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Muon tomography for dual purpose casks (MUTOMCA) project

D. Ancius[4], P. Andreetto[1], K. Aymanns[3], M. Benettoni[1], G.Bonomi[6,7], P. Calvini[8], L. Castellani[1], *P. Checchia[1], E. Conti[1], F. Gonella[1], A. Jussofie[5], A. Lorenzon[2,1], F. Montecassiano[1], M. Murtezi[4], K. Schoop[4], M.Turcato[1], G. Zumerle[1].

[1]Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Padova, Via Marzolo, 8, 35131 Padova, Italy.
[2]Dipartimento di Fisica e Astronomia, Università di Padova, Via Marzolo, 8, 35131 Padova, Italy.
[3]Forschungszentrum Jülich GmbH, IEK-6, 52425 Jülich, Germany.
[4]European Commission, DG ENER, Euratom Safeguards, 1, rue Henri M. Schnadt, 2530, Luxembourg.
[5]BGZ Gessellschaft für Zwischenlagerung mbH, Frohnhauser Str. 67, 45127, Essen, Germany.
[6]Department of Mechanical and Industrial Engineering, University of Brescia, Via Branze 38 Brescia, Italy
[7]Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Pavia, Via Bassi 6 Pavia, Italy.
[8]Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Genova, Via Dodecanneso 33 Genova, Italy.

ABSTRACT

In case of Loss of Continuity of Knowledge of a Dual Purpose Cask (DPC) Safeguards Inspectorates need to re-verify its content avoiding unloading of the cask. Reverification of spent nuclear fuel stored in a DPC is a major challenge as there is no readily available adequate Non Destructive Assay technique for this task.

Recent development of innovative imaging techniques using cosmic muons and muon trackers (muon tomography) offers unique opportunities for safeguards. Cosmic muons can penetrate meters of dense material and therefore can be used to image the contents of DPC. Information about the material distribution inside the DPC can be obtained thanks to muon transmission and multiple Coulomb scattering, provided muon detectors can be placed around the DPC.

The research project, named MUTOMCA (muon tomography for shielded casks), has started in September 2020. The main parties of this project are INFN Padova and Forschungszentrum Jülich GmbH (FZJ). Two other parties, EURATOM and BGZ Company for Interim Storage (BGZ Gesellschaft für Zwischenlagerung mbH) are also involved in this project.

A detector based on the drift tube technology will be produced and installed in the proximity of a partially loaded DPC during a field test. The objective of the field test will be recording of sufficient quantity of muons that have passed through the DPC. The recorded data then will be used to create the image of the contents of DPC thus allowing validation of earlier performed Monte Carlo calculations, which show that a missing assembly (assemblies) can be detected with the muon trackers. MUTOMCA experiment has a purpose to prove that the muon trackers could be used as efficient Non Destructive Assay safeguards technique for reverification of DPC.

Keywords: Safeguards, muon detection, muon tomography, spent fuel, CASTOR.

1 INTRODUCTION

Cosmic Muon Tomography [1] is a technique derived from particle Physics aimed at studying the content of inaccessible volumes. The scope of the MUTOMCA project is to investigate such a technology as a method to detect the diversion of spent fuel assemblies in shielded casks for safeguards re-verification purposes. In case of Loss of Continuity of Knowledge of a Dual Purpose Cask (DPC) Safeguards Inspectorates need to re-verify its content avoiding unloading of the cask. Making use of available cosmic muons shows a promising way towards a tool that helps inspectors to optimize inspection approaches.

A pilot field test has been performed in 2018 in the interim storage facility of the EnKK nuclear power station at Neckarwestheim (Germany). A prototype of a drift tube detector has been successfully tested in proximity of a CASTOR® V/19 cask loaded with spent fuel where, despite of the significant radioactivity emanating from spent fuel stored in the DPC, it has been proven that muon tracks can be successfully reconstructed [2].

