Technical Report

Muon Tomography for Reverification of Spent Fuel Casks (the MUTOMCA Project)

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Abstract

The MUTOMCA (MUon TOMography for shielding CAsks) project investigates the suitability of muon tomography for the reverification of spent fuel casks. Spent fuel casks are stored, for decades, in dedicated locations and are under constant surveillance by international agencies through unattended monitoring equipment. In the hypothetical case that these instruments would temporarily fail, thus leading to a loss of Continuity of Knowledge (CoK), a reverification of the spent fuel enclosed in self-shielding casks would be required. The reverification is particularly challenging for conventional nondestructive assay (NDA) methods since thick-walled spent fuel casks considerably attenuate the radiation emitted by the spent fuel. On the other hand, inspectorates need a high degree of assurance on the amounts of nuclear material stored in those casks. With the aim of proving the ability of muon tomography to detect a diversion of fuel assemblies in closed spent fuel casks, an experimental apparatus was designed, developed, constructed, and commissioned. The detectors were used during the first months of 2023, in a field trial at a dry storage facility in Germany to examine CASTOR®V/19 casks. Preliminary results are presented along with the potentials and drawbacks of the experimental apparatus.

Keywords: cosmic-ray muons, muon tomography, muon radiography, spent fuel reverification
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1. INTRODUCTION

The great majority of commercial nuclear power reactors are Pressurized Water Reactors (PWR) with the common concept that the fissile material is encapsulated in long, Zirconium-based rods. These rods are assembled in quadratic fuel assemblies placed in the reactor core. The initial nuclear fuel consists of UO_2 with an enriched content of the ^{235}U isotope or, much less common, a mix of uranium and plutonium isotopes, so-called mixed oxide (MOX) fuel. The fuel is fabricated in small pellets with a diameter of approximately 1 cm and stacked to an approximate height of 3.5 meters. Including all structural parts, the fuel assembly is around 4 meters high. The exact geometry as well as the number of fuel rods in an assembly might vary, depending on the design of the assembly and reactor type.

After their service in the reactor and the radiation induced isotopic change of the nuclear fuel, the assemblies are stored in a cooling pond next to the reactor to cool off a major part of the decay heat. Depending on the waste management strategy, the fuel assemblies get eventually loaded into so-called spent fuel casks. In case of a CASTOR®V/19, the cask is constructed from a single piece of thick-walled cast iron body with two stainless steel lids bolted to the cask. Neutron and gamma shielding is provided by the thick cask walls and additionally by polyethylene rods inside the cask wall and polyethylene slabs at the top and bottom of the cask. For a better heat transfer and to increase the cooling capacity, circumferential cooling fins surround the cask body. The CASTOR®V/19 can store 19 PWR fuel assemblies. The loaded casks are stored in spent fuel storage facilities (SFSFs) until the next step in the waste management strategy. In some countries, e.g., Germany, spent fuel is foreseen to be disposed of in deep geological formations whereas other countries prefer reprocessing of spent fuel.

Maintaining and confirming Continuity of Knowledge (CoK) of the spent fuel stored in dry spent fuel storage facilities for the upcoming decades is a key element of safeguards. The loaded spent fuel casks in dry storage are subject to continuous safeguards measurements. Worldwide, IAEA inspectors are responsible for safeguarding nuclear material; in the EU member states, verifications are performed jointly with EURATOM. Accordingly, in Germany, the inventory of spent fuel casks is verified by both the EURATOM and IAEA inspectorates to ensure that a possible diversion of nuclear materials is detected in a timely manner. However, as of today, no sufficiently precise method is available for the reverification of the content of a thick-walled self-shielding cask. The risk of a loss of CoK cannot be ignored, and a suitable method to verify the content without the need to open the cask should be identified.

Well-established nondestructive assay (NDA) methodologies for safeguards, based on ionizing radiation emitted by nuclear materials, pose challenges when applied in this case. These methods, indeed, permit the quantification of the mass and/or isotopic composition of nuclear materials, if the material to be measured is not too shielded. Accordingly, traditional NDA techniques are not suitable for self-shielding spent fuel casks because their thick wall significantly attenuates the radiation emitted by spent fuel [1].

Muon tomography, a technology developed from the knowledge acquired in particle and nuclear physics experiments, has the potential to enable a 3D reconstruction of the inventory of thick-walled, self-shielding casks. The MUTOMCA (MUon TOMography for CAsks) project aims to investigate such potentiality as a nondestructive method.

