Application of Muon Radiography to Blast Furnaces: the BLEMAB project

A. Lorenzon, P. Andreetto, P. Checchia, I. Calliari, L. Pezzato, F. Ambrosino, L. Cimmino M. D'Errico G. Saracino V. Masone, L. Bonechi, S. Bottai, C. Cialdai, R. Ciaranfi, O. Starodubtsev, L. Viliani V. Ciulli, R. D'Alessandro, S. Gonzi, G. Bonomi, D. Borselli, T. Buhles, F. Finke, A. Franzen, J. Sauerwald, U. Chiarotti, V. Moroli, F. Volzone, B. Glaser, B. V. Rangavittal, O. Nechyporuk, D. Ressegotti

Muon radiography is a non-invasive imaging technique that exploits cosmic ray muons to explore the content of large, dense and otherwise inaccessible volumes. The European project BLEMAB (BLast furnace stack density Estimation through on-line Muon ABsorption measurements) represents an exemplary application of this technique in the industrial field: the aim of the project is indeed to investigate the capability of muon radiography to scan the inner part of active iron-making blast furnaces. In particular, the focus of the study is the characterization of the so-called "cohesive zone", which could be of great interest for steel-making companies. The project foresees the construction of a dedicated muon imaging detector, that will be installed at the blast furnaces in the ArcelorMittal site in Bremen (Germany). This paper describes the status of the project, including the development of software simulations and the manufacturing of the detector.

KEYWORDS: BLAST FURNACE, IMAGING, MUON RADIOGRAPHY;

INTRODUCTION: MUON RADIOGRAPHY

Muon radiography is an innovative and non-destructive imaging technique that relies on the detection of cosmic-ray muons passing through the volume to be inspected. Muons are charged elementary particles that are naturally produced in the interactions of primary cosmic rays coming from the outer space (mainly protons) with the Earth atmosphere. After the collisions of the primary particles with the nuclei in the atmosphere, a lot of secondary particles are created in cascade (air shower) and propagates down towards the Earth's surface: the majority of these secondaries can't reach the ground, except for muons, which enjoy a relatively long lifetime and a high penetration power. With a flux rate of ~170 Hz/m^2, they are the most numerous charged particles at sea level [1]: the natural abundance and the continuous availability of muons are two key aspects that favored the development of imaging techniques exploiting these particles, such as muon radiography. Similarly to X-ray radiography, this technique allows to reconstruct the internal structure of the targeted object, but thanks to the higher penetration power of muons with respect to X-rays, muon radiography can be applied to more large, massive and dense bodies. The method is based on the measurement of the attenuation of the cosmic ray muon flux [2]: in fact, depending on the thickness and the composition of the volume under

A. Lorenzon, P. Andreetto, P. Checchia, I. Calliari, L. Pezzato
University of Padua, Padua, Italy

F. Ambrosino, L. Cimmino M. D'Errico G. Saracino V. Masone
University of Naples "Federico II", Naples, Italy

L. Bonechi, S. Bottai, C. Cialdai, R. Ciaranfi, O. Starodubtsev, L. Viliani V. Ciulli, R. D'Alessandro, S. Gonzi
University of Florence, Florence, Italy

G. Bonomi
University of Brescia, Brescia, Italy - INFN, Pavia Division, Pavia, Italy

D. Borselli
University of Perugia, Perugia, Italy

T. Buhles, F. Finke, A. Franzen, J. Sauerwald
ArcelorMittal Bremen GmbH, Bremen, Germany
University of Padua, Padua, Italy

