The MUTOMCA Project: Investigation of muon tomography for re-verification purposes of spent fuel casks

A. Lorenzon[1,2], P. Andreetto[2], K. Aymanns[3], M. Balling[4], M. Benettoni[2], N. Bez[2], G. Bonomi[5,6], L. Castellani[2], P. Checchia[2], E. Conti[2], J. Dackner[7], F. Gonella[2], A. Jussofie[4], F. Montecassiano[2], M. Mosconi[7], M. Murtezi[7], J. Niedermeier[4,8], I. Niemeyer[3], J. Pekkarinen[7], D. Scarpa[9], M. Turcato[2], G. Zumerle[2].

[1] Dipartimento di Fisica e Astronomia, Università degli Studi di Padova, Italy.
[2] Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Padova, Italy.
[3] Forschungszentrum Jülich, Germany.
[4] BGZ Gesellschaft für Zwischenlagerung mbH, Germany.
[5] Dipartimento di Ingegneria Meccanica e Industriale, Università degli Studi di Brescia, Italy.
[6] Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Pavia, Italy.
[7] European Commission, Directorate General for Energy, Luxembourg.
[8] Lehrstuhl für Nukleartechnik, Technische Universität München, Germany.
[9] Istituto Nazionale di Fisica Nucleare (INFN), Laboratori Nazionali di Legnaro, Italy.

The MUTOMCA (MUon TOMography for shielding CAsks) project is dedicated to investigate the suitability of muon tomography for the re-verification of loaded spent fuel casks. The loss of continuity of knowledge (CoK) in the hypothetical case that the containment and surveillance measures of EURATOM/IAEA would temporarily fail during the decades of dry storage of spent fuel, requires a technology for re-verification of the spent fuel enclosed in self-shielding casks. In such a case the inspectorates need to have a high degree of assurance on the amounts of nuclear material stored in the dual-purpose casks (casks for transport and storage). The re-verification is particularly challenging for conventional non-destructive-assay (NDA) methods, as the thick-walled CASTOR® V cask considerably attenuates the radiation emitted by the spent fuel.
With the aim of proving the ability of muon tomography to detect a diversion of fuel assemblies in closed spent fuel casks, a two-module muon detector was designed, developed, constructed and commissioned. The detector, which is based on drift tube technology, was used in a field trial in the first months of 2023 in a dry storage facility in Germany to measure two CASTOR® V casks with different inventories. During the implementation of the field trial sufficient data was recorded to secure the evaluation of the capability of the muon tomography to fulfil the safeguards requirements for re-verification. Based on the results of the field test, this contribution will assess the potentials and the drawbacks of the experimental apparatus for the application of the reconstruction technique and will present a preliminary evaluation of the data.
The MUTOMCA research project was established by INFN Padova and Forschungszentrum Jülich GmbH (FZJ) in collaboration with BGZ Company for Interim Storage (BGZ Gesellschaft für Zwischenlagerung mbH) and the European Commission, Directorate-General for Energy.

1. Introduction

Since 2011 Germany has started to phase out the production of nuclear energy stepwise; finally, the last three operating nuclear reactors have been recently taken off the power grid in April 2023. Hence, 17 German nuclear power reactors have been shut down in the past twelve years. Approximately in 2028, the defueling of the spent fuel ponds at the reactor sites will be completed. The spent fuel will have been loaded into transport and storage casks and transferred to the dry spent fuel storage facilities (SFSFs) close to the reactor sites. In total more than 1.000 spent fuel

casks will be stored in 16 German SFSFs for several decades until a disposal facility will become available.
The MUTOMCA (MUon TOMography for shielding CAsks) project investigates the question whether muon tomography is suitable for the re-verification of loaded spent fuel in case of loss of continuity of knowledge (CoK). The spent fuel casks are stored in the interim storages for decades. Temporary loss of CoK, due various internal or external factors, cannot be excluded. The validity of the results of conventional non-destructive assay (NDA) methods is limited with respect to the reverification of loaded spent fuel casks, since these thick-walled self-shielding casks significantly attenuate the radiation emitted by spent fuel assemblies. Ultimately, it must be demonstrated that the muon tomography technology provides a sufficient level of precision to enable EURATOM/IAEA to obtain a sufficiently reliable knowledge of the quantities of nuclear material present in spent fuel casks.
Muon tomography is an innovative and non-invasive imaging technique that exploits cosmic-ray muons to investigate the content of large, dense and otherwise inaccessible volumes. Muons are charged elementary particles; they are naturally produced in the earth atmosphere by the interactions of cosmic rays coming from the outer space with the atomic nuclei of the atmosphere and they reach the ground with a flux rate of ~170 Hz/m^2 [1]. The natural abundance and the continuous availability of muons are two crucial factors in the development of imaging techniques based on these particles. Besides these two aspects, the use of muon tomography has several advantages over other imaging techniques: it is non-invasive, it does not emit harmful radiation and it can penetrate through thick layers of materials. For these reasons, muon tomography has found applications in a wide range of fields, including geology, archaeology, civil engineering, transport and nuclear controls [2].
Recently, muon tomography has been proposed also as a potential NDA for loaded spent fuel casks [3]. The MUTOMCA project was born precisely with this intention; a detailed description of the project is given in the following Section 2.

