MUTOMCA: AN EXPERIMENT TO INVESTIGATE SPENT FUEL CASKS WITH MUON TOMOGRAPHY

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Abstract

Spent fuel stored in thick-walled strongly shielding casks can be indirectly verified through the application of containment and surveillance measures. Assuring Continuity of Knowledge (CoK) of the spent fuel stored in dry spent fuel storage facilities (SFSFs) for the upcoming decades is a cornerstone of safeguards. In the unlikely event that all Safeguards-related containment and surveillance measures fail, a cask would need to be opened in the loading pond of a reactor. Therefore, substantially improved re-verification capabilities applicable to dry SFSFs are to be aimed at. The development of an adequate non-destructive (re)-verification method for casks, proving the unchanged inventory of the verified spent fuel, would be a real advantage for safeguards.

Muon tomography could be a suitable method for the re-verification of self-shielding thick-walled spent fuel casks. To prove that the technology can detect the diversion of fuel assemblies, a two-modules muon detector has been designed and built. It will be installed in the proximity of a spent fuel cask during a field test at a dry SFSF in Germany. The status of the project and preliminary results will be presented.

1. INTRODUCTION

Muon tomography, a technology based on particle physics, enables a 3D reconstruction of spent fuel assemblies in thick-walled, self-shielding casks for transport and storage. The European project MUTOMCA (MUon TOMography for CAsks) aims to investigate muon tomography as a non-destructive method to detect a diversion of spent fuel assemblies in self-shielding casks for safeguards re-verification purposes in the unlikely event that all safeguards-related containment and surveillance measures fail. In this regard a muon detector capable of imaging the interior of a self-shielding cask with its spent fuel assemblies has been developed by INFN and is currently under construction.

The project is the result of an international collaboration between INFN, the European Atomic Energy Community (EURATOM), Forschungszentrum Jülich GmbH (FZJ) and the German operator of storage facilities BGZ Gesellschaft für Zwischenlagerung mbH (BGZ)

The current process of phasing out the production of nuclear energy in Germany leads to more than 1,000 loaded spent fuel casks, which will be stored in dry SFSFs. The stored spent fuel in the SFSFs is subject to safeguards. Wordwide, the inspectorates, IAEA and EURATOM verify spent fuel casks during inspections to ensure that a diversion of nuclear materials from its declared peaceful use will be timely detected. Maintaining the CoK of verified spent fuel is a key element of the strategy of EURATOM and IAEA. Consequently, the risk of its loss is challenging as today no sufficiently precise method is available for the re-verification of spent fuel enclosed in thick-walled self-shielding casks.

Well-established safeguards non-destructive assay (NDA) measures are based on the ionizing radiation emitted by nuclear materials. These methods permit the quantification of the mass and/or isotopic composition of nuclear materials, if the material to be measured is not too shielded. In case of self-shielding spent fuel casks, the nuclear material is currently not accessible enough for traditional NDA techniques as the wall of self-shielding spent fuel casks significantly attenuate the radiation emitted by spent fuel [1].

In this context the technology investigated within the MUTOMCA project represents a promising solution for the re-verification of spent fuel enclosed in thick-walled self-shielding casks., the spent fuel in the centre of the casks "covered" by the spent fuel stored in the external positions and therefore inaccessible to current used detection methods with neutrons and X or gamma rays. While X-rays cannot cross more than a few tens of centimetres, muons can pass through large thicknesses of matter, even a ten of meters: a feature that allows these particles to be used to create three-dimensional images of the internal structures of thick-walled casks, in particular of the individual fuel assemblies contained therein, in complete safety, without any artificial radiation exposure. Muon tomography is a technique applied for the first time, in the 1960s, to the study of the internal structure of the pyramids and, more recently, to the study of volcanoes. Today it finds several other applications [2] in the control of means of transport, in order to combat nuclear smuggling, in industrial processes, to avoid accidents due to melting of radioactive sources in foundries and to optimize the cycle of blast furnaces.

