Workshop su "Prospettive di applicazioni industriali sulla Tomografia Muonica"

Applicazioni concrete, costi, realtà imprenditoriali

Germano Bonomi

University of Brescia and INFN Pavia

- applicazioni di ricerca (1)
- applicazioni di ricerca (2)
- costi
- realtà industriali nel mondo
- considerazioni finali

APPLICAZIONI DAL MONDO DELLA RICERCA (1)

[radiografia muonica]

Muon radiography

Basic idea: to use the information on absorption of muons to measure the thickness of the material crossed by the muons themselves

The **first ever** civil application of the **cosmic rays** to inspect large volumes dates back to 1955 when the thickness of rock above a underground tunnel was measured by E. P. George **[1]**

Another application, much more spectacular, was realized by the Physics Nobel Price L.W. Alvarez [2] that in 1970 made a “radiography” of the Chefren pyramyd looking for hidden chambers … finding none. In 2017 a similar measurement (but more sophisticated) was performed on another pyramid [3]

[1] E. P. George, “Cosmic rays measure overburden of tunnel”, Commonwealth Engineer, (1955), 455.
[2] L.W. Alvarez et al., “Search for hidden chambers in the pyramids using cosmic rays”, Science 167 (1970) 832.
[3] Morishima, K. *et al. Nature* http://dx.doi.org/10.1038/nature24647 (2017).

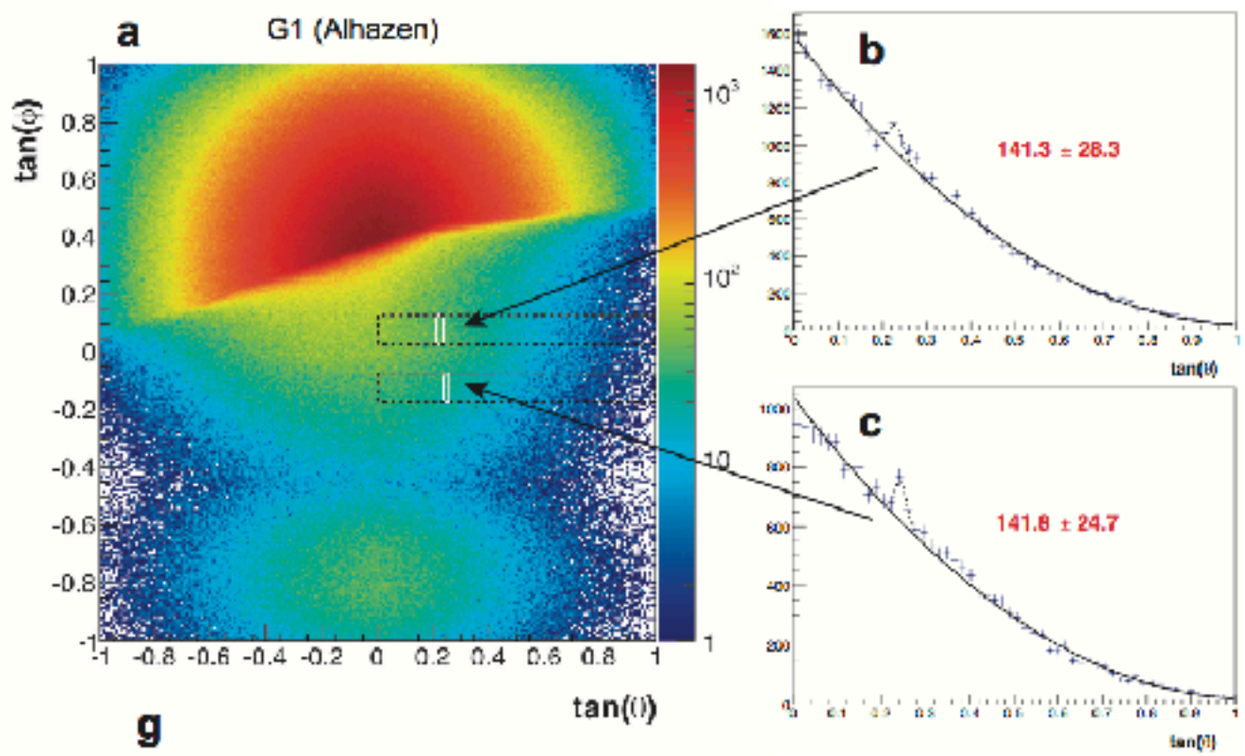
Muon radiography
Measure the number of muons surviving the passage through the material: same as x-ray radiography

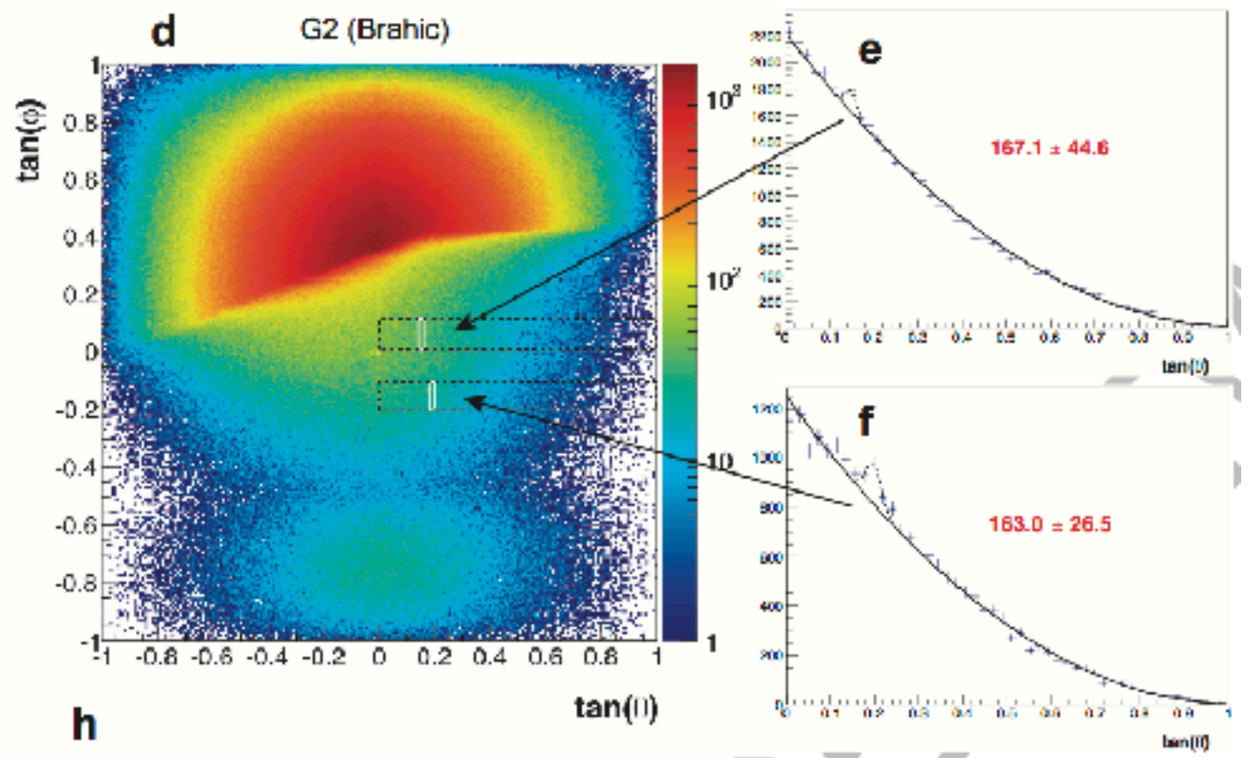
Muon radiography

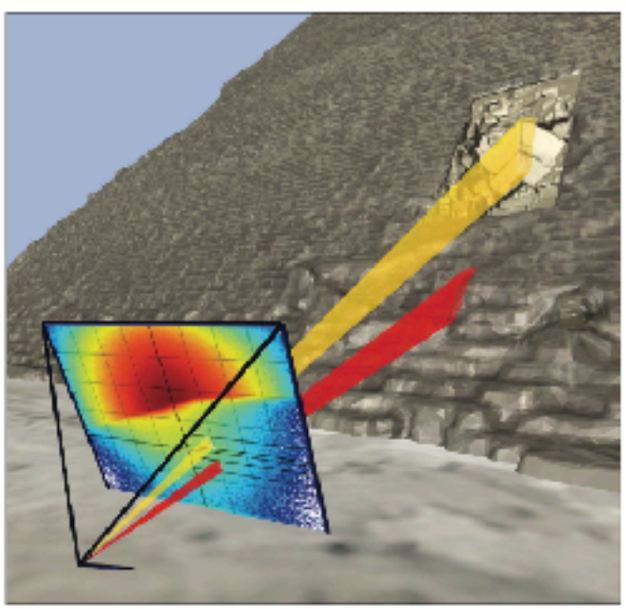
nature Accelerated Article Preview

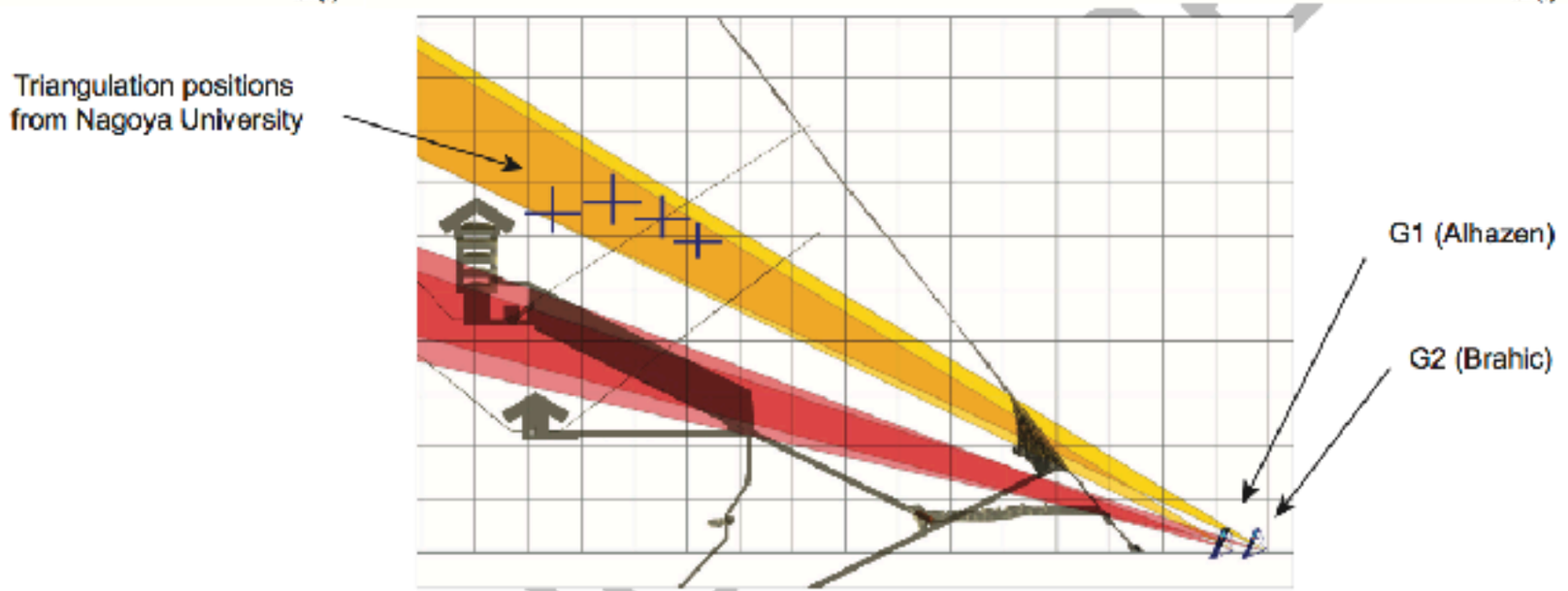
LETTER
doi:10.1038/nature24647

Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons





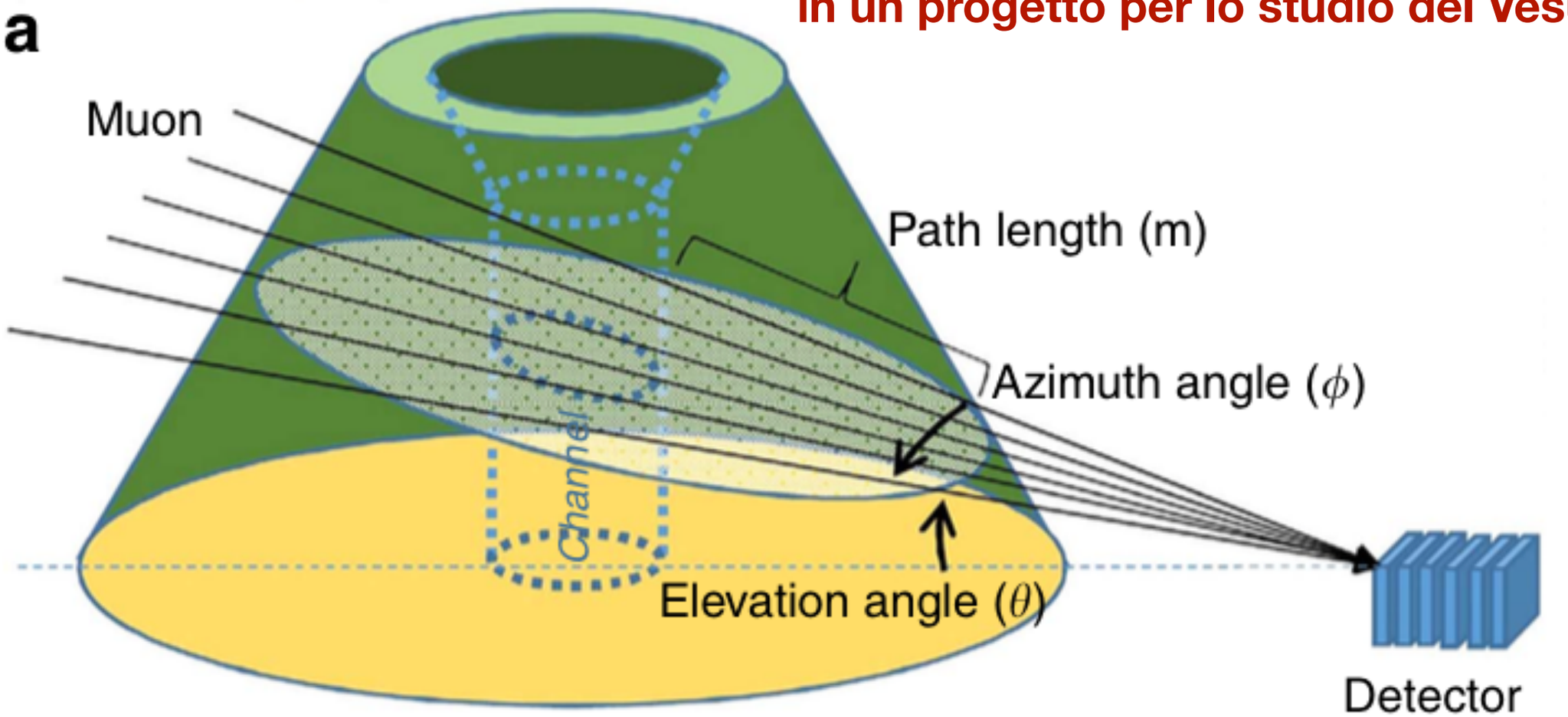




Muon radiography

Recently the same technique has been used to inspect the inner part of a vulcano [1], for geological studies [2], etc. [*the shadow of the moon …*]

Gruppo di Napoli/Firenze è impegnato in un progetto per lo studio del Vesuvio



[1] K. Nagamine et al., "Method of probing inner-structure of geophysical substance with the horizontal cosmic ray muons and possible application to volcanic eruption prediction", Nucl. Inst. Meth. A 356 (1995), 585.