2. Overview of the MUTOMCA Project

The MUTOMCA project is the result of an international collaboration between the INFN Padova, the Forschungszentrum Jülich GmbH (Jülich), BGZ Gesellschaft für Zwischenlagerung mbH (BGZ) and the European Commission, Directorate-General for Energy. The aim of the project is to verify the capability of muon tomography to inspect the inventory of spent fuel casks. To achieve this purpose, a dedicated muon detector has been developed and constructed by INFN. It is composed of two modules that can be positioned close to the cask and can be moved to different measurement positions around it, in order to achieve the full 360° angular coverage. A detailed description of the components of the detector is given in the following Section 3.
The detector is used to measure the trajectories of muons that enter the cask and (eventually) exit it. A muon passing through a dense object, such as a loaded cask, undergoes two different processes [1]: a loss of its energy, so that it can eventually be absorbed inside the cask, and the deviation of its initial trajectory. Placed at opposite sides of the cask, the two detector modules allow to observe these phenomena and to exploit them in order to visualize the inner cask structures. More details of the imaging algorithms and examples of tomographic reconstructions with the MUTOMCA experimental apparatus can be found in Section 4.
For the MUTOMCA project, a highly configurable software simulator was developed. Several Monte Carlo simulations have been performed for the following reasons: designing the

experimental apparatus, defining a data-taking strategy as well as studying and testing the software reconstruction chain. The simulator will be described in Section 4.

The construction and test phase of the muon detector has been completed during the two-year period 2021-2022 at the INFN National Laboratories of Legnaro (LNL). In early 2023 a field test has been carried out in the SFSF at Grafenrheinfeld site. To validate the method, measurements were performed with two CASTOR® V/19 casks, one loaded with dummy elements and spent fuel assemblies and the other solely loaded with spent fuel assemblies. Preliminary results from the field test will be given in Section 5.

3. Experimental Apparatus

In order to decrease costs and to simplify the construction, a muon detector consisting of two modules has been designed to roughly cover one third of the cask shell surface. This design was considered as adequate to demonstrate the feasibility of the re-verification approach based on muon tomography. However, this approach causes a higher level of complexity in the image reconstruction phase compared to a single-module detector covering the entire 360° surface of the cask shell.

The muon detector has been assembled and validated by the INFN Padova group. It is based on the drift tubes technology and it consists of two distinct modules, shown in Figure 1; each module includes 183 Al tubes, with a 2.5 cm radius, a 1.5 mm thickness and a 4.5 m height. The tubes are flushed with a mixture of Ar/CO_2 in a ratio of 85%/15%. Each tube is equipped with a coaxial 50 µm radius Cu-Be wire, tensioned at 6 N; while the tubes are grounded, a ~3000 V voltage is applied to the wires, in order to generate the electric field necessary to collect the signal from the drift electrons produced by muons passing through the gas mixture. The tubes are arranged in 6 layers of 30/31 tubes each; a special separation between the 3rd and the 4th layer is added to minimize geometrical ambiguities during the reconstruction of muon tracks. With this configuration, a good spatial resolution can be achieved (~350 µm) in the transversal coordinate (orthogonal to the wires).

