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# Large Industrial and Natural Objects Investigation by the Muon Radiography on the Basis of Track Detectors

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**ABSTRACT:** The first test experiments carried out by the authors open the series of pilot muon radiography experiments starting in Russia. Distributions of the measured muon flux show good agreement with computational predictions for inhomogeneities in the studied structure. The experiments aim to demonstrated the potential of the method for the inner structure monitoring of large natural and industrial objects which condition may be a threat for population, infrastructure or environment.

**KEYWORDS:** Nuclear emulsion, muon radiography, non-destructive control of large natural and industrial objects.

### I. INTRODUCTION

Cosmic ray particles make it possible to obtain information not only about space physics processes, but also of the physical phenomena occurring in the Earth. In particular, the cosmic ray muons are successfully used in the method of muon radiography. Muon radiography is a method for studying the inner structure of large size natural and industrial objects, based on the analysis of the cosmic muon scattering and absorption as a result of their passage through the object. [1-2]. Muon radiography uses the same basic principles as medical radiography: detector registers a particle flux (the muons of cosmic origin instead of X-rays) attenuated after passage through a layer of some dense substance (rock, concrete or some other materials instead of the patient body). The method advantages consist in its noninvasiveness and the natural radiation sources usage. The cross section of these particles interaction for the typical observed energies makes them a perfect radiography agent, as their absorption length is comparable with the scale of the studied large objects [3]. The maximum depth of the cosmic ray muon registration is 8.6 km of water equivalent (about 2 km of the rock). At present, cosmic ray muon radiography applications are geophysical research, geological exploration, mining geophysics [4-5], alternative geophysical methods of seismic process analysis [6], the study of volcanoes (information about the internal cavity of the crater and lava movements) [7-8]. Muon radiography method has been already successfully used for nondestructive testing of large industrial facilities, such as bridges, dams, blast furnaces, etc. [9], for radiation monitoring of nuclear power facilities [10] and for large archaeological object radiography: the first successful archaeological research of Khafre pyramid in Egypt was carried out in the 70s of the 20th century by group of scientists under the leadership of Nobel laureate Luis Alvarez [11]. During last ten years physicists of Italy, Japan,

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Switzerland and other countries for these purposes have actively developed the muon radiography on base of track detectors with nuclear emulsions as a recording elements [8, 12-15], many model calculations and experimental measurements are made. Part of our results of a model experiments including two detectors were represented in [16]. It was shown that the reconstruction of the inner structure of objects with size larger than 100 m is much more effective if the reduced values of flux are used. Russian scientific groups in collaboration with the INFN (Naples scanning laboratory, Italy) about two years engage of the development and testing of the muon radiography method based on emulsion track detectors in Russia.

### II. THE ADVANTAGES OF EMULSION TRACK DETECTOR USING IN THE MUON RADIOGRAPHY

Up to date, in the world practice the research of various objects by the method of muon radiography the electronic equipment was often used, even it is much more cumbersome and complicated than the emulsion track detectors [9, 10, 17-20]. Emulsion track detectors, in addition to small size and design simplicity, have today's best spatial resolution (<1 micron), large information capacity. They are easy to transport and easy to operate in difficult conditions, for example, in the mountains. In the period of data accumulation these detectors require no power supply and electronic reading systems, as well as direct human intervention. Progress in the development of automated systems for scanning and processing of nuclear emulsions, allowed to implement a number of ambitious successful nuclear physics experiments with usage of tons of nuclear emulsion, and to begin large-scale applied research using the muon radiography method. The scanning speed of modern European high-tech automated microscopes for the emulsion data processing is from 20 up to 800 cm<sup>2</sup> of the emulsion layer an hour with up to 50<sup>x</sup> magnification. It removes any restrictions on the area and volume of the exposed detector. For example, in an OPERA experiment, first detected the tau neutrinos from muon neutrino oscillations, emulsion layers with a total surface of about eight football fields were used [21-24].

In Russia experiments of this type were not held until recently because of nuclear emulsions reliable manufacturer lack. However, in recent years the production of nuclear emulsions with characteristics required for relativistic particle registration has been set up at "Slavich" company in Pereslavl, Yaroslavl region.

