Muon radiography

A.K.Managadze - Romania 2013

General muon features

Muon (μ) is a light charged elementary particle with spin ½ belonging to leptons.

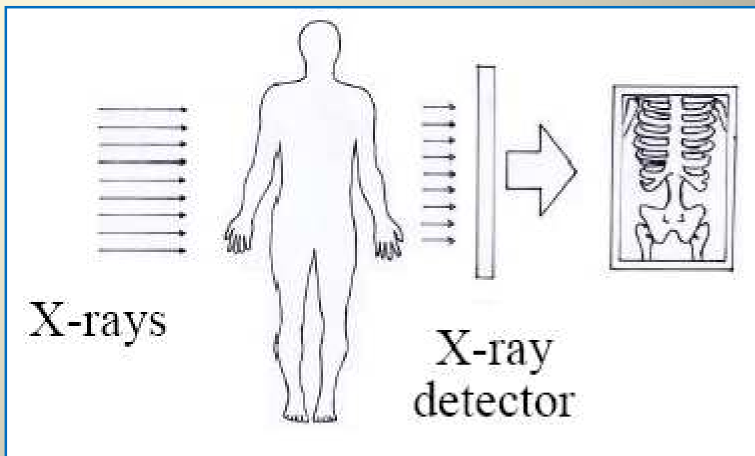
Many characteristics of muon and electron are similar, but the muon mass (106 MeV) is 207 times more than the electron mass. Therefore the muon path length is thousands times longer than for electron. Muon lifetime is around 2.2 μs.

Muon penetration ability

Muons penetrate through the planet surface with intensity 10 000 particles/(m^2·min) and therefore through everything situated upon Earth.

Even at rather moderate energy 10 GeV muons are able to pass not only complete Earth atmosphere, but to penetrate deep into the ground. Maximal depth, where highest energy muons were detected, was about 8600 m of water equivalent.

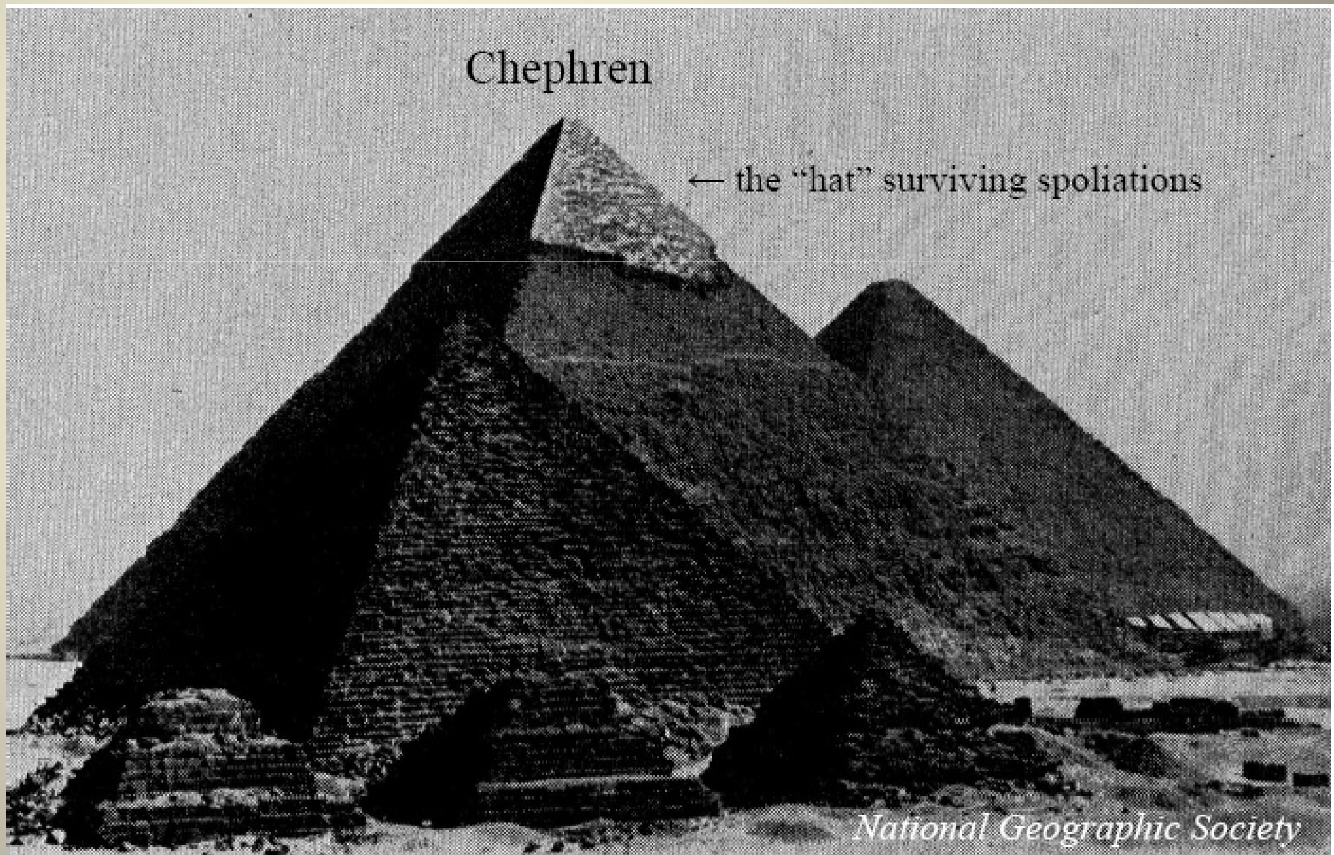
Muon radiography uses the same main concepts as medical radiography: beam absorption (muons instead of X-rays) while passing through matter (rock or building materials instead of human flesh) and a sensitive device. **Advantages** of the method are its **non-invasiveness** and employment of **natural origin** of radiation.



