1}^{\mathrm{M}} \left[\frac{\delta\theta_i^2}{2\sigma_i^2(\underline{\lambda})} + \ln\left(\sigma_i(\underline{\lambda})\right)\right] \tag{3.5}$$

in the set of N variables $\underline{\lambda}$. This is achieved through an iterative Expectation-Maximization algorithm. This technique, proposed originally by [13, 16], is the base of most of the applications described in the next section. Noise reduction methods have also been proposed to improve the overall procedure [17].

4. Present research activities

What follows is an extended list of present research activities in muon radiography and tomography. It doesn't pretend to be exhaustive, but it may be useful to understand the variety of ideas and the numerousness of the research groups involved in this field. The applications have been divided into different areas of research, namely nuclear safety and security, industry and other civil applications.

4.1 Nuclear safety and security

The Los Alamos group that originally proposed the technique continued the study related to muon tomography and proposed to apply it to inspect containers at ports and borders to detect special nuclear materials (SNM). For this particular goal, a commercial spin-off took shape, that finally, also with the help of a fund of the U.S.A. Department of Homeland Security, built a complete muon tomography system. The Decision Sciences (this is the name of the company) [18] portal has been completed in 2015 and it is now operated in Bahamas. The cosmic ray muons are tracked with detectors based on drift tubes. The system is able to detect high-Z materials in a short time, thus allowing the discovery of SNM, or of shielding for other radioactive materials, without introducing delays in day-by-day operations in ports and borders.

Another similar project is the *Muon portal collaboration* (see [19] and references therein) that planned to build a large area muon detector for a noninvasive inspection of shipping containers in the ports, searching for the presence of potential fissile (U, Pu) threats. The detector is based on scintillating-fibers. To our knowledge the portal was constructed and operated in test mode.

In Canada a similar system, called *CRIPT* - Cosmic Ray Imaging and Passive Tomography [20], is under construction. The project has been proposed to inspect cargo in shipping containers and to determine the presence of special nuclear materials.

Another commercial company [21], with base in Israel, is also proposing a solution based on muon tomography for detection of SNM.

More activities, dealing with safeguards more than safety and security, are undergoing in various countries. For example the Los Alamos group recently proposed to inspect the damaged cores of the Fukushima reactors [22]. Big detectors (7 x 7 m^2) based on drift tubes have been constructed and are waiting to be placed around the reactor. In the meanwhile a muon radiography has commissioned by Tepco and had been realized by another Japanese research group. The results were summarized in the following figures (see Fig. 3).

At the University of Glasgow, with the *Muon Tomography Project* [23], a prototype of a system able to monitor nuclear waste containers has been constructed. This effort also generated the birth of a commercial spin-off [24]. Their detectors are based on scintillating-fibers. The University of Bristol on the other hand is trying to use a different type of detectors, the resistive plate chambers (RPC) to develop a system for the muon tomography [25].

4.2 Industry

One of the mayor concerns of the metal recycling industry is the accidental melting of radioactive sources [26]. Even though the reported events are rare (few events per year), the consequences

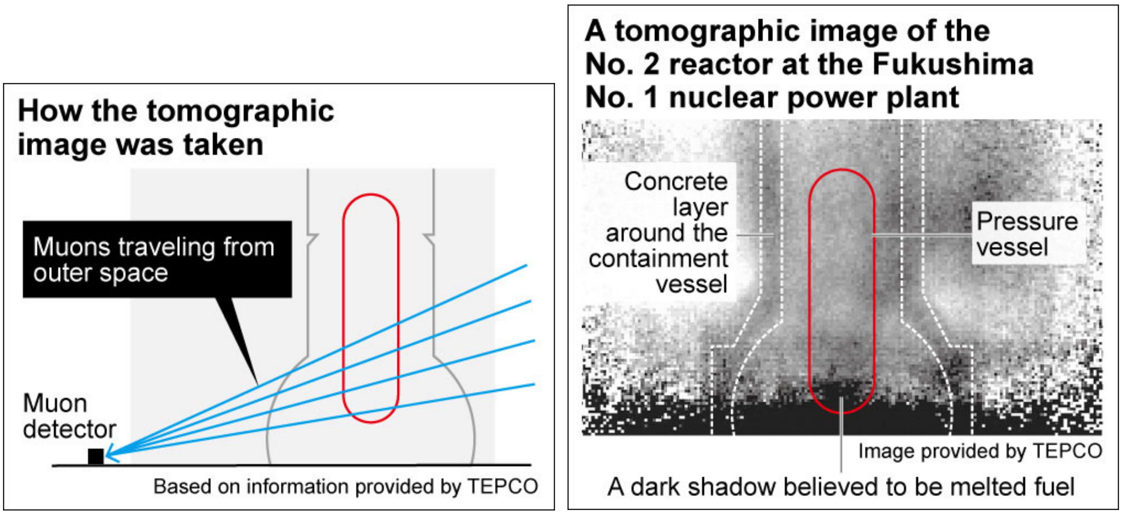

Figure 3: Images provided by Tepco, summarizing the results of the muon radiography of the Fukushima Reactor 2.