2 THE PROJECT

The MUTOMCA project concerns the realization of a Muon Detector based on the drift tube technology to be installed in the proximity of a DPC and a field test with sufficient data taking time and data analysis. To reduce costs and construction complexity, the detector will cover only about one third of the DPC surface which 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.

3 THE MUON DETECTOR

The Muon Detector is constituted by two modules out of six constituting a full DPC coverage Muon Detector of hexagonal shape, as depicted in red in Fig.1. A configuration which ensures a reasonably good performance at a moderate cost, would be a Muon Detector module based on 6 layers of 4.5 meters long Al tubes with the geometry shown in Fig. 2. Each tube has a 5 cm diameter with 1.5 mm thickness and it is equipped with a coaxial 100 μm Cu-Be wire tensioned at about 6 N. The wires act as anodic electrodes being connected to a 3000 V electric potential generating the electric field required to collect the drift electron signal.

The 3rd and the 4th layers are separated in order to minimize the path ambiguities due to drift time circular symmetry. The support structure design allows to move one segment in order to compensate for acceptance losses in the peripheral regions and to ensure, with longer data recording time, a reasonable reconstruction. Such a setup requires 366 tubes (Fig. 2).

A dedicated system based on double read-out ensures a low precision (~20 cm) measurement of the coordinate along wires, which could be sufficiently accurate given the geometry of this application.

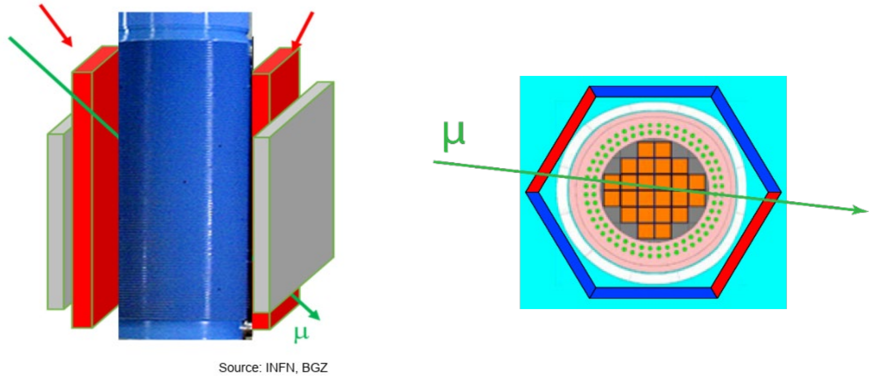


Figure 1. Schematic view of a hexagonal 1/3 and full coverage Muon Detector (red and blue segments, respectively).

In order to study the performance of the proposed Muon Detector with the precise measurement of only one coordinate and the possible need of a precise measurement of the second coordinate, existing INFN Muon Detectors will be used during the field test as shown in Fig. 3 (a and b).