Muon radiography in archaeology.

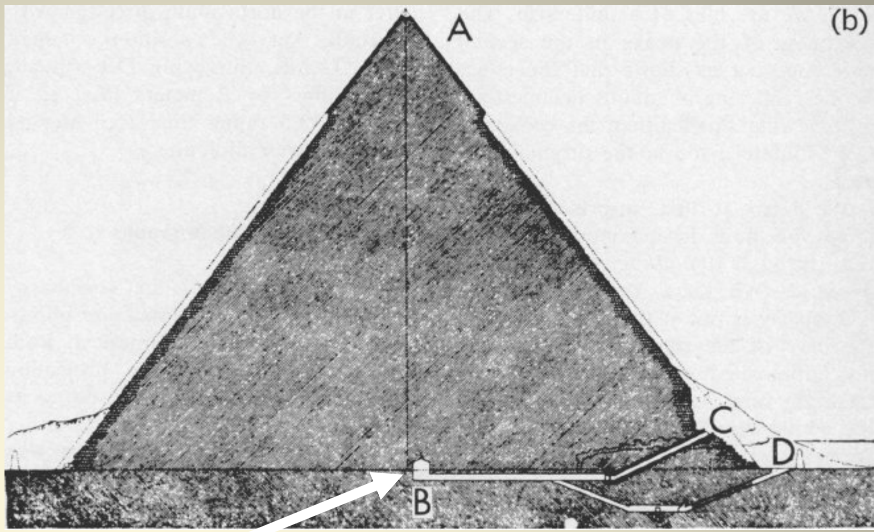
For the first time the idea of CR muon flux application for detection of density fluctuations in the structure of archaeological objects was arised about 40 years ago due to Luis Alvarez. This idea was employed for sectret chamber search in Chephren pyramid.

