Imaging of the inner zone of blast furnaces using the muon radiography: the BLEMAB project

International Workshop on Cosmic-Ray Muography - Muography2021

Sandro Gonzi
for the **BLEMAB Collaboration**

RINA Consulting Centro Sviluppo Materiali SpA (CSM)

ArcelorMittal Bremen GmbH (ABG) and ArcelorMittal Maizières Research (AMMR)

Istituto Nazionale di Fisica Nucleare (INFN)

Università degli Studi di Firenze (UNIFI)

Università degli Studi di Napoli “Federico II” (UNINA)

Università degli Studi di Padova (UNIPD)

Royal Institute of Technology (KTH)

Research Fund for Coal and Steel (RFCS)

BLEMAB Home page
https://www.blemab.eu/

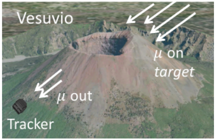
Introduction

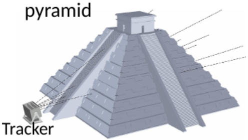
Premise

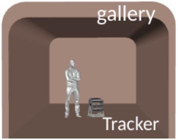
The **BLEMAB (BLast furnace stack density Estimation through on-line Muon ABsorption measurements)** European project provides for the application of the **Muon Transmission Radiography (MTR)** in internal volume imaging of **blast furnaces (BF).**

The useful features of the **Muon Transmission Radiography** applied in this field are:

- non-invasive imaging technique;
- tested results in various fields of application (archaeological, geological, civil and nuclear safety, industrial field, monitoring of large structures);
- possibility of installing the detectors in small and difficult to access places.







Goal

The main aim of the BLEMAB project is to establish a **non-invasive** investigation methodology for **on-line monitoring** of internal **density variations** of blast furnaces.

BLEMAB project

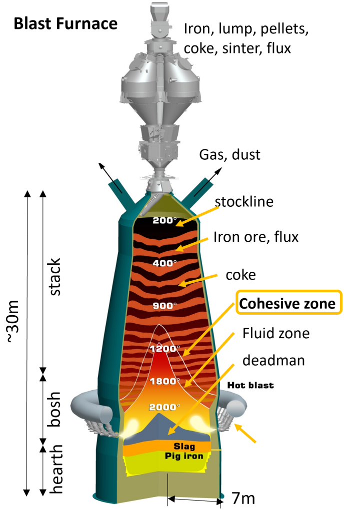
BLEMAB is an evolution of the previous **Mu-Blast** European project which, through simulations, had tested the feasibility of muographic measurements at blast furnaces, finding the **muon tomography absorption** approach the best in terms of costs [1,2].

The BLEMAB project currently represents the only non-invasive way of monitoring a blast furnace.

Blast furnaces are large structures (tens of meters high, a few meters thick and with internal temperatures of over 1500 °C) that transform iron, coke and flux introduced from above into cast iron.

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 monitor the **geometric development** and **density** of the **cohesive zone**.



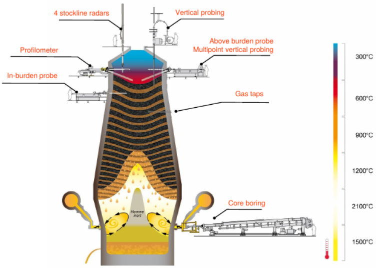
---

[1] S. Vanini *et al.*, *Phil. Trans. R. Soc. A* **377** (2018), 20180051.

[2] P. Zanuttigh *et al.*, *Publications Office of the European Union*, **ISSN 1831-9424** (2019).

Process monitoring

In **Iron-making**, the study of the internal state of the blast furnaces and the capability to measure the shape, position and thickness of the **cohesive zone** are fundamental.



Different methods of direct measurement of the **cohesive zone** position were developed in the past:

- **tracking of radioisotopes** injected into the furnace and vertical probes with conductive cables;
- conventional instruments, such as a **Multi-Point Vertical Probe (MPVP)**, providing essential information on the internal volume state;
- **measurement of the position of the melting surface**, using a very expensive excavation of the burden material, through **core drilling** or **blast furnace dissection**.

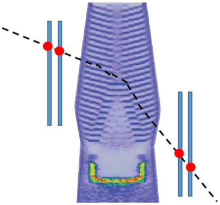
However, conventional instruments have generally **limited area coverage** and **intermittent way of operation**.