The read-out is performed from both ends of the tubes: the time difference of the signal arrival recorded by both ends results in a measurement of the vertical coordinate (parallel to the wires),

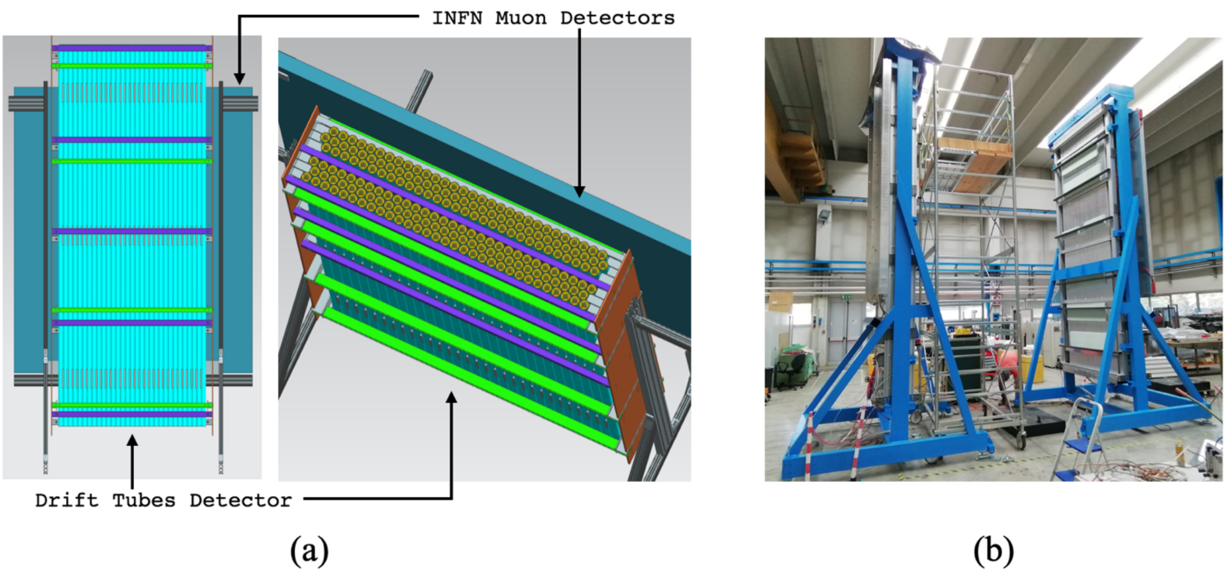
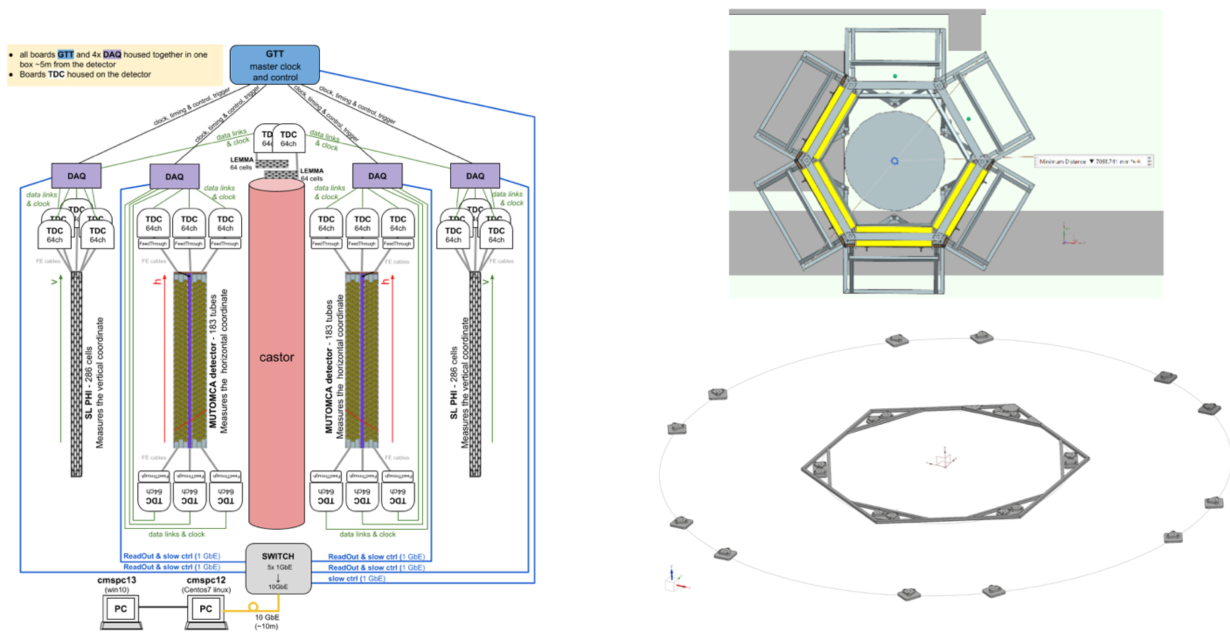