The MUTOMCA collaboration is working on the construction of a muon detector based on the use of "drift tubes", a technology used to detect charged particles and applied, for example, to the muon detectors of the LHC accelerator experiments at CERN. The detector is composed of two modules, each consisting of six layers of 30 or 31 tubes, filled with a particular mixture of gas and with a thin copper and beryllium wire in the centre, placed at a voltage of 3000 V. The detector will be able to detect the passage of cosmic muons by measuring their position and direction with extreme precision: information that will allow to reconstruct the image of the internal structure to be analysed. In a pilot field trial, a prototype of a drift tube detector has been successfully tested in proximity of a CASTOR® V/19 cask loaded with spent fuel. It has been shown that muon tracks can be successfully reconstructed despite of the significant radiation field surrounding the loaded spent fuel cask [3].

After a brief description of the detector hardware, preliminary tests results from the experiment simulation software and of the method for the tomographic image reconstruction, results will be presented in the following.

2. DETECTOR DESCRIPTION

To reduce costs and construction complexity, the detector covers only about one third of the shell surface of the cask but it will be rotated in several positions to reach full coverage. This approach should be sufficient to prove the feasibility of the re-verification method based on muon tomography at the price of a much more complex image reconstruction. As a consequence, the muon detector is constituted by two modules based on 6 layers of 4.5 meters long aluminium tubes as shown in Fig. 1. 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 have been tensioned at about 6 N. The wires are connected to a ~3000 V electric potential to generate the electric field required to collect the drift electron signal, since the tubes are connected to ground. To minimize the path ambiguities due to drift time, circular symmetry, the 3rd and the 4th layers are separated by 4.33 cm.

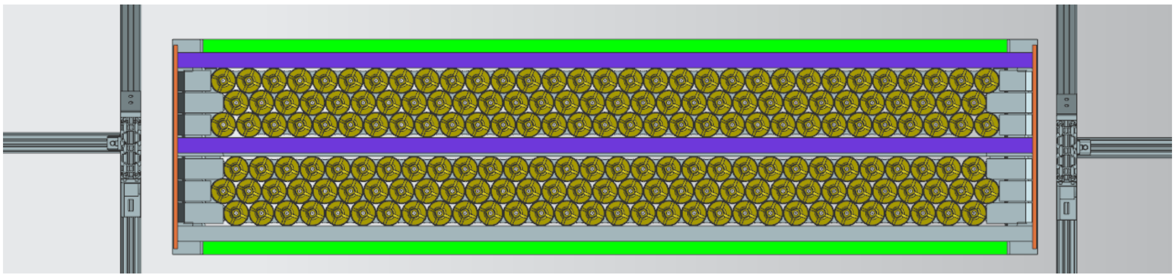

FIG. 1. Top view of a six-layer drift tube muon detector module.

Each module requires 183 tubes for a total of 366 tubes. A double read-out at the two wire extremes ensures a high precision measurement (~300 μm) of the particle radial distance from the wire and a low precision (~20 cm) measurement of the coordinate along wires. The radial measurement relies on the drift time necessary to electrons to reach the wire while the latter profits of the signal propagation along wires and could be sufficiently accurate given the geometry of this application.

To evaluate the possible need of a precise measurement of the coordinate parallel to wire directions, existing INFN Muon Detectors (IMD) have been added to the tube modules and they will be used during the field trial. These detectors are made of 4 layers of rectangular drift cells with wires orthogonal to the tubes. Both, tubes and cells, are filled with a gas mixture Ar/CO_2 (85/15%). The whole setup with the IMD mounted on the external side of the tube module is shown in Fig. 2.

FIG. 2. Picture of a detector segment obtained by adding the INFN Muon Detector (upper part) to the drift tube module (lower part).

The electronics, developed by the INFN Padova group [3,4], has been mounted on both modules allowing trigger and data acquisition.

The support structure (Fig. 3) has been designed and realized to move both modules around the cask to obtain a full coverage of the CASTOR® V/19 cask.

FIG. 3. Picture of the two support structure modules where the detector segments will be mounted.

The detector has been assembled, instrumented and validated in Laboratori Nazionali di Legnaro (LNL) by the INFN Padova group. In the coming weeks it will be mounted on the structure to allow recording data in the operational position.