Muon Transmission Radiography (MTR) vs. Multiple Scattering Muon Tomography (MSMT)

The **MTR** technique offers some advantages with respect to the **MSMT** technique.

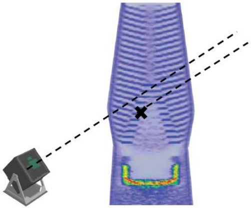
Mu-Blast

Muon tomography based
on multiple scattering



BLEMAB

Muon radiography based
on muon transmission



1. it reduces the **measurement time**: 30 minutes - 1 hour:
    - the bed of a medium-sized blast furnace takes about 8 hours to cover the full height of the blast furnace and therefore density and melting zone changes are expected to take off in a time of about one hour.
2. comparable results can be achieved with much **lower dimensions**, **costs** and **weights** of the detector:
    - the detector can be **moved** to change the direction of the angle of view and then to scan specific areas of the blast furnace;
    - the contemporary use of two detectors from two different points leaves the possibility to have a **stereoscopic vision** of the blast furnace inner zone.

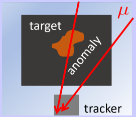
Muon Transmission Radiography (MTR)

The MTR technique needs to evaluate the measured and simulated **fluxes** $\boldsymbol{\Phi^M}$ and $\boldsymbol{\Phi^S}$ for each observation **zenith** angle $\boldsymbol{\theta}$ (or its complementary **elevation** angle $\boldsymbol{\alpha}$) and **azimuth** angle $\boldsymbol{\varphi}$ in a **target** (*T*) and **free-sky** (*FS*) configuration.

2D/3D target density maps

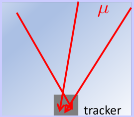
Target measurement (presumed anomaly)

$\Phi^M_T(\theta,\varphi)$



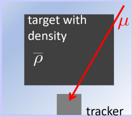
Free-sky measurement

$\Phi^M_{FS}(\theta,\varphi)$



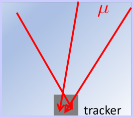
Target simulation (no anomaly, density $\bar{\rho}$)

$\Phi^S_T(\theta,\varphi,\bar{\rho})$



Free-sky simulation

$\Phi^S_{FS}(\theta,\varphi)$



Same orientation of the tracker

Same orientation of the tracker

Measured transmission of $\boldsymbol{\mu}$:

$$T^M(\theta,\varphi) = \frac{\Phi^M_T(\theta,\varphi)}{\Phi^M_{FS}(\theta,\varphi)}$$

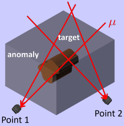
Simulated transmission of $\boldsymbol{\mu}$:

$$T^S(\theta,\varphi,\bar{\rho}) = \frac{\Phi^S_T(\theta,\varphi,\bar{\rho})}{\Phi^S_{FS}(\theta,\varphi)}$$

Relative transmission of $\boldsymbol{\mu}$:

$$R(\theta,\varphi,\bar{\rho}) = \frac{T^M(\theta,\varphi)}{T^S(\theta,\varphi,\bar{\rho})}$$

- Varying $\bar{\rho}(\theta,\varphi)$: $R(\theta,\varphi,\bar{\rho}) = 1$ → **2D density map** $\boldsymbol{\rho^{target}(\theta,\varphi)}$
- Combining 2D density maps from different points of view → **3D density map** $\boldsymbol{\rho^{target}(x,y,z)}$



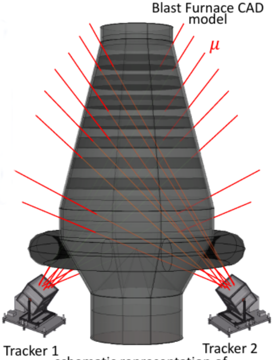
Work planning

Hardware

- construction of **two muon trackers** for a stereoscopic vision and for a continuous monitoring of the BF;
- realization of the **mechanical structure** that should be resistant, able to withstand high temperatures and to allow the orientation of the detector;
- realization of the **electronics** to read signals.

Software

- development and optimization of an appropriate **data analysis software** (starting from previous experiences);
- development of a **simulations** tool with a realistic BF model (using the Geant4 software);
- **mathematical modelling** of the BF inner zone.



schematic representation of BLEMAB measurements

Muographic measurements

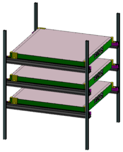
- **installation** at the ArcelorMittal steel plant in Bremen (DE) for a long period;
- comparison of the **muography** results with **standard sampling methods** that are based on the use of probes such as MPVP (Multi-Point Vertical Probe).