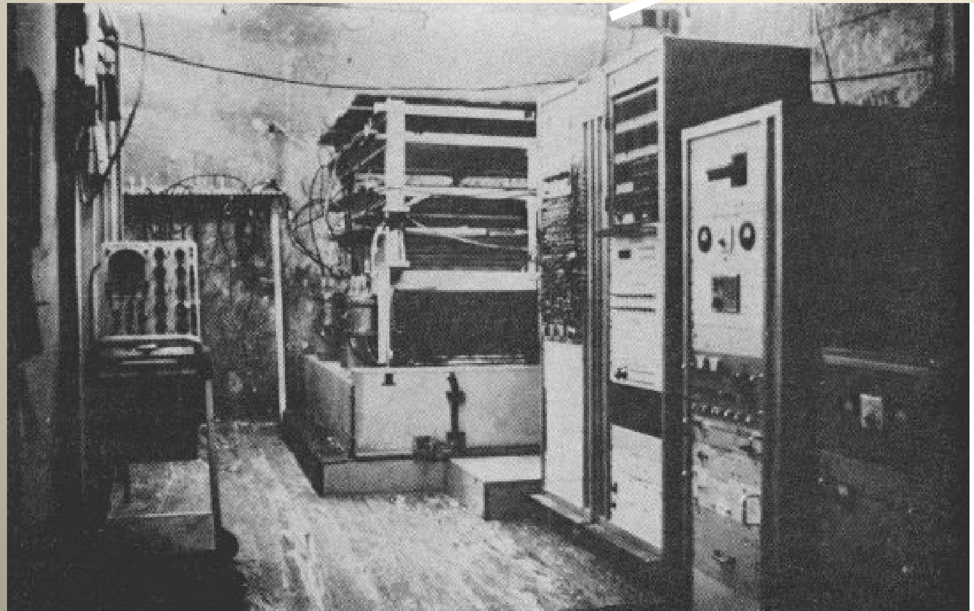
Muon flux inside pyramid was measured by streamer chambers. More than million events were detected by 2 streamer chambers with area 1.8 m^2 each. Researchers determined the absence of secret cavities in the pyramid body.



The Luis Alvarez 1970 muon experiment

Chephren
Pyramid





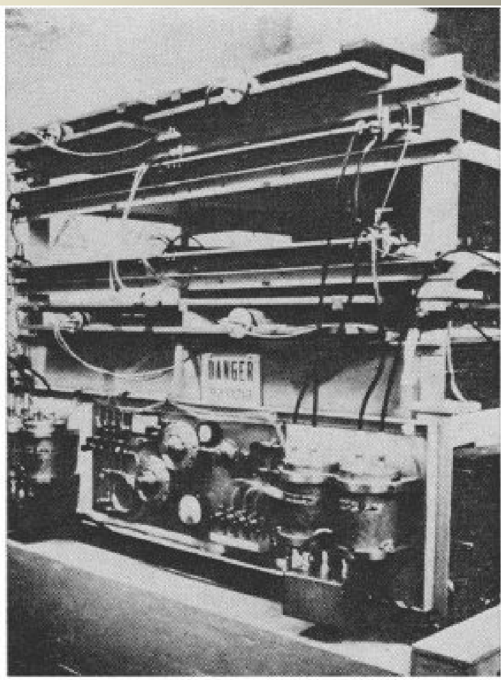
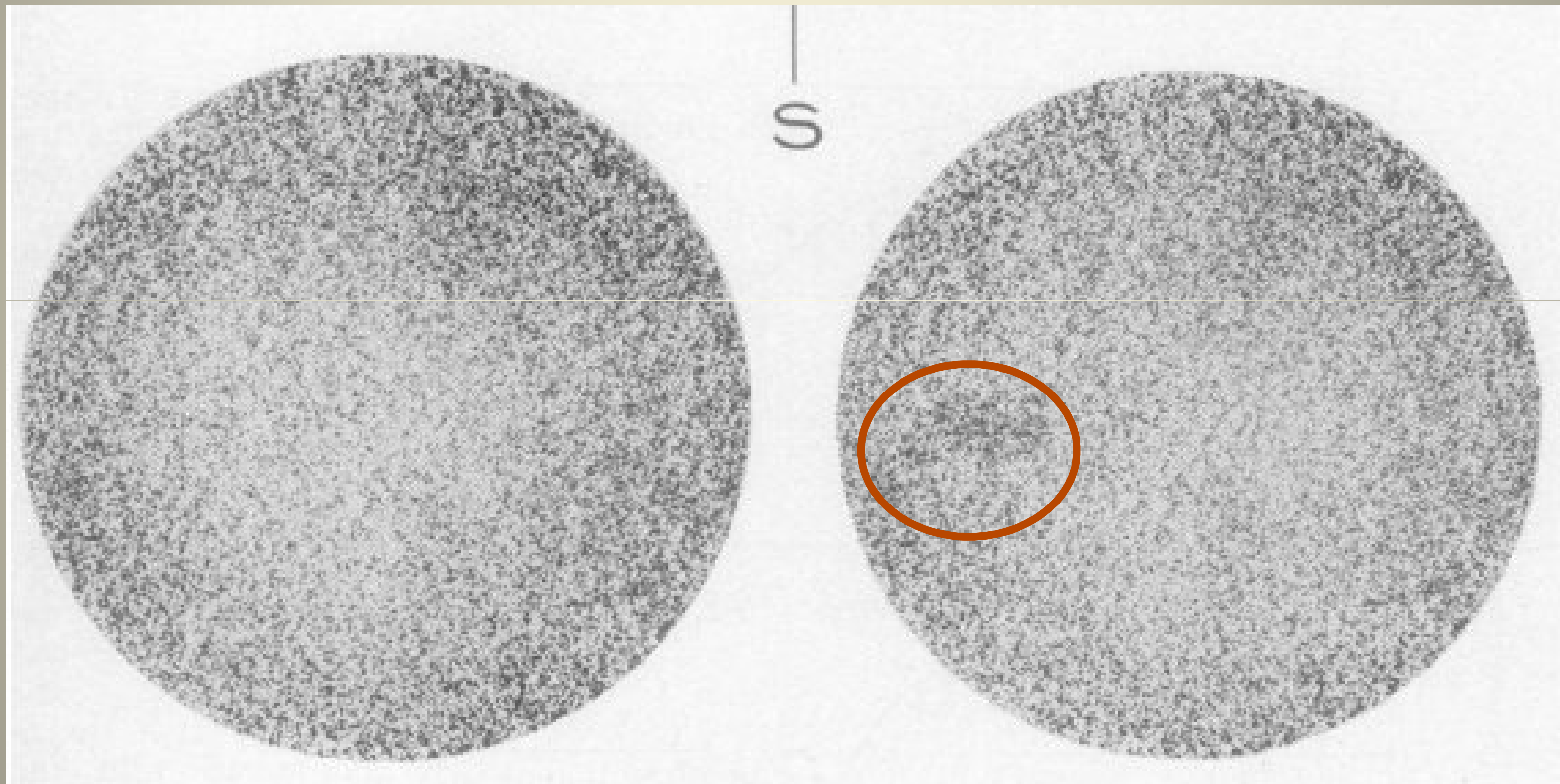