[2] L. Oláh et al., "Cosmic Muon Detection for Geophysical Applications", Advances in High Energy Physics Volume 2013, Article ID 560192

[…. etc]

Muon radiography

Il distretto tecnologico STRESS e TECNOIN SPA

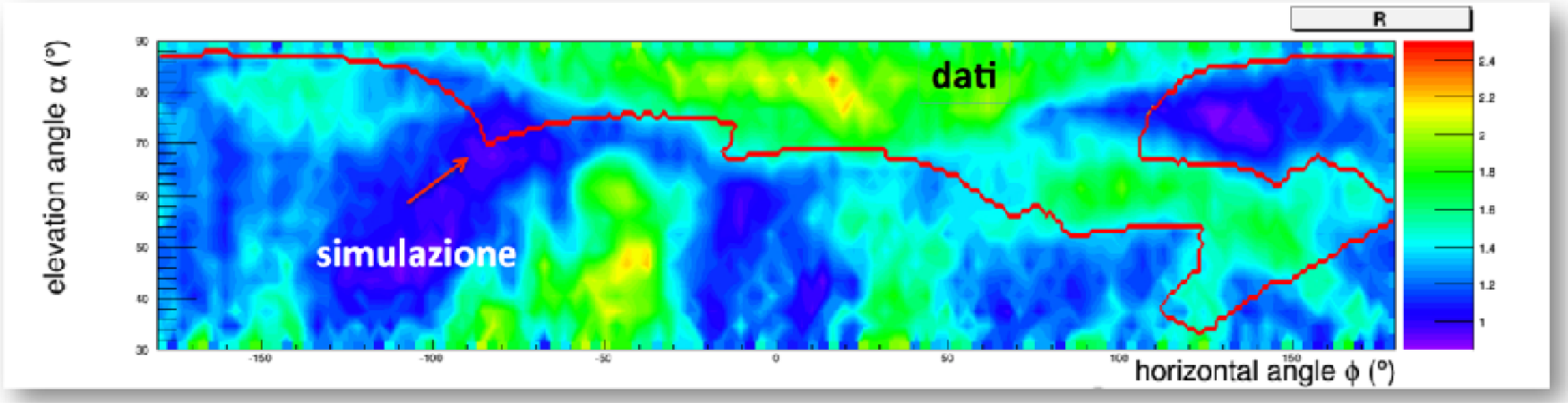
STRESS: DISTRETTO AD ALTA TECNOLOGIA PER LE COSTRUZIONI SOSTENIBILI
S.C.a R.L. senza fini di lucro con soci pubblici e privati

Partner Industriale

Muon radiography

Antica Partenope greca del VII sec. A.C.

Confronto dati e simulazione



APPLICAZIONI DAL MONDO DELLA RICERCA (2)

[tomografia muonica]

Applications: muon TOMOGRAPHY

- **security/safety**
  border and port controls, nuclear waste/spent fuel …

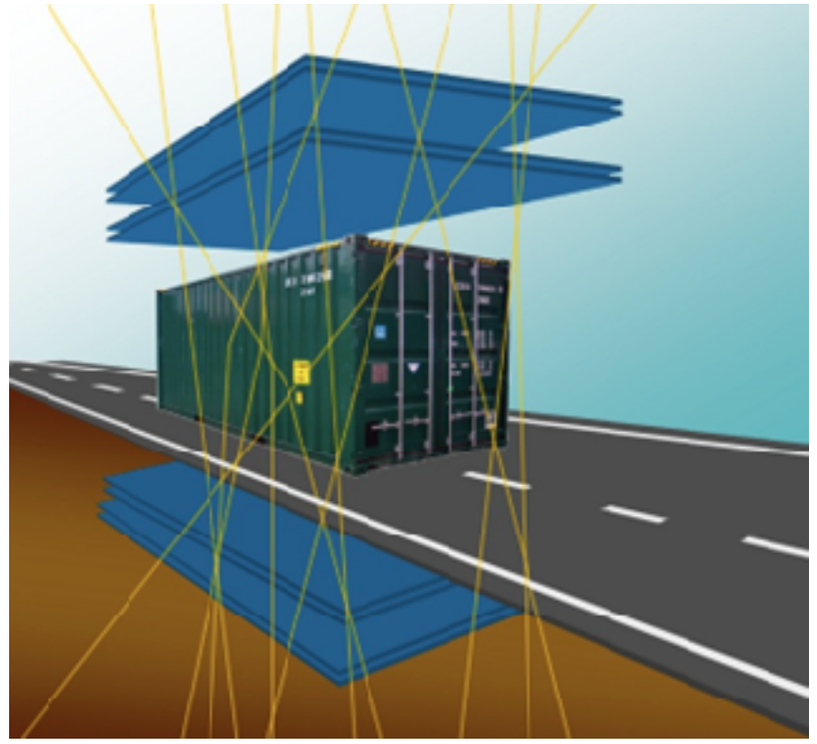
- **industry**
  steel foundries (gate truck controls), steel mill inspections …

- **precision measurements**
  material composition, liquid level measurement, building stability ..

Applications: security/safety

Control of containers (ports) and trucks (borders) to detect Special Nuclear Materials [high-Z]

A portal based on drift tube technology is in operation in Freeport (Bahamas) - Decision Sciences (Los Alamos spin-off)



Another Muon-Portal project is active in Catania - Italy

- large area detectors (tens of squared meters)

- good angular resolution (~ 10 mrad)

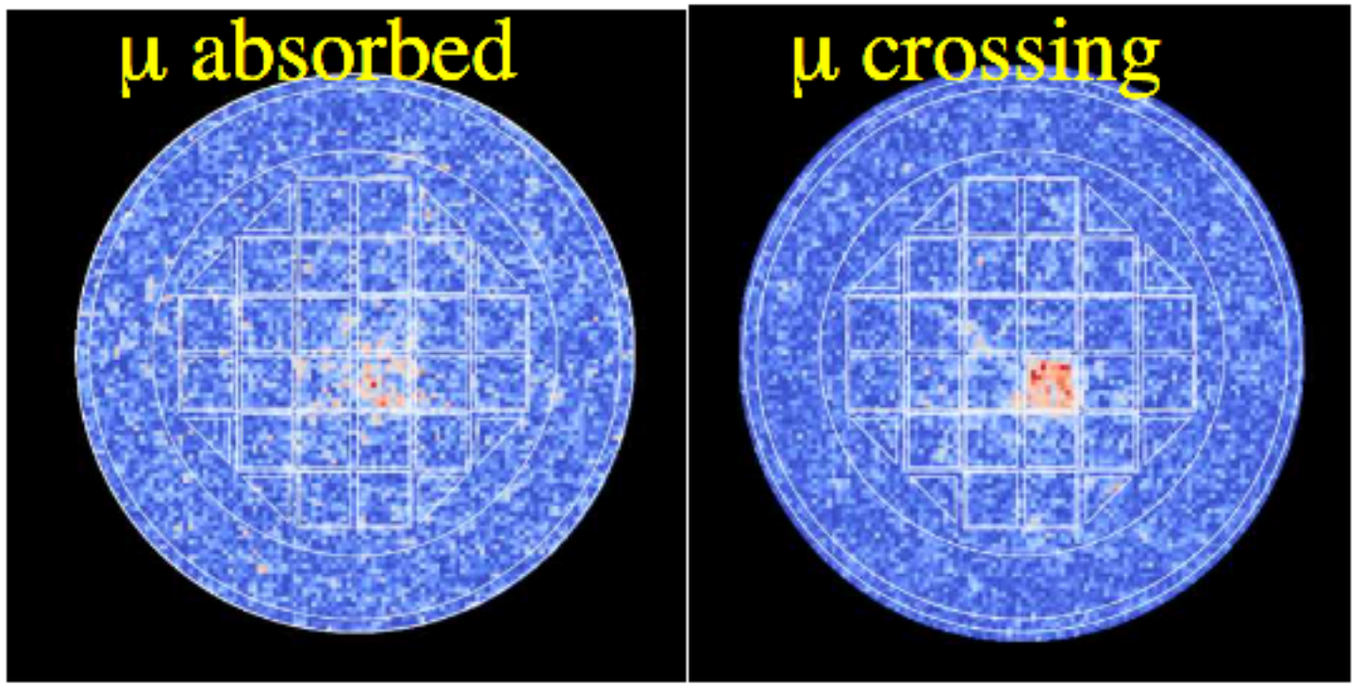
Applications: security/safety

Control of spent nuclear fuel (nuclear waste) deposits and of nuclear reactors (Fukushima)

No validated methods to verify the content of spent nuclear fuel storage containers without opening. Possible solutions: neutrons or muons

University of Glasgow (scintillating fiber tracker), University/INFN Padova (drift tubes) and Los Alamos

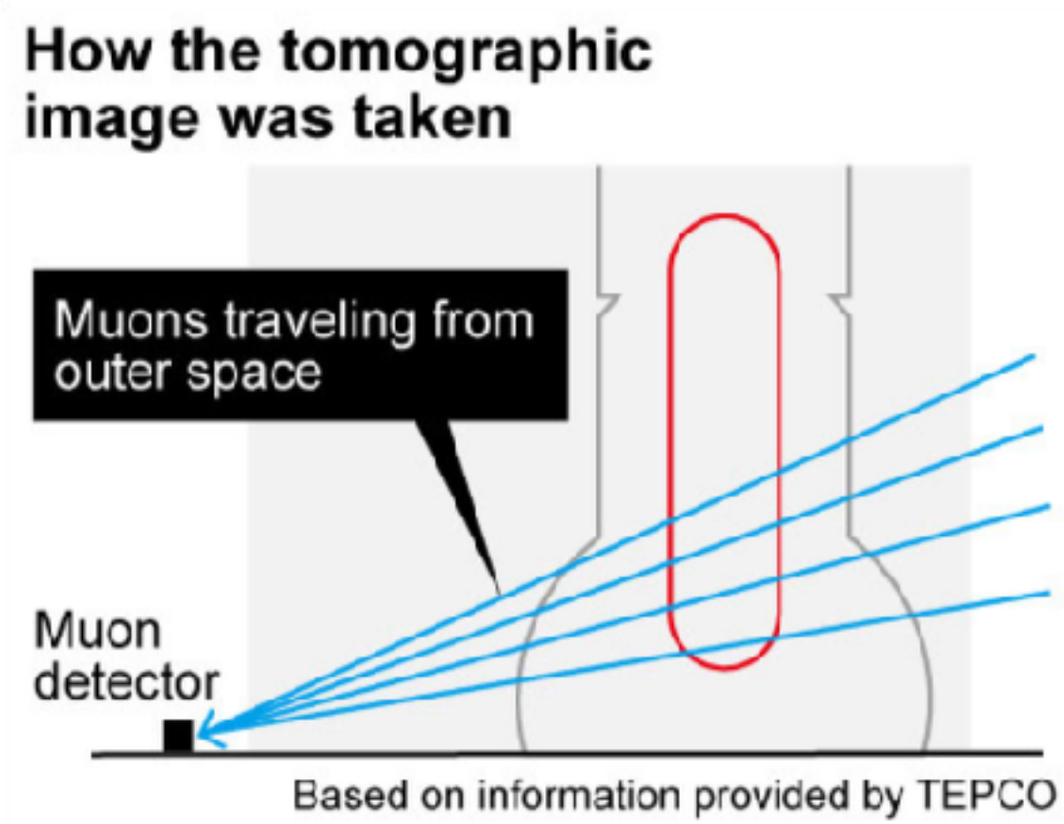
both absorption (radiography) and multiple scattering (tomography) may be useful

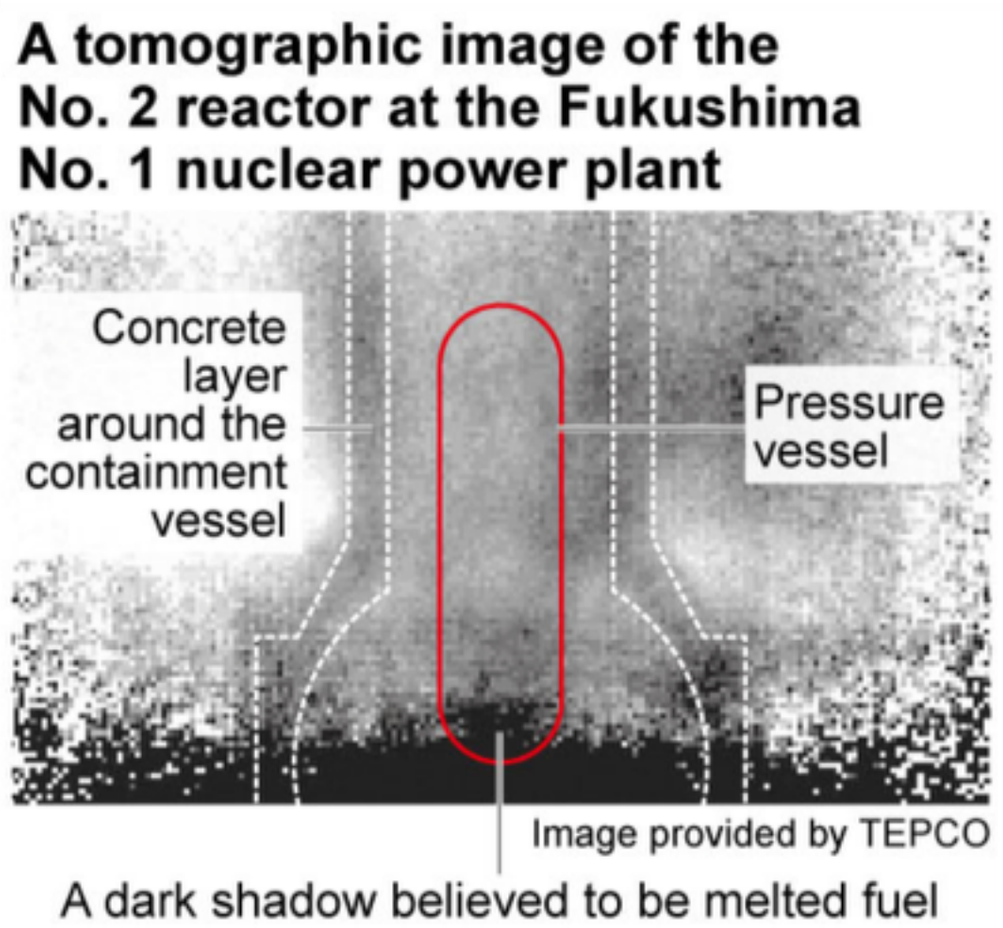


Applications: security/safety

Control of spent nuclear fuel (nuclear waste) deposits and of nuclear reactors (Fukushima)