Muon tomography is a technique applied for the first time in the 1960s, to study the internal structure of pyramids and, more recently, to study volcanoes. Today, there are several other scopes of applications [2] in controlling means of transportation, preventing nuclear smuggling and industrial processes, avoiding accidents due to the melting of radioactive sources in foundries, and optimizing the cycle of blast furnaces.

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.

The MUTOMCA collaboration constructed an experimental apparatus based on the use of a drift tube technology used to detect charged particles and applied, for example, to the muon detectors of the LHC accelerator experiments at CERN. Details about the apparatus are given in the specific section below. The detectors are able to detect the passage of cosmic muons by measuring their position and direction with high precision. Using that information allows us to reconstruct the image of the internal structure to be analyzed [3, 4, 5]. The constructed detector consists of two detector modules delivered with a special transport to the BGZ-operated SFSF at the Grafenrheinfeld site in Germany. The installation process was performed in the reception area of the SFSF. The practical phase of the field test took place from January 18th to February 24th, 2023.

After a brief description of the detector hardware, the simulation software, and the method for the tomographic image reconstruction, some preliminary results from the practical phase of the field test at the Grafenrheinfeld site are presented in the following.

2. THE EXPERIMENTAL APPARATUS

To validate the muon tomography method, measurements were performed with two CASTOR®V/19 casks, one loaded with 3 dummy elements and 16 spent fuel assemblies and the other solely loaded with 19 spent fuel assemblies. Before describing the muon detection system, it is worth reminding here of the main characteristics of a spent fuel cask, such as the CASTOR®V/19 [6]. As for the dimensions, the overall height is 594 cm, the outer diameter is 244 cm, and the cask's empty mass (without spent fuel assemblies) is 108 tons. Up to 19 spent fuel assemblies from a PWR can be loaded into a basket, which is in the internal cask cavity. An assembly is a structure 495 cm tall with a square $(23.3 \times 23.3)\,\mathrm{cm}^2$ base, consisting of an assembly of fuel rods each filled with spent fuel pellets.

The MUTOMCA experimental apparatus was designed and constructed considering the features of the CASTOR®V/19. Given the size of the volume to inspect, it was decided to use a drift tube technology detector [7, 8]. The main components of the experimental apparatus are two detecting modules (Drift Tubes modules, or simply DTs, in the following), each consisting of six layers of 4.5-meter-long aluminum tubes as shown in Figure 1.

The tubes have a 2.5 cm radius with 1.5 mm thickness and are all equipped with a coaxial 100 μm Cu-Be wire which has been tensioned at about 6 N. The wires are kept to a 3 kV electric potential with respect to the tubes to generate the electric field required to collect the electrons. To minimize the ambiguities in the reconstructed muon path, the third and the fourth layers are separated by 4.33 cm. Each layer is composed of 30 or 31 tubes; consequently, each module comprises 183 tubes, for a total of 366 tubes. A double read-out at the two wire extremes ensures a high precision measurement ($\sim$300 μm) of the particle radial distance from the wire and a low precision ($\sim$20 cm) measurement of the coordinate along wires. In this way, a precise measurement of the muon track line in the x-y plane (see Figure 1) is possible, and a course evaluation in the x-z plane can be extracted.

The DTs have been designed, constructed, assembled, instrumented, and validated in Laboratori Nazionali di Legnaro (LNL) by the INFN Padova group. Additionally, existing INFN detectors were added to the DTs. They increase the capabilities of the detection system and permit a precise measurement of the coordinate parallel to wire directions (x-z plane of Figure 2).

These detectors are made of four layers of rectangular Drift Cells with wires orthogonal to the tubes. They have, with respect to the DTs, similar spatial resolution, and in the following, they are referred to as Drift Cells modules (or DCs). Both DTs and DCs are filled with an Ar/CO2 gas mixture (85/15%). The whole setup with the DCs is mounted on the external side of the DTs as shown in Figure 2. The electronics, developed by the INFN Padova group [3, 4, 5], have been mounted on both modules allowing trigger and data acquisition.

A support structure (visible in Figure 5) was designed and realized to move both detector modules around the cask to obtain full coverage of the CASTOR®V/19 cask.