3. SIMULATION

The MUTOMCA project makes use of a full system simulation both to better design some details of the detector and to train the reconstruction algorithms before the final detector construction. The simulation has been important also to test different configurations of data taking, for example in selecting the best geometric position of the two detectors around the cask, to minimize the time of the measurements and to improve the image reconstruction. The Monte Carlo simulation included: (i) a detailed model of the CASTOR® V/19 cask loaded with spent fuel, (ii) a realistic representation of the detector modules and of their response to the passage of particles and (iii) a reliable cosmic-ray muons generator package. The interaction of particle with the cask and the detectors has been handled using the GEANT4 package [5], a toolkit developed at CERN that includes all the physics about the interaction of muons with matter, a complete range of functionality including tracking, geometry, physics models and hits. The MUTOMCA simulation packages is also based on the VMC project [6] that incorporates the ROOT analysis framework [7].

Since muon radiography applications are sensitive to the angular distribution of cosmic muons and to their momentum distribution, an accurate simulation of the dependency of the muon flux on momentum and direction was a key requirement for the cosmic-ray muons generator. For this reason, the MUTOMCA project relies on the EcoMug package [8], based on a parametrization of experimental data. An important feature of this generator, that allowed the MUTOMCA simulation to be fast and efficient, is the capability to generate from 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 Fig. 4 here below.

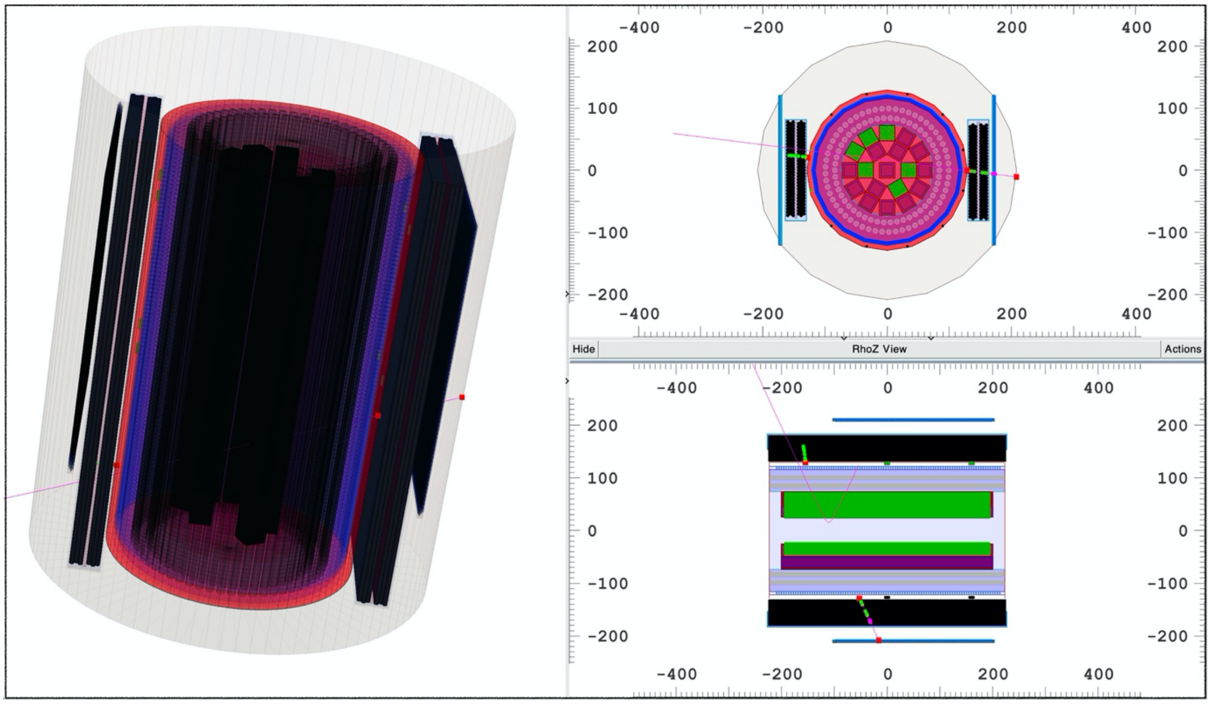

Fig. 4: Visualization of the MUTOMCA Monte Carlo simulation including the CASTOR® V/19, the detector modules and the generated cosmic-ray muon.