A Japanese research group installed a muon detector system at the reactor n. 2 of the Fukushima plant to inspect its content



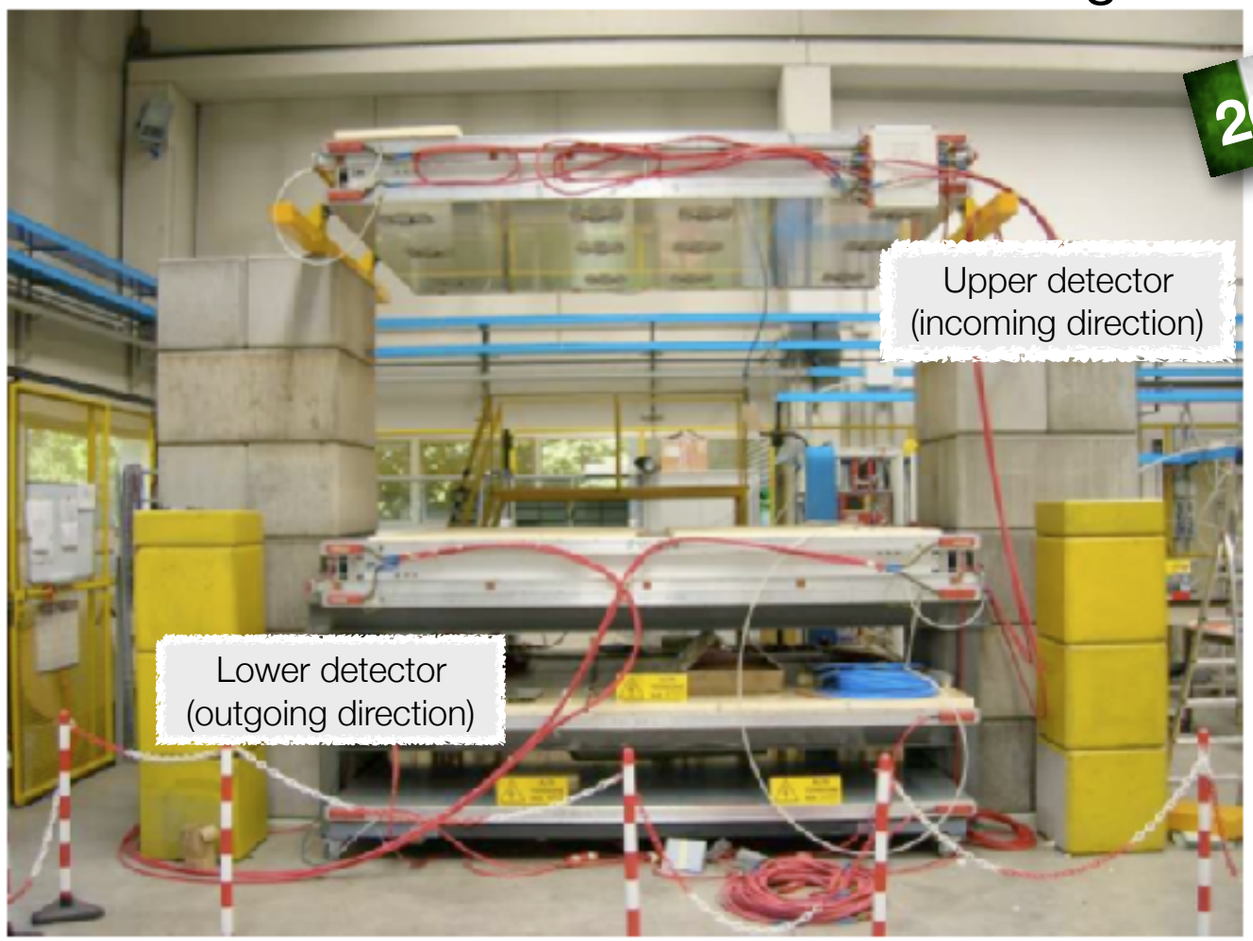


"Los Alamos" is ready to install their own system (waiting for approval)
- 2 drift tube detectors, each with an active area of ~7 x 7 m^2
- each detector has 6 x-planes and 6 y-planes
- angular resolution of 12 mrad

Muon tomography: full scale prototype

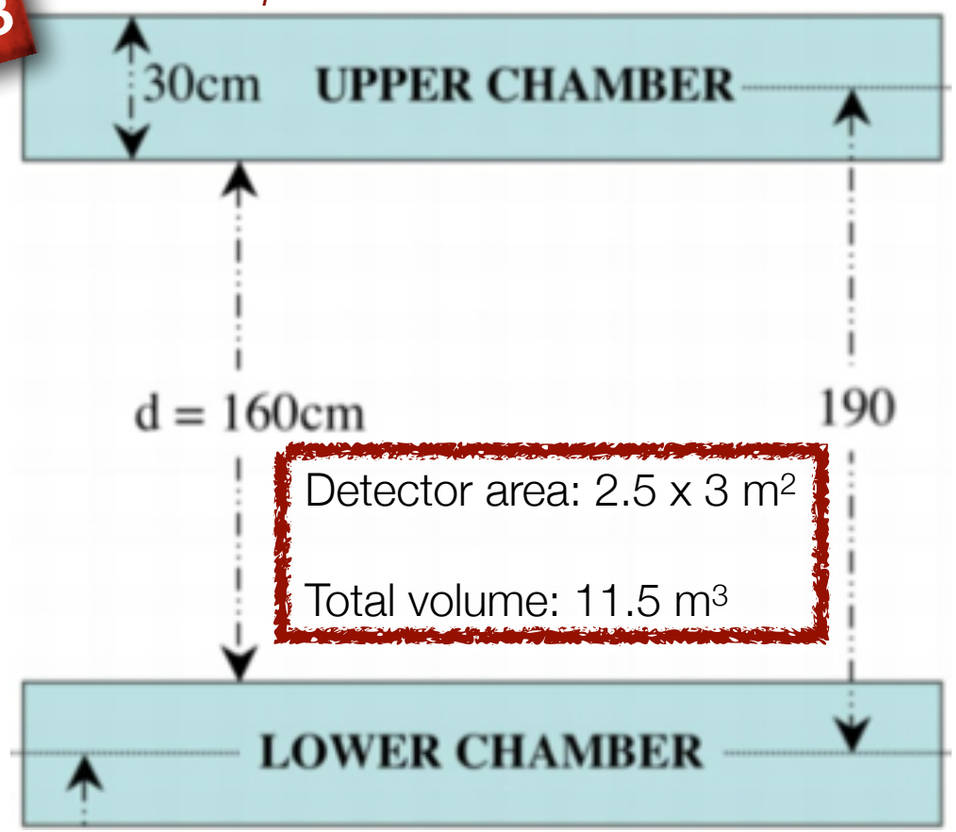
Padova University | Brescia University | Genova University

The first “large-scale” muon tomography ever built is hosted in the INFN-LNL “Laboratori Nazionali di Legnaro” (Padova)



2008

CMS spare muon “chamber” detectors



First results


Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

First results on material identification and imaging with a large-volume muon tomography prototype

S. Pesente [a], S. Vanini [a,*], M. Benettoni [a], G. Bonomi [b], P. Calvini [c], P. Checchia [a], E. Conti [a], F. Gonella [a], G. Nebbia [a], S. Squarcia [c], G. Viesti [a], A. Zenoni [b], G. Zumerle [a]

[a] INFN Sezione di Padova, via Marzolo 8, 35131 Padova, Italy
[b] University of Brescia, via Branze 38, 25123 Brescia and INFN Sezione di Pavia, via Bassi 6, 27100 Pavia, Italy
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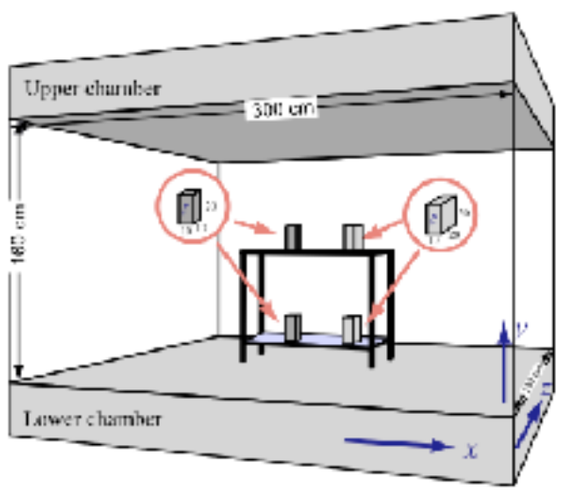
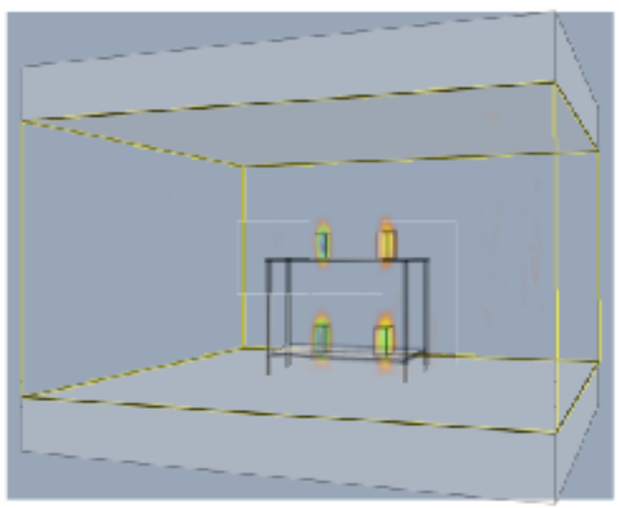
[d] Universita of Padova and INFN Sezione di Padova, via Marzolo 8, 35131 Padova, Italy

Nucl. Instr. and Meth. A 604 (2009) 738





Applications: industry

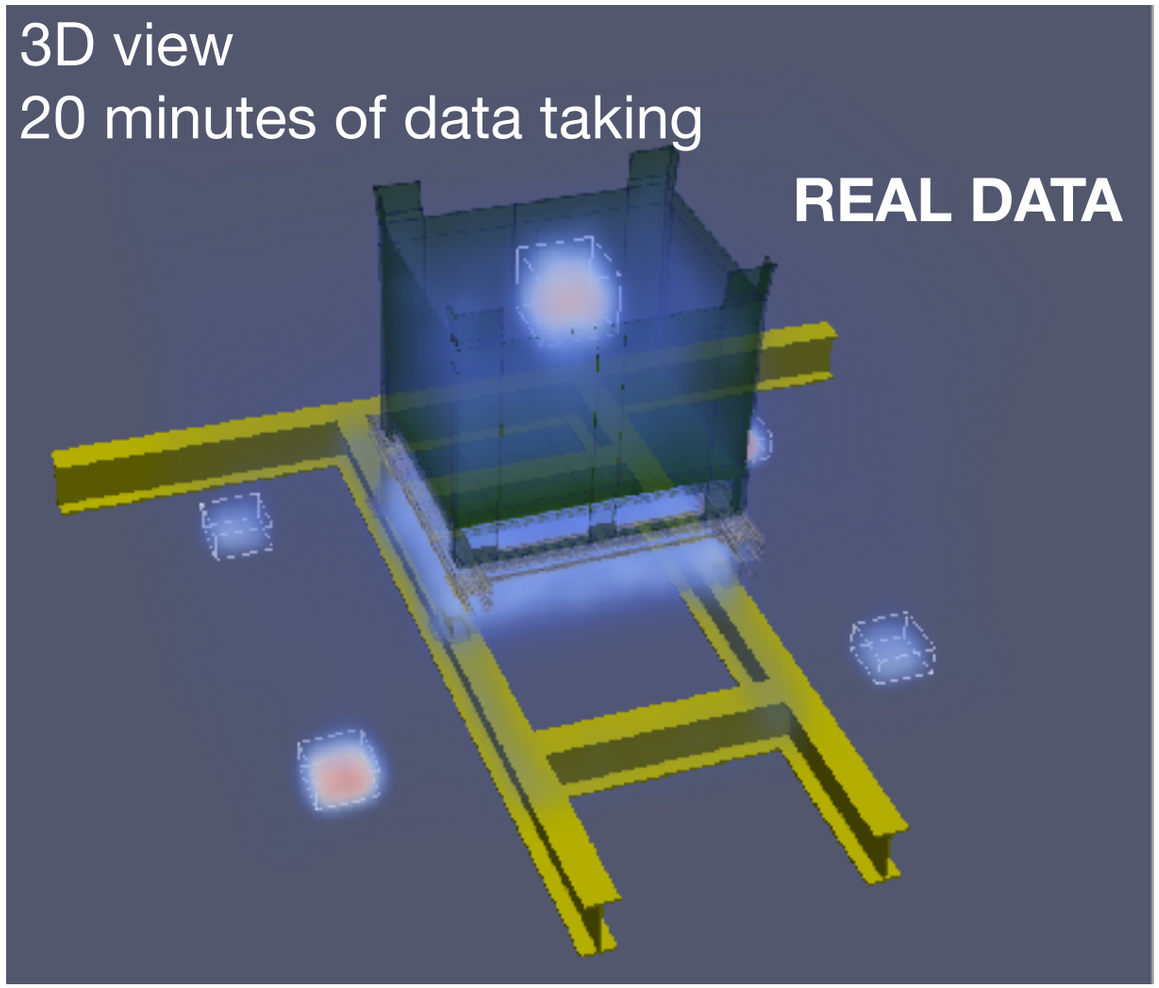
Control of trucks when entering steel foundries to detect hidden radioactive sources that if melted (as it happened in many cases around the world) can cause huge environmental and economical damages