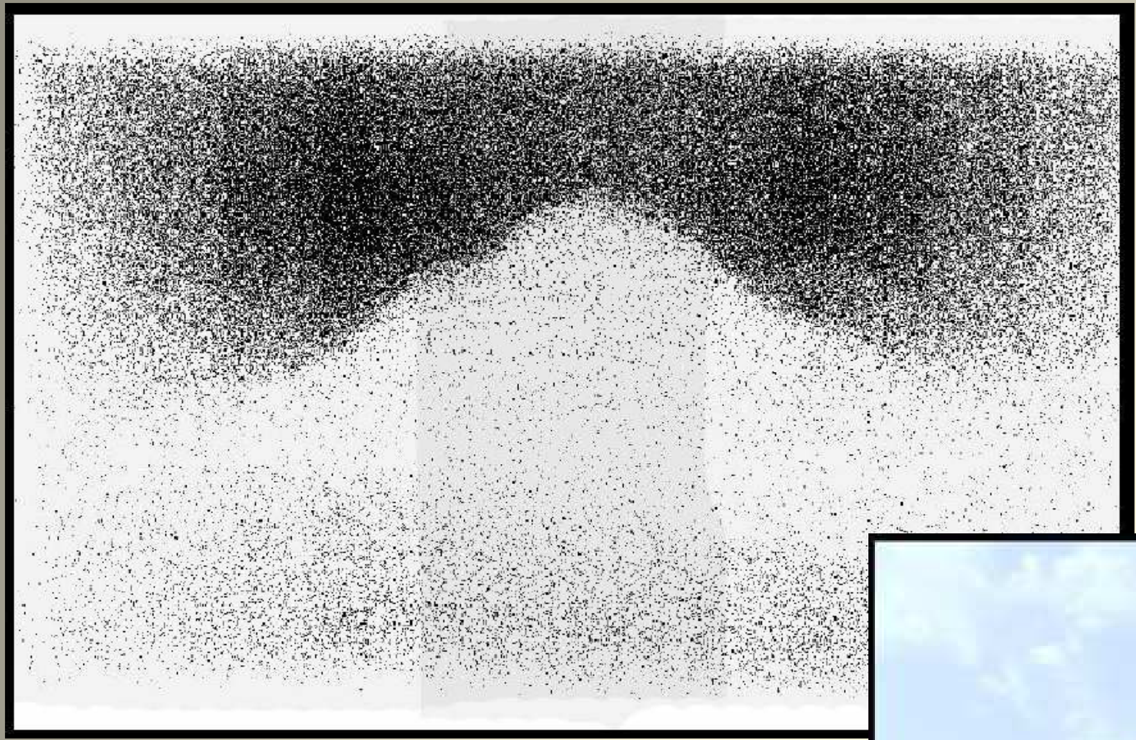
Fig. 6 (left). The equipment in place in the Belzoni Chamber under the pyramid.
Fig. 7 (right). The detection apparatus containing the spark chambers.