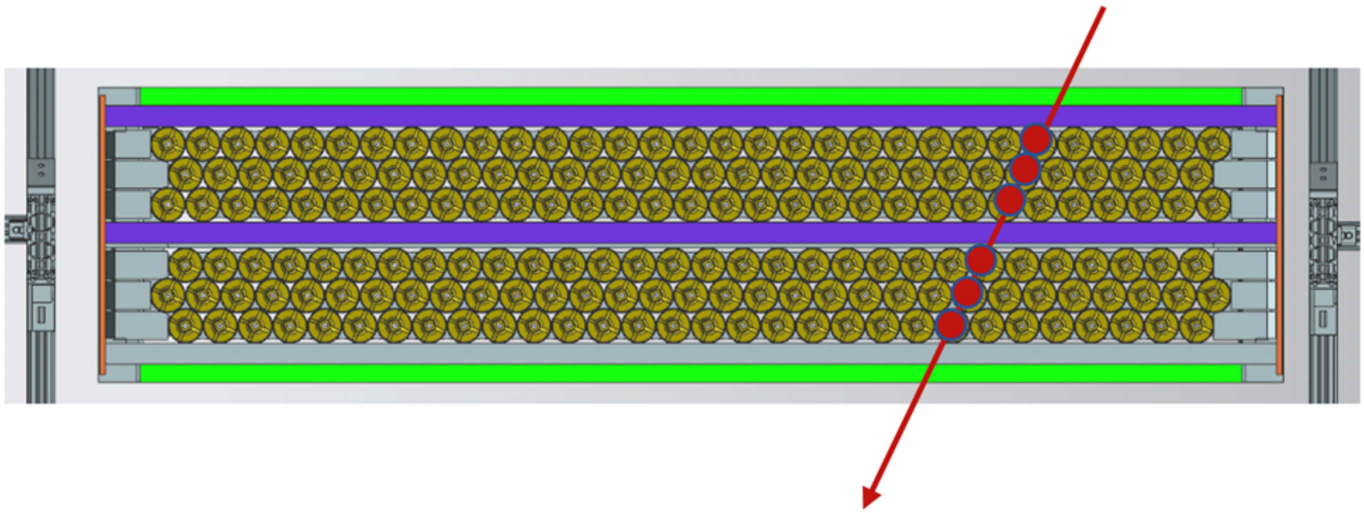

FIGURE 1: Top view of a drift tube muon detector module. The circles represent the Drift Tubes. The red arrow shows an example of a possible muon track crossing the tubes.