### III. OBNINSK EXPOSURE

One of the first test experiments on muon radiography in Russia was carried out at a depth of 30 m in an underground mine, located on the territory of the Geophysical Survey RAS, Oboinsk [25, 26]. As a result of measurements it was expected to register a difference of flow of the atmospheric muons on the earth's surface and at depth, for what on both observation levels two detector sets were installed. In addition, the experiment objectives included the estimate of opportunities of the vertical cavity (elevator shaft) "discovery" in the soil by the muon radiography detector with nuclear emulsions located at a depth of 30 m. The relative location of the lift shaft and underground detectors, X and Y axes orientation in the detector, a direction to the lift shaft, the vertical diagram of the relative position of the detector and elevator shaft are show at fig.6, 7 in [26]. These figures shows trajectories of muons passing at different zenith angles  $\theta$  to the detector surface. When  $\theta \sim 25^\circ$  and  $\phi \sim 135^\circ$  i. e. in the direction to the elevator shaft the absorption of the muon flux is weakened due to the cavity presence, and therefore the muon flux from that direction should significantly exceed the background.

Two types of nuclear emulsions, produced by the Russian company "Slavich" and by the Japanese company Fuji Photo Film used in experiment OPERA, were applied in this experiment. Detectors prepared for the tests consisted of densely packed stacks of 6 or 10 double side poured emulsion plates of  $10 \times 12 \text{ cm}^2$ , rigidly fixed in an aluminum frame. The appearance of the four detectors in the field of underground exposition is given in Fig.1.

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Fig.1. Underground detectors location.

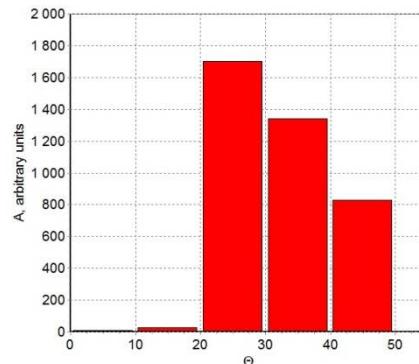


Figure 2. The value of the muon flux abundance over background  $\Delta F$  in the  $\phi$  angle range of 130 to 140 degrees (the direction to the mine) for 5 equal intervals of the zenith angle  $\theta$ .

To determine the degree of the atmospheric muon flux attenuation while passing through the soil the four cameras were placed in an underground chamber and the two ones - in the building on the surface

Furthermore an additional inspection of this method capabilities was carried out. For this aim the narrow peak in the direction  $\phi \sim 135$  degrees (the direction to the expected signal from the mine) in the five intervals of zenith angle  $\theta < 50$  degrees with step of 10 degrees was measured. Due to detector position it follows that the maximum value of the signal must be at  $\theta \sim 25$  degrees, and its amplitude decreases with  $\theta$  increasing. When  $\theta$  is less than 20 degrees the peak should disappear. The measurement results presented in Fig. 2 are in agreement with such a behavior. Thus, the method makes it possible not only to register the mine location, but also to investigate a fine structure of the object studied.