MU-STEEL

RFCS CT-2010-000033

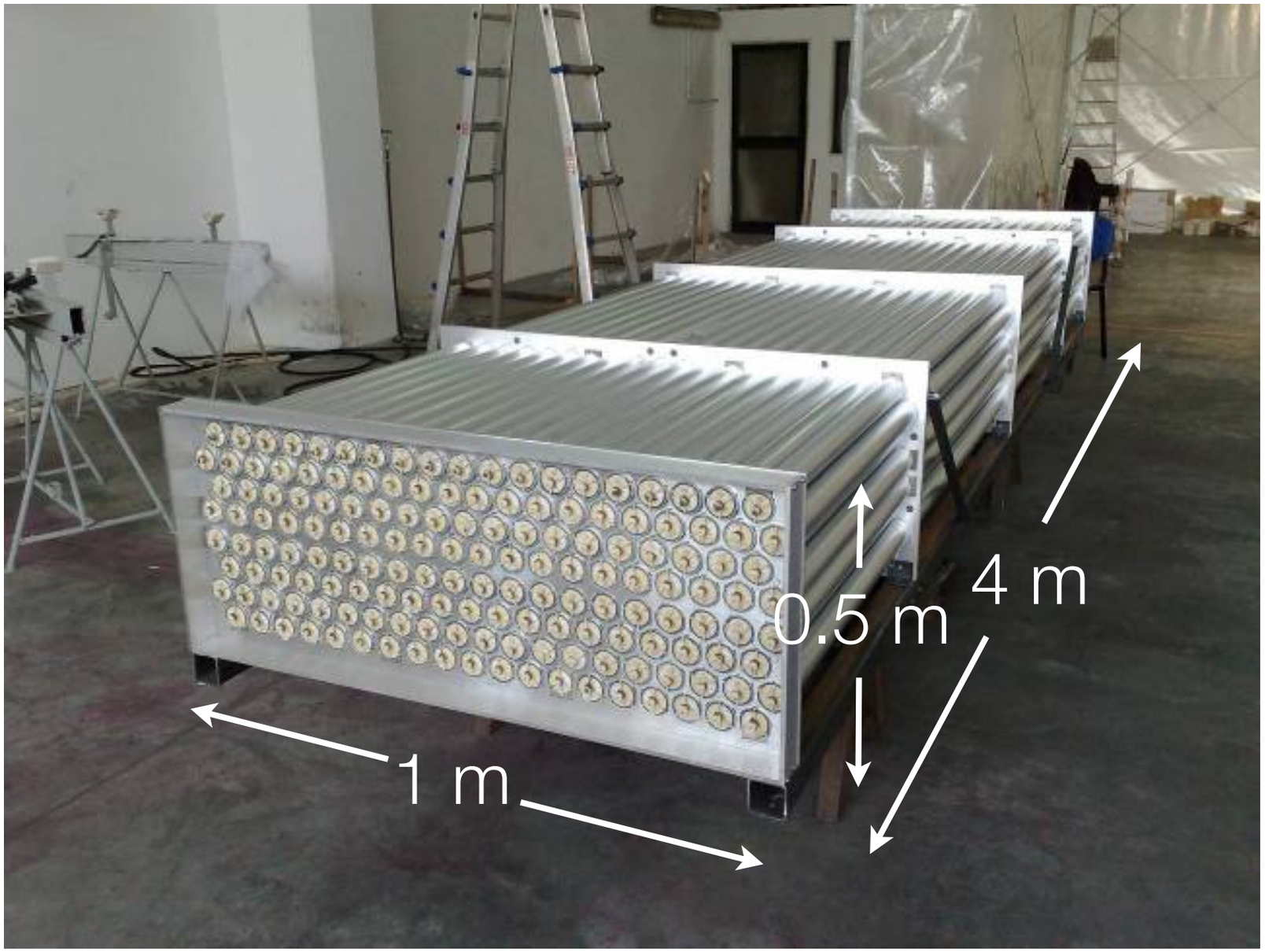
mid 2010
end 2012

Research Fund for Coal & Steel

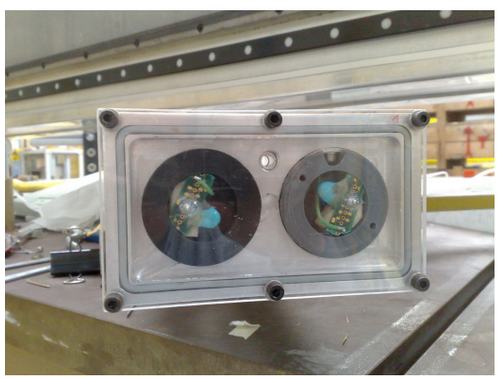


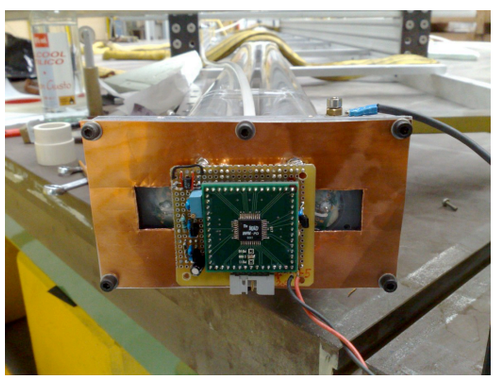
Great improvements have been obtained in the 3D image tomographic reconstruction software

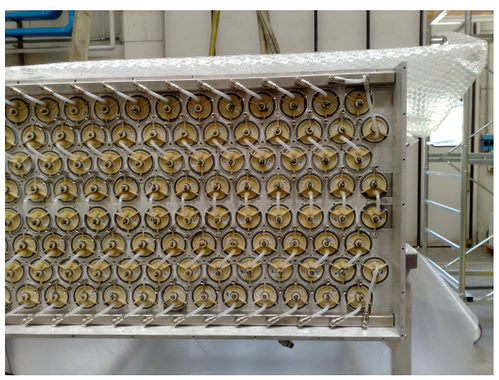
Applications: industry



some photos







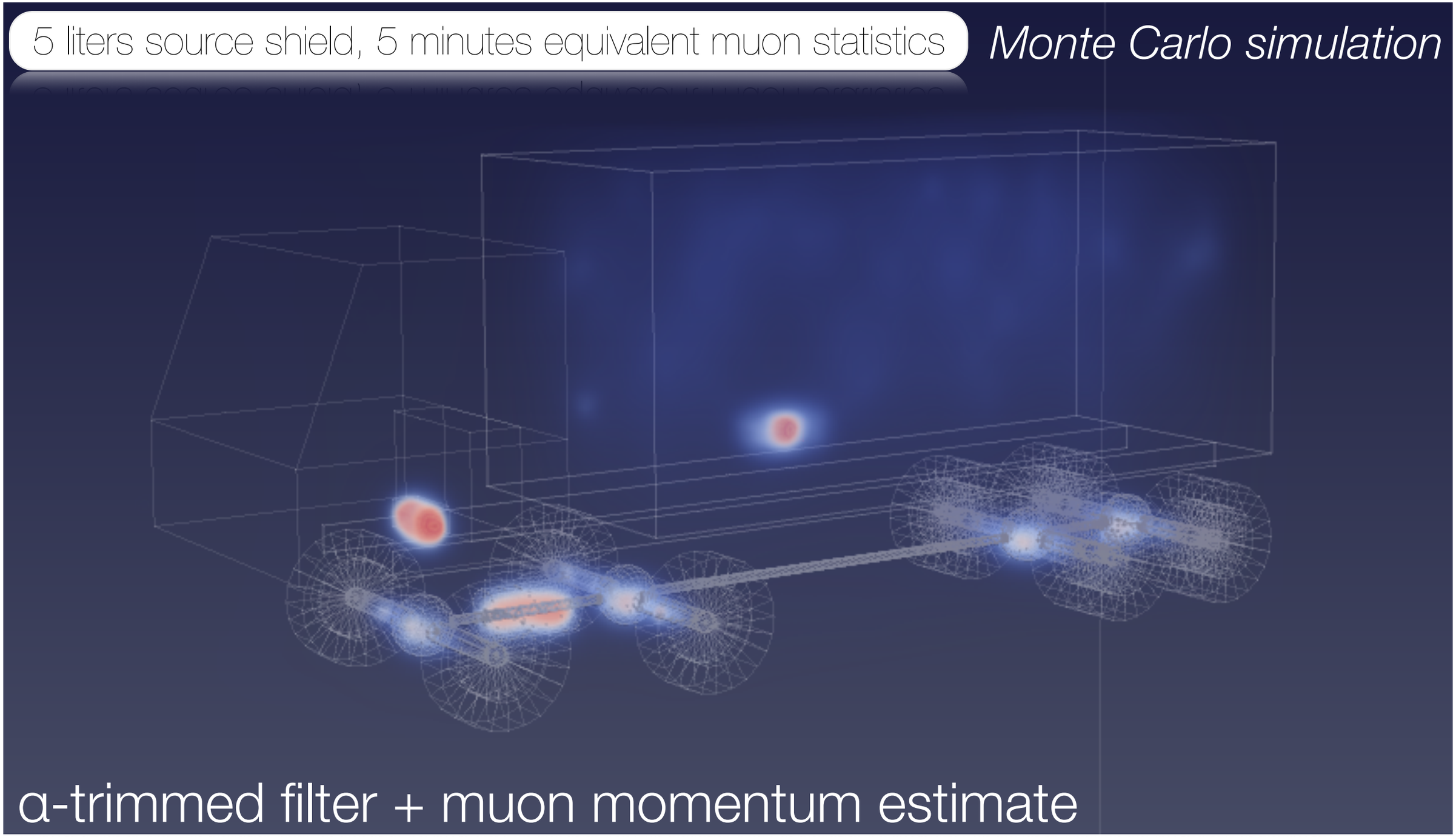
Applications: industry

MU-STEEL

cubic 5x5x5 voxels mask
Gaussian shaped smoothing (σ = 0.5)
muon momentum in-processing

5 liters source shield, 5 minutes equivalent muon statistics

Monte Carlo simulation

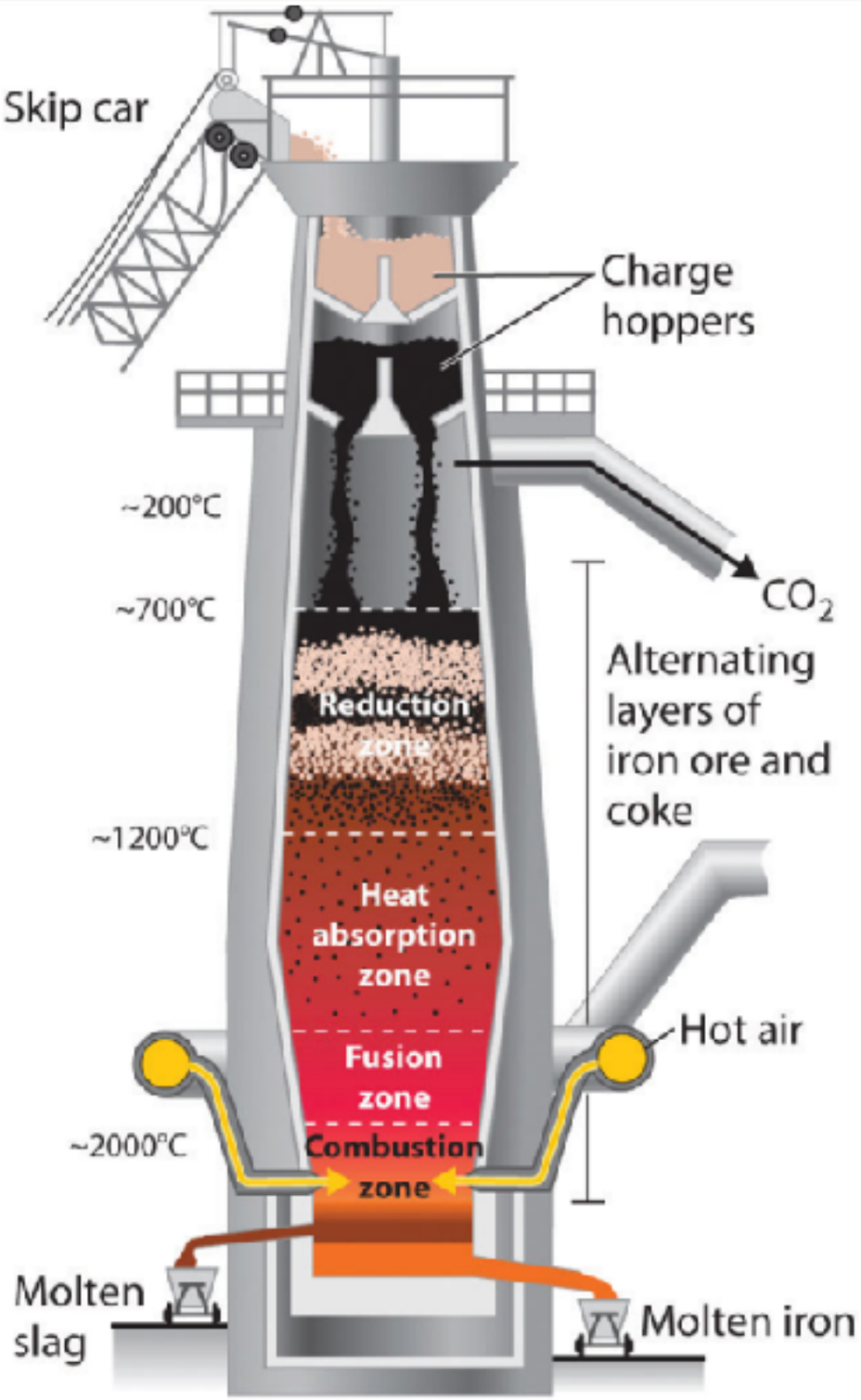


α-trimmed filter + muon momentum estimate

5 liters [2 liters] source shield (17x17x17 cm^3 [13x13x13 cm^3]) is detected in **4 [7] minutes** with 100% efficiency and 0% false alarms [MC estimates]

Applications: industry

How can we inspect the inner structure of a blast furnace?