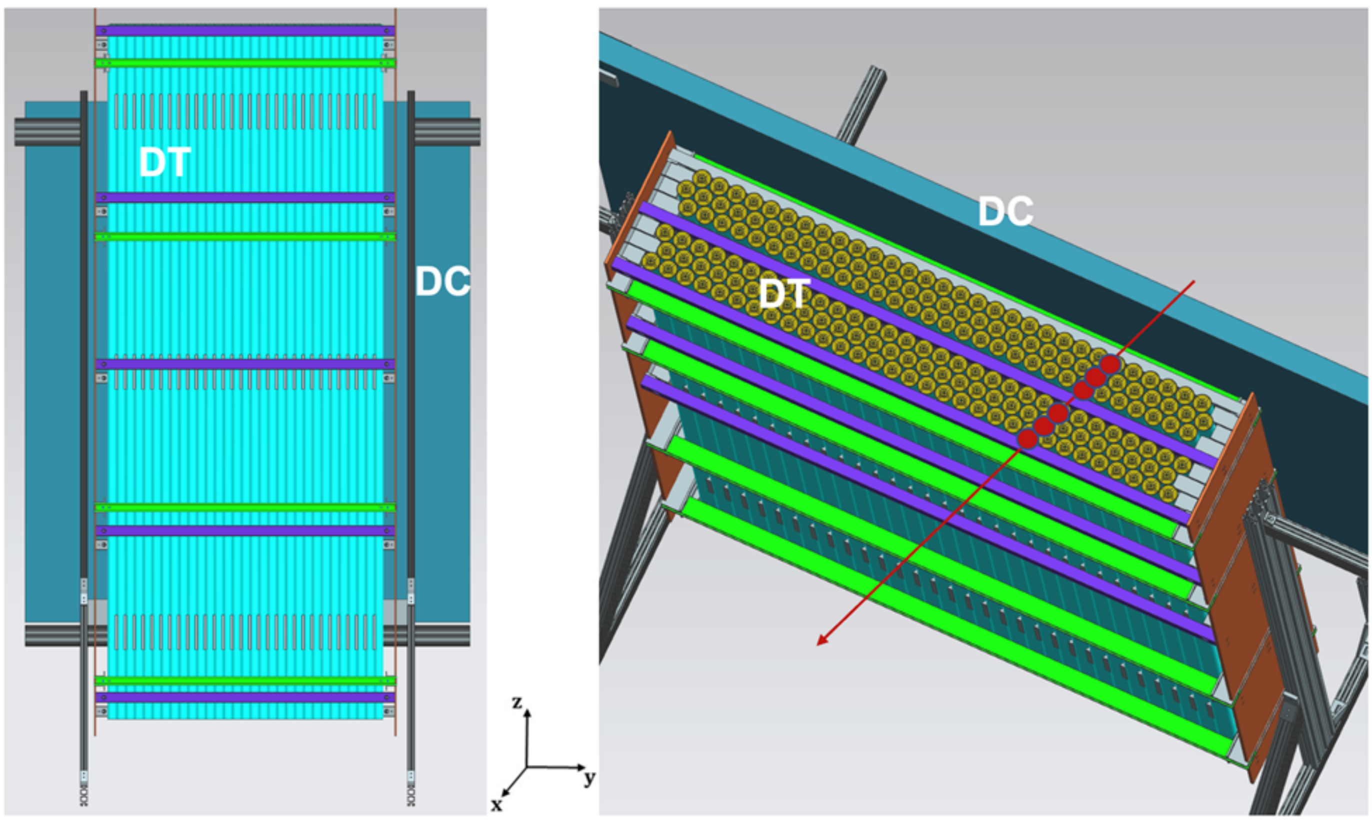

FIGURE 2: Scheme of the overall experimental detector apparatus including the INFN Drift Cells (DCs) and rectangular blue object attached on the back of the Drift Tubes (DT) modules. Left: one detector module in the z-y plane. Right: top view with an exemplary muon track hitting the tubes (red).

The two detector modules, each consisting of a DT-DC pair and placed at opposite sides of the cask, cover roughly one-third of the shell surface of a cask but can be rotated to achieve full coverage. To avoid the construction of even bigger detectors, this approach is needed and considered sufficient to prove the feasibility of the reverification method based on muon tomography. The disadvantage is a lower quality of the reconstructed image due to a reduction of the covered solid angle (for example, muons crossing the CASTOR®V/19 far away from the center are disfavored).

3. SIMULATION AND IMAGE RECONSTRUCTION

The overall MUTOMCA project was designed to make use of a full system simulation. This tool allowed us to define some details of the detector modules and to develop the reconstruction algorithms without the need for real data. The simulations were important to test different configurations of data taking. For example, they helped to select the best geometric position for the two detectors around the cask, minimize the time of the measurements, and improve the image reconstruction. The MUTOMCA simulation package relies on the potentiality of the CERN GEANT4 toolkit [9] that incorporates all the physics about the interaction of muons with matter, a complete range of functionalities including tracking, geometry, physics models, and hits. It has been developed making use of the VMC framework [10] and the ROOT utilities [11].

The Monte Carlo simulation included a detailed model of the CASTOR®V/19 cask loaded with spent fuel, a realistic representation of the detector modules and of their response to the passage of particles, and a reliable cosmic-ray muons generator, namely, the EcoMug package [12]. This particle generator is based on a parametrization of experimental data and allows the generation over a cylindrical surface around the CASTOR®V/19, while keeping the correct angular and momentum distribution of generated tracks. Additional tools were developed to visualize the simulation output, as represented in Figure 3.