Figure 1 (a) Design of one detector module developed for the MUTOMCA project. (b) A picture of the complete muon detector assembled in Laboratori Nazionali di Legnaro.

but with poor resolution (~20 cm). For this reason, the modules are equipped with an additional muon detector, called INFN Muon Detector, as shown in Figure 1: it is a specific tracking layer of the muon chambers that were produced in LNL for the CMS experiment at CERN, which consist of 286 rectangular drift cells filled with the same gas mixture as the tubes, arranged in 4 layers of 71/72 cells each.
A decisive step of the imaging reconstruction technique is the exact determination of the positions of the two detector modules around the cask (alignment). For this purpose, muons were also measured by using an additional muon detector: a smaller version of the CMS muon chamber was placed in a fixed position on top of the cask, so that it served as a reference to determine the position of the two modules.
The data acquisition system (Figure 2) utilizes XILINX technologies, in particular the Field Programmable Gate Array (FPGA) Artix7 (28 nm) and the System On Chip (SoC) Zynq UltraScale+ (16 nm). The system is constructed with: (i) 24 TDC cards for time to digital conversion of roughly 1000 channels, (ii) 4 DAQ cards for the trigger signal processing and TDC readout, (iii) 1 GTT card for the overall trigger processing and the clock control, and (iv) 12 FeedThrough boards used as an interface between the detector and the TDC boards. Prototypes for each board type have been successfully tested both individually and after the assembly of the complete electronics system. In addition, as required by the licensing and supervisory authority for the SFSF at Grafenrheinfeld site, the Bavarian State Ministry for the Environment and Consumer Protection (STMUV), the proof was provided by an accredited laboratory that the measurement system used by INFN in the SFSF does not represent an electromagnetic interference source.
The support structure for the detector modules was designed and realized with the aim of ensuring a high stability of the modules and to allow their movement around the cask by means of a crane. In order to achieve a precise individual positioning of the detector modules down to the millimeter



(a) (b)

Figure 2 (a) Scheme of the electronics of the MUTOMCA experimental setup. (b) Scheme of the detector positions in the test location and system of support pads for precise positioning.

level while minimizing the stay time of the staff for movement operations in presence of the loaded cask, a support pad system, shown in Figure 2, has been developed.
A summary of the detector construction phase and preliminary tests carried out by INFN can be found in [4].

4. Software Simulations and Imaging Algorithms

For the MUTOMCA project, a comprehensive Monte Carlo simulation is implemented to optimize the design of the detector components and the reconstruction algorithms prior to the actual detector manufacture. In addition, the simulation is crucial in trying different data acquisition setups, i.e. optimizing the positioning of the two detector modules adjacent to the cask with the aim of reducing measurement time and enhancing image reconstruction.
The simulation is implemented in the Virtual Monte Carlo (VMC) framework [5]: in this framework, particle diffusion is handled by Geant4 [6], a toolkit which is widely used in particle physics as it allows to simulate particle interactions and their passage through matter. It has various functionalities, like particle tracking and handling a complex geometry, and can be easily adapted to different applications. The VMC framework also incorporates the ROOT [7] package, originally developed at CERN to manage data analysis.
The Monte Carlo simulation developed for the MUTOMCA project includes (i) a detailed description of the CASTOR® V/19 cask, where the arrangement of fuel assemblies/dummy elements is fully configurable; (ii) a realistic model of the two-module detector, that can be positioned in different configurations around the cask; (iii) a reliable muon generator, the EcoMug package [8], that allows to reproduce the correct angular and momentum distribution while using different generation surfaces (e.g. flat sky, sphere or cylinder). A visualization tool allows to see generated events, as shown in Figure 3.

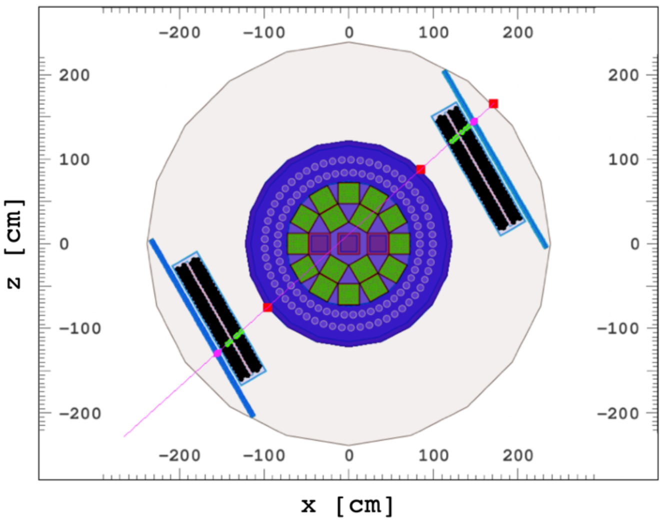


Figure 3 A display of one event generated with the MUTOMCA Monte Carlo simulator. The simulated CASTOR V/19® contains three dummy elements in the center.