can be extremely serious, with a huge environmental and economical impact on the workers, on the surroundings and on the industry. Indeed the melting can cause the radioactive contamination of workers, buildings, neighborhood, production lines and materials. For these reasons a European Commission project (Mu-Steel) was financed in 2010-2012 by the Research Fund for Coal and Steel [27]. The goal of the Mu-Steel project was to study the feasibility of building a portal based on muon tomography to monitor truck containers filled with scrap metals entering steel mill foundries to detect shielded radioactive sources. It is important here to underline that by means of the muon tomography, the portal is able to detect the shield of the source and not the source itself. For this reason, such a system would be used only in association with a traditional radiation portal. The project studies, that took advantage of a large scale muon tomography demonstrator that was build at the Laboratori Nazionali di Legnaro of the INFN [28], proved that a 5 liters source shield (17x17x17 cm^3) could be detected in about 5 minutes.

Based on this experience, another European Project was also funded by the Research Fund for Coal and Steel in 2014-2016 [29] for a feasibility study to assess the use of muon tomography to inspect blast furnaces (BF). These are huge structures, as high as 30 meters and there are no other ways to "see through" them when they are functioning. The study proved that despite the low number of almost horizontal muons and the movement of the burden, muon tomography imaging of the interior of a BF is possible. The detectors should be designed carefully for example to be able to give a rough estimate of the momentum.

Within the framework of this project, core-drilled samples coming from a research blast furnace were also placed in the LNL muon tomography demonstrator [28]. The conventional and the muon tomography measurements agreed very well, within errors. This proved that the scattering density of a material of small samples can be measured with a precision of about 10%. Clearly it is not competitive with chemical measurement, but it is surely interesting when the sample is not directly accessible.

A start-up company based in Bilbao is also investigating the possibilities of muon technologies for applications in big industrial installations [30].

Another very interesting application of cosmic ray muons is the one in geological surveys. A spin-off company [31] of the Triumf Canadian National Laboratory has developed and commercialized a system able to scan the rocks above underground tunnels reconstructing 3D images and detecting dense bodies, such as polymetallic or high grade uranium. Clearly they rely on muon radiography, that is on absorption/transmission effects. On the other hand this gives the possibility to perform measurements also at very high depth, such as 600 m underground. Similarly, also in the United Kingdom, at the Boulby Underground Laboratory, studies are underway to explore the use of muon tomography for deep 3D geological surveying applications [32].

4.3 Civil applications

In 2007 a different approach, with respect to muon tomography, was proposed [33] for measurement applications in civil and industrial engineering, for the monitoring of alignment and stability of large civil and mechanical structures. Based on that work, more recently a new application for the stability monitoring of historical buildings has been proposed and investigated [34, 35, 36]. The main component of the suggested monitoring system is a *muon-telescope*. It is composed by a set of three muon detector modules supported by an appropriate mechanical structure and axially aligned at a distance of 50 cm one from the other. The muon-telescope is mechanically fixed to a structural element of the building, that constitutes the reference system, with its axis aligned in the direction corresponding to the part of the structure whose displacements should be monitored. A fourth muon detector module, with the same geometry and structure of the previous ones, is positioned as *muon-target* on the point to be monitored. Thanks to their high penetrability, cosmic ray muons are able to cross the system of four detectors as well as the interposed building structures. In this way it is possible to continuously monitor the horizontal displacements of the muon-target relative to the muon-telescope fixed on the masonry structure of the building.

Another interesting application was recently proposed by a French research group. Investigating the possibilities of monitoring temporal opacity fluctuations of large structures with muon radiography [37], they tested their system to monitor the level of liquid in a water tank.

5. Final considerations and conclusions

Muon radiography and tomography have raised more and more interest in the last years. Various research groups and some private companies, mostly spin-off of Universities or Laboratories, are investigating the possibility to develop new applications in the fields of safeguards, nuclear security and safety, industry and every day life. Some of them are actually commercially available. The advantages of this technology is that it relies on a natural and continuous radiation source, namely cosmic ray muons. No artificial sources are needed and thus no radiological risk is present. Moreover, since the muons have the capability to cross high thicknesses of materials, in many cases there are no other technologies that can do the job. Muon radiography and muon tomography are also based on very common and standard techniques and methods developed in nuclear and particle physics since decades. This means that, at least for what concerns the detectors, it doesn't need big developments. The first applications indeed date back to more than 40 years ago.