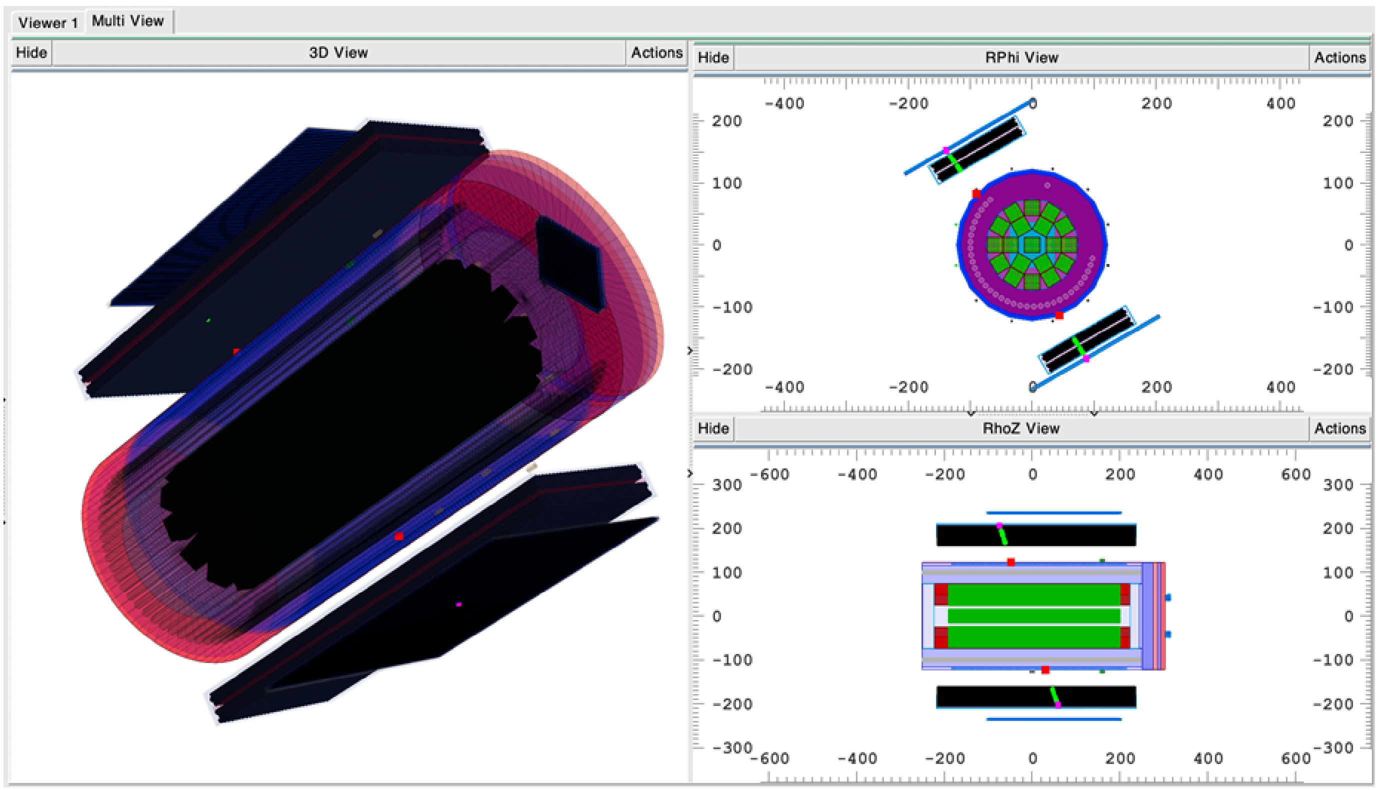

FIGURE 3: The figure shows a screenshot of the program used for visualizing the MUTOMCA Monte Carlo simulation including the CASTOR®V/19 and the detector modules. Additionally, one generated cosmic-ray muon track is shown (red, pink, and green dots).

The Monte Carlo simulations were used to develop and test two image reconstruction algorithms, based on two physical processes. The first one is the energy loss occurring to charged particles when they pass through a medium, which depends roughly on the density of the crossed material times the distance traveled by the particle inside the object. Because of this energy loss, only muons with sufficient initial energy can cross the whole cask. Hence, a significant fraction of muons is absorbed instead. The presence of detector modules positioned around the cask allows measuring the absorption rate as a function of the different muon directions. The reconstruction algorithm [3, 4] based on muon absorption can reconstruct a 3-dimensional map of the mean energy loss per distance, the Stopping Power (SP), by comparing the number of absorbed muons measured by the two detector modules with the theoretical predictions derived from the thickness of the material and the muon energy distribution.

The second physical process is Multiple Coulomb Scattering (MCS), which is responsible for the deviations of charged particles from their initial trajectory when crossing a medium. Although the average deviation is null, the width of the scattering angle distribution depends on the thickness of the material and approximately on the product of its density times its atomic number. The width of the distribution depends also on the inverse of the particle momentum, which is generally unknown. However, by collecting a large number of events, useful information on the material properties can be derived anyway. The installation of the detector modules allows us to measure muon trajectories before they enter the cask and after they exit it. This information allows us to determine the scattering angle of individual muons. An algorithm based on the Maximum Likelihood Expectation Maximization

(MLEM) technique [3, 4, 13] is used for image reconstruction in this case: the outcome is a 3-dimensional map of a quantity roughly proportional to the density times the atomic number of the material.