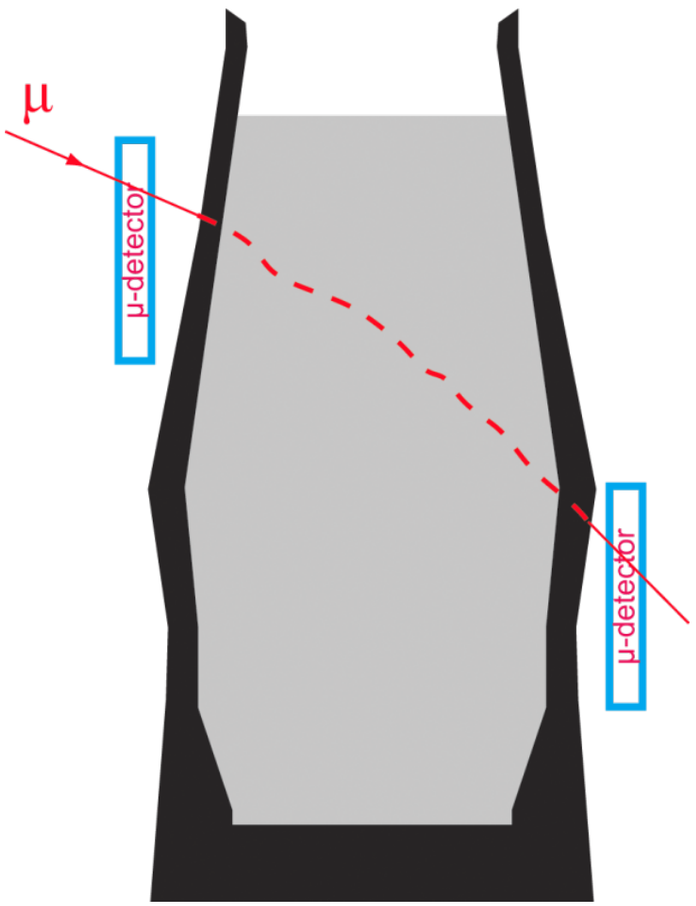


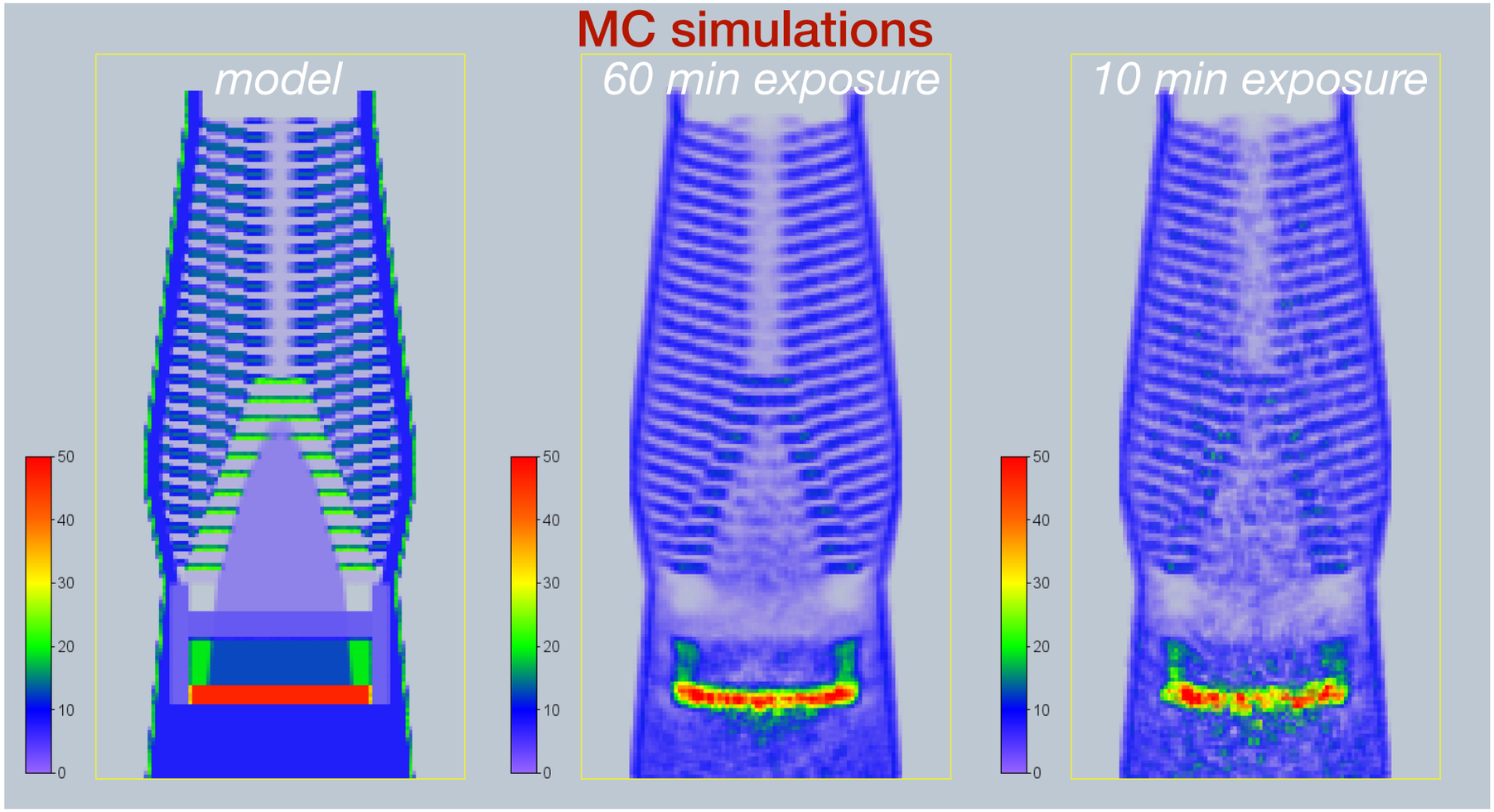
Applications: industry

Mu-Blast - RFCS CT-2014-00027

mid 2014- mid 2016

How can we inspect the inner structure of a blast furnace?





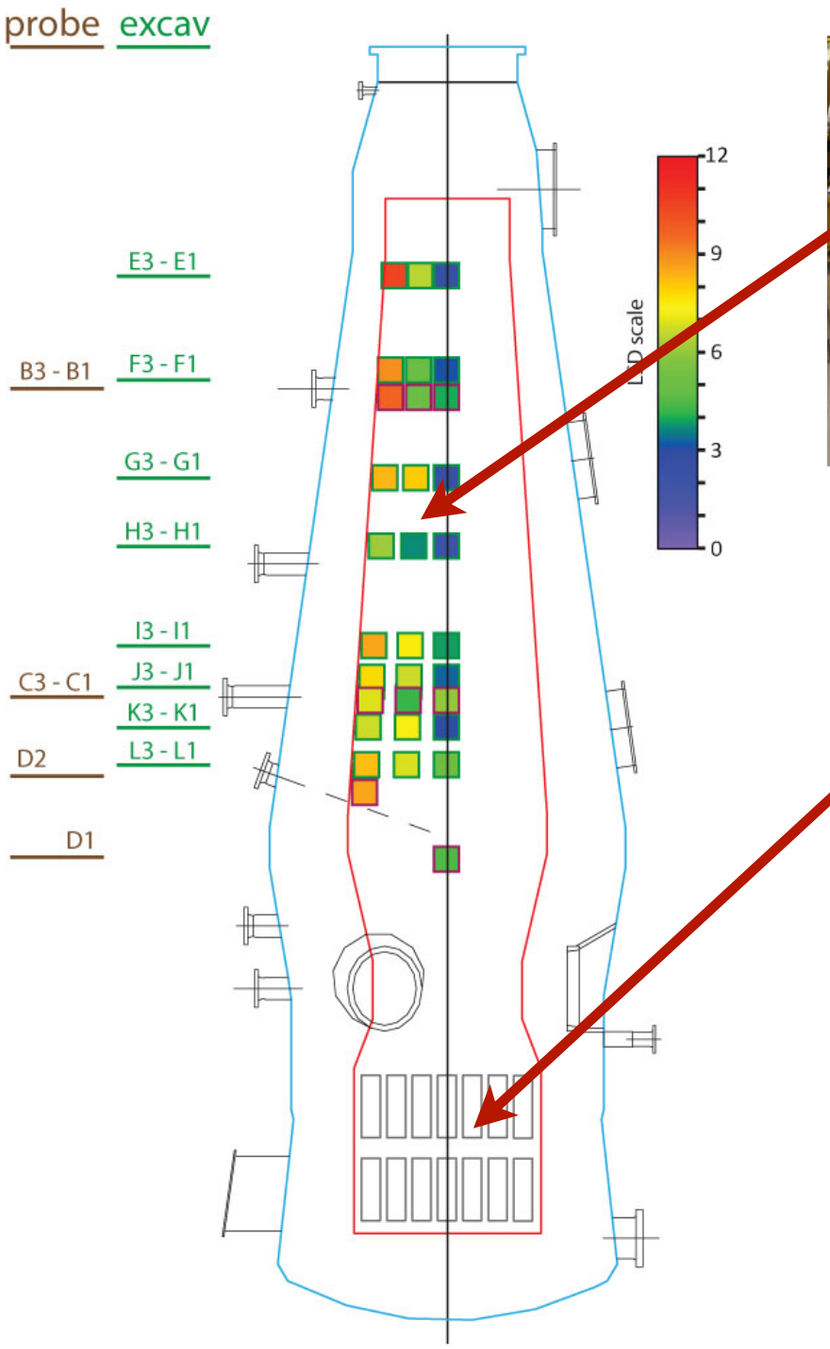
Project output:

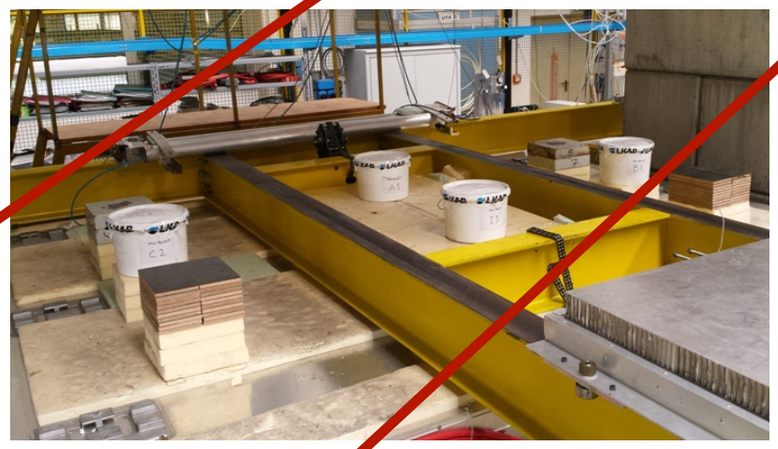
- despite the low number of “almost horizontal” muons and the movement of the burden, muon tomography imaging of the interior of a BF is possible. The detectors should be designed carefully for example to be able to give a rough estimate of the momentum.

Applications: precision measurement

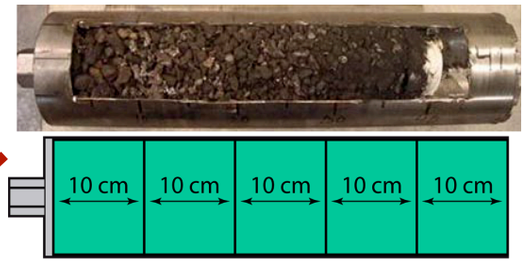
How can we inspect the inner structure of a blast furnace?