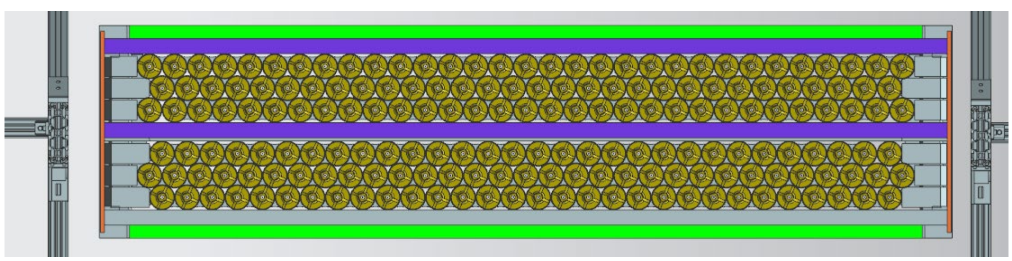
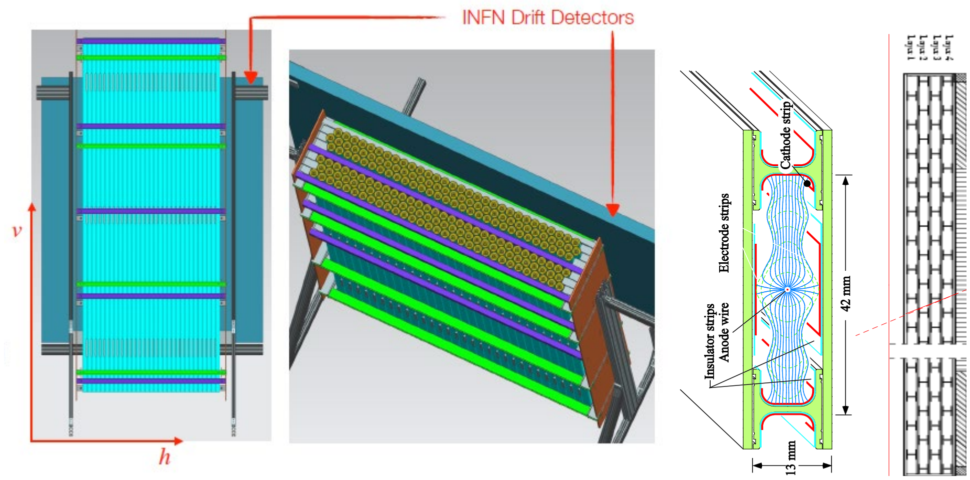


Figure 2. Detailed view of a Muon Detector module assembled with six layers of drift tubes. The 3rd and 4th layers are separated in order to minimize the path ambiguities due to drift time circular symmetry.

These detectors, referred to as Horizontal Layers (HL), are available as a leftover of the muon chamber production for the CMS experiment at CERN. They are made of 4 layers of rectangular cells with dimensions and layout shown in Fig. 3 c and d, respectively. All tubes and HL cells are filled with a gas mixture Ar/CO_2 (85/15%).



(a) (b) (c) (d)

Figure 3. Schematic view of the additional Muon Detectors to be used during the field test(a and b). Detail of a drift cell (c) and layout of the layers.

<u>3.1 Status of Detector Production.</u> Concerning the mechanical construction, all tubes have been fully equipped with end caps, pins and wire (Fig. 4). All end caps have been treated in groups of about 70 units with epoxy glue to obtain a gas tight inner volume (Fig. 5). All tubes passed strict tests on gas tightness and dark current measurement, all resulting as ready to be used.

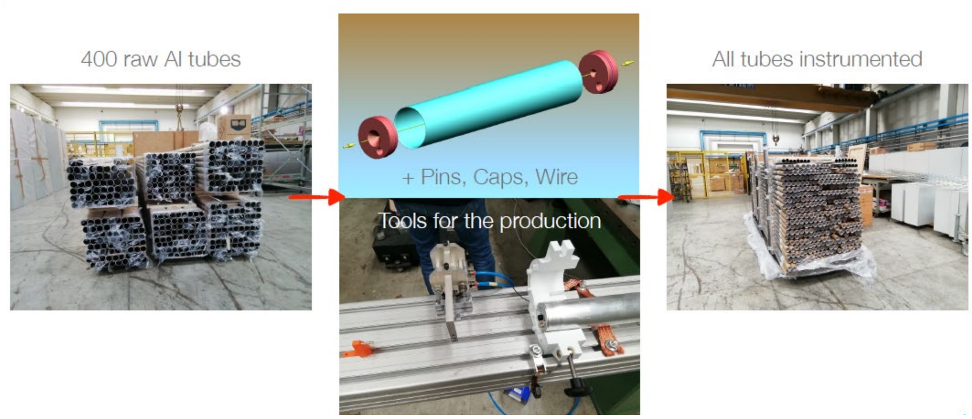


Figure 4. Steps in tube production.