Muon tracking detector: design

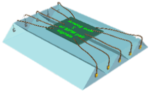
Two independent trackers will be realized, with the same structure as the MU-RAY, MURAVES and MIMA detectors used for previous muon radiography measurements.

Detector x2

- 3 XY tracking modules consisting of 64 triangular section plastic scintillator bars, with angular resolution of a few mrads;
- XY tracking module: size of (83x83x8) cm^3 and mass of 37 kg;
- single bar size: (10x25x800) mm^3;
- each bar is read by means of 2 SiPM with size of (4x4) mm^2.



BLEMAB tracker



Single plane of a XY module

Electronics x2

Custom DAQ:

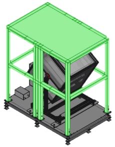
- 12 Slave boards (4 for each XY module)
- 1 Master board + Raspberry Pi

Slave board

Master board

Mechanics x2

- protective aluminum mechanics;
- total size: (83x83x80) cm^3;
- altazimuth orientation system with 0.5° resolution in azimuth;
- dedicated platform.



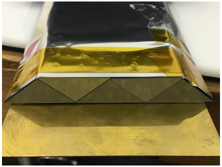
Detector with a protection frame

Muon tracking detector: test setup

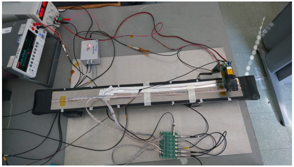
A first partial **prototype** of the **tracking plane** has been produced to estimate the detection efficiency and spatial resolution that is possible to obtain in the BLEMAB configuration.

Test design:

- a prototype tracking plane made of **5 scintillator bars** (80 cm length);
- a digital oscilloscope used as DAQ system;
- a protective aluminum box (for mechanical structure and darkening cover);
- two 4x4 mm^2 SiPM optical sensors (signals are summed together);
- an external trigger system (2 plastic scintillators read by means of standard PMTs).



Disposition of the 5 scintillator bars



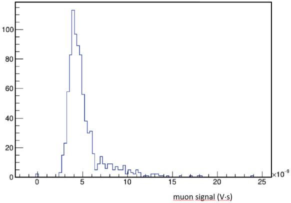
Prototype under test

Muon tracking detector: test results

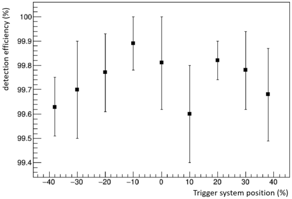
A study of the dependence of **detection efficiency** on the **impact coordinate** of muons along the bars has been carried out.

Test procedure:

- data taking was repeated for seven different positions of the trigger system, with steps of 10 cm, in order to cover the whole prototype's length;
- for each position a total of approximately 1000 muon events have been collected.



Distribution of signals for a fixed position of the external trigger



Dependence of the detection efficiency on the muon impact point coordinate

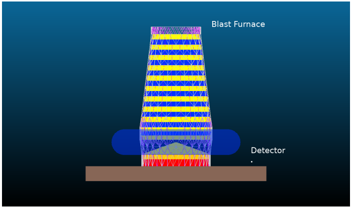
All measured values of detection efficiency on the impact coordinate are beyond **99.6%**.

Simulations: custom tool

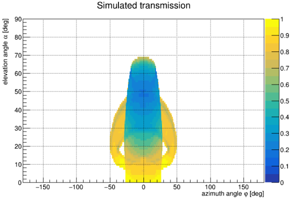
A preliminary simulation has been carried out with a fast and simplified custom tool.

Custom simulation tool design:

- accurate representation of the ArcelorMittal blast furnace:
    - **geometry** from a CAD design;
    - assigned average **density** for each component;
- realistic **muon generator**, based on ADAMO experiment data at ground level [3];
- description of muons **interaction with matter** (without **multiple scattering**);
- point-like **detector**.



Blast furnace prototype with a point-like detector



Simulated transmission map

The custom simulation tool has successfully been used for many applications of MTR.

---

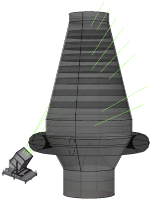
[3] L. Bonechi *et al.*, *29th International Cosmic Ray Conference* **9** (2005), 283-286.

