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The BLEMAB European project: Muon radiography as an imaging tool in the industrial field

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Summary. — The European project called BLEMAB (BLast furnace stack density Estimation through on-line Muons ABsorption measurements), provides for the application of the muon radiography technique in the industrial environment. The project represents a non-invasive way of monitoring a blast furnace and in particular aims to study the geometric and density development of the so-called "cohesive zone", which is important for the performance of the blast furnace itself. The installation of the detectors is expected in 2022 at the ArcelorMittal site in Bremen (Germany). This paper describes the status of the project, the experimental setup and the first results obtained with preliminary simulations.

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1. – Introduction: muon radiography and imaging methodology

Muon radiography is a non-invasive imaging technique based on cosmic muon absorption measurements. The principle of operation is the same as for a common X-ray radiography: thanks to the great penetrating power of cosmic muons [1], it is possible to create images of the inner part of large massive structures under study as volcanoes and pyramids and for this reason it is used as a valid alternative to the common prospecting techniques developed in the archaeological, geological, civil security and industrial fields.

The imaging methodology consists of various steps involving measurements and simulations and allows converting the different muon absorption values into target material's density values. The *first step* is the measurement in the *target configuration* with the (*muon tracker*) detector oriented towards the target structure. The corresponding angular 2D map of muon counts $N_{target}(\alpha, \beta)$ in a given acquisition time with (α, β) respectively, the zenith and azimuth angle is obtained. This quantity depends on the density and shape of the target but also on the flux of cosmic muons at ground level [1] and on the detector acceptance and efficiency. In order to get rid of the dependencies not related to the target, a *second step* is required: a *freesky configuration* measurement that is performed without objects between the detector and the sky and with the tracker oriented in the same target configuration's direction. Comparing these two measurements, assuming that the detector conditions (trigger efficiency and acceptance) have remained the same, the measured muon transmission can be obtained $T_{meas}(\alpha, \beta) = (N_{target}(\alpha, \beta) \cdot t_{freesky})/(N_{freesky}(\alpha, \beta) \cdot t_{target})$, where t is the acquisition time in the two different configurations. To translate the information on muon transmission to average density of the material crossed, (*third step*) simulations are generated. Simulations must contain a valid model of the differential flux of cosmic rays at the Earth's surface and the known geometry of the target. Comparing measurements with simulations, an angular 2D average density map $\overline{\rho}(\alpha, \beta)$ is obtained. It is possible to identify anomalies in the expected density of materials and locate them angularly. Through the *triangulation technique*, which implies multiple target measurements at different points on the installation site, it is possible to reconstruct the anomalies in 3D.

2. – The BLEMAB European project

BLEMAB (BLast furnace stack density Estimation through on-line Muons ABsorption measurements) is the development of the previous European Mu-Blast project [2] which, through simulations, had tested the feasibility of muographic measurements at blast furnaces, finding the absorption muon radiography the best in terms of costs. The BLEMAB project includes: the construction of two muon trackers, the development and the optimization of data analysis software already developed in other muographic experiences [3, 4], the development of simulations and the installation in 2022 at the ArcelorMittal steel plant in Bremen (Germany) for a long period. The results obtained with muon radiography will be compared with standard invasive sampling methods that are based on the use of probes such as multipoint vertical probes (MPVP). Particularly important for the performance of a blast furnace is the "cohesive zone"(the zone where the melting of the materials begins) which has a different density from the other zones. BLEMAB aims to online monitor the internal geometric development and density variations of the cohesive zone in a time scale from few hours to some days.

2˙1. *The detectors*. – Two muon trackers will be assembled in early 2022 in order to install them at the same blast furnace to have a stereoscopic vision (fig. 1(a), left). Each tracker will consist of three XY tracking modules of surface dimension $80 \times 80\,\text{cm}^2$ that measure two orthogonal coordinates of muon impact points. Each module consists of two planes of 63 good quality fast organic polystyrene plastic scintillator bars with triangular section. Each bar is read by two silicon photomultipliers (SiPMs) $4 \times 4\,\text{mm}^2$ located on the triangular faces. In the two planes of a module, bars are arranged orthogonally. Each XY module is readout by four custom DAQ slave boards containing an EASIROC1B 32 channel front-end-chip and an ASIC to control the transmission of data to a central custom DAQ master slave. In the master slave the trigger logic and data collection are implemented. A Raspberry PI computer is connected to the master slave to setup all the electronic chain and to write data on a physical support. Through the internet connection provided by ArcelorMittal, it will be possible to manage and control the detectors remotely and synchronize the data on a remote server. The detectors will be enclosed in a protective aluminum mechanics (fig. 1(a), right) and will rest on a dedicated platform that will allow the altazimuth orientation. The mechanics will be housed in a metal structure to protect the apparatus from possible drops of liquid and high temperature corrosive vapors. In the same protection mechanics a cooling system, based on a water chiller, has been designed.