Concerning the electronics, the data acquisition system (Fig. 6) is based on the Field Programmable Gate Array (FPGA) Artix7 (28 nm) and the System On Chip (SoC) Zynq UltraScale+ (16 nm) from XILINX technologies. Briefly the system is built over 4 types of boards: i) 22 TDC cards which instrument the about 1000 tubes with time to digital converter; ii) 4 DAQ cards which elaborate a trigger signal and enable the TDC readout; iii) 1 GTT card which processes a global trigger by composing those coming from DAQ boards. It is also responsible for clock distribution and control of the system; iv) 12 FeedThrough that are simple interface boards between detector and TDC boards. A prototype for each of the 4 types of board has been assembled and tested. No design or assembly issues were found.

Figure 5. Steps in cap gluing to complete tube readiness.

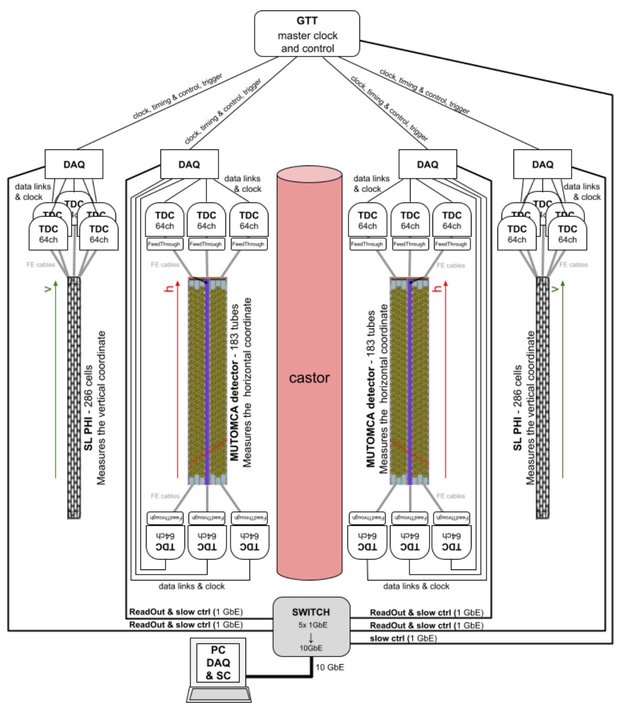
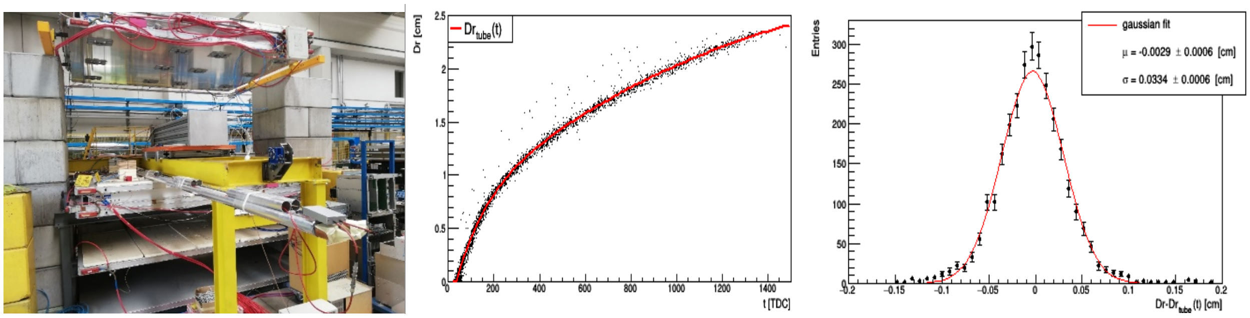


Figure 6. Layout of electronic and read-out system

A sample of tubes has been put in the INFN muon tomography Demonstrator [3] available at Laboratori Nazionali di Legnaro (LNL) which is used to measure the performance (in terms of efficiency, noise, time response, resolution etc.) of new detectors, on the basis of reconstructed cosmic muon tracks. Fig. 7a shows the setup with two tubes installed in the demonstrator and Fig. 7b and 7c show the time response and the measured position resolution, respectively. A resolution of about 350 μm can be easily obtained.