Results from the Luis Alvarez experiment Chephren Pyramid



Observed

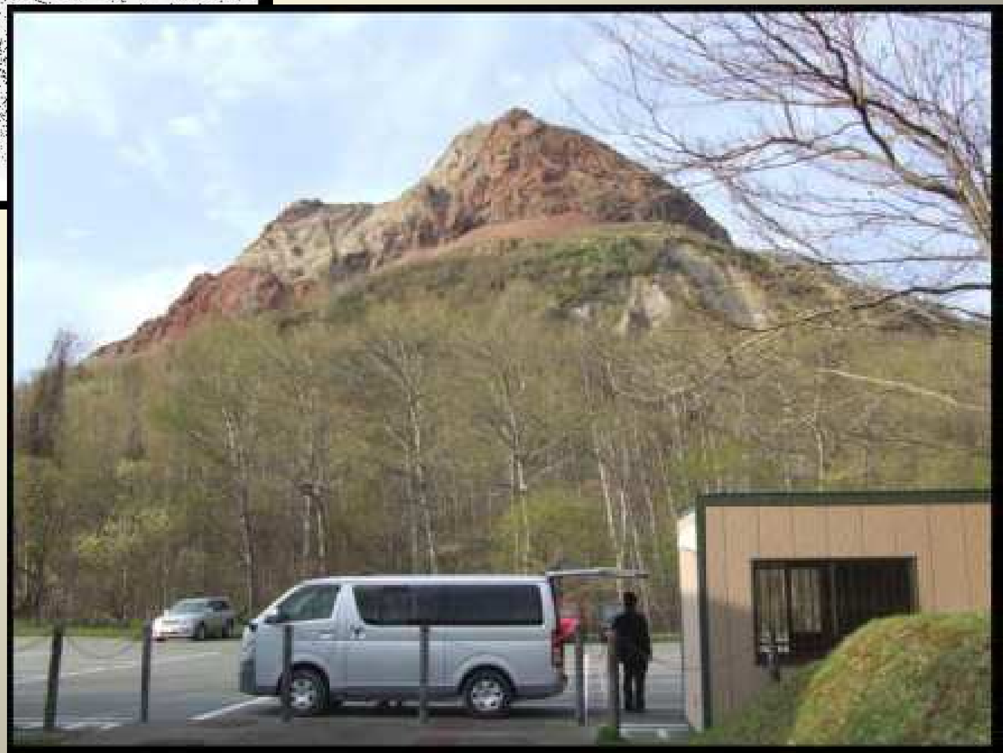
Simulation with a chamber