Simulations: custom tool

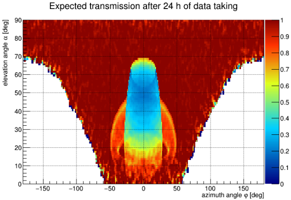
A **daily** expected transmission map has been estimated starting from the given simulated transmission map (**1° bin size** for both elevation and azimuth angles).

A MIMA-like detector [4] with a (40x40) cm^2 incoming surface, tilted 45° with respect to the zenith and with the center placed in the previous point-like detector position, has been implemented in the custom simulation tool with real free-sky data available.

Simulations have been performed for a **MIMA**-like detector because it is the operating detector closest to the chosen design for the **BLEMAB** project.



Blast furnace prototype with a realistic MIMA-like detector



Expected transmission map after 24 h of data taking

The shape of the blast furnace seems to be clearly visible after 24 h of data taking.

---

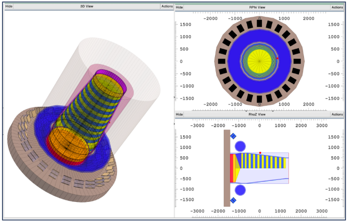
[4] G. Baccani *et al.*, JINST **13** (2018) no.11, P11001.

Simulations: blemab-simulator tool

A more detailed simulation tool has been developed and is currently available.

BLEMAB-SIMULATOR tool design:

- based on the Geant4 software package;
- with the recently developed atmospheric muon software generator EcoMug [5].



blemab-simulator tool scene

BLEMAB-SIMULATOR tool features:

- it is possible to replicate some identical detectors and place them all around the blast furnace at a given radius to the centre;
- the multiple detection systems allow maximizing the ratio between the number of events entering the detector's acceptance and the total number of simulated muon events.

The results of a sample of 300 milions of events generated on a cylinder surface and detected by 48 BLEMAB-like detectors are currently under study.

---

[5] D. Pagano *et al.*, *Nucl. Instr. Meth. A* **1014** (2021), 165732.

Conclusions

Status of the project

- a study of the dependence of detection efficiency on the impact coordinate of muons along the bars has shown that all measured values are beyond 99.6%;
- the simulations performed with a fast and simplified custom tool have shown that the shape of the blast furnace will already be visible with one day of data taking.

On going

- assembly of the tracking planes;
- production of the complete mechanics;
- test on prototype electronic boards;
- analysis of the simulations results;
- mathematical modelling of the BF inner zone.

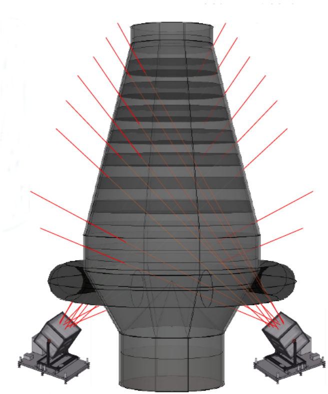
Site of the ArcelorMittal in Bremen (DE)

Future program

- the installation at the ArcelorMittal site in Bremen (DE) is planned for 2022;
- the detectors will stay on site in 2022-23 for several months at the aim of observe the cohesive zone of a given blast furnace;
- at the same time, a campaign of measurements will be made with Multi-Point Vertical Probe (MPVP) in order to have a comparison between the two methods.

Thank you

for your attention



Research Fund for Coal and Steel GRANT AGREEMENT NUMBER: 899263 - BLEMAB

Backup slides

BLEMAB Collaboration

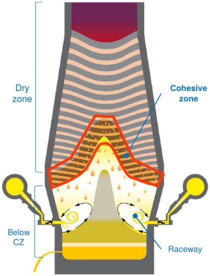
F. Ambrosino[1,2], P. Andreetto[3], L. Bonechi[4], G. Bonomi[5,6], D. Borselli[4,7], S. Bottai[4], T. Buhles[8], I. Calliari[9], P. Checchia[3], U. Chiarotti[10], C. Cialdai[4], R. Ciaranfi[4], L. Cimmino[1,2], V. Ciulli[11,4], R. D'Alessandro[11,4], M. D'Errico[1,2], R. Ferretti[12], F. Finke[8], A. Franzen[8], B. Glaser[13], S. Gonzi[11,4], Y. Liu[13], A. Lorenzon[14,3], V. Masone[2], O. Nechyporuk[15], L. Pezzato[9], B. V. Rangavittal[13], D. Ressegotti[16], G. Saracino[1,2], J. Sauerwald[8], O. Starodubtsev[4] and L. Viliani[4]