The MUTOMCA simulator has been used to simulate the field-test configuration and to test the image reconstruction techniques. As mentioned in Section 2, two different kind of image reconstruction algorithms are available, based on two physical processes.
In particular, a muon travelling in a medium can lose its energy by ionization/excitation; the energy loss per unit of length depends roughly on the density of the crossed material. If its initial

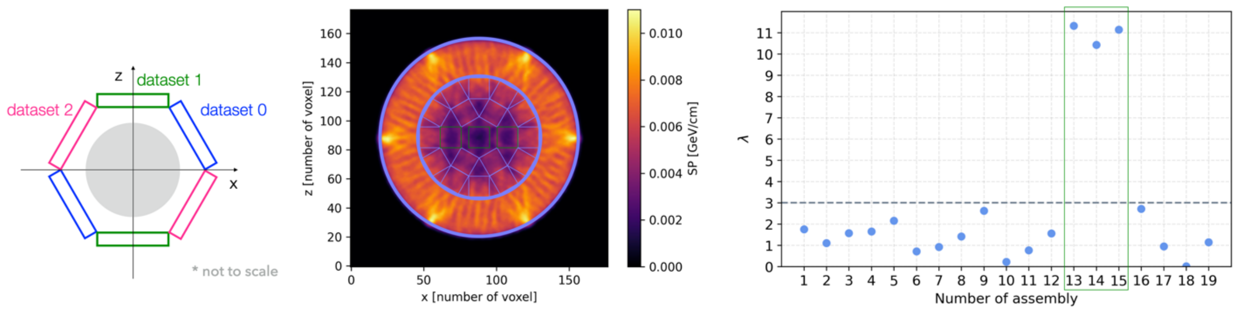
energy is not enough, the muon does not survive and it is absorbed inside the cask. Given the large amount of material inside a loaded cask (both in the spent fuel and in the shielding), it is expected that a non-negligible fraction of muons is stopped inside the cask. The reconstruction algorithm based on muon absorption and implemented by the MUTOMCA project is called µCT [9]: it produces a map of the Stopping Power (SP) as an output, i.e. the mean energy loss per unit distance.

A muon can also be deflected from its initial trajectory due to multiple Coulomb scattering. The average deviation is null but the width of the scattering angle distribution is related to the thickness of the crossed material, to its density and its atomic number. The reconstruction algorithm based on the measurement of the scattering angle and displacement is a Maximum Likelihood Expectation Maximization (MLEM) algorithm [10][11]; in this case the result is a map of the Linear Scattering Density (LSD), a quantity related to the width of the scattering angle distribution.

In the following Figure 4(b), the results of a µCT reconstruction obtained with the simulated dataset of a cask with three dummy elements in the inner part are shown; the reconstruction is performed assuming the same data-taking configuration implemented at the field test, as schematized in Figure 4(a). Figure 4(c) shows the distribution of the compatibility λ between the SP measured from a reconstruction of a cask with three dummy elements and the SP measured from a reconstruction of a cask solely loaded with fuel assemblies:

$$\lambda = \frac{\left|\langle SP_{full}\rangle - \langle SP_{dummies}\rangle\right|}{\sqrt{{\sigma_{SP}}_{full}{}^2 + {\sigma_{SP}}_{dummies}{}^2}}$$

where $\langle SP\rangle$ and σ_{SP} are the average value and the error of the stopping power measured inside the assembly volume, respectively. The difference of the two measurements in the three central positions is statistically significant in the case of dummy elements with respect to spent fuel bars (the compatibility has higher values, in particular $\lambda > 3$).