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Concerning the limitations, since the muon flux is fixed by nature, there are no ways to speed-up the data taking. The precision, or resolution, of the measurement indeed depends heavily on the available statistics and this is clearly connected with the number of muons that cross the object under investigation. This is an intrinsic limit of the technology: it is not suitable where measurements need to be done in seconds. Also, for the same reason, it can be applied only to static or quasi static situations. On the other hand, if the waiting time can be of the order of minutes, various studies proved that with a suitable detector and reconstruction technique, system based on muon radiography or tomography can be efficiently used.

It is interesting to note that, as in many other fields of science, the progress in basic research can generate, with some delay in time, applications that will have an impact on everyday life. It is not yet the case for muon radiography or tomography, but the field is evolving rapidly and there are many possibilities for new applications. The following years will be very important to see if this interesting technology based on cosmic ray muons will produce results and applications that can have an impact on our society.

References

[1] J. Beringer *et al.* (Particle Data Group), Phys. Rev. D86, 010001 (2012).

[2] W. R. Leo, "Techniques for nuclear and particle physics experiments" (Springer-Verlag, Berlin 1987).

[3] G.F. Knoll, Radiation detection and measurements (Wiley, New York 1989).

[4] E.P. George, Commonwealth Engineer, July 1, 1955, p. 455.

[5] L.W. Alvarez *et al.*, Science 167 (1970) 832.

[6] K. Nagamine *et al.*, Nucl. Instr. and Meth. A 356 (1995) 585.

[7] H. Tanaka *et al.*, Nucl. Instr. and Meth. A 507 (2003) 657.

[8] H. Tanaka *et al.*, Nature Communications 5 (2014), doi:10.1038/ncomms4381.

[9] P. M. Jenneson *et al.*, Chemical Engineering Journal 130 (2007) 75.

[10] L. Oláh *et al.*, Advances in High Energy Physics (2013) 560192 (doi 10.1155/2013/560192).

[11] Yu. M. Andreyev *et al.*, Cosmic Research 40 (2002) 604 - A. V. Karelin *et al.*, Cosmic Research 53 (2015) 128.

[12] K.R. Borozdin *et al.*, Nature 422 (2003) 277.

[13] L. J. Schultz *et al.*, Nucl. Instrum. Meth. A, 519 (2004) 687.

[14] G.Z. Moliere, Z. Naturforsch. 2a (1947) 133; G.Z. Moliere, Z. Naturforsch. 3a (1948) 78.

[15] H.A. Bethe, Phys. Rev. 89 (1953) 1256.

[16] L. J. Schultz *et al.*, IEEE Transaction Image Process., 16 (2007) 1985.

[17] M. Benettoni et al., 2013 JINST 8 P12007.

[18] http://www.decisionsciences.com.

[19] P. La Rocca *et al.* JINST 9 (2014), C01056.

[20] J. Armitage et al., Int. Jou. Mod. Phys. Conf. Ser., 27 (2014) 1460129.

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[21] http://www.lingacom.com.

[22] K. R. Borozdin *et al.*, Physical Review Letters, 109 (2012) 152501.

[23] R. Kaiser *et al.*, EPJ Web of Conferences 66 (2014) 10005, doi:10.1051/epjconf/20146610005.

[24] https://www.lynkeos.co.uk.

[25] P. Baesso *et al.* JINST 9 (2014) C10041, doi:10.1088/1748-0221/9/10/C10041.

[26] D. S. Harvey, K. Baldry and A. Bishop, La Revue de Métallurgie-CIT, 285 (April 2004).

[27] G. Bonomi *et al.*, Int. Jou. Mod. Phys. Conf. Ser., 27 (2014) 1460157 [European Commission Mu-Steel project (RFCS - CT-2010-000033)].

[28] S. Pesente et al., Nuclear Instruments and Methods in Physics Research A 604 (2009) 738.

[29] European Commission Mu-Blast project (RFCS-630643) [2014-2016].

[30] http://muon.systems.

[31] http://www.crmgtm.com.

[32] http://www.stfc.ac.uk/Boulby.

[33] I. Bodini, G. Bonomi, D. Cambiaghi, A. Magalini and A. Zenoni, Meas. Sci. Technol. 18 (2007) 3537.

[34] A. Donzella, Il nuovo cimento, Vol. 37 C (2014) 223.

[35] G. Bonomi et al., Proceedings of the 28th European Conference on Modelling and Simulation, ISBN: 978-0-9564944-8-1.

[36] A. Zenoni, Proceedings of the 4th Conference on Advancements in Nuclear Instrumentation Measurement Methods and their Applications (ANIMMA) 2015, DOI: 10.1109/ANIMMA.2015.7465542.

[37] K. Jourde et al., Scientific Reports, Nature Publishing Group, 2016, 6, pp.23054 (DOI: 10.1038/srep23054.