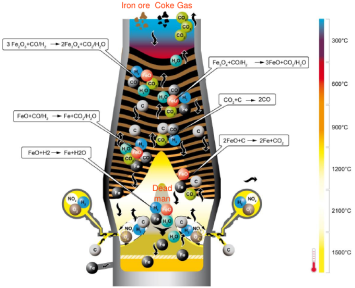
[1] *Physics Department "Ettore Pancini", University of Naples Federico II, Naples, Italy*
[2] *INFN, Naples, Italy*
[3] *INFN, Padua, Italy*
[4] *INFN, Florence, Italy*
[5] *Department of Mechanical and Industrial Engineering, University of Brescia, Brescia, Italy*
[6] *INFN, Pavia, Italy*
[7] *Department of Physics and Geology, University of Perugia, Perugia, Italy*
[8] *Ironmaking Department, ArcelorMittal Bremen GmbH, Bremen, Germany*
[9] *Department of Industrial Engineering, University of Padua, Padua, Italy*
[10] *Rina Consulting - Centro Sviluppo Materiali SpA, Rome, Italy*
[11] *Department of Physics and Astronomy, University of Florence, Florence, Italy*
[12] *Rina Consulting - Centro Sviluppo Materiali SpA, Terni, Italy*
[13] *KTH Royal Institute of Technology, Stockholm, Sweden*
[14] *Department of Physics and Astronomy, University of Padua, Padua, Italy*
[15] *ArcelorMittal Maizieres Research SA, Maizieres-Les-Metz, France*
[16] *Rina Consulting - Centro Sviluppo Materiali SpA, Dalmine (BG), Italy*

Blast furnace representation

The inner volume of a typical blast furnace can be separated in four distinct zones:

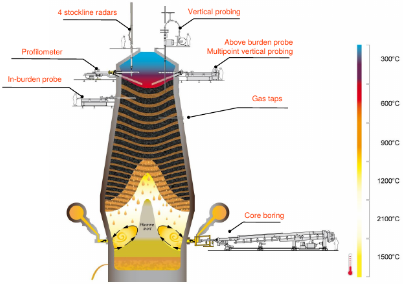
- **dry zone**, where the iron-bearing materials conserve their solid state;
- **cohesive zone**, where the iron-bearing materials soften and eventually melt. This zone is typically located in the temperature range 1200-1400 °C;
- **below cohesive zone** the liquid iron and slag percolate trough coke bed;
- in **raceway** the coke and additional fuel are burnt. Raceway can be considered a cavity into which the coke sinks.

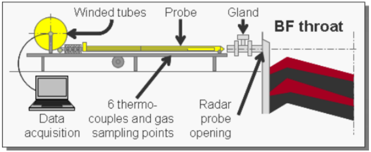




Blast furnace instrumentation

Conventional instruments, such as a **Multi-Point Vertical Probe (MPVP)**, provide essential information on the internal volume state.





Overview of MPVP technology

Objective:

- typical MPVP measures gas temperature and chemical composition (CO, CO_2, H_2) across the radius from charging level down to 1300 °C.

MPVP:

- typical probe is equipped with 6 thermocouples and 6 gas sampling lines spread over its length;
- introduced inside the furnace by means of a driving bench, usually that of a profilometer probe which has to be removed for this specific occasion.

Productivity

An important and widely discussed parameter in the blast furnace process is the **productivity**: the quotient between possible gas throughput per unit of time and required specific gas generation for one ton of hot metal.

- an **increase in productivity** requires an **increase in the gas throughput**, which implies improvement in furnace permeability, and a reduction in the specific gas requirement that can be achieved by increased oxygen enrichment if there is capacity available;
- this implies a deep knowledge of the process along the height of the blast furnace;
- in other projects the inner state has been explored by indirect measurements.

Models development is an activity typically used for optimizing blast furnace operation, especially the measuring and process monitoring to control the processes in the inner part of the furnace.

Mu-Blast project

The aim of the **Mu-Blast** project (RFSR-CT-2014-00027) [2] was to explore the capacity of using the **Multiple Scattering Muon Tomography (MSMT)** technique to image the material composition inside a **Blast Furnace (BF)**, which can be useful to optimize the BF operation.