The result of both image reconstruction algorithms consists of a grid of "voxels", namely, 3-dimensional cubic pixels of homogeneous density. Many simulations have been produced with different configurations of assemblies (i.e., the cask fully loaded or completely empty). Figure 4 shows, for example, the outcome of the first reconstruction algorithm of a Monte Carlo simulation where the cask is loaded with fuel assemblies except for three dummy elements in the inner part. The detector modules are moved around the cask in the same configuration as the field trial (see below for details). A diagram of the internal structure of the cask is superimposed on the image to help the reader identify the areas corresponding to the spent fuel assemblies: unlike the areas corresponding to the spent fuel assemblies, those of the dummy elements feature a void in the inner part. It is important to highlight here the presence of some artifacts (see, for example, the six yellow star-like ends close to the CASTOR®V/19 exterior), as the full coverage is obtained by moving the detectors around the cask. They would not be present with an ideal 360° surrounding detector.

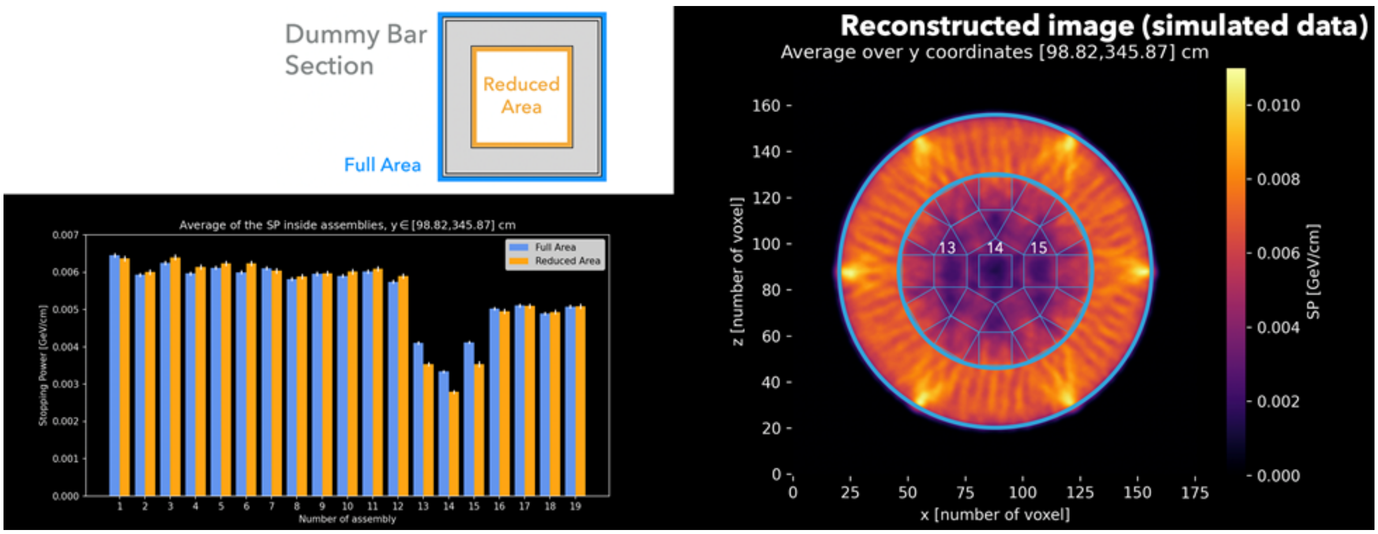

FIGURE 4: Left: a diagram showing the average of the SP inside assemblies can be seen. Right: example of a reconstructed image of a simulation of a CASTOR®V/19 cask with three dummy elements corresponding to position numbers 13, 14, and 15. The image has been obtained using the absorption algorithm.

4. THE FIELD TRIAL AT THE GRAFENRHEINFELD SITE

Once the detector modules were tested and proved operational, they were moved, alongside the support structure, to the interim storage facility at the Grafenrheinfeld site (Germany). All authorizations for the field test are described in [14]. Given the size of the whole apparatus, a specific transportation with a special truck had to be organized, taking care to avoid damages to the detectors. Once arrived at the destination in the third week of January, the detector modules were placed in the reception area of the storage building, where the spent fuel casks are usually located prior to their emplacement in the adjacent storage area. The readout electronics, the computers, the gas mixture to operate the detectors, and all the other required instrumentation were transported separately and arrived at the destination simultaneously. After completion of the experimental setup, the detector modules were turned on and took data, without a spent fuel cask in the vicinity, for a few days. At this point a CASTOR®V/19, with three dummy elements, was moved from the adjacent storage area between the two detector modules (see Figure 5). Unfortunately, due to safety reasons when handling and moving the cask, the detectors needed to be placed at a greater relative distance than assumed and simulated. The first mixed-loaded CASTOR®V/19 was then replaced by another cask, fully loaded with spent fuel assemblies. In total, the data taking lasted from January 24th to February 24th, 2023. In the case of the first mixed-loaded cask, the measuring time was 18 days. In the case of the second cask, fully loaded with spent fuel assemblies, it was eleven days. In total, nearly one TB of data was generated.