U. Chiarotti, V. Moroli, F. Volzone
RINA Consulting, Centro Sviluppo Materiali SpA, Rome, Italy

B. Glaser, B. V. Rangavittal
KTH Royal Institute of Technology, Stockholm, Sweden

O. Nechyporuk
ArcelorMittal Maizières Research SA, Maizières-lès-Metz, France

D. Ressegotti
RINA Consulting, Centro Sviluppo Materiali SpA, Dalmine (BG), Italy

inspection, a certain number of muons will be absorbed. A dedicated muon detector can be placed downstream of the target volume to get a measurement of the muon flux: by comparison with the measurement of the muon flux in the same direction but in the absence of the target (free-sky) and with numerical simulations, a 2-dimensional map of the density distribution of the target can be obtained. By repeating the measurements from different angles (or equivalently by using more muon detectors at once), a 3-dimensional reconstruction can also be performed.
Since its first application in 1955 by E.P. George, who gave a measurement of the thickness of rock overlying an underground powerhouse in Australia's Snowy Mountains Scheme by exploiting cosmic-ray muons [3], this technique has been used in a growing number of fields. A striking example dates back to 1970, when the Nobel prize winner L. W. Alvarez and his team placed a muon detector inside Chepren's pyramid to probe its inner structure in search of secret hidden chambers [4], opening the path for muon radiography application to archaeological surveys, such as [5][6]. One of the most widespread applications of muon radiography is the imaging of volcanoes for hazard prevention: several volcanoes around the world have been monitored through cosmic-ray muons, e.g. [7][8]. Besides volcanology there are many others geological applications that have been explored by cosmic-ray muons: mineral explorations [9] and research of natural caves [10], just to cite a few. This technique has been proposed also in other fields, such as nuclear controls, to inspect the content of nuclear waste containers [11], and civil engineering, where the detection of hidden underground cavities can be interesting for infrastructure stability [12]. A complete review of muon radiography applications can be found at reference [2].

THE BLEMAB PROJECT

The main goal of the BLEMAB European project (BLast furnace stack density Estimation through on-line Muon ABsorption measurements) is to test the imaging capability of the muon radiography technique on the inner volume of active blast furnaces. A blast furnace is a vertical shaft furnace used in metallurgical industries to produce liquid metals (generally pig iron but also lead and copper), for subsequent processing and industrial utilization. In an ironmaking blast furnace, iron-bearing materials (iron ore pellets) and a reducing agent (coke) are charged in layers at the top of the furnace, while a hot blast of air under pressure is introduced at the bottom. As the burden descends through the shaft and heats up, chemical reactions take place with the ascending combustion gases, to produce molten iron and slag.

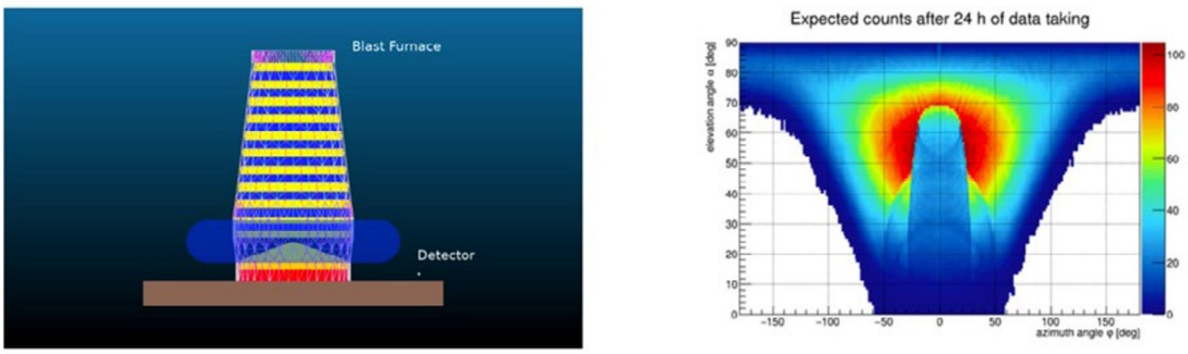


Fig.1 - (Left) Geometry of the furnace implemented in the fast simulation tool; the elements constituting the blast furnace geometry are indicated with different colors. (Right) Expected angular distribution of muon events after 24h of data-taking. Picture from [22]. / (Sinistra) Geometria dell'altoforno implementata nel simulatore fast; i diversi colori indicano i vari elementi che costituiscono la geometria dell'altoforno. (Destra) Distribuzione angolare dei muoni prevista in 24h di presa dati. Immagine da [22].

A crucial region inside the blast furnace is the cohesive zone, usually located in the central part of the shaft, where temperatures are such that the iron-bearing material begins to soften until it melts completely. From dissection of quenched blast furnaces it was clear that there is an important relationship between the shape and the location of the cohesive zone and the operation conditions of the blast furnace [13], such as the distribution of the charging materials, the descent behavior of the burden and the conditions in the combustion zone: without a proper shape, the