(a) (b) (c)

Figure 4 (a) Scheme of the data-taking strategy: the detector is moved in three different positions around the cask. (b) Result of a µCT reconstruction of a cask with three dummy bars in the central part. A scheme of the assembly disposition is over imposed to the reconstruction and the three central dummy bars are shown highlighted green. (c) Distribution of the compatibility λ between the average SP measured from a µCT reconstruction of a cask with three dummy elements and the average SP measured from a µCT reconstruction of cask solely loaded with fuel assemblies. The two reconstructions were performed with the same parameters and statistics. The values corresponding to the central assemblies (namely number 13, 14 and 15), are highlighted with a green box.

5. Field Test and Preliminary Results

The practical phase of the MUTOMCA project took place in the SFSF at Grafenrheinfeld site, Germany, from January 18th to February 24th 2023. The detector was delivered with a special truck to Grafenrheinfeld. The place identified for carrying out the field trial was chosen in compliance with the maximum load requirements of the ground in the reception area [12]: the noise caused by the radiation emitted by the cask meant that longer measurement times were necessary for the individual measuring positions. Therefore, only a minimal data-taking routine could be performed considering solely three measuring positions, which were realized by three detector movements as depicted in Figure 4(a). The pictures in Figure 5 taken at the SFSF show the arrival of the muon detector at Grafenrheinfeld site and the test setup inside the reception area during data-taking. The time available for data collection was sufficient to take measurements on two casks. After the setup and testing of the experimental apparatus, a total of 18 days were dedicated to the measurement of a cask that contains three dummy elements in the inner basket positions of the cask, like the one shown in Figure 3, and the last 11 days were used for the measurement of a cask solely loaded with spent fuel assemblies.

(a) (b) (c)

Figure 5 (a) Pictures of the detector arrival at the SFSF site of Grafenrheinfeld, January 18th 2023. (b) Picture of the experimental setup during data-taking. (c) Experimental apparatus seen from above: the small drift chamber used for alignment purposes is visible on the top of the cask.

The main difficulty of such a measurement is caused by the radiation emitted by the loaded cask: neutrons and gamma radiation lead to random signals (a.k.a. “hits”) in the detector during the time window of the muon track acquisition. For this reason, in 2018 a pilot field trial was conducted by EURATOM in cooperation with INFN, Energie Baden-Württemberg AG (EnBW), BGZ and Jülich [13]. The trial was conducted in the SFSF at Neckarwestheim site, where the performance of a small-scale prototype of a drift tube detector developed by INFN was successfully tested in proximity of a fully loaded CASTOR® V/19, demonstrating its ability to reconstruct muon tracks in the presence of the emitted radiation.

In order to cope with radioactivity, the architecture of the trigger, i.e. the electronic system that quickly checks the criteria that must be verified in order to record an event, was developed in such a way to be highly configurable. Thanks to this feature, some tuning of the trigger conditions was possible prior to the actual data collection. This resulted in a reduction of the number of noise-only events that happen to satisfy the trigger conditions, although the noise level was found to be