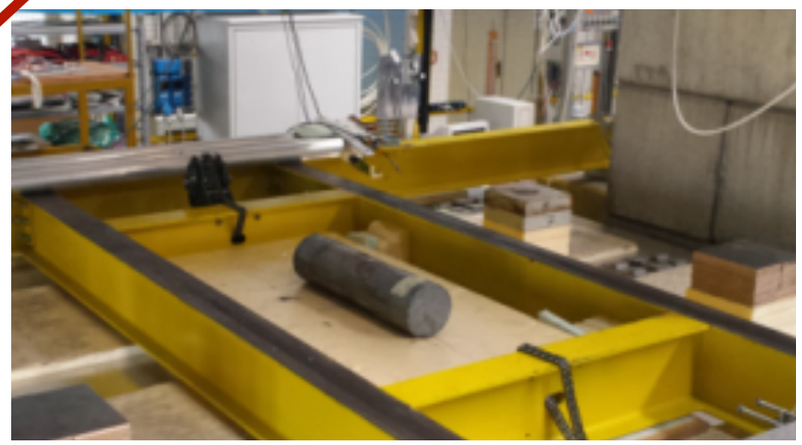
Mu-Blast - RFCS CT-2014-00027

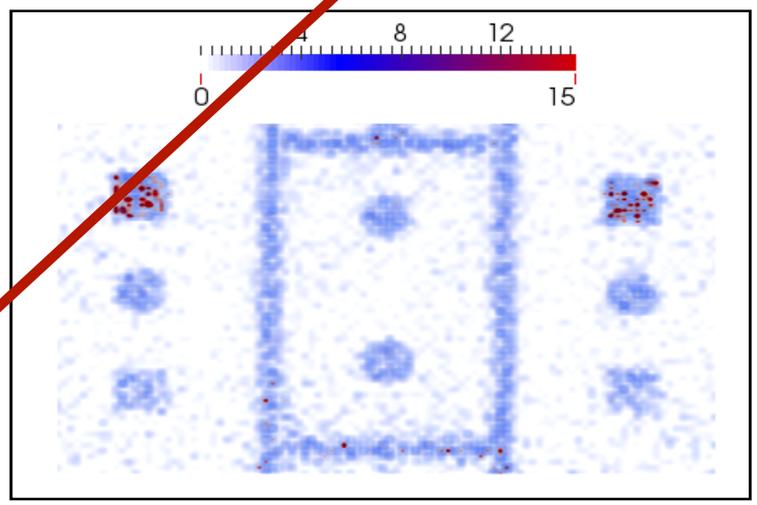


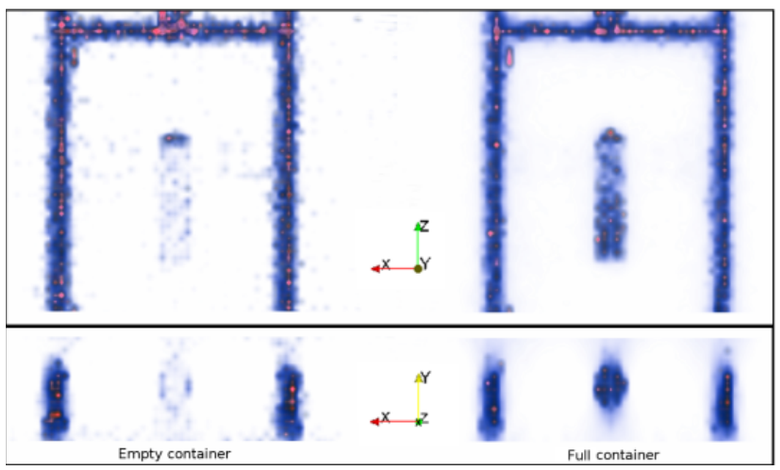


core-drilled







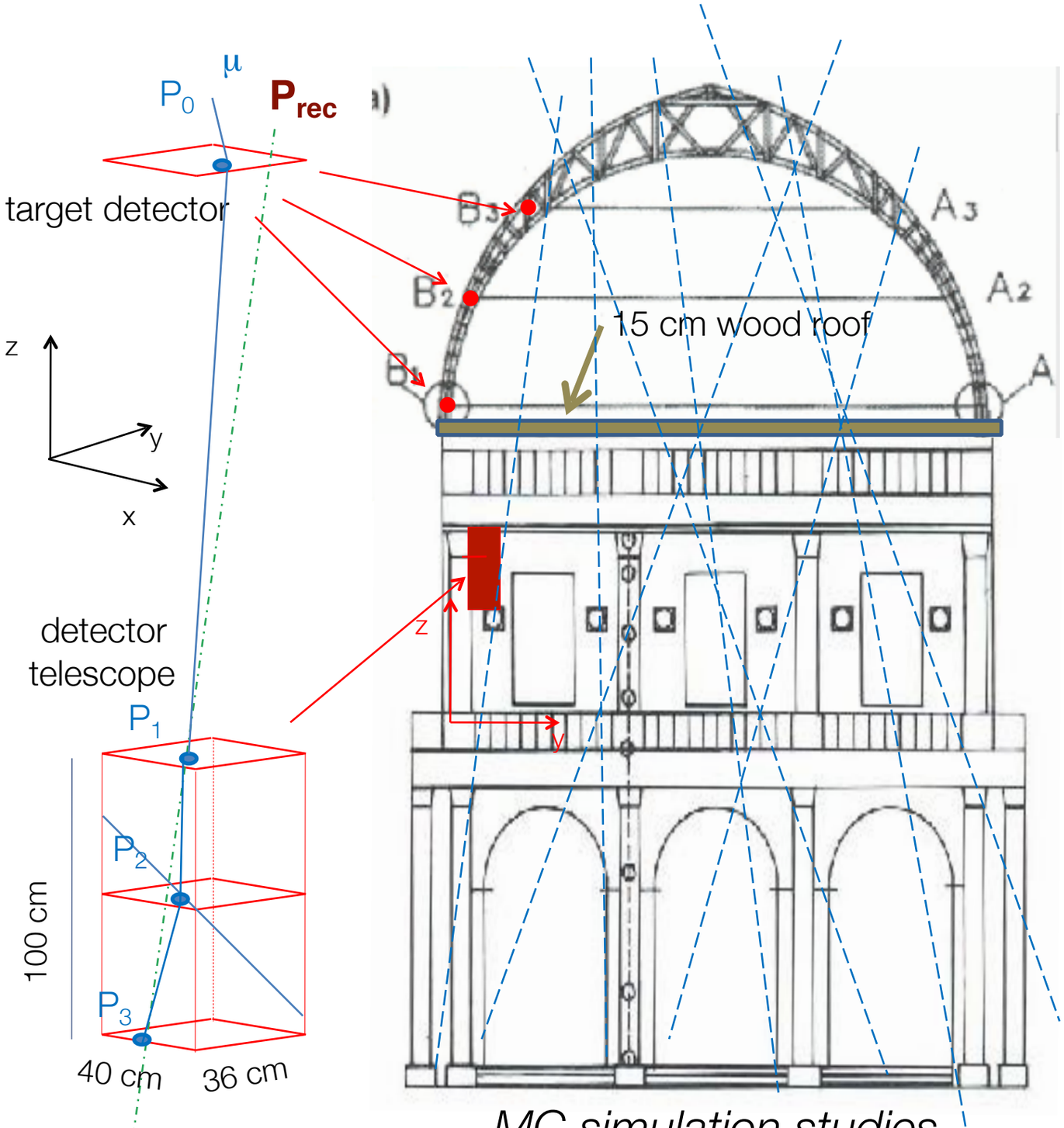


The conventional and the muon tomography measurements agree very well, within errors. The “scattering density” of a material of small samples can be measured with a precision of about 10% (clearly not competitive with chemical measurement - **interesting when the sample is not directly accessible**)

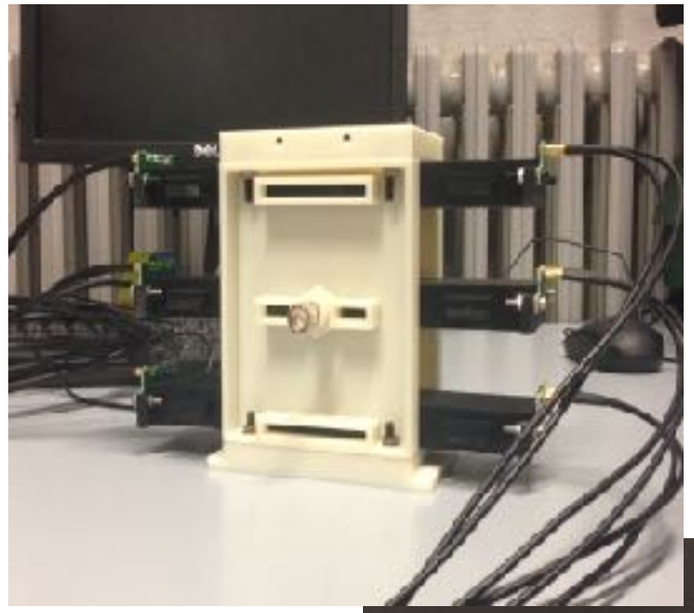
Applications: precision measurements

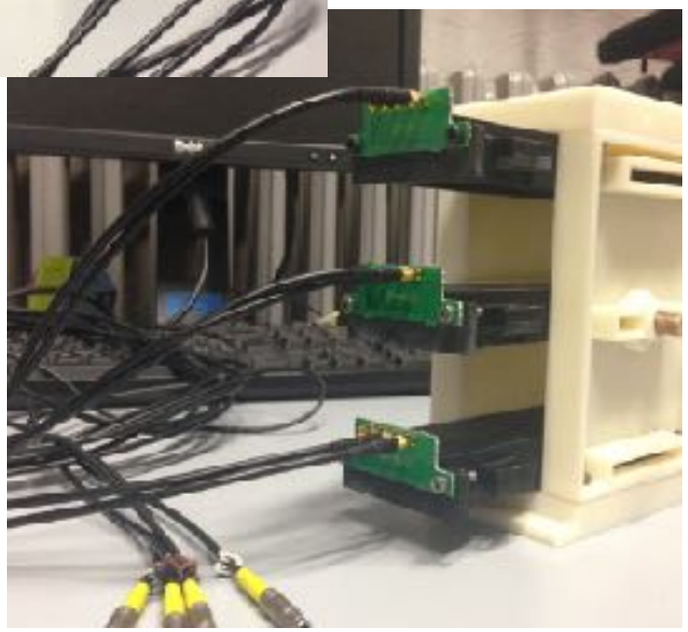
MONSTER&CO PROJECT (2013-15)

Idea: use the cosmic rays to monitor the alignment of physical part of a given structure (tower, pillar, mechanical press, historical buildings etc., etc.)



MC simulation studies





designing a small-size prototype based on scintillator fibers

Applications: water (liquid) levels

www.nature.com/scientificreports

SCIENTIFIC REPORTS

OPEN

Received: 13 November 2015
Accepted: 24 February 2016
Published: 14 March 2016

Monitoring temporal opacity fluctuations of large structures with muon radiography: a calibration experiment using a water tower

Kevin Jourde[1], Dominique Gibert[2,3], Jacques Marteau[4], Jean de Bremond d'Ars[2], Serge Gardien[4], Claude Girerd[4] & Jean-Christophe Ianigro[4]

Usage of secondary cosmic muons to image the geological structures density distribution significantly developed during the past ten years. Recent applications demonstrate the method interest to monitor magma ascent and volcanic gas movements inside volcanoes. Muon radiography could be used to monitor density variations in aquifers and the critical zone in the near surface. However, the

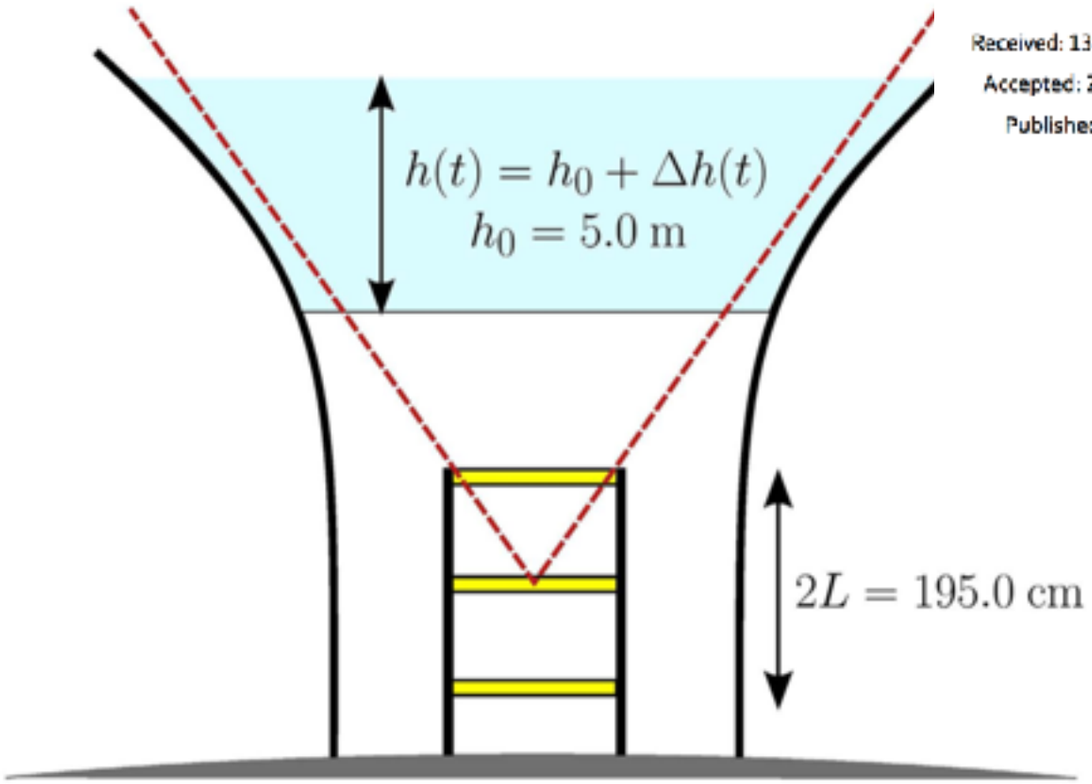


Figure 1. Sketch of the SHADOW experiment. The three yellow rectangles are the detection matrices (each with 16×16 pixels of $5 \times 5\,cm^2$), the red dotted lines encompass the detection solid angle and the blue surface represents the water volume.

costi

Costs: detector costs

Costs: in the following we will only discuss about the “raw” costs for the detectors required to build an application that will use the cosmic rays. All other costs (manpower, development, logistics, etc. etc.) are not included.

The cost of a muon detector system depends on the specific application and its requirements. However, the following rough estimates may be illustrative.

Many of the potential products below are have not been developed as off-the-shelf products. The estimates below are rough order of magnitude estimates for products produced in reasonable volumes (e.g., tens or hundreds of units), after the product development has been completed. Costs to prototype, demonstrate, develop and launch products are significantly more than the cost of a single product. The estimates below are based on volume production of these potential products.

Costs: detector costs

1. Liquid Level Measurement in Large Tanks (e.g., 10 m high tank)

Requirement: Measure height of liquid with an accuracy in the range of 10 cm over 10 m (e.g., 1%) with a liquid of known density.

Rough order of magnitude cost: 10k€

2. Portable Muon Radiography Imaging System (1m^2, 2 mrad resolution)

Rough order of magnitude cost: 50k€ (scintillator or thick GEM PCB-based detector)

3. Portable Muon Scattering Object Scanner (1m^2 panels, 2 sides)

Rough order of magnitude cost: 100k€ (scintillator or thick GEM PCB-based detector)

Costs: detector costs

4. Full Dry Storage Cask Imaging for Verification, Detection of missing bundles

Depends on size, shielding requirements and resolution

Rough order of magnitude cost: 150 – 300 k€

5. Truck/container muon portal

a. Secondary inspection of target identified by high energy x-ray system

Rough order of magnitude cost: 500 k€

b. Primary inspection of cars, minivans, small trucks

Rough order of magnitude cost: 1 M€

c. Primary inspection of full truck or containers (10 m detector length)

Rough order of magnitude cost: 2 M€

Costs: detector costs

The rules of thumb costs for muon trackers by technology for 1-side can be summarized as follow. Costs depend on size, resolution and other requirements related to the application.

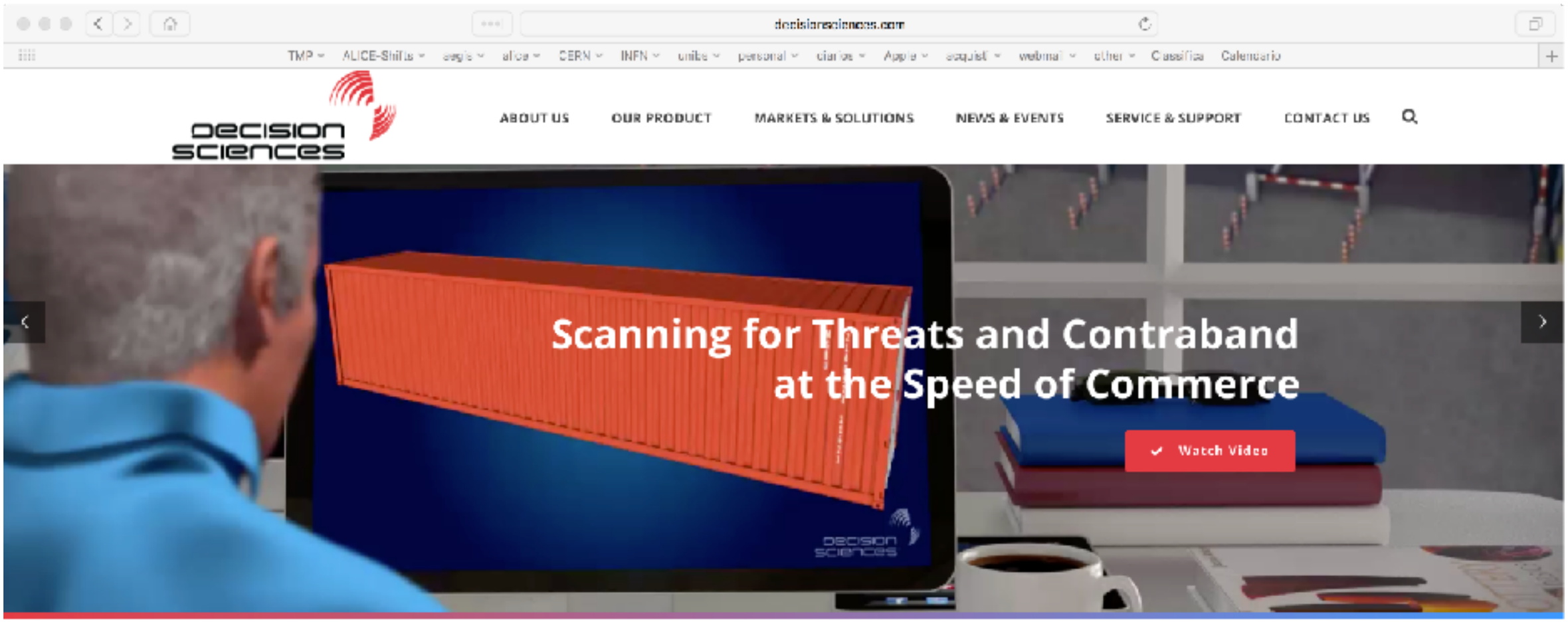
In general:

- Costs for large systems based on drift tubes, thick GEM or scintillators depend primarily on the number of channels required. Therefor costs scale with:
  - Sqrt√(Area)

- For scintillator or thick GEM type detectors there is another factor for cost. The number of channels required depends on resolution required. Therefor for these systems the cost also scales with:
  - 1 / Resolution