cohesive zone would block the gas flow through the coke layers, giving rise to erratic burden descent [14]. It is a common practice in many blast furnaces to adjust the shape of the cohesive zone based on the distribution of materials at the charging, relying on indirect estimations and experience. Therefore, the development of a method to get an accurate measurement of the position and shape of the cohesive zone has become an important issue, and would be of great interest for steel-making companies as it could lead to a stable and efficient operation of blast furnaces.
Currently the investigations on the cohesive zone are carried out using a combined approach based on mathematical models and direct measurements of the internal state of the furnace. In the past, several techniques of direct measurements have been developed, including (i) the tracking of radioisotopes injected into the blast furnace [13], (ii) vertical probes with conducting cables [13], (iii) multi point vertical probes (MPVP) [15], (iv) core drilling and furnace dissection [16]. In this context, muon radiography could provide a direct and accurate measurement of the cohesive zone, but with some advantages with the respects to the investigation methods mentioned above: in particular it is a non-invasive technique, it exploits a natural and freely-available source of radiation (the muons) and it is not dangerous for operators. For these reasons, in the past there have been some proposals to investigate the interior of blast furnaces with muon imaging techniques [17] [18]. In particular, the European project Mu-Blast [19] has demonstrated the feasibility to study the inner part of blast furnaces with muon-based imaging techniques. Building on the achievements of the Mu-Blast studies, the BLEMAB project proposes to use the muon radiography technique to obtain a precise and direct information on the blast furnace inner state during its operation including the measurement of the position and the shape of the cohesive zone: for this purpose a dedicated muon detector will be constructed and installed at the blast furnaces in the ArcelorMittal site in Bremen (Germany); the collected data will be elaborated through a dedicated reconstruction software and compared with the results of simulations. The software simulations and the experimental apparatus developed for the BLEMAB project will be described in the following sections. The measurements obtained with the muon radiography technique will be compared for validation with the measurements of a new enhanced Multi Point Vertical Probe (eMPVP) and with mathematical blast furnace models. The eMPVP is developed by ArcelorMittal Maizières Research (AMMR) starting from the technology currently in use at ArcelorMittal sites and it will be able to measure the gas temperature along the whole furnace height; the mathematical modeling of the blast furnace is carried out with two different approaches by RINA Consulting - Centro Sviluppo Materiali (CSM) and the Royal Institute of Technology (KTH).

SOFTWARE SIMULATIONS

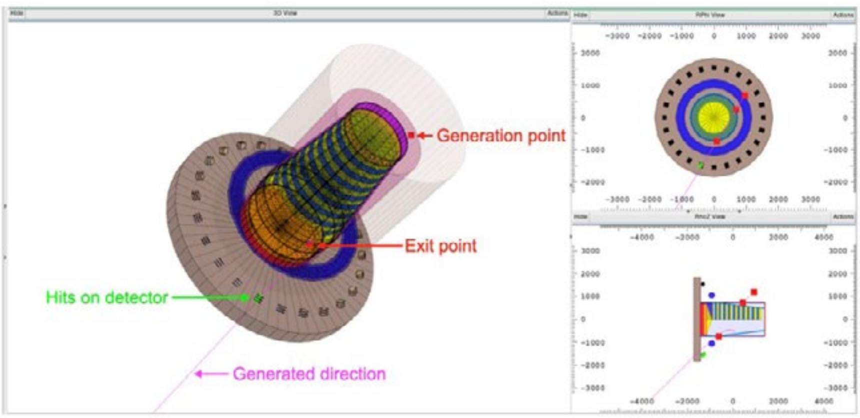


Fig.2 - Display of one event generated with the full MC simulation tool. The elements constituting the blast furnace are indicated with different colors; it is also possible to observe the generated muon trajectory and the detector's geometry, which is reproduced in 24 copies around the blast furnace in order to maximize the number of simulated events available for the reconstruction of the density map. / Display di un evento generato con il simulatore completo. Gli elementi che costituiscono la geometria dell'altoforno sono visibili in diversi colori; è possibile osservare anche la traiettoria del muone generato e la geometria del rivelatore, che è riprodotto in 24 copie intorno alla fornace per massimizzare il numero di eventi simulati che è possibile utilizzare per la ricostruzione della mappa di densità.

In the BLEMAB project software simulations are implemented for two main reasons: firstly, to get a preliminary estimate of the muon rate, so that the characteristics of the experimental apparatus can be defined, and secondly, to perform a comparison with the experimental data and obtain the density distribution of the material inside the blast furnace. To address these issues, two different implementations has been developed: a fast simulation tool and a full Monte Carlo (MC) simulation tool.