### IV. DATA ANALYSIS

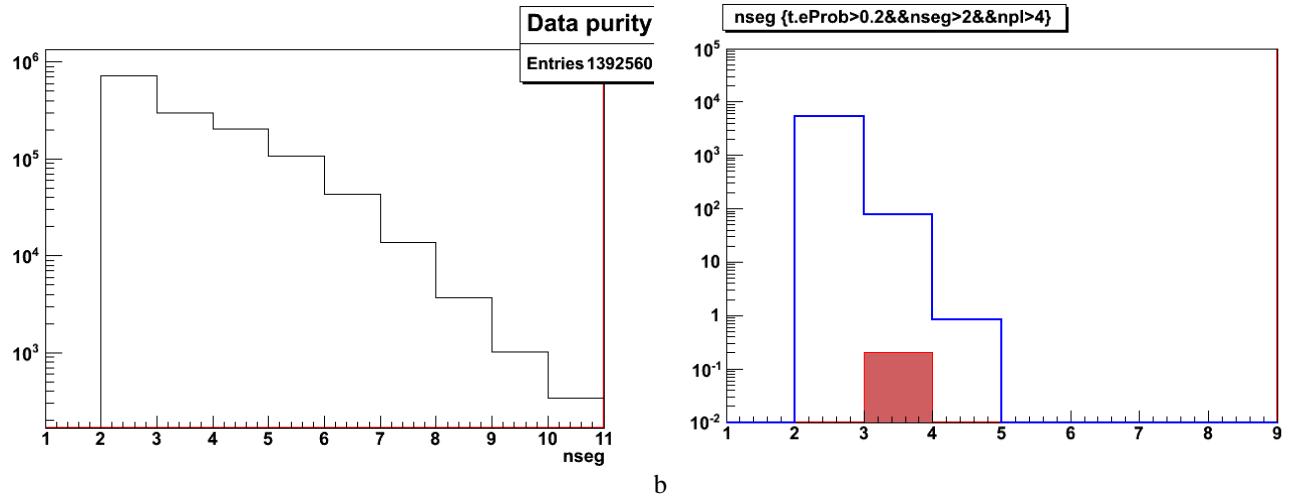
#### FEDRA track reconstruction

The emulsion detector with an area  $0.48 \text{ m}^2$  was irradiated at a depth of 30 m. In order to determine the optimal exposure time sufficient to obtain the necessary information different periods of detector irradiation, 2 and 4 months, were chosen. Data analysis showed that 2 months' exposure time was not statistically sufficient. Therefore, the main data taking was extracted from data set of two modules of 4 months exposure. Each module included 3 and 2 doublets of emulsion films, individually packed in vacuum light shielded envelopes what is 10 emulsion films per module in total. The total emulsion film area in one module was  $0.12 \text{ m}^2$ . Each emulsion film is a plastic base of  $205 \mu\text{m}$  thickness coated on both sides with  $(43\text{--}45) \mu\text{m}$  active nuclear emulsion layers. After about a 4 months exposure and detector disassembly the emulsions were developed in National laboratory Gran Sasso, INFN, Italy. The emulsion data was analyzed at INFN Naples scanning laboratory, Italy and on the PAVICOM facility in P.N.Lebedev Physical Institute, Russia. The LASSO automatic scanning system (SS) [27] was used for data taking. In each emulsion layer all registered "microtracks" are ionizing particle paths reconstructed by the SS. Each micro track consists of 6-12 silver grains recovered from AgBr as a result of the ionizing particle passing. One grain position resolution is about 1  $\mu\text{m}$  and angular resolution of micro tracks is of the order of 10 mrad. After that the scanning linking procedure for each micro tracks is applied to reconstruct "base tracks", track segments consisting of 2 micro tracks detected in two sensitive layers of the same film. Due to the high emulsion spatial resolution the emulsion base tracks angular resolution on the base of  $200 \mu\text{m}$  is better than 3 mrad. It is the most important parameter for the muon radiography telescope. Using the base tracks found in all 10 plates the pattern recognition and the volume tracking are performed to reconstruct long tracks crossing the whole module during the exposure period in this particular sequence and geometry. This operation allows to separate tracks accumulated during the exposure from all other tracks fixed in each emulsion plate during its active "life" from production to the development. The offline reconstruction was performed with FEDRA [28]. Different combinations for reconstructed tracks in the detector volume (10 emulsion films) are presented in Fig.3a. The tracks considered consist from 2 to 10 base tracks respectively.

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a  
 Fig.3. a) Illustration of the data purity. b) Volume track reconstruction in emulsion detector after misalignment procedure.

To minimize combinatoric background, the so called misalignment procedure was used. This procedure is ideologically similar to tracking one, but the emulsion planes are shifted and rotated relative to each other so that a real track made of base tracks is not reconstructed under these conditions.

The data set obtained after the misalignment procedure is presented as the distribution on Fig.3b (the blue one) and shows the number of reconstructed by chance tracks. After some shifts and rotations of the emulsion planes some volume tracks formed by 2 or 3 base tracks still can be reconstructed, however the number of tracks is much less than the real one. To minimize combinatoric background in the data only volume tracks consisting of more than 3 base tracks were used. Taking into account the volume track length, a track passing emulsion detector (10 plates) should cross 4 emulsion films or more. The probability of the volume track reconstruction in fact the majority under the conditions is extremely small, see distribution on Fig.3b (shaded one).