REALTÀ IMPRENDITORIALI NEL MONDO

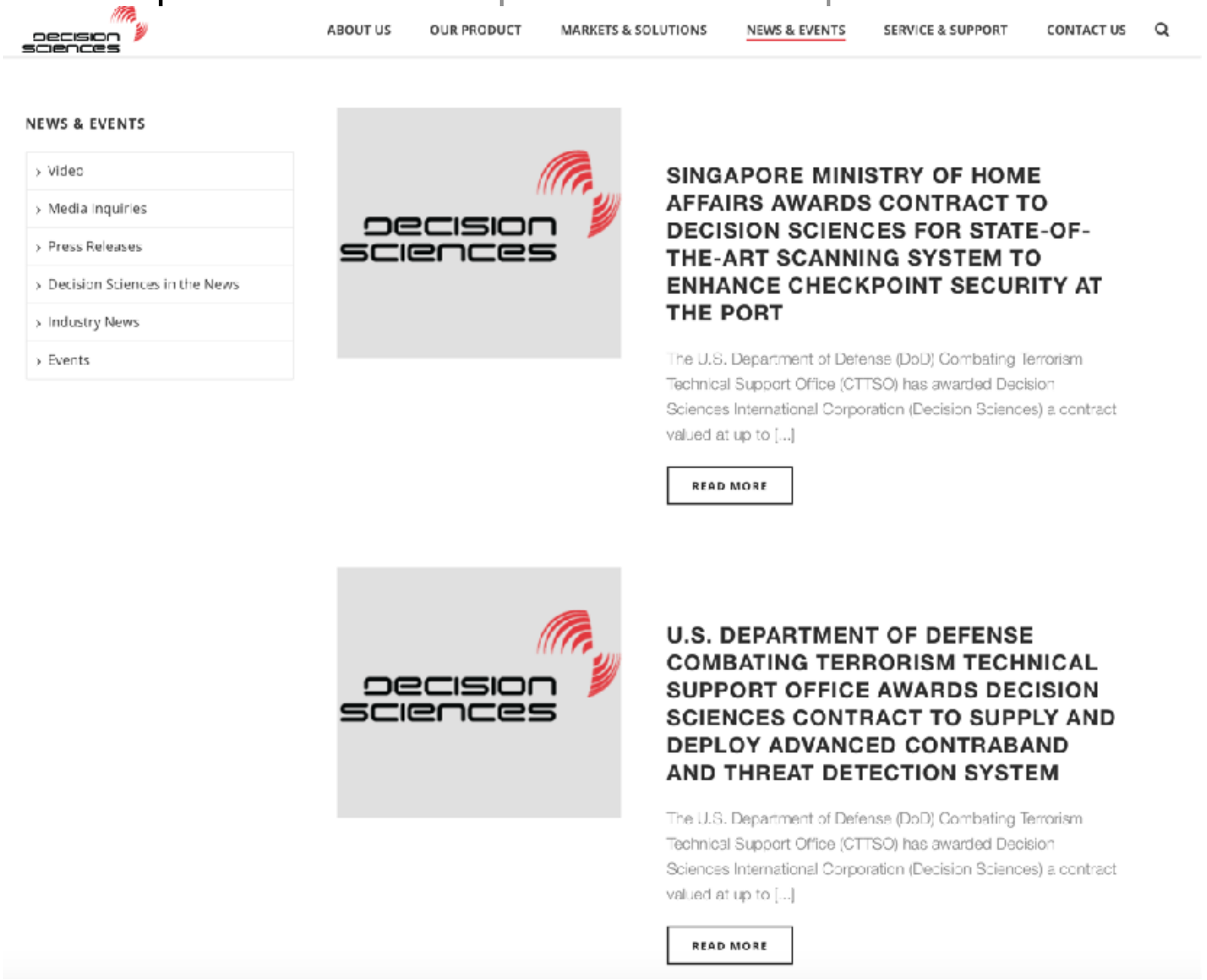
Realtà imprenditoriali: qualche esempio



Spin-off di Los-Alamos: finanziamenti pubblici (governativi) per il primo portale ora sono sul mercato

Realtà imprenditoriali: qualche esempio

Realtà imprenditoriali: qualche esempio



Realtà imprenditoriali: qualche esempio

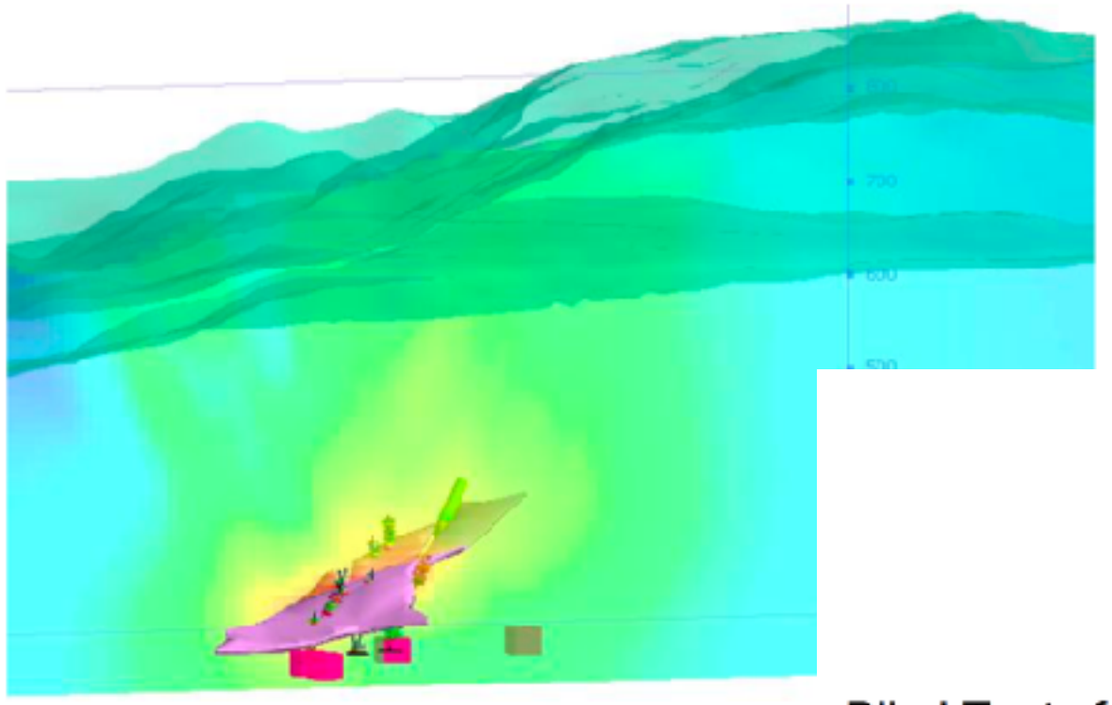
Spin-off del laboratorio canadese TRIUMF

Realtà imprenditoriali: qualche esempio

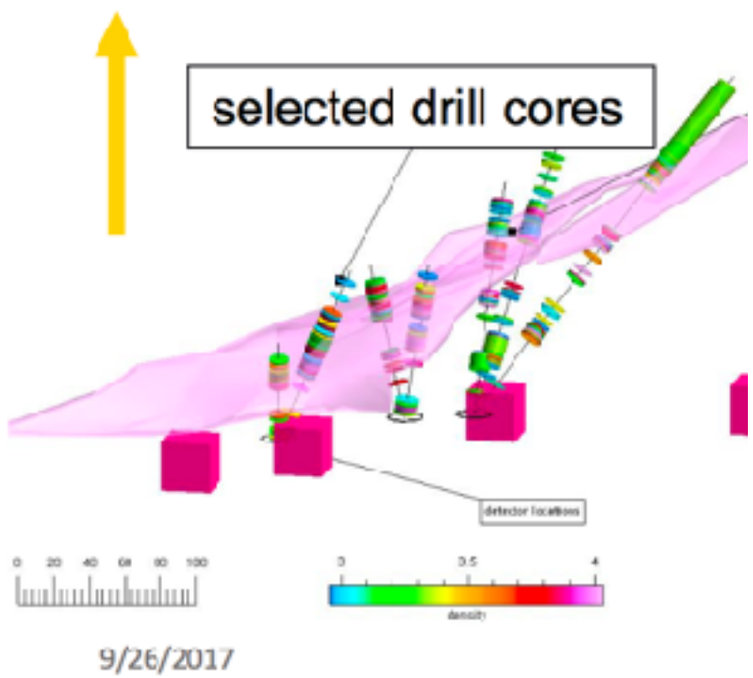
Pend Oreille Survey

Teck

GEO CRM TO MOG RAPHY TECHNOLOGIES



- **blind** muon tomography survey of MVT lead/zinc deposit in WA, USA
- 650+ meters, four sensor locations
- extensively drilled (270+ holes) allowed verification of muon data



9/26/2017

ASEG-PESA 2015
Geophysics and Geology together for Discovery
24th International Geophysical Conference and Exhibition
15–18 February 2015 Perth, Western Australia

Blind Test of Muon Geotomography for Mineral Exploration

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SUMMARY

Muon geotomography is a new geophysical imaging technology that creates 3D images of subsurface density distributions. Similar in concept to computed tomography scanning, muon geotomography uses naturally occurring cosmic radiation that gets attenuated when traversing matter. Cosmic ray muon data were acquired in the Pend Oreille Zn-Pb mine in Metaline Falls, Washington State, USA without prior knowledge of the presence or absence of ore bodies. The resulting 3D density distribution

of ore bodies in the region being surveyed was provided prior to the study.

MUON GEOTOMOGRAPHY AT THE PEND OREILLE Zn-Pb MINE

The Pend Oreille mine is a Mississippi Valley Type (MVT) Zn-Pb deposit located in Metaline Falls in northeastern Washington State, USA at an elevation of approximately 2300 ft above sea level. The region's mountainous topography was measured by an aerial LIDAR survey. St. Marie and Kesler

Realtà imprenditoriali: qualche esempio

Lingacom

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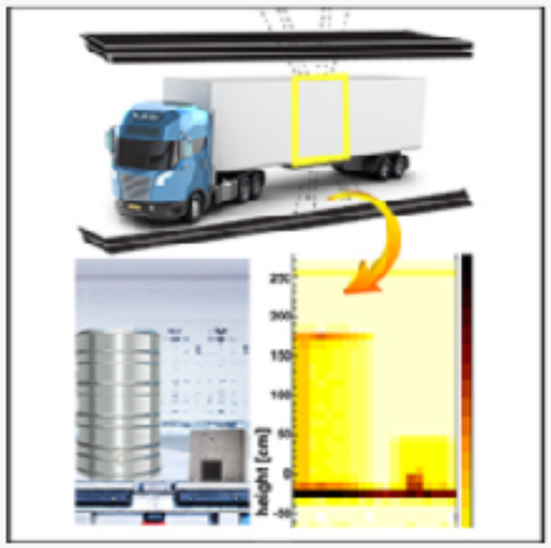
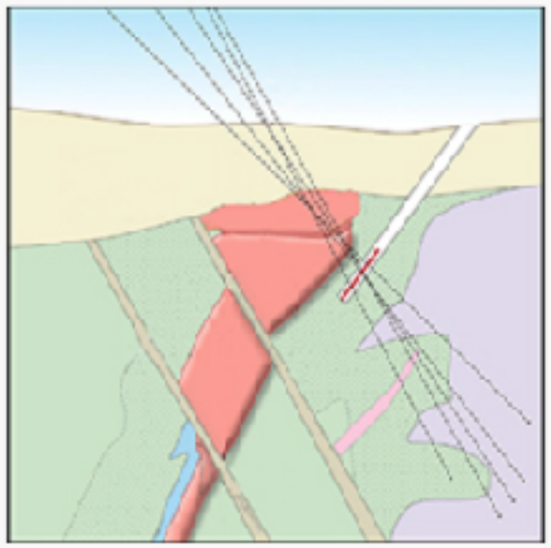
Solutions



Inspection of Containers & Vehicles

solutions for seaports, airports, cross border points



Mineral Mapping for Mining Exploration

solution for minerals exploration

Imaging of Large Geological Objects

solutions for map geological and civil objects

Realtà imprenditoriali: qualche esempio

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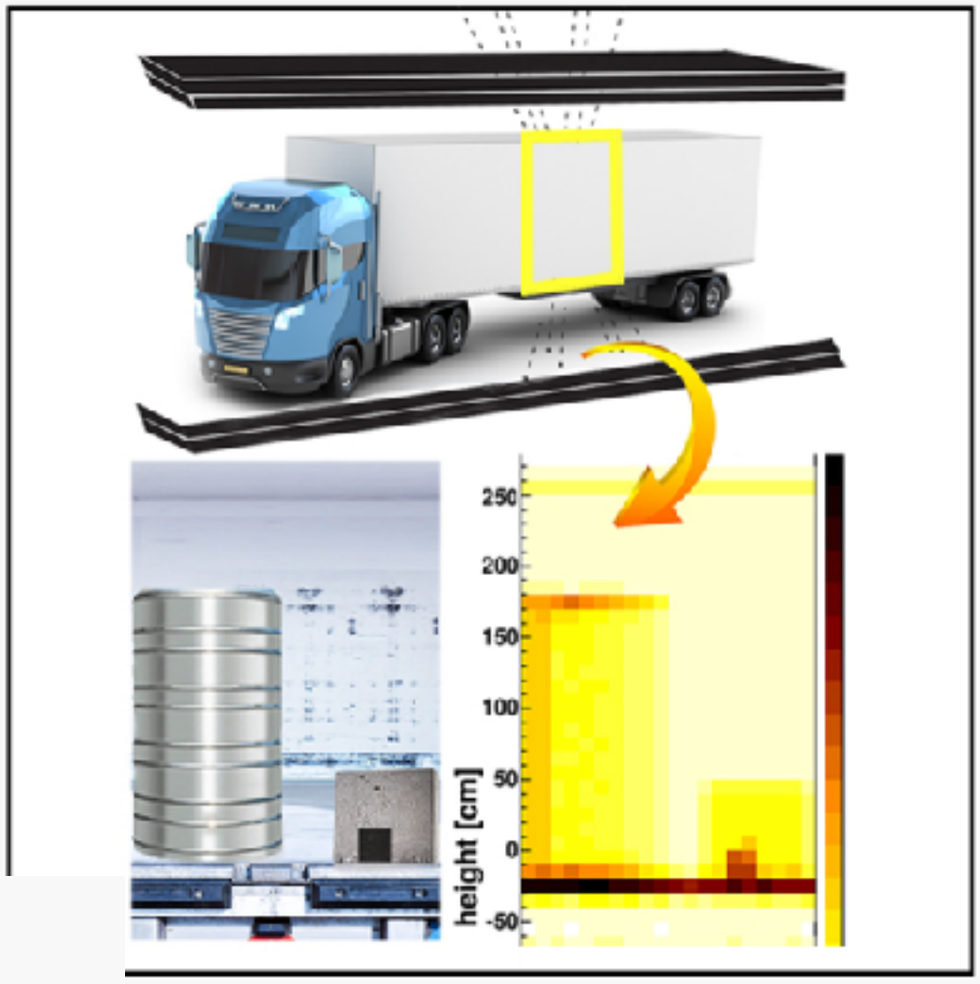
Inspection of Containers & Vehicles

Lingacom's state of the art Muon detection system provide security agencies and personnel with an efficient and radiation-free solution for seaports, airports, border controls, critical infrastructure, and other sensitive locations. Our technology is useful in detecting high-Z materials, such as shielded nuclear and radioactive materials (i.e. "Dirty Bombs") in containerized cargo and vehicles. Lingacom's proprietary detection solutions and 3D imaging algorithms leverage the penetration of Muon particles through all materials in dense containers, especially those in mid- to high-attenuating cargo.