The fast simulation tool is used for the evaluation of the feasibility of the experiment; it has been developed starting from a software already available and successfully used in other muon radiography applications [20]. This simulation contains the geometry of the blast furnace and a realistic muon generator, that was developed on the basis of the measurements conducted with the ADAMO magnetic spectrometer in Florence [21], so that the simulated muons reproduce the same energy and angular distribution of the observed ones. In this tool, the interactions of muons with the matter are not simulated, and the detector is simplified to a point-like object. Fig. 1 shows the CAD model of the furnace used for fast simulations and the expected muon counts after 24h of data-taking.

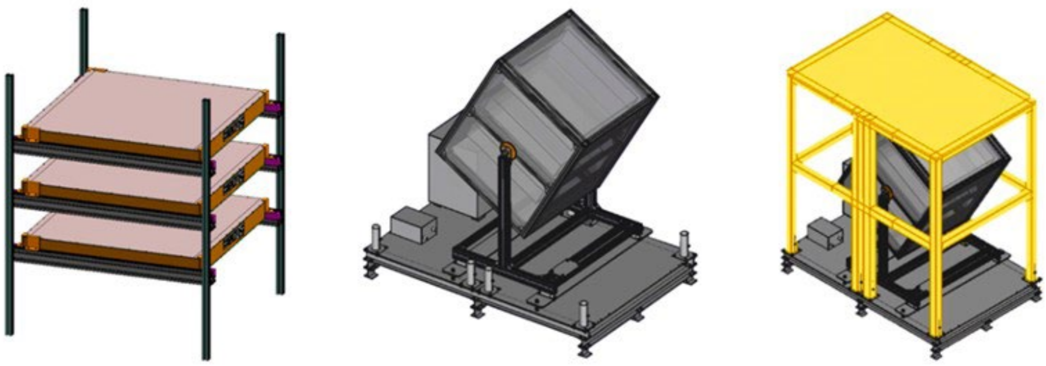


Fig.3 - (Left) Design of the BLEMAB detector: the muon tracker is made of three modules, each of them giving the (x,y) coordinates of the muon trajectory. (Center) The detector will be enclosed in an aluminum box and mounted on a rotating platform that allows to setup its inclination. (Right) The metal frame housing the detector and the cooling system is shown only partially in yellow. / (Sinistra) Design del rivelatore BLEMAB: il tracciatore è costituito da tre moduli, ognuno dei quali fornisce le coordinate (x,y) della traiettoria del muone. (Centro) Il rivelatore sarà racchiuso in un involucro di alluminio e montato su una struttura che consentirà di impostarne l'inclinazione. (Destra) In giallo è indicata la struttura metallica, qui visibile solo parzialmente, che racchiuderà il rivelatore e il sistema di raffreddamento.

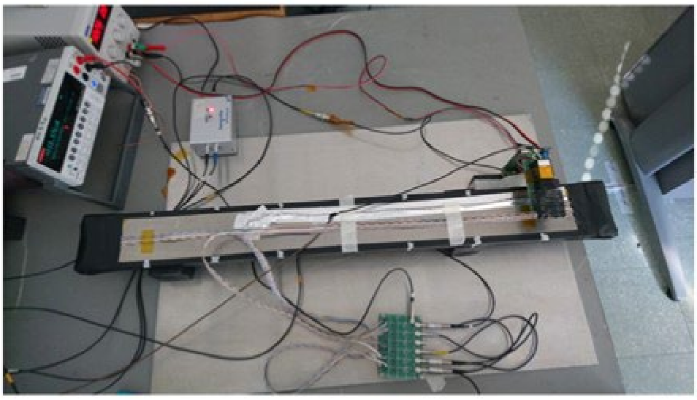
The full MC simulation tool is developed inside the Virtual Monte Carlo (VMC) [23] framework, that includes the Geant4 package [24] and the ROOT package [25]. Geant4 is a toolkit widely used in particle physics to simulate the passage of particles through matter and their interactions: it offers a large range of functionalities, such as tracking particles, handling complex geometry, replicating the functioning of a detector, and it can be easily adapted in different applications. ROOT is a framework for data processing originally developed at CERN, that includes all the packages required to handle and analyze data. The BLEMAB full MC simulation contains (i) a realistic representation of a blast furnace, with all its elements and their relative material composition; (ii) a realistic representation of the detector that will be used for data-taking; (iii) a realistic muon generator, based on the EcoMug package algorithms [26].