Since the tomographic image software relies on the muon tracks reconstructed by means of the two detector modules placed at opposite sides of the cask, the relative position of the modules needed to be known with high precision. A mechanical system was thus constructed to place and fix the detector module support structures (and consequently the detectors that were anchored to the structure) in specific and known positions. It consisted of a system of support pads and tools harbored to a hexagonal-shaped iron structure. Clearly, the system was limited to the precision achievable by a mechanical structure, but it ensured a reliable way to move the detector modules efficiently and fast to the three realized measurement positions. If necessary, a better alignment could be reached using the reconstructed muon tracks in the detector modules as usually done in high energy and nuclear physics experiments.

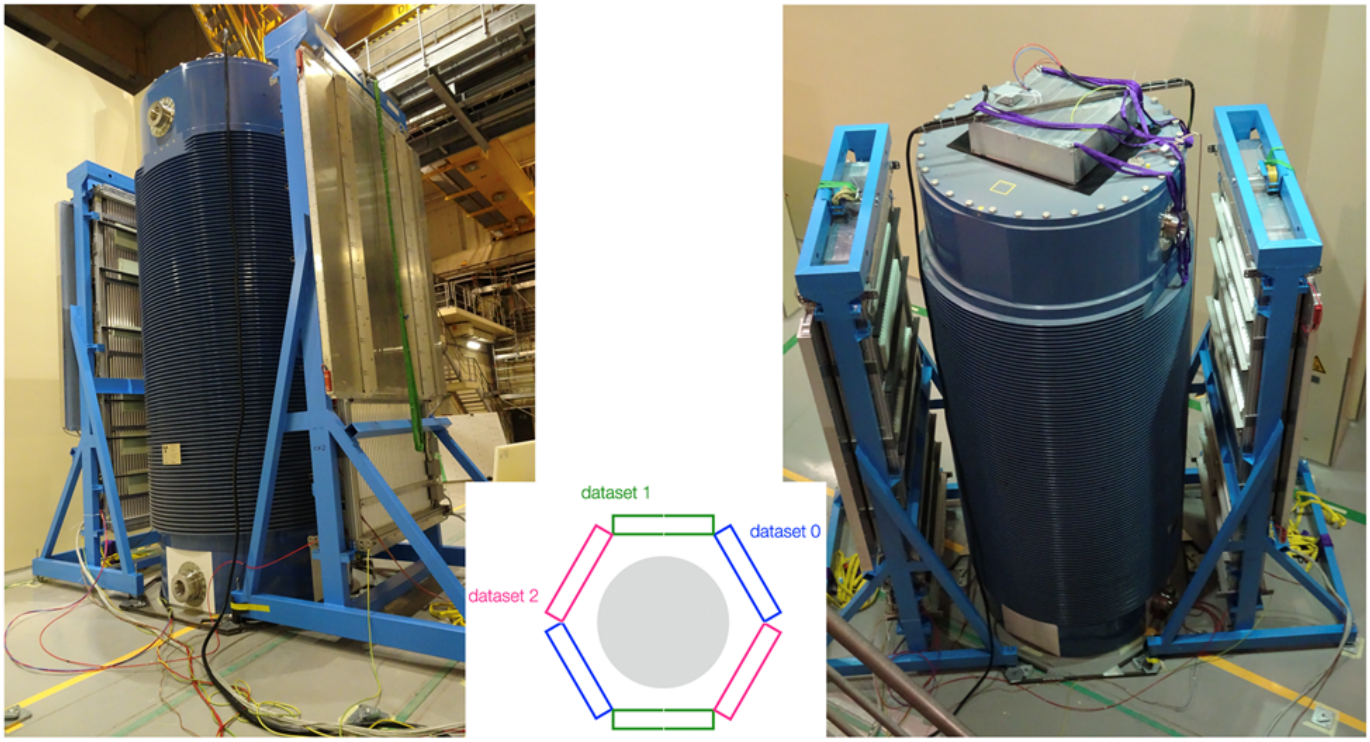

FIGURE 5: Photos of the Grafenrheinfeld field test installation. The detector, the support structure, and the CASTOR®V/19 cask are shown. The position of the detector modules during the data taking is summarized in the central graphic.