It was organized along two different but complementary research lines:

- **sample selection** (material from laboratory and from the Experimental Blast Furnace) and its analysis both with conventional methods and with MSMT;
- **MSMT analysis** of a **simulated** BF in order to produce 3D images of the different components (burden materials, hot metal, *etc.*) during BF operation.

Study of core samples extracted from a blast furnace

Simulated tomographic reconstruction after 1 h exposure time assuming a full detector coverage of the blast furnace

The most promising applications are believed to be the detection of the **cohesive zone** and the **refractory linings**. More fundamental studies are required to understand the feasibility of applying MSMT technique in the other aspects of the BF.

---

[2] P. Zanuttigh *et al.*, *Publications Office of the European Union*, **ISSN 1831-9424** (2019).

Mu-Blast project results

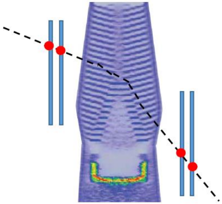
Mu-Blast project has demonstrated that muons can be used to produce images of the BF interior both using **scattering tomography** and **muon absorption** [2].

- **Muon scattering tomography** requires quite large and heavy detectors, that could pose problems of compatibility with existing BF infrastructures and would be difficult to move to explore different BF zones:
    - this technique produces 3D maps of the material density in the central part of the BF, showing the position in space, the shape and the density of material structures inside the BF;
    - it was out of the scope of the present project to study the precision with which the absolute Linear Scattering Density (LSD) values can be measured.
- **Muon absorption** needs smaller and simpler detectors, but can produce only 2D projections of the stopping power of the crossed BF section:
    - placing two or three such small detectors around the BF could give a partial insight of the 3D characteristics of the internal BF structures;
    - the DAQ time depends on the detector size, but can easily be smaller than 1 hour;
    - since the measuring process is much simpler, the absolute value of the stopping power is easier to be obtained.

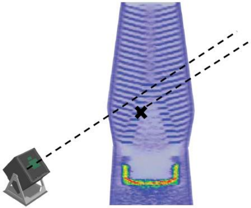
---

[2] P. Zanuttigh *et al.*, *Publications Office of the European Union*, **ISSN 1831-9424** (2019).

From Mu-Blast to BLEMAB



Mu-Blast
Muon tomography based
on multiple scattering



BLEMAB
Muon radiography based
on muon transmission

Mu-Blast provides a clear, fast and detailed reconstruction of the 3D structure, but:

- necessity to surround the target with detectors;
- interference with activities;
- large area detector (∼5x5 m^2);
- cost.

BLEMAB:

- comparison of transmitted flux with free-sky flux;
- requires simulations to get a 2D angular average density map;
- smaller detectors are requested;
- placement of detectors “far” from the target to avoid interferences.

Measurements in MTR technique

The aim of the MTR technique is the measurement of the **transmission**, defined as the ratio (as a function of the zenithal and azimuthal angles, θ and φ) between muon fluxes upstream and downstream of the target object.

Detectors are **charged-particle trackers** that are able to determine the angles defining the detected muon arrival direction by reconstructing in space its trajectory.

The upstream flux is not accessible for large targets: a **free-sky measurement** replace it by pointing the detector in the same direction but without the target in its field of view.

The experimental apparatus and its operating conditions are the same for the two measurements ⇒ most factors (sensitive area of the muon tracker, its angular acceptance, the trigger efficiency and the analysis efficiency) cancel in the ratio.
By assuming that the detector live time coincide with the acquisition time, the **measured muon transmission** T^M is given by:

$$T^M(\theta,\varphi) = \frac{N_T(\theta,\varphi)}{N_{FS}(\theta,\varphi)} \cdot \frac{t_{FS}}{t_T}$$

where $N_T(\theta,\varphi)$ and $N_{FS}(\theta,\varphi)$ are the angular distributions of muon reconstructed tracks measured respectively downstream from the target (T) and looking at the free-sky (FS) in the respective data acquisition time t_T and t_{FS}.