The datasets generated with the full MC simulation tool will be used for comparison with the measurements obtained from experimental data. Fig. 2 represents an event display of one event generated with the full MC simulation tool: the muon is generated on a cylindrical surface surrounding the blast furnace (a method that has been shown to be CPU-time efficient for the production of high statistic MC samples), it travels inside the volume of the furnace and exits on the other side, where it is detected by the BLEMAB tracking system.

EXPERIMENTAL APPARATUS

In order to perform a muon radiography, a muon tracking system, i.e. a device that collects a signal of the passage of the muon and allows to reconstruct its trajectory, must be installed downstream of the object to be studied. For the BLEMAB application, two independent muon trackers will be constructed: they could both be installed at the same blast furnace, in order to get a measurement of the object from two points of view and perform a 3D reconstruction; otherwise they could be placed at two different furnaces at the same time, so that a comparative analysis of the two plants could be carried out.

The muon trackers will be developed with the same technology already used for the MURAVES [27] and the MIMA [28] projects: each of them will be made of three 80 x 80 cm^2 tracking modules equally spaced. Each module will be composed by a double layer of 64 scintillator bars, a material that emits light at the passage of ionizing particles such as muons, the two layers being orthogonally oriented to give the measurement of the muon hit on a xy plane. The scintillator bars are 80 cm long and have a triangular cross-section with a 2.5 cm base and a 1.25 cm height. The light emitted by the scintillator bars will be collected by Silicon Photomultipliers (SiPM) and transformed into electrical signals. Each tracking module will be read out by four custom data acquisition (DAQ) slave boards, housing a 32-channel Extended Analogue SiPM Integrated Read-Out Chip (EASIROC 1B [29]) and an application specific integrated circuit (ASIC) to control the transmission of data to a central custom DAQ master board, where the trigger logic and the data collection are implemented. A Raspberry PI [30] computer will be connected to the DAQ master to control the electronic chain and to write data on a physical support. The network connection provided at the ArcelorMittal site will allow online control of the detector and data synchronization on a remote network.



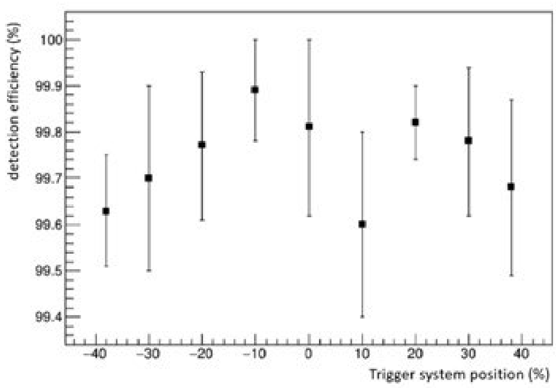


Fig.4 - (Left) Experimental setup for the preliminary test conducted with the prototype detector. (Right) The picture shows the detection efficiency as a function of the position along the bars where the efficiency is measured; the measured values are all greater than 99.6%. Picture from [22] / (Sinistra) Apparato sperimentale del test preliminare compiuto con il prototipo di rivelatore. (Destra) Il grafico mostra l'efficienza del rivelatore in funzione della posizione lungo le barre in cui è stata misurata; i valori misurati sono tutti superiori al 99.6%. Immagine da [22].

In order to cope with the harsh conditions in the proximity of a blast furnace, each muon tracker will be enclosed in an aluminum box and mounted on a platform that allows to set its altazimuth orientation. The whole system will then be hosted inside a large metal frame, completely covered by metal panels, that provides protection from liquid drops and corrosive vapors; finally a cooling system powered by a water chiller will be positioned inside the frame and put in contact with the detector's box, in order to protect the optical sensors from the high temperatures outside the blast furnace. Fig. 3 shows the design of the BLEMAB muon tracker.

Currently, a prototype of a tracking plane consisting of five scintillator bars has been produced and tested; in particular, the detection efficiency has been measured in different positions along the 80 cm length of the bars: approximately 1000 muons were collected in each position and all the measured values of the detection efficiency are greater than 99.6% [31], as can be seen also from Fig. 4.

CONCLUSIONS

The European project BLEMAB represents an important example of the application of muon imaging techniques in the industrial field: in particular the aim of this project is to exploit the muon radiography technique to obtain an on-line map of the material distribution inside active blast furnaces, focusing on the shape and the location of the cohesive zone. This could lead to the development of a new methodology to get a direct information of the inner state of the furnace and to control the burden process for a stable and efficient operation, thus it could be of great interest for steel-making companies.