As previously reported, the detection system, when the modules at the two sides of the cask were facing one another, covers only about one-third of the shell surface of a CASTOR®V/19. Consequently, the modules placed at opposite sides of the cask were moved, each time, by 60° (see insert in Figure 5) splitting the data taken into three datasets.

A first analysis of the data, which took place during the data taking itself, showed that the radiation emitted by the cask itself was causing background noise in the detector modules that was higher than expected. This caused a change in the hardware trigger selection strategy, to reduce the amount of useful data written to disk. Most of the data were collected requiring hits in both the DT and the DC of the same DT-DC pair. Nevertheless, an average number of roughly eleven noise signals caused by cask radiation was detected for each saved event. In the last months, a robust noise canceling strategy has been implemented in the track reconstruction software to remove the background radiation hits recorded together with muon tracks. About 15 million reconstructed muon tracks are now available for the image reconstruction of the cask content. The reconstructed effective scattering angle distribution, measured without a cask and with a fully loaded cask, and a comparison to the Monte Carlo simulation can be seen in Figure 6.

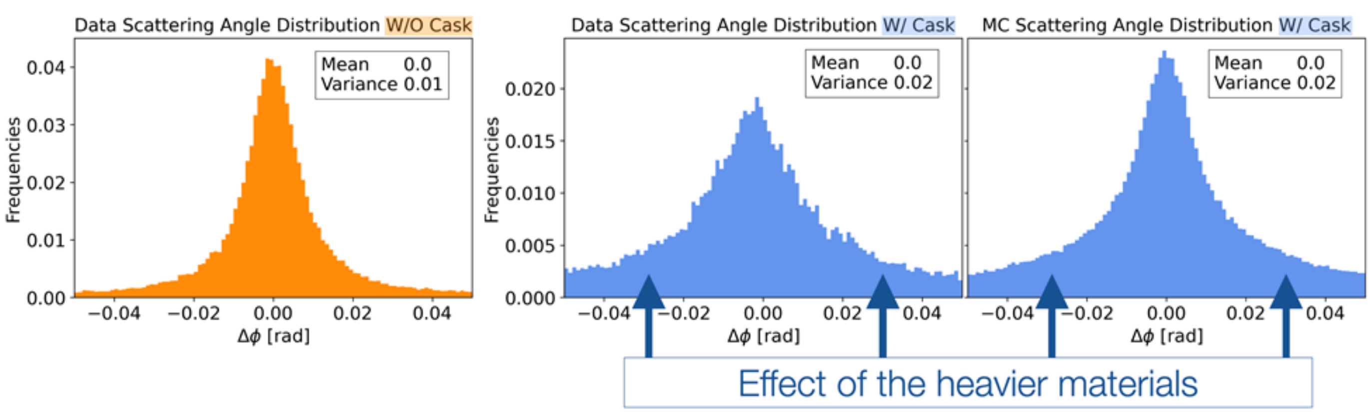

FIGURE 6: The reconstructed effective scattering angle distribution, measured without (left) and with (center) a fully loaded cask, and a comparison to the Monte Carlo simulation (right).

In the coming months, these useful tracks will be used to try to reconstruct an image of the content of the spent fuel casks subjected to field trial at the Grafenrheinfeld site.

5. CONCLUSIONS

A detector dedicated to the reverification of spent fuel casks using cosmic muons has been constructed and operated in proximity of CASTOR®V/19 casks in the interim storage facility at the Grafenrheinfeld site in Germany to carry out a field trial of the muon tomography technology. A successful month of data taking was completed, and the data proved to be useful to apply the tomographic reconstruction algorithms developed with the Monte Carlo simulation. There are some differences between assumed simulation conditions and the real experimental conditions at the Grafenrheinfeld site, which led to an increasing effort in data analysis. Firstly, the background radiation turned out to be higher than expected. Secondly, the detectors needed to be placed at a greater distance than assumed, making the overall solid angle covered by the detectors smaller. Nevertheless, we are confident in reaching the final goal of assessing the feasibility of reconstructing the inner part of spent fuel casks with muon-based imaging.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

ACKNOWLEDGMENTS

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