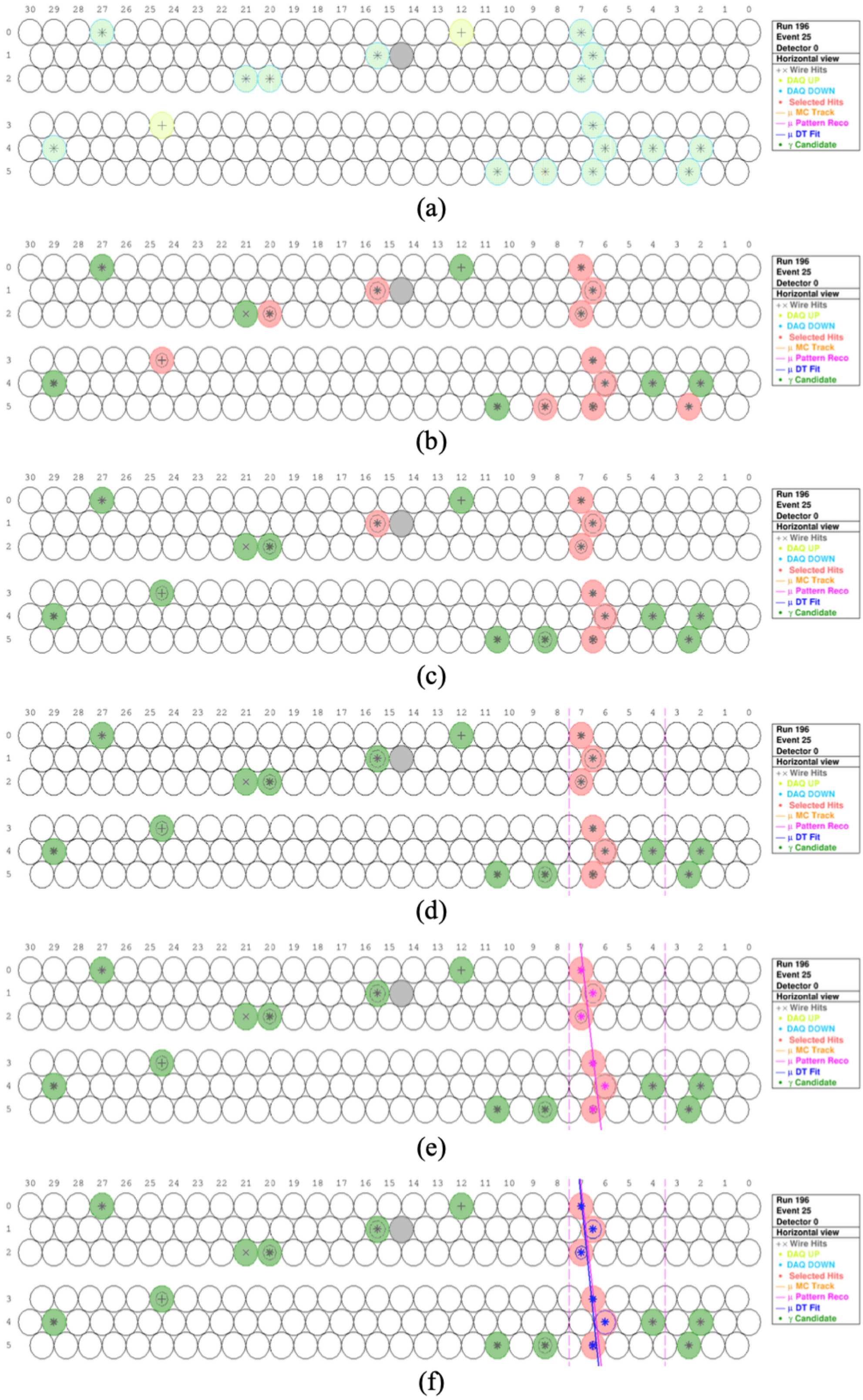


Figure 6 (a) Hit collection of one event recorded during MUTOMCA field test, in presence of a cask with three dummy bars. (b) Effect of the time filter. (c) Effect of the space filter. The filter does not apply to the tubes close to a dead channel (in grey) in order to avoid further inefficiencies in that area. (d) Area selected by the clustering algorithm. (e) Track candidate find by Pattern Recognition step. (f) Drift Time fit.

higher than expected from the results of the previous trial at Neckarwestheim site.
Moreover, a robust noise cancelling strategy was implemented to remove the random radioactivity hits recorded together with muon tracks: an average number of ~11 noise signals from cask radiation was found for each saved event. The noise cancelling strategy includes: (i) a time filter, (ii) a space filter, (iii) a clustering filter. The time filter assumes that the hits that originate from a muon track are correlated in the arrival times, while hits that are due to neutron or gamma radiation are randomly distributed in the time window open for the acquisition. The space filter is based on the simple assumption that the muon hits forming a track are connected, whereas noise hits will more likely remain isolated. Finally, the clustering filter allows to identify the area of the detector where a major cluster of hits can be found. Then, the Pattern Recognition process identifies the track candidate, and finally a Drift Time Fit algorithm extracts the parameters of the muon track. In Figure 6, the steps of noise cancelling and track fitting are illustrated for a typical event recorded during the field test.
Up to now, a reduced statistical sample of all the data collected has been processed, with the aim of optimizing the track reconstruction process before analysing the entire amount of data. From this sample, corresponding to ~4 hours of data-taking time, the extrapolated number of specific events suitable to be used for an image reconstruction is in order of 10^7 for the measurement of the cask with three dummy elements and $6x10^6$ for the measurement of the fully loaded cask, which should be sufficient for a satisfactory image reconstruction. Other control distributions, such as the scattering angle distribution shown in Figure 7, are found to be in good agreement with Monte Carlo simulations.