For this purpose, software simulations and a dedicated muon tracking system, described in the previous sections of this work, are under development; a preliminary detector prototype has already been realized and tested to provide experimental validation of the apparatus. The installation of the tracking system at the blast furnaces in the ArcelorMittal site in Bremen (Germany) is scheduled for late 2022: the detectors will collect data for several months and the results obtained with the muon radiography technique will be compared for validation with the measurements of a new eMPVP and mathematical blast furnace models.

AKNOLEDGEMENTS

This project has received funding from the European Union's Research Fund for Coal and Steel 2019 Programme, under grant agreement no. 899263.

REFERENCES

[1] Zyla PA, et al. Review of Particle Physics. PTEP. 2020;2020(8):083C01.

[2] Bonomi G, Checchia P, D'Errico M, Pagano D, Saracino G. Applications of cosmic-ray muons. Progress in Particle and Nuclear Physics. 2020;112:103768.

[3] George EP. Cosmic rays measure overburden of tunnel. Commonwealth Engineer. 1955;455.

[4] Alvarez LW, Anderson JA, El Bedwei F, Burkhard J, Fakhry A, Girgis A, et al. Search for Hidden Chambers in the Pyramids. Science. 1970 Feb;167(3919):832-9.

[5] Morishima K, Kuno M, Nishio A, Kitagawa N, M Y, Moto M, et al. Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons. Nature. 2017 Nov;552(7685):386-390.

[6] Saracino G, Amato L, Ambrosino F, Antonucci G, Bonechi L, Cimmino L, et al. Imaging of underground cavities with cosmic-ray muons from observations at Mt. Echia (Naples). Scientific Reports. 2017 04;7:1181.

[7] Tanaka H, Kusagaya T, Shinohara H. Radiographic visualization of magma dynamics in an erupting volcano. Nature Communications. 2014;5(3381).

[8] Gonidec Y, Rosas-Carbajal M, de Bremond d'Ars J, Carlus B, Ianigro JC, Kergosien B, et al. Abrupt changes of hydrothermal activity in a lava dome detected by combined seismic and muon monitoring. Scientific Reports. 2019 02;9:3079.

[9] Schouten D. Muon geotomography: selected case studies. Philosophical Transactions of the Royal Society A. 2019;377(2137):20180061.

[10] Oláh L, Barnaföldi GG, Hamar G, Melegh HG, Suranyi G, Varga D. CCC-based muon telescope for examination of natural caves. Geoscientific Instrumentation, Methods and Data Systems. 2012;1(2):229-34.

[11] Ambrosino F, Bonechi L, Cimmino L, D'Alessandro R, Ireland DG, Kaiser R, et al. Assessing the feasibility of interrogating nuclear waste storage silos using cosmic-ray muons. Journal of Instrumentation. 2015 jun;10(06):T06005-5.

[12] Thompson LF, Stowell JP, Fargher SJ, Steer CA, Loughney KL, O'Sullivan EM, et al. Muon tomography for railway tunnel imaging. Phys Rev Research. 2020 Apr;2:023017.

[13] Committee on Reaction within Blast Furnace, Joint Society on Iron and Steel Basic Research, The Iron and Steel Institute of Japan. Blast Furnace Phenomena and Modelling. Elsevier Applied Science; 1987.

[14] Geerdes M, Chaigneau R, Lingiardi O. Modern Blast Furnace Ironmaking: An Introduction (2020). Ios Press; 2020.

[15] Zaimi SA, Campos T, Bennani M, Lecacheux B, Danloy G, Pomeroy D, et al. Blast Furnace models development and application in ArcelorMittal Group. Metallurgical Research & Technology. 2009;106(3):105-11.

[16] Kanbara K, Hagiwara T, Shigemi A, Kondo Si, Kanayama Y, Wakabayashi Ki, et al. Dissection of Blast Furnaces and Their Inside State Report on the Dissection of Blast Furnaces-1. Tetsu-to-Hagané. 1976;62(5):535-46.

[17] Nagamine K, Tanaka HK, Nakamura SN, Ishida K, Hashimoto M, Shinotake A, et al. Probing the inner structure of blast furnaces by cosmic-ray muon radiography. Proceedings of the Japan Academy, Series B. 2005;81(7):257-60.