4. TEST SETUP

The field test is planned to be carried out in the BGZ operated SFSF at Grafenrheinfeld site (Germany) within 2022. As discussed above, given the detector reduced acceptance, it is necessary to move the modules in several positions in order to cover the entire shell surface of the cask. The space available around the CASTOR® V/19 for handling the detector modules should be sufficient to realize all the required measuring positions by means of a crane. To determine the individual positions of the detector modules with sufficient precision (of the order of mm) and to simplify and speed up movement operations in the presence of the loaded test cask, a system of support pads has been produced together with tools to place them in the correct position as shown in Fig. 5.

For the field trial, it is planned to measure dummy elements in comparison to real spent fuel assemblies. Therefore, the best solution would be to measure two CASTOR® V/19 casks, one containing spent fuel assemblies and dummy elements and a second cask loaded solely with spent fuel assemblies. In order to cope with the working hours at the storage, it has been estimated that for each detector position a measuring time of about one day of data taking on each measuring position will be necessary in consideration that the measurement by the two opposite detector modules takes place simultaneously.

All authorisations for the field test are described in [9].

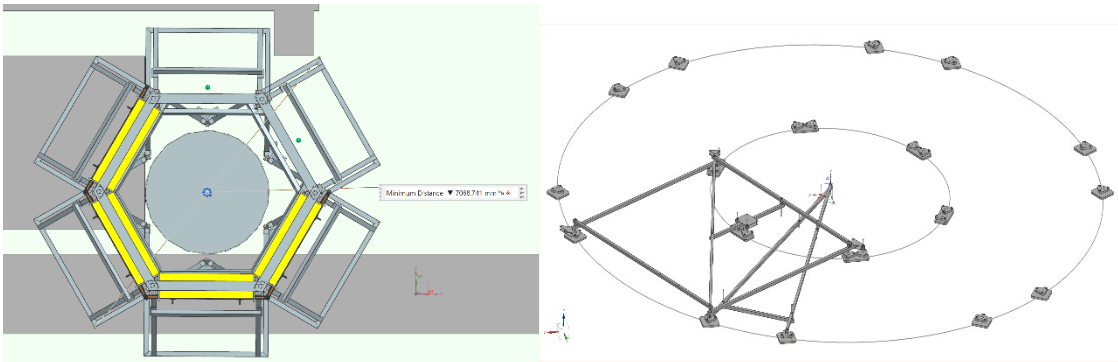

FIG. 5. Scheme of the detector positions in the test location (left panel). System of support pads with tools for precise positioning (right panel).

5. TOMOGRAPHIC RECONSTRUCTION

The image reconstruction algorithms are based on two physical processes. The first one is the energy loss occurring to charged particles when they pass through a medium, that depends roughly on the density of the crossed material times the distance travelled by the particle inside the object. Because of this energy loss, only muons with a sufficient initial energy can cross the whole cask; hence, a significant fraction of muons is instead absorbed. The presence of two detectors modules positioned around the cask allows to measure the absorption rate as a function of the different muon directions. The reconstruction algorithm [3] 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 the Multiple Coulomb Scattering (MCS), that 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 in general unknown. However, by collecting a large number of events one can overcome this problem and derive useful information on the material properties anyway. The installation of two detector modules allows to measure muons’ trajectories before they enter the cask and, if enough energetic, after they exit it and hence to determine the scattering angle of individual muons. An algorithm based on the Maximum Likelihood Expectation Maximization (MLEM) technique [3,10] is used for image reconstruction in this case: the outcome is a 3-dimensional map of a quantity roughly proportional the density times the atomic number of the material.

The results of both image reconstruction algorithms consist of a grid of “voxels” (namely 3-dimensional cubic pixels of homogeneous density). Fig. 6 shows the outcome of the first reconstruction algorithm on a Monte Carlo simulation where the cask is fully loaded except for three dummy elements in the inner part (see also Fig. 4) and the two detector modules are rotated around the cask in the same data-taken configuration of the field trial, shown also in figure 5. A diagram of the internal structure of the cask is superimposed on the image to help the reader to 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.