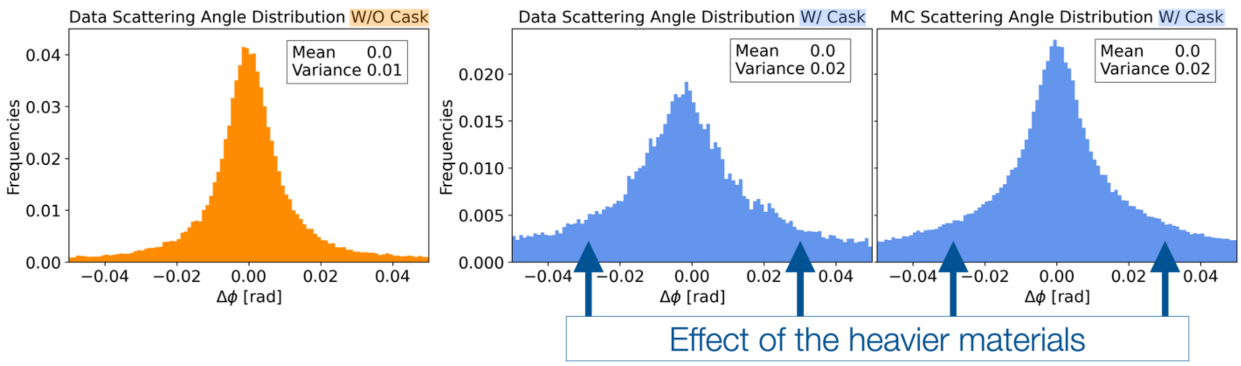


Figure 7 From left to right, distribution of the scattering angle in data without cask, in data with cask and in MC simulations with cask.

6. Conclusions

The muon tomography technology has the potential to be a reliable alternative for verifying spent fuel that is stored in self shielding casks. For the measurements, a cask was selected which preferably contains the dummy elements in the inner basket positions of the cask, since in such loading configurations the inner dummy elements are masked by the outer fuel assemblies. For this reason, the inner fuel assemblies and dummy elements are much more difficult to be identified by conventional neutron- and X- or gamma-ray detection methods than those that are in the outer basket positions. Therefore, the MUTOMCA project was launched to assess the feasibility of reconstructing the inner part of spent fuel casks with muon-based imaging techniques: for this purpose, a muon detector has been designed and constructed and a field test has been carried out recently at the SFSF of Grafenrheinfeld. The analysis of the data collected with a cask containing three dummy elements and a cask solely loaded with spent fuel assemblies is still ongoing: the primary focus is on minimizing the noise from the radiation emitted by the cask in order to improve the analysis of muon data. However, the statistics and the preliminary distributions look promising.

ACKNOWLEDGEMENTS

The project on which this paper is based was funded by the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection under the funding code 02W6279. Responsibility for the content of this publication lies with the authors.

References

[1] Walker LR et al (Particle Data Group). Review of Particle Physics. Progress of Theoretical and Experimental Physics. 2022; 2022(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] Pagano D, Lorenzon A. Civil and Industrial Applications of Muography. In: Scampoli P, Akitaka A, editors. Cosmic Ray Muography. World Scientific; 2023. p. 253-291.

[4] Ancius D, Andreetto P, Aymanns K, Benettoni M, Bonomi G, Calvini P, et al. Muon tomography for dual purpose casks (MUTOMCA) project. In: INMM/Esarda Joint Annual Meeting; 2021.

[5] 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.

[6] 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.

[7] 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.

[8] 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.

[9] Vanini S, Calvini P, Checchia P, Garola A, Klinger J, Zumerle G, et al. Muography of different structures using muon scattering and absorption algorithms. Philosophical Transactions of The Royal Society A Mathematical Physical and Engineering Sciences. 2019 01;377:20180051.

[10] Schultz L, Blanpied G, Borozdin K, Fraser A, Hengartner N, Klimenko A, et al. Statistical Reconstruction for Cosmic Ray Muon Tomography. IEEE Transactions on Image Processing. 2007 08;16:1985-93.

[11] Benettoni M, Bettella G, Bonomi G, Calvagno G, Calvini P, Checchia P, et al. Noise reduction in muon tomography for detecting high density objects. Journal of Instrumentation. 2013 07;8.

[12] Aymanns K, Niemeyer I, Jussofie A, Balling M, Carter J, et al. New Technologies for Safeguarding Spent Fuel Storage Facilities. In: IAEA Symposium on International Safeguards; 2022.

[13] Checchia P, Barcellan L, Benettoni M, Gonella F, Montecassiano F, Zumerle G, et al. Muography of spent fuel containers for safeguard purposes; a feasibility test in proximity of a CASTOR container. In: IAEA Symposium on International Safeguards, 2018.