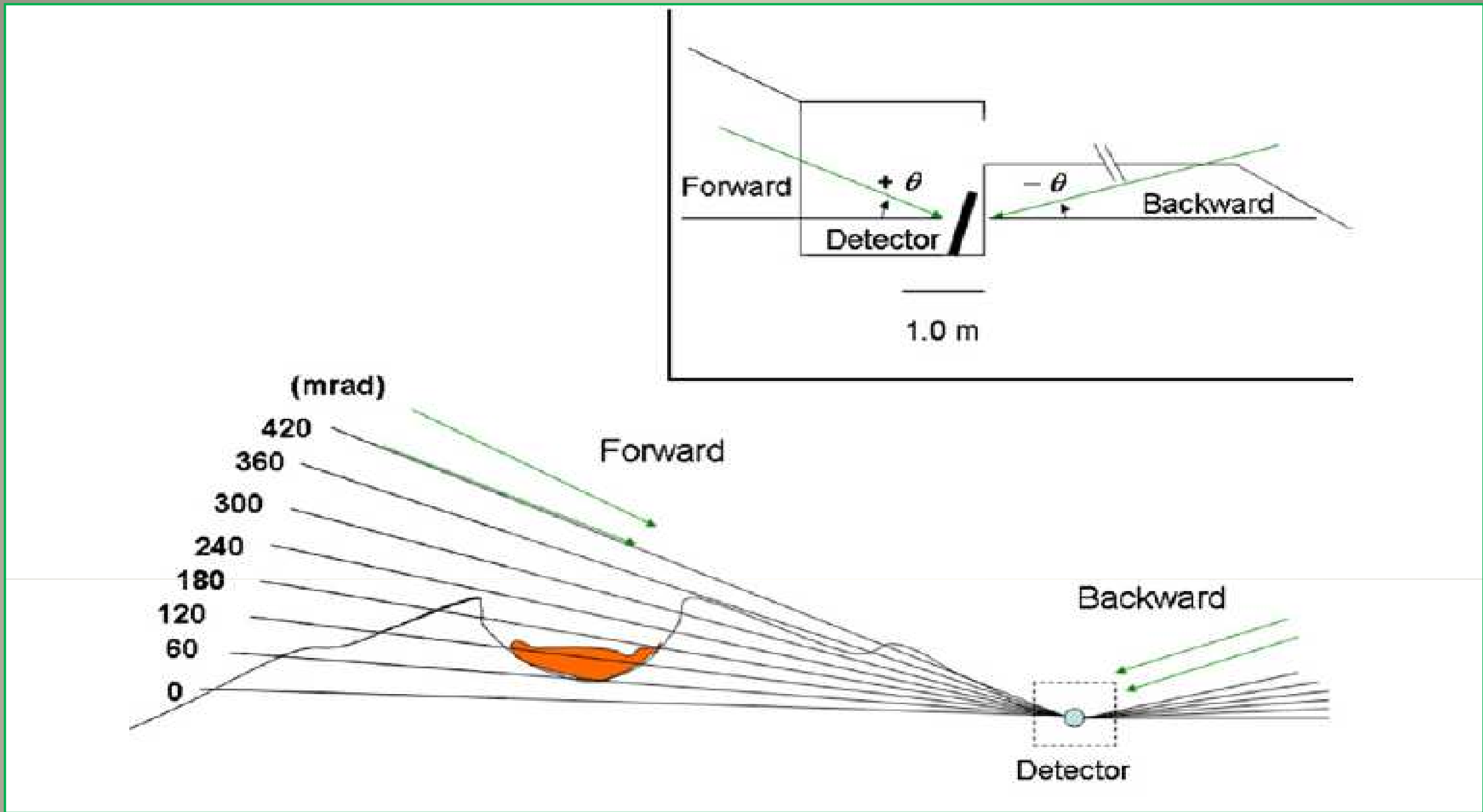


Muon radiography in volcanology

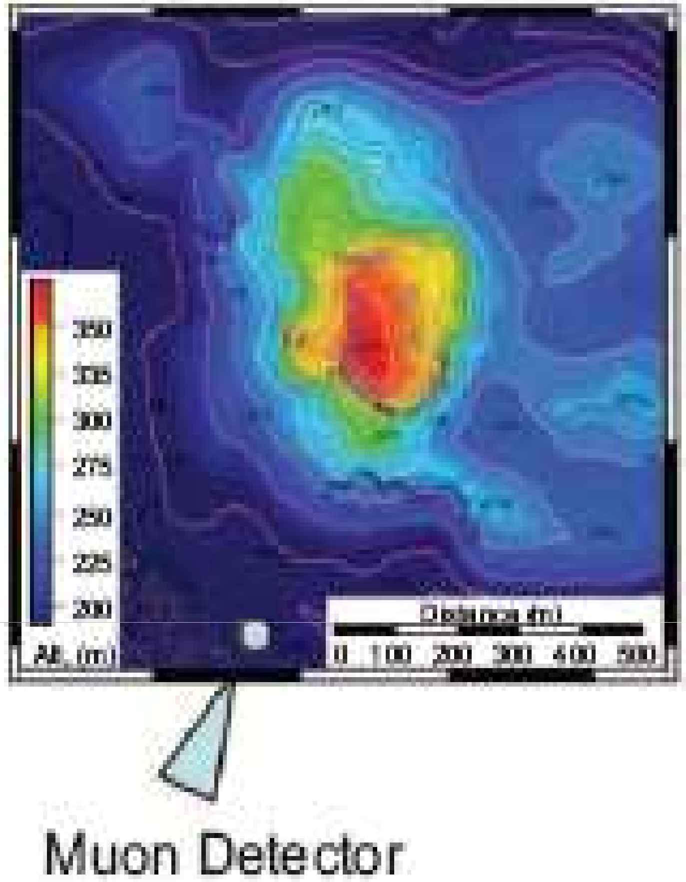
Cosmic-ray Photograph
of a Volcano (Showa-Shinzan)