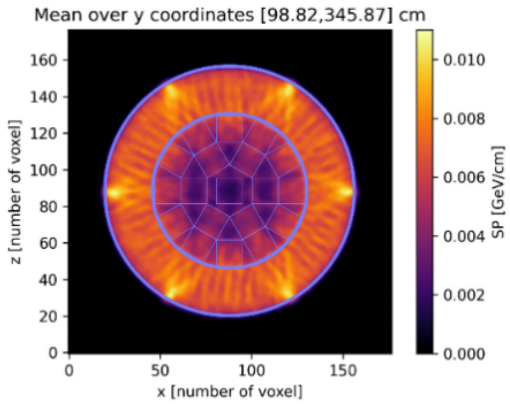

FIG. 6. Example of reconstructed image of a simulation of a CASTOR® V/19 cask with three dummy bars. The image has been obtained with the absorption algorithm and with the produced detector modules rotated around the cask

6. PRELIMINARY TESTS AND WORKING PLANS

As discussed in Sect. 2, the detector has been completely instrumented and operated at high voltage and gas flux working conditions and cosmic ray data have been recorded in horizontal position. Both modules of tubes and IMC can reconstruct cosmic ray tracks with reasonable efficiency and precision. Examples of reconstructed tracks are shown in Fig. 7.

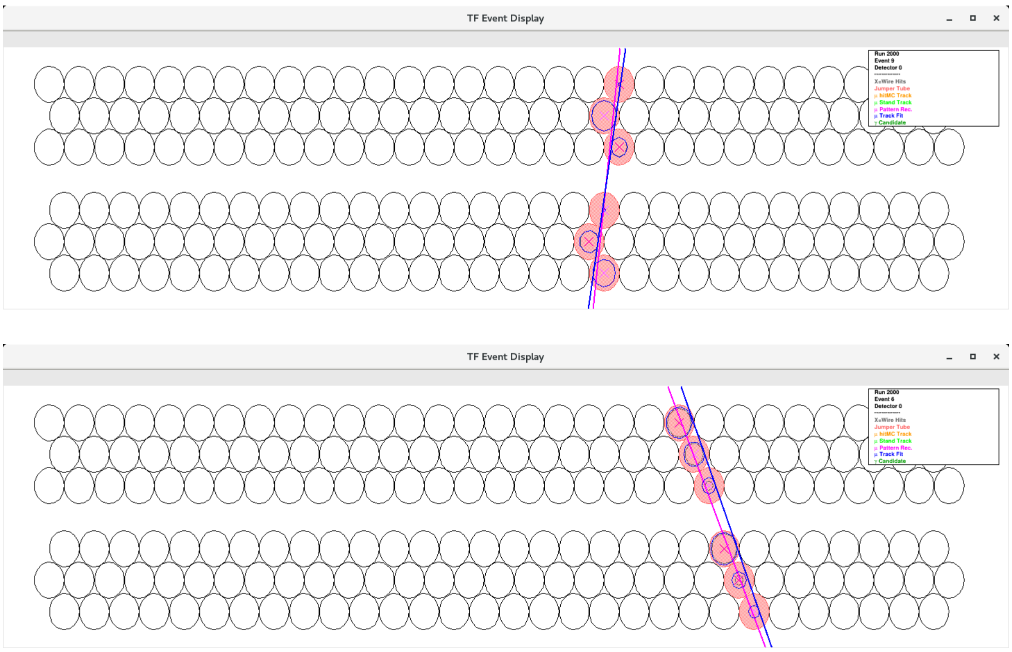

FIG. 7. Examples of reconstructed tracks in the tube module 1 (upper panel) and in the module 2. Pink circles correspond to the tubes giving a signal on both edges, red lines are the raw direction obtained as result of the pattern recognition and the blue lines represents the fitted tracks.

In a short time, the detector segments will be mounted on the support structure and data will be taken at LNL in a condition similar to the one expected during the field trial. Then a measurement of the electromagnetic interference emitted by the detector electronics, as required by authorities, will be done by a certified company. Once the test will be passed, detectors will be sent to Germany to start the field trial.

7. CONCLUSIONS

A detector dedicated to the re-verification of spent fuel casks using cosmic muons has been constructed and will be installed in proximity of CASTOR® V/19 casks in the SFSF at Grafenrheinfeld site in Germany to carry out a field trial of the muon technology. If the working plan will proceed without showstoppers, the field trial is expected to be performed within 2022.

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