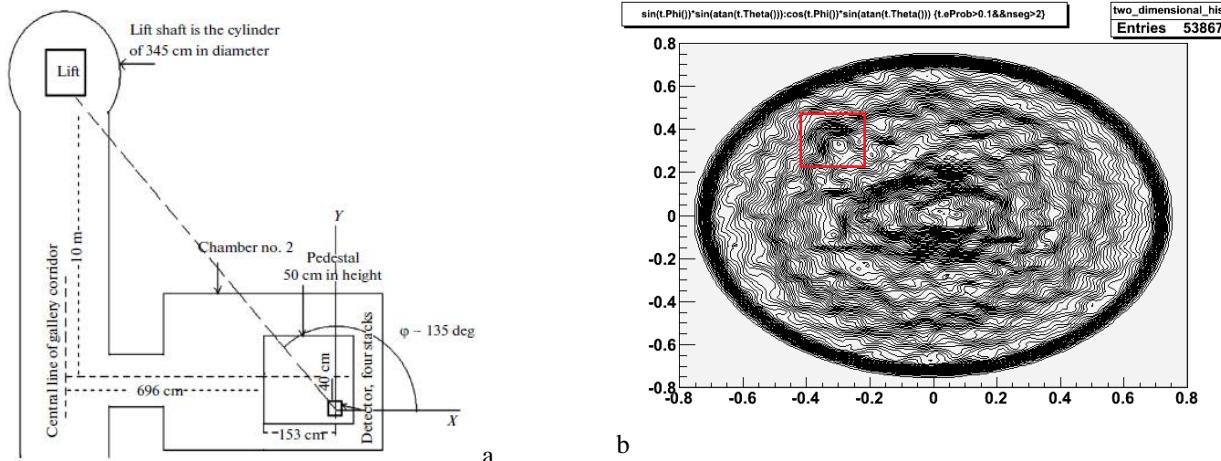


Fig. 4. a)Relative location of the lift shaft and underground detectors (top view). X and Y axes orientation in the detector and a direction to the lift shaft are shown; b) Experimental two-dimentional angle distribution of muons, passed through the emulsion detectors being exposed at a depth of 30 meters.

After the track reconstruction procedure it is possible to obtain a track density distribution. The data is presented by imaging methods as a function of the 2 components:  $\sin(\phi) * \sin(\theta)$  and  $\cos(\phi) * \sin(\theta)$  indicating the track slope relatively to the axis normal to the emulsion plane. The two-dimensional angle distribution is presented on Fig 4.

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The data presented shows experimental distribution of muons, passing through the emulsion detectors exposed at a depth of 30 meters for 4 months. Even in the absence of model calculations the only experimental data shows a good agreement with the signal expectation. The clearly visible signal is marked on the figure with square frame.

### **Efficiency correction**

As the part of used emulsion age has exceeded 10 years old it is susceptible to the edging effects. Due to the emulsion lower sensitivity and higher background level the muon detection efficiency is reduced to nearly a factor of 2 from the nominal 90%. This efficiency has the slope dependency and is to be corrected in the muon radiography detector. In the detectors used there are 10 emulsion plates so the long tracks consisting of 2-10 segments could be reconstructed. Only tracks satisfying the criteria "t.eProb>0.2&&nseg>2&&npl>4" were used for the following analysis. The mean efficiency of track registration by a single emulsion plate was estimated using so-called "fill factor" of found tracks as  $(nseg-2)/(nplates-2)$ . Here only inner segments were taken into account excluding the first and the last ones. The overall detector efficiency i.e. the probability to register track in 10 plates satisfying the above criteria was estimated using the integral of the binomial distribution:

$$f(k; n, p) = \Pr(X = k) = \binom{n}{k} p^k (1-p)^{n-k},$$

where  $n=10$ ,  $k>4$ ,  $P$  is a single plate probability estimated using the "fill factor" as described above.

The angular dependence of the detector efficiency is shown on the fig 5a. The distribution was interpolated by the smooth polynomial function to get rid of the statistical fluctuations of the bins. On the fig 5b the correction function is presented as a 2D histogram. Fig.5c shows the 2D angular distribution of the reconstructed tracks. On the fig 5d the data corrected to the efficiency is given – the correction was obtained as the ratio of data and the efficiency histograms.

### **Expected signal simulation**

To reveal the density variations from the above to detector ground layers the comparison of the observed and the expected muon angular distribution is required. The muon spectrum parametrization from [29] was used. To obtain possibly realistic spectrum on the exposure depth the muons generated on the surface were traced in 30 m depth layer of standard rock using the GEANT4 [30] package. The resulting angular distribution of simulated muons is shown on fig. 5e. We consider this distribution as a pedestal for the signal and on fig.5f the difference between 5d and 5e is presented. The peak corresponding to the elevator shaft at (-0.4, 0.4) is clearly seen on the data plots on fig7 c, d, f. One can see how it's significance, or a "contrast" level, improves after each step of the analysis by efficiency correction and pedestal subtraction.