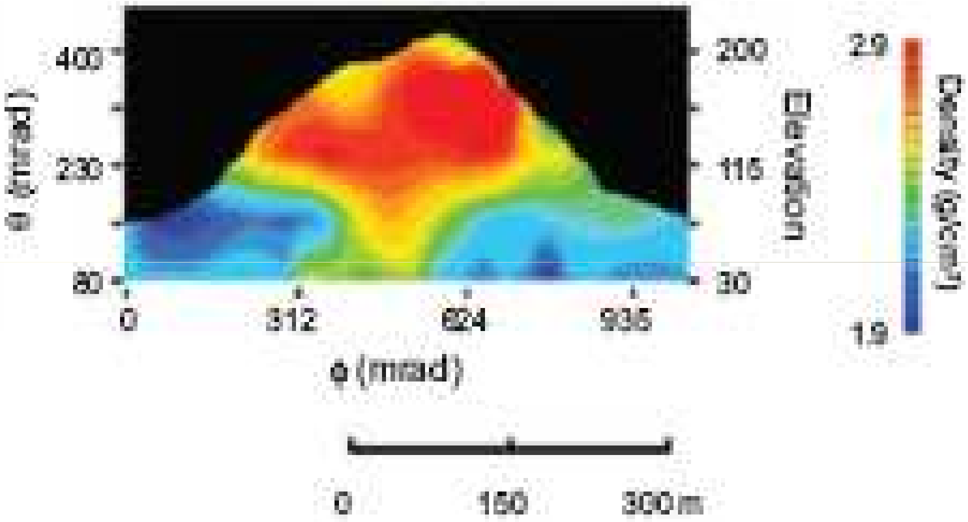
1dot=1muon
Angular space distribution





Profile of Asama mountine showing geometrical location of the measuring detector. Data o muons from opposite flux were also used for confirmation of detector efficiency and of muon flux isotropy.
The detector was fixed in underground cave to cancel the background from other particles.





Radiographycal image of volcanic crater under dome lava.

Left – lava dome map and muon detector position.

Right – volcano appearance and the distribution of rock density in vertical plane. (Elevation in m).