[18] Åström E, Bonomi G, Calliari I, Calvini P, Checchia P, Donzella A, et al. Precision measurements of linear scattering density using muon tomography. Journal of Instrumentation. 2016 jul;11(07):P07010-0.

[19] Commissione europea, Direzione generale della Ricerca e dell'innovazione, Zanuttigh P, Vanini S, Calliari I, Hu X, Checchia P, Forsberg F, et al. Study of the capability of muon tomography to map the material composition inside a blast furnace (Mu-Blast) : final report. Publications Office; 2019. Available from: doi/10.2777/24858

[20] Bonechi L, Baccani G, Bongi M, Brocchini D, Casagli N, Ciaranfi R, et al. Multidisciplinary applications of muon radiography using the MIMA detector. Journal of Instrumentation. 2020;15(05):C05030.
[21] Bonechi L, Bongi M, Fedele D, Grandi M, Ricciarini S, Vannuccini E. Development of the ADAMO detector: test with cosmic rays at different zenith angles. In: 29th International Cosmic Ray Conference, Pune, India. vol. 9;2005. p. 283-286.
[22] Gonzi S, Ambrosino F, Andreetto P, Bonechi L, Bonomi G, Borselli D, et al. Imaging of the Inner Zone of Blast Furnaces Using Muon Radiography: The BLEMAB Project. Journal of Advanced Instrumentation in Science. 2022 May;2022.
[23] Hrivnacova I, Adamova D, Berejnoi V, Brun R, Carminati F, Fasso A, et al. The Virtual Monte Carlo. arXiv e-prints. 2003 May:cs/0306005.
[24] Agostinelli S, Allison J, Amako K, Apostolakis J, Araujo H, Arce P, et al. Geant4 - a simulation toolkit. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 2003;506(3):250-303.
[25] Brun R, Rademakers F. ROOT - An object oriented data analysis framework. Nuclear instruments and methods in physics research section A: accelerators, spectrometers, detectors and associated equipment. 1997;389(1-2):81-6.
[26] Pagano D, Bonomi G, Donzella A, Zenoni A, Zumerle G, Zurlo N. EcoMug: An Efficient COsmic MUon Generator for cosmic-ray muon applications. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 2021;1014:165732.
[27] D'Errico M, et al. Muon radiography applied to volcanoes imaging: the MURAVES experiment at Mt. Vesuvius. Journal of Instrumentation. 2020 3;15(03).
[28] Baccani G, Bonechi L, Borselli D, Ciaranfi R, Cimmino L, Ciulli V, et al. The MIMA project. Design, construction and performances of a compact hodoscope for muon radiography applications in the context of archaeology and geophysical prospections. Journal of Instrumentation. 2018 nov;13(11):P11001-1.
[29] École Polytechnique and CNRS/IN2P3, OMEGA - Centre de Microélectronique (website). https://portail.polytechnique.edu/omega Accessed June 24, 2022.
[30] Raspberry Pi Foundation, Raspberry Pi (website). https://www.raspberrypi.com Accessed June 24, 2022.
[31] Bonechi L, Ambrosino F, Andreetto P, Bonomi G, Borselli D, Bottai S, et al. BLEMAB European project: muon imaging technique applied to blast furnaces. Journal of Instrumentation. 2022 apr;17(04):C04031.

Applicazione della Radiografia Muonica agli Altiforni: il progetto BLEMAB

La radiografia muonica è una tecnica di imaging non invasiva, basata sull'utilizzo di muoni cosmici per esplorare il contenuto di volumi molto grandi, densi e altrimenti inaccessibili. Il progetto Europeo BLEMAB (BLast furnace stack density Estimation through on-line Muon ABsorption measurements) rappresenta un'applicazione esemplare della radiografia muonica in ambito industriale: lo scopo di questo progetto è infatti quello di studiare la capacità di questa tecnica di scansionare la parte interna di altiforni attivi. In particolare, l'analisi sarà focalizzata sulla caratterizzazione della cosiddetta "zona coesiva", considerata di particolare interesse dall'industria siderurgica. Il progetto prevede la realizzazione di un apposito rivelatore di muoni, che verrà installato presso gli altiforni dello stabilimento ArcelorMittal a Brema (Germania). In questo articolo verrà descritto lo stato di avanzamento del progetto, in particolare lo sviluppo di simulazioni software e la costruzione del rivelatore.

PAROLE CHIAVE: ALTOFORNO, IMAGING, RADIOGRAFIA MUONICA;

TORNA ALL'INDICE >