2·2. *Test of prototype tracking plane*. – A prototype of a tracking plane consisting of five triangular section scintillator bars was assembled for the study of the efficiency at the variation of the muon impact point along the bars (80 cm length). As in the final project, each bar is read by two $4 \times 4\,\text{mm}^2$ SiPMs. The signal of the two SiPMs is sampled through custom electronics. The prototype is enclosed in protective aluminum mechanics. Through an external trigger system, consisting of two small plastic scintillators arranged so as to select a small area of the system under test, efficiency measurements were made for various positions along the prototype with steps of 10 cm. About 1000 events were acquired for each position, finding an efficiency greater than 99.5%. Figure 1(b) shows the setup and the measurement results.

2·3. *Simulations tools*. – Two different simulations have been generated: the first one is based on a fast simulation and allows having an estimate of the muon rate expected per day; the second one, more complete, allows to compare with real measurements.

The fast simulation has been completed. The simulation tool is based on a realistic geometry of the blast furnace with internal different material structure and on a muon generator based on realistic data acquired in Florence with the ADAMO magnetic spectrometer [5]. In this tool, the radiation-matter interaction between muons and detectors is not included. To have an estimate of the number of muons arriving in a BLEMAB-like

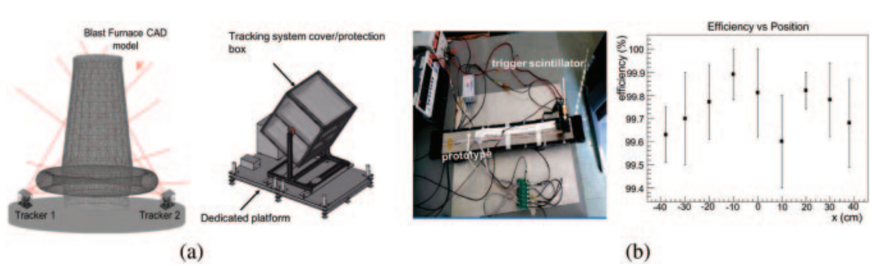

Fig. 1. – (a) Tracking system inside a protection box on the rotating platform and scheme of a possible measurement with both trackers (not in scale). (b) The experimental setup for efficiency measurements *vs.* muon impact point coordinate and the results (the x-axis is oriented parallel to the scintillator bars).

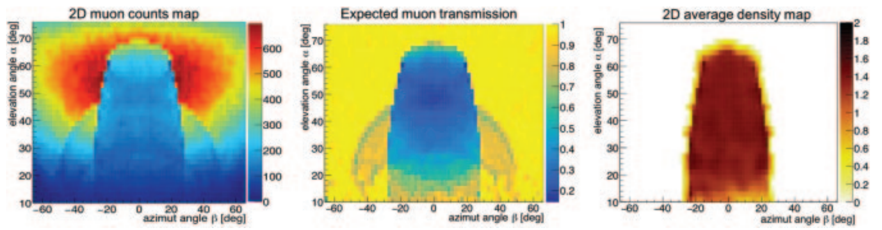

Fig. 2. – From the left: the 2D angular $2° \times 2°$ map of muon counts expected in 10 hours of data taking, the corresponding muon transmission map and the average density map without torus and external blast furnace's skin contributions.

detector in 10 hours the 2D muon counts map in fig. 2 (left) was generated. The presence of the blast furnace can be identified in the area in which the number of detected muons is suppressed. In order to have an expected angular 2D average density map of the blast furnace's internal composition, the *expected transmission* is evaluated (fig. 2, centre) and translating these values into density values, the angular average density map after 10 hours of acquisition data was obtained (fig. 2, right). Since we are interested in the development in density of the materials inside, the contributions of the torus and of the outer blast furnace's shell composed by Fe and Cu have been subtracted from this map. The density values found are compatible within 10% with those expected. Results are shown above a 10-degree elevation angle due to insufficient statistics below, as the muon flux is small and the average muon energy is larger, which makes difficult measuring a small deviation from an expected transmission close to unity.

The complete simulation tool is based on GEANT4 software package and on a recently released atmospheric muon generator [6]. The results are being studied.

3. – Conclusions and prospects

The BLEMAB project represents a non-invasive method of blast furnace's imaging. For this project, a dedicated muon detection system and precise simulations are under development. Detection efficiency test of the detector's scintillator strips were made obtaining an efficiency $\epsilon > 99.5\%$. Preliminary simulations allowed to estimate the number of muons expected in a few hours of data taking and to demonstrate that the blast furnace's average density distribution can be measured at 10% accuracy in this time. The future program involves: the installation in situ at Bremen in 2022 for a measurement of several months and the comparison of the results with those obtained with other standard methods as MPVP.

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