(a) **(b)** **(c)**

Figure 7. Setup of the test measurement with two tubes (a). Distance of the reconstructed cosmic muon track from the tube wire as a function of the measured drift time (b). Position resolution obtained after converting the measured time to a distance from the wire (c).

The next steps toward the complete detector construction foresee to mount the tubes in the designed structure, to connect gas pipes and check the gas tightness of whole detectors and to complete with end plates and mount electronics and cables. At that point the vertical support structure can be mounted to hold the detector and the HL. The estimated time for detector completion is by the end of 2021.

Once both modules will be completed, a dry run with the modules operated in similar conditions but in absence of DPC will be performed in LNL.

4 THE FIELD TEST

The Field test is expected to be carried out at the Grafenrheinfeld interim storage facility in Germany in 2022. As discussed above, having a detector of reduced dimensions requires to move the modules in several positions in order to cover the whole DPC volume. Several options have been considered, the most convenient is to take data in nine positions as shown in Fig. 8. The required data taking time per position can be obtained within ten hours but the working conditions could oblige to take one day per position since it may be impossible to move the modules outside working hours. However, the final decision on the module position is subject to the approval of the interim storage facility management and hence it is not guaranteed that the test results will correspond to what is presented here.

5 SIMULATION

In order to better design the detector and to train the reconstruction algorithms, a simulation of the full system, that is the CASTOR® V/19 cask loaded with spent fuel and the detector modules, has been developed. It has been based on the GEANT4 package [3]. Indeed, this toolkit, developed at CERN, includes all the physics about the interaction of muons with

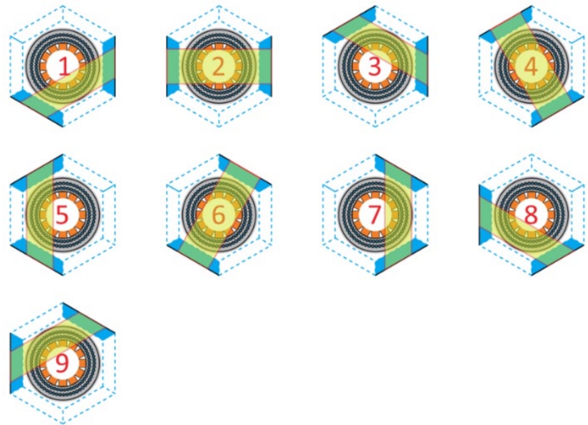


Figure 8. Data taking positions around the DPC (to be approved by the interim storage facility management).

matter, a complete range of functionality including tracking, geometry, physics models and hits. It is the result of a worldwide collaboration of physicists and software engineers. It is the most complete, reliable and basically the de facto statutory software for this kind of simulations. The MUTOMCA simulation packages is also based on the VMC project [4] that incorporates the ROOT analysis framework [5]. 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 is a key requirement also for the MUTOMCA project. The cosmic muons are thus generated according to a parametrization of experimental data [6]. The simulation has been furtherly improved introducing the possibility of generating from a cylindrical surface around the CASTOR® V/19, while keeping the correct angular and momentum distribution of generated tracks. The behavior of the detector modules has also been carefully reproduced.