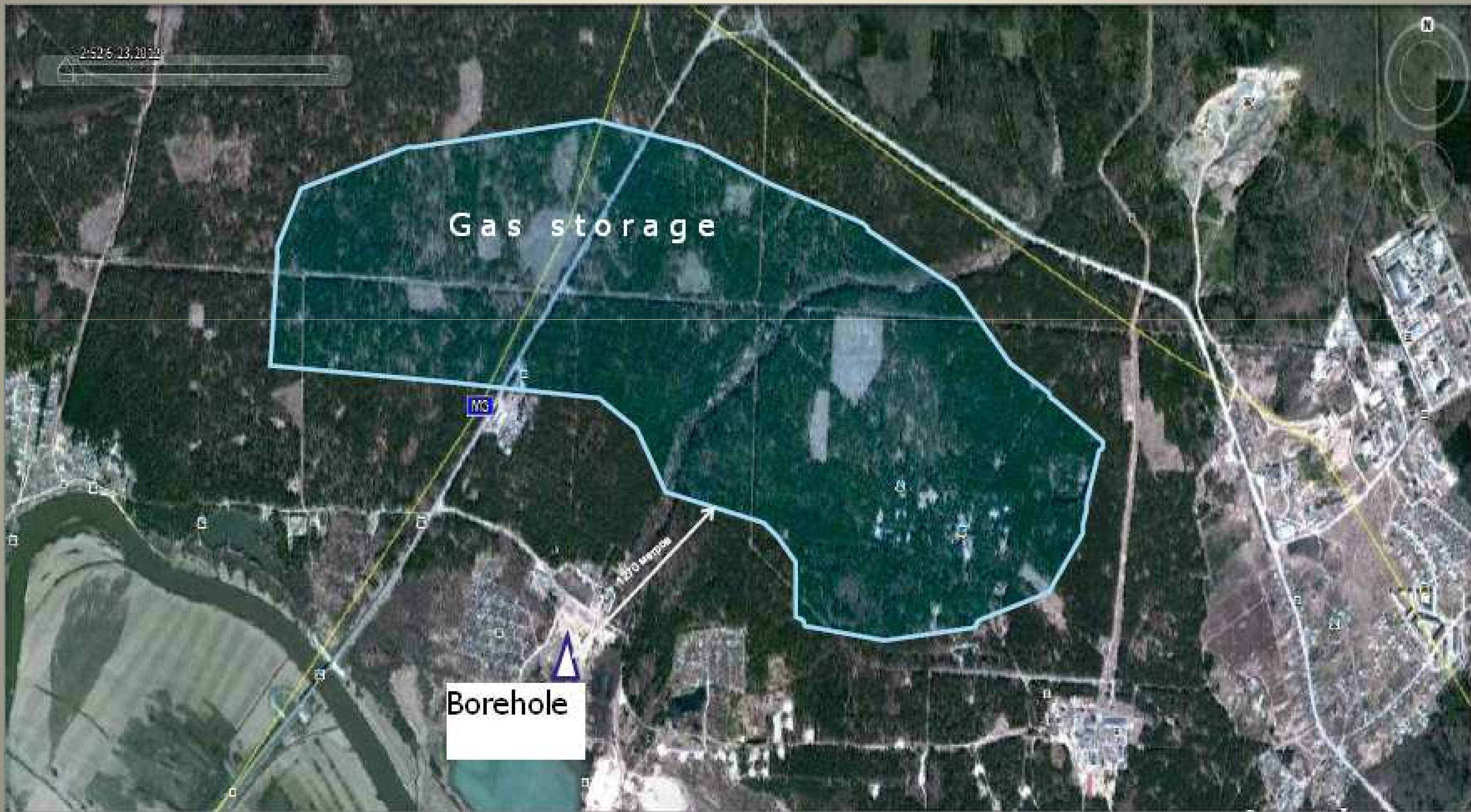
Industrial objects radiography.

Muon tomography method can be used also for inspection of the conditions of huge industrial objects (bridges, dams, blast furnaces and so on), when it is necessary to estimate technical state or safety of such bodies (for example, crack appearance, internal construction conditions, groundwater level and so on).

Radiography when manipulating with nuclear materials.

Since muons are highly penetrating and sensitive to materials with high Z (with large charge of atomic nucleus, in particular nuclear materials), muon radiography began to develop as effective method of detection of such inclusions in packed cargo and loads.

Disposition of borehole and underground gas storage as an example of muon radiography opportunity

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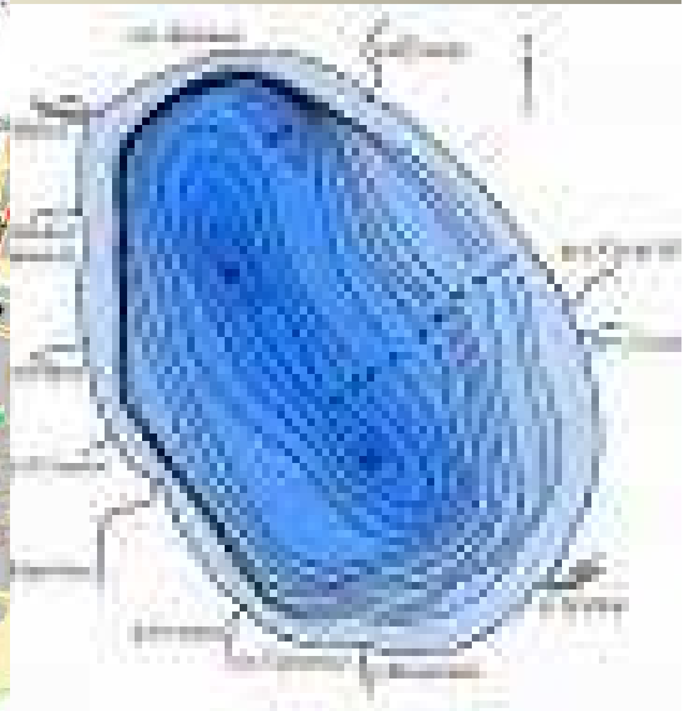