- Imaging of Large Geological and Civil Objects
- Inspection of Shipping Containers and Vehicles
- Mapping Minerals in Mining Exploration



Lingacom Awarded 1 Million Euro by Horizon 2020 for Muon-Based Vehicle Scanning Solution

By Vered Mavor | February 11, 2016 | Press Releases | No Comments

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LYNKEOS TECHNOLOGY LTD

HOME ABOUT US OUR TECHNOLOGY

NATURAL SOLUTIONS TO MANMADE PROBLEMS

ABOUT LYNKEOS

Lynkeos was formed based on advanced research carried out at the University of Glasgow. We have worked in partnership with the UK nuclear industry and have commercialised Muon Tomography for use in a range of applications.

Lynkeos is the first company in Europe that specialises in Muon Tomography technology, which addresses some of the most complex technical challenges facing society today.

March 10, 2017

Lynkeos Secures £1.6 million Innovate UK First-Of-A-Kind Deployment of Innovation Contract

It has just been announced that Lynkeos Technology Ltd. has been successful in their application for funding through Innovate UK's pioneering First-Of-A-Kind (FOAK) Deployment of Innovation competition. This 12-month 100%-funded contract worth £1.6 million will begin on 1st April 2017. During this yearlong contract, Lynkeos will work alongside the University of Glasgow, National Nuclear Laboratory ...

Spin-off (Start-up) dell'Università di Glasgow

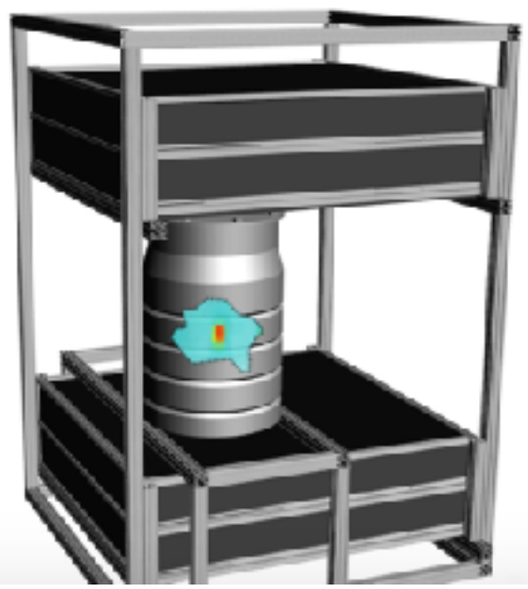
USING MUON TOMOGRAPHY

High-energy cosmic rays create showers of particles (Muons) in the upper atmosphere.

Using the **Lynkeos Muon Imaging System** we are able to noninvasively scan objects and differentiate between different materials.

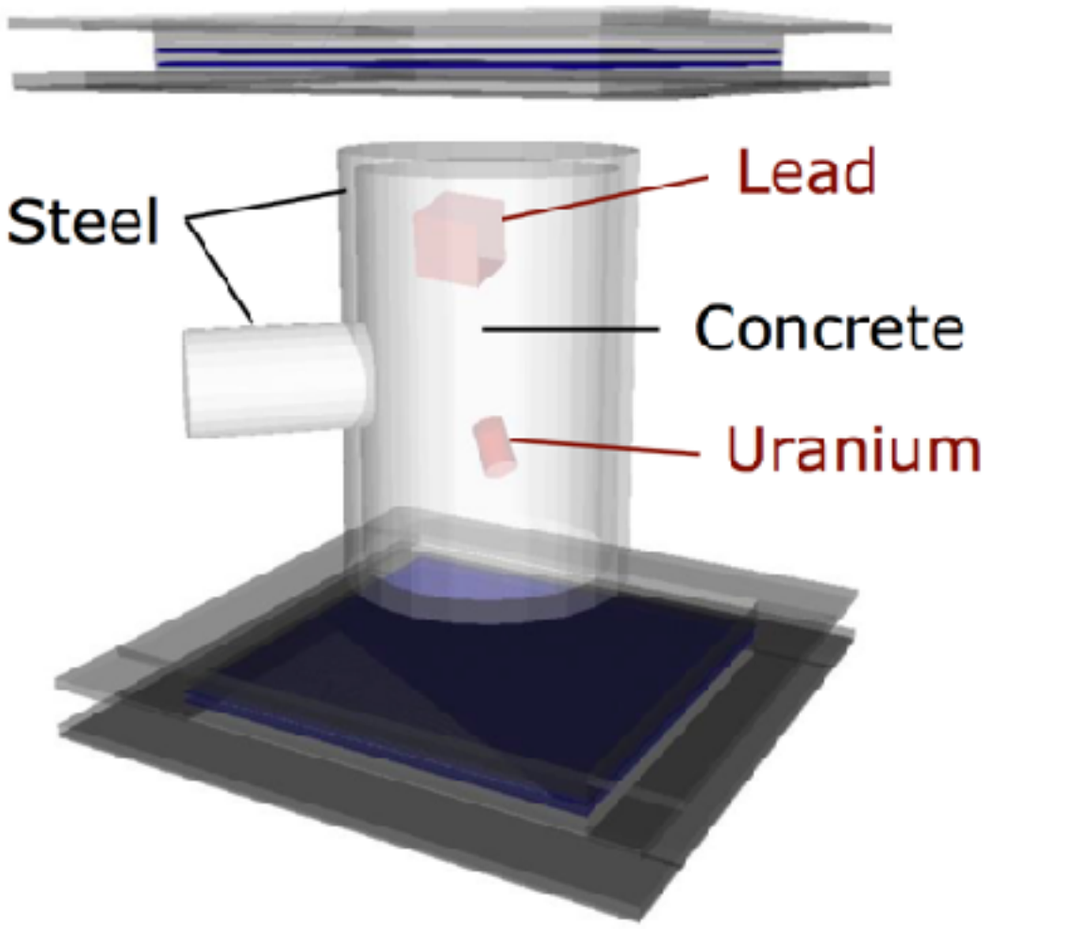
The system is ideal for scanning Intermediate Level Nuclear Waste.

MORE



Realtà imprenditoriali: qualche esempio

Small-scale Prototype



30cm x 30cm x 30cm
active volume

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21

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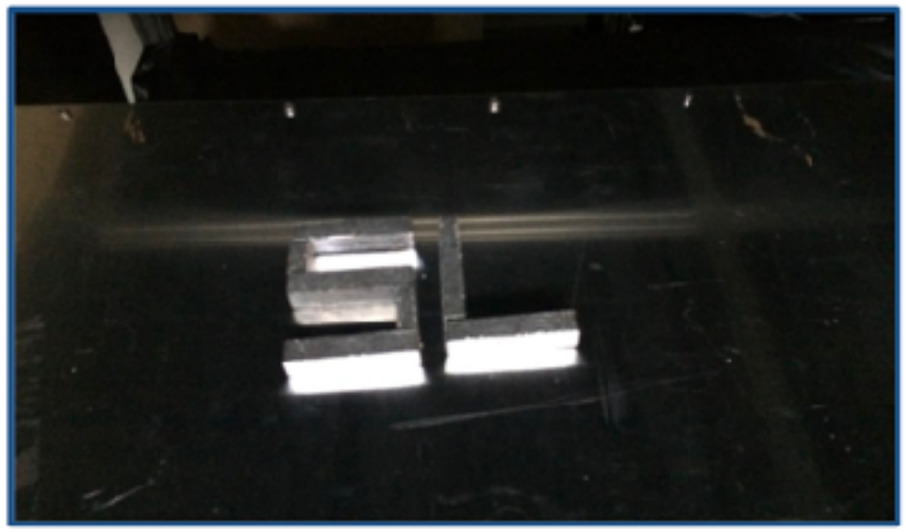
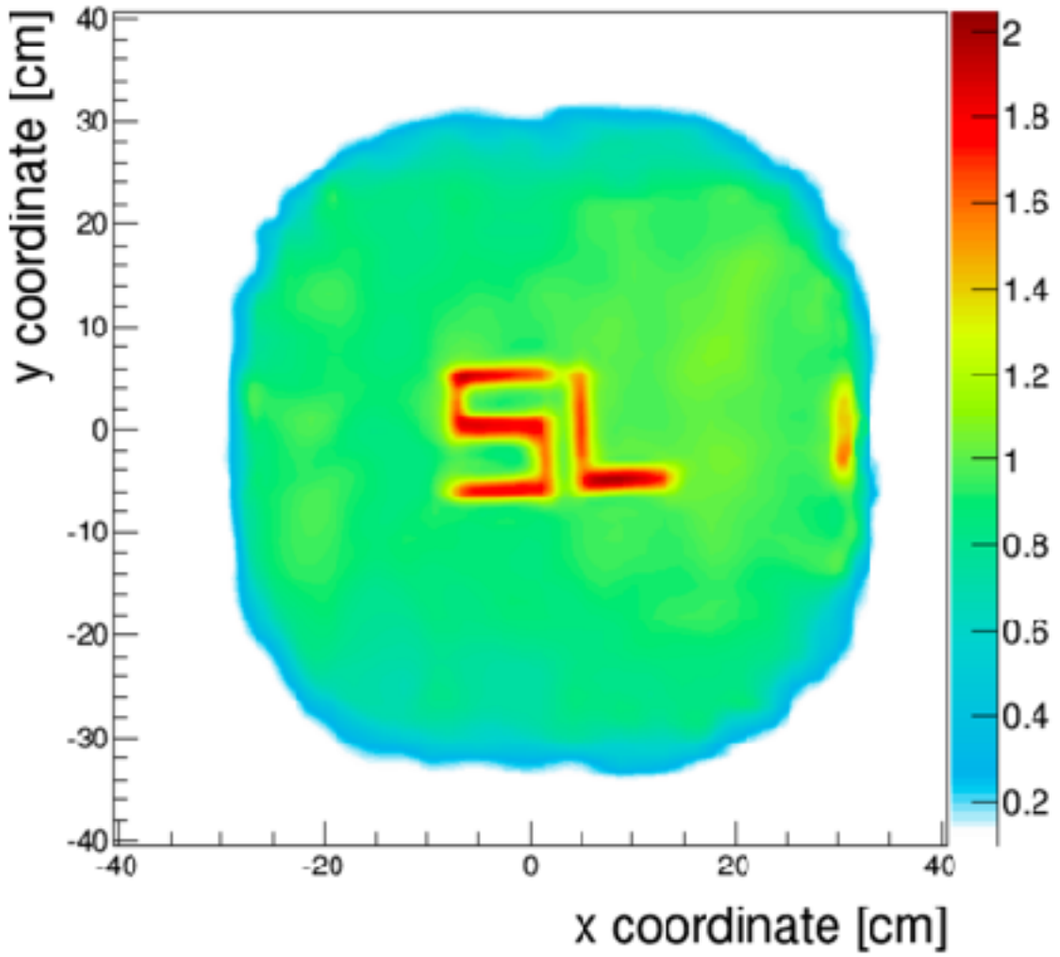
First Full-scale Image



1.5cm thick lead letters



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23

Realtà imprenditoriali: qualche esempio

Spin-off dell'Università di Santander

Realtà imprenditoriali: qualche esempio

MUON systems

INICIO TECNOLOGÍA SERVICIOS NOSOTROS EMPLEO CONTACTO Español

INDUSTRIA

Control de calidad en paredes de altos hornos y calderas industriales:

Un problema muy común en el ámbito de la industria siderúrgica es la predicción correcta y precisa del desgaste paulatino de las paredes de los altos hornos. Debido a las altas temperaturas de la colada (material contenido en el horno), las paredes sufren un desgaste, comprometiéndose así su integridad estructural.

Los hornos son con frecuencia enfriados y vaciados para comprobar el nivel de este desgaste, con el consecuente gasto económico. La tomografía muónica puede ser de gran ayuda en la determinación de este deterioro, sin la necesidad de detener o enfriar el horno.

SEGURIDAD

Detección de materiales pesados en contenedores de mercancías dentro de los puertos:

La circulación no controlada de material fisible como el Uranio constituye hoy en día un grave problema de seguridad para muchos países. La entrada ilegal de uranio oculto en contenedores destinados al transporte marítimo es una amenaza potencial y requiere de nuevas tecnologías de detección.

La tomografía muónica es una técnica particularmente adecuada para este tipo de aplicación, ya que, debido a su alta penetrabilidad, puede traspasar los materiales que se encuentren alrededor del elemento fisible, y que actúan como "escudo" para otro tipo de radiaciones como los rayos X.

INGENIERÍA CIVIL

Sistemas de inspección portátiles para el estudio de cavidades, vetas de material y fallas estructurales:

Tanto en minería como en el ámbito de la ingeniería civil resulta fundamental conocer las propiedades del interior de las estructuras. La aparición de cavidades, burbujas o de zonas de diferente densidad pueden suponer un riesgo para la estabilidad de dichas estructuras. De la misma forma, la presencia de zonas de mayor densidad puede ser indicativa de una veta de material en el contexto de la

Este tipo de problemas, en el que aparecen potencialmente estructuras de gran tamaño, resulta muy complicado para las técnicas tradicionales de tomografía. La alta capacidad de penetración de los muones resulta muy adecuada para este tipo de aplicaciones.

CONCLUSIONI

Final remarks

Muon tomography has taken ground as a new technique for civil applications

Pros

✓ natural radiation, continuous

✓ no artificial source, no radiological risks

✓ muons cross materials [it is possible to see “through” - with optical systems it is not]

✓ measurements with “standard” techniques in physics

Cons

✓ the need to accumulate enough statistics and thus wait the required time

✓ best suited for “vertical” applications

✓ applicable only to “static” or “quasi static” situations

Conclusions

- ... as in many other fields of physics, the progress in **research** can generate applications for **everyday life** ...

- the technology of **nuclear and particle detectors**, used for apparatuses calibrations since decades in physics research (even in LHC experiments) are now being used (or starting to be used) in various **civil applications**

- the measurement of the **muons** at the entrance/exit of a given volume can give important insights of the geometry and composition of the content of such volume. This technique is generally called **Muon Tomography**

- various applications have been tested and are being now developed:
  (inspections of large volumes such as volcanos and blast furnaces, geological inspections, monitoring of nuclear waste, detection of “hidden” nuclear materials, monitoring of stability, etc.)

- this field is **evolving quickly** and there are many possibilities for new applications ... **let’s see what the future (and the muons) hold for us**...

Thank you for your attention