6 RECONSTRUCTION ANALYSIS

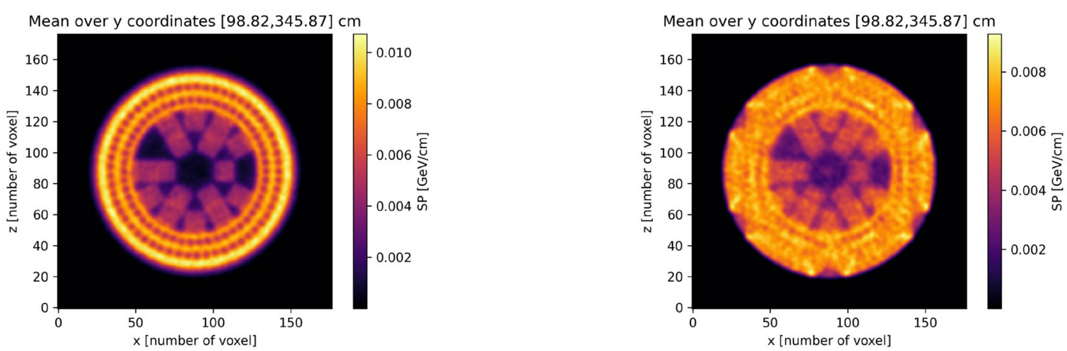
The image reconstruction is based on methods related to two physical processes.

The first method considers the absorption of a significant fraction of muons due to the particle energy loss in the crossed material. In fact, for any charged particle as muons, the energy loss per unit of length depends roughly on the density of the crossed material. Therefore, only muons having a sufficient energy can cross the whole DPC. The reconstruction algorithm implementing the method based on muon absorption is called μCT [7]. This algorithm relies on the definition of the so-called Line-of-Response (LoR), in which the measured fraction of absorbed muons is compared with the theoretical predictions derived from the thickness of the transverse material and the muon energy distribution. The outcome is a 3-dimensional map of the Stopping Power (SP), i.e. the mean energy loss per distance travelled by muons in the material.

The second method is related to the multiple Coulomb scattering that makes charged particles to deviate from their original direction when crossing material. The average deviation is null but the width of the scattering angle distribution is related to the thickness of the crossed material and approximately to the product of its density and its Atomic number. The width depends as well on the inverse of the individual particle momentum, which is in general unknown, but collecting a large number of events one can derive useful information on the material properties anyway. A Maximum Likelihood Expectation Maximization (MLEM) algorithm is applied in this case for image reconstruction [8-9]. The result in this case is a map of the Linear Scattering Density (LSD), which is the quantity related to the width of the scattering angle distribution that carries the information about the material properties.

Both methods require the installation of two detector modules, in order to measure muons' trajectories before they enter the DPC and, if enough energetic, after they exit from it.

The outcome of the reconstruction process is a grid of "voxels" (namely 3D cubic pixels of homogeneous density, in our case of approximately 2 cm side) surrounding the simulated cask: a value of SP or LSD is associated with each voxel. Results from both reconstruction methods applied to simulated data are shown in the following subsections: images are smoothed through a αβ-trimmed filter [10] for noise reduction.



(a) **(b)**

Figure 9: μCT reconstruction of a simulation with three missing bars: 2D-map of the SP mean in the central region of the DPC cask, obtained assuming a 360° detector coverage (a), and two 60°-acceptance modules, rotated around the cask in different positions (b).

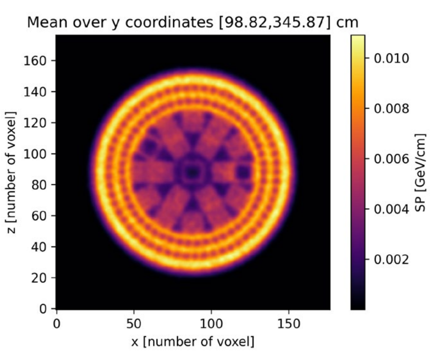
<u>6.1 Image reconstruction through μCT algorithm.</u> We show in Fig. 9 the results obtained with the μCT algorithm on a simulation of a cask with sixteen fuel assemblies and three missing bars. The simulated dataset corresponds to approximately 48h of data taking. While Fig. 9(a) shows the results of a reconstruction performed in the idealistic case of 360° detector coverage, Fig. 9(b) is realized with the configuration shown in Fig. 8; in both cases the missing bars can be clearly identified, even if with the 9-position data-taking the image loses some definition, and part of the external shield is cut.