Simulations in MTR technique

This simulations tool requires the knowledge of the the **material opacity**:

$$X(\theta, \varphi, \bar{\rho}) = \bar{\rho} \cdot \ell(\theta, \phi)$$

where $\ell(\theta, \varphi)$ is the **material thickness** seen from a **point-like detector** along each direction (from a CAD or DTM file) and $\bar{\rho}$ is the estimated **average density** of the medium.
We compute then the **simulated muon integral flux** Φ^S for target and free-sky:

$$\Phi^S_T(\theta, \varphi, \bar{\rho}) = \int_{E_{min}(X)}^{\infty} \phi(\theta, \varphi, E)\, dE$$

$$\Phi^S_{FS}(\theta, \varphi) = \int_{E_0}^{\infty} \phi(\theta, \varphi, E)\, dE$$

where $\phi(\theta, \varphi, E)$ is the differential muon flux, $E_{min}(X)$ is the minimum energy that muons must have to cross the opacity X, E_0 is the minimum energy required to cross the detector.
The differential muon flux $\phi(\theta, \varphi, E)$, is the one measured by the ADAMO experiment [3].
The minimum muon energy $E_{min}(X)$ is obtained from the literature [6].
The **simulated muon transmission** T^S is computed as:

$$T^S(\theta, \varphi, \bar{\rho}) = \frac{\Phi^S_T(\theta, \varphi, \bar{\rho})}{\Phi^S_{FS}(\theta, \varphi)}$$

---

[3] L. Bonechi *et al.*, *29th International Cosmic Ray Conference* **9** (2005), 283-286.

[6] D. E. Groom *et al.*, *Atom. Data Nucl. Data Tabl.* **78** (2001), 183-356.

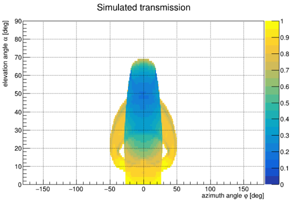
Results expected after 24 h of data taking

A **simulated transmission** map (**1° bin size** for both elevation and azimuth angles) has been computed for a **point-like detector** placed **8 m** far from the wall of the **blast furnace** (CAD design and density available for each piece).

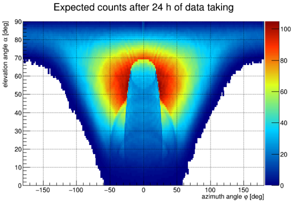
Considering the simulated trasmission as an **hypotetical measured** one $T^M(\theta,\varphi)$, a daily angular distribution of muon events $N_T(\theta,\varphi)$ has been estimated for a MIMA-like detector [4] placed with its centre in the same position of the simulated point-like detector and tilted 45°:

$$N_T(\theta,\varphi) = T^M(\theta,\varphi) \cdot N_{FS}(\theta,\varphi) \cdot \frac{t_T}{t_{FS}}$$

where $N_{FS}(\theta,\varphi)$ is the angular distribution of muon events in a free-sky configuration measured by the MIMA experiment in a time t_{FS} of about 15 days and t_T is 24 hours.



Simulated transmission map



Expected counts map after 24 h of data taking

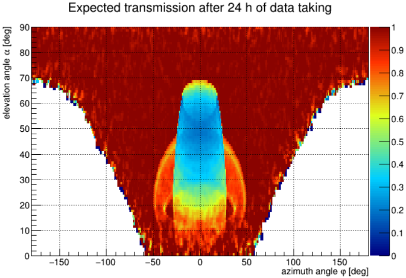
---

[4] G. Baccani *et al.*, JINST **13** (2018) no.11, P11001.

Results expected after 24 h of data taking

Whit a second set of angular distribution of muon events $N'_{FS}(\theta,\varphi)$ measured by the MIMA experiment in a free-sky configuration in a time t'_{FS} of about 15 days and fixing t_T to 24 hours, a daily expected transmission $T^{M'}(\theta,\varphi)$ map has been estimated as:

$$T^{M'}(\theta,\varphi) = \frac{N_T(\theta,\varphi)}{N'_{FS}(\theta,\varphi)} \cdot \frac{t'_{FS}}{t_T}$$



Expected transmission map after 24 h of data taking

Estimations have been performed for a **MIMA**-like detector because it is the operating detector closest to the chosen design for the **BLEMAB** project.

References

[1] S. Vanini *et al.*, *Phil. Trans. R. Soc. A* **377** (2018), 20180051.

[2] P. Zanuttigh *et al.*, *Publications Office of the European Union*, **ISSN 1831-9424** (2019).

[3] L. Bonechi *et al.*, *29th International Cosmic Ray Conference* **9** (2005), 283-286.

[4] G. Baccani *et al.*, JINST **13** (2018) no.11, P11001.

[5] D. Pagano *et al.*, *Nucl. Instr. Meth. A* **1014** (2021), 165732.

[6] D. E. Groom *et al.*, *Atom. Data Nucl. Data Tabl.* **78** (2001), 183-356.