### **Results and discussion**

On the fig.6a the distribution same to fig.5d is shown as a 2D contour map. On fig.6b is the relative one: (signal-peDESTAL)/peDESTAL, the radial grid with 10 deg. step is superimposed on the plot for the convenience. We clearly see the peak corresponding to the elevator shaft at approximately  $\varphi=132^\circ$ ,  $\theta=27^\circ$  degrees. The overall domination of the central part of the distribution (inside  $\theta=20-30$  degrees) can be partially explained by the effect of the room where the exposure was performed. Using the simulated spectrum, we verified that 2.5 m of empty space corresponds to about 10-15% of muons excess. We considered here only the tracks entering to detector with the momentum  $> 0.5$  GeV. Other structures visible on the map could correspond to cavities, density variations or constructions in the upper layers or on the earth surface above the detector.

It should be noted also, that there is some features as concerned as very large objects with sizes much more than 100 m. But passing through such objects, muons are strongly scattered on its atoms changing their momentum in both magnitude and direction, that can introduce the distortions to the result. We calculated this additional muon scattering effect using the GEANT4 software package [30]. The simulation was performed in wide energy and length L ranges for iron and rock ground [16, 31]. The result shows that the divergence from initial direction  $\theta$  can be approximated with function  $F = A \cdot \theta \cdot \exp(-(\delta\theta)^2)$  with the parameter  $\delta$  linear depending on energy at fixed L. It is necessary take into account this fact in future work.

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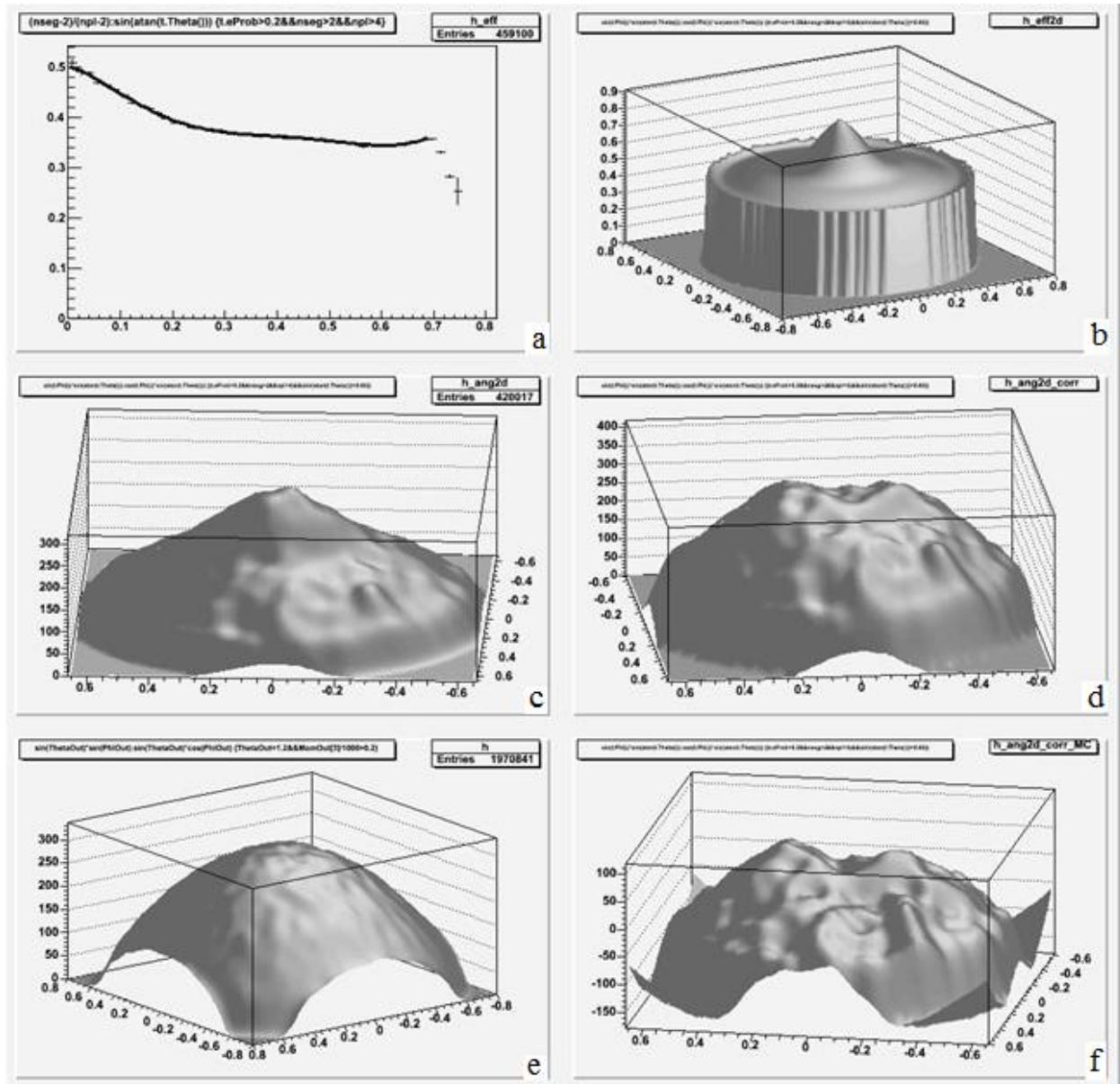


Figure 5. As angular variables the projections of the unit vector  $\mathbf{e} = \{\mathbf{ex}, \mathbf{ey}, \mathbf{ez}\}$ , directed along a particle track, on OX ( $\mathbf{ex} = \cos(\theta)\sin(\phi)$ ) and OY ( $\mathbf{ey} = \sin(\theta)\sin(\phi)$ ) axes are chosen.

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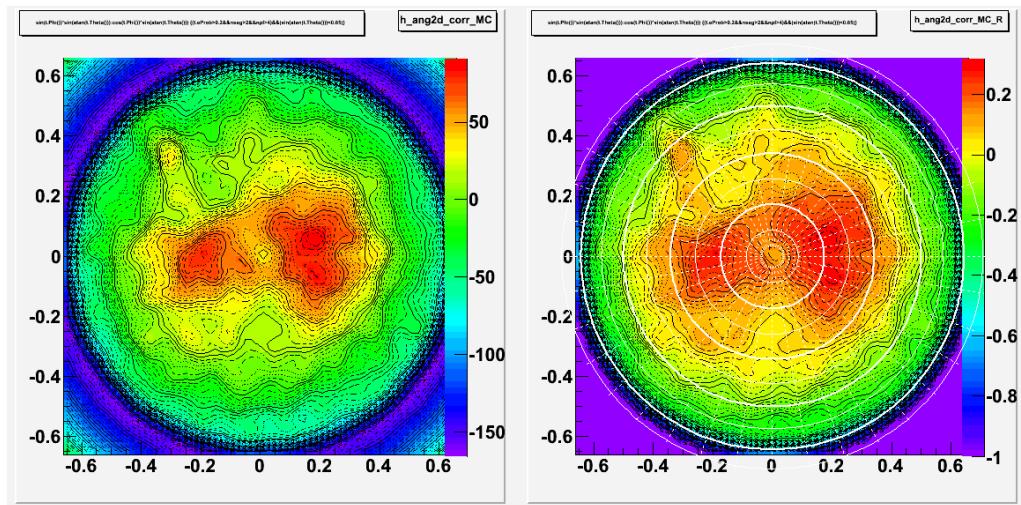


Fig. 6. a) and b) the same as for 7d and 7f, but in 2D contour maps

### V. CONCLUSION

The first test experiments carried out by the authors demonstrated the potential of the method [32]. Distributions of the muon flux measured show good agreement with computational predictions for inhomogeneities in the studied structure. Developing capabilities of GPU (Graphical Processing Units) [33], in particular, improving the efficiency of track reconstructing and increase of the data processing speed in a continuous scanning regime up to  $800 \text{ cm}^2$  of the emulsion layer an hour allowed to considerably hasten the emulsion data processing [34-37].

Production of the relativistic nuclear emulsion for muon radiography by Russian company "Slavich" and advanced innovation in electronics in the field of image processing open large perspectives of implementation of the method in various fields of research, such as nondestructive testing of large industrial facilities, monitoring of nuclear reactors, geological exploration, alternative method of seismic process analysis, volcanology.

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