An alternative scenario is to have the so-called "dummy" bars instead of empty spots in the cask basket. This is indeed a harder challenge to tackle, since the presence of additional material can make it more difficult to identify the absence of fuel assemblies. However, μCT algorithm performs well also in this case, as it can be seen from Fig. 10, where the results of the reconstruction of a 48h simulation with three dummy assemblies are shown.

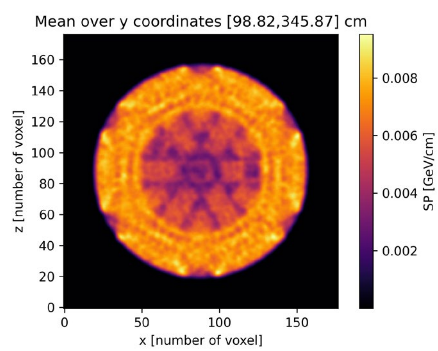
6.2 Image reconstruction through MLEM algorithm. In Fig. 11 the results obtained with the MLEM algorithm on the simulation of a cask with sixteen fuel assemblies and three missing bars are shown. The comparison of the reconstruction with a detector of 360° angular coverage and with two modules of 60° angular acceptance rotated as in Fig. 8 shows no significant difference, at least in the inner part of the cask. For both reconstructions we assumed to have no information about the value of the individual muon momentum, so a fixed value of momentum is used for all muons.

7 CONCLUSIONS

Within the MUTOMCA project, a detector dedicated to the re-verification of DPC using cosmic muons is under construction. The detector will be installed in proximity of a DPC in the Grafenrheinfeld interim storage facility in Germany to carry out a field test of the muon technology. Simulation data, reproducing the experimental setup and the precise description of the cask have been produced and analyzed showing that a positive response from the test, in terms of the recognition of the substitution of fuel assemblies, is expected.



(a)



(b)

Figure 10: µCT reconstruction of a simulation with three dummy bars: 2D-map of the SP mean in the central region of the DPC cask, obtained assuming a 360° detector coverage (a), and two 60°-acceptance modules, rotated around the cask in different positions (b).

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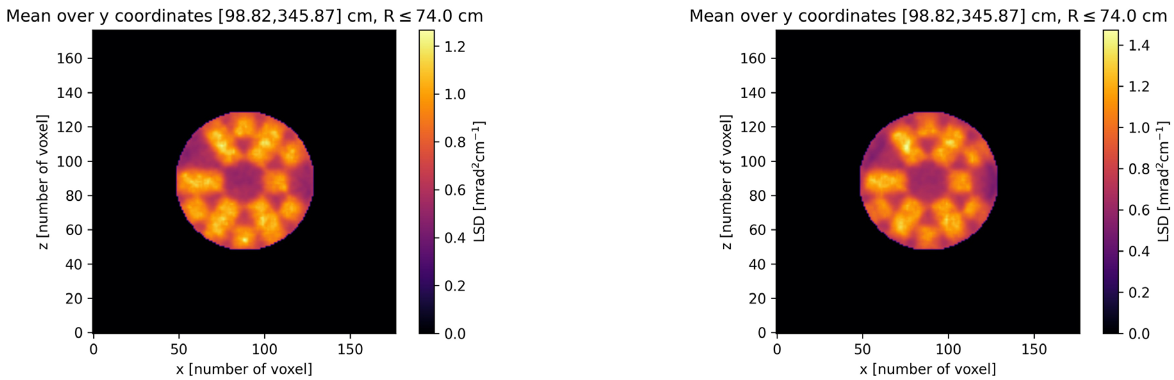

(a) **(b)**

Figure 11: MLEM reconstruction of a simulation with three missing bars: 2D-map of the LSD mean in the central region of the DPC cask, obtained assuming a 360° detector coverage (a), and two 60°-acceptance modules, rotated around the cask in different positions (b). The external shield is cut to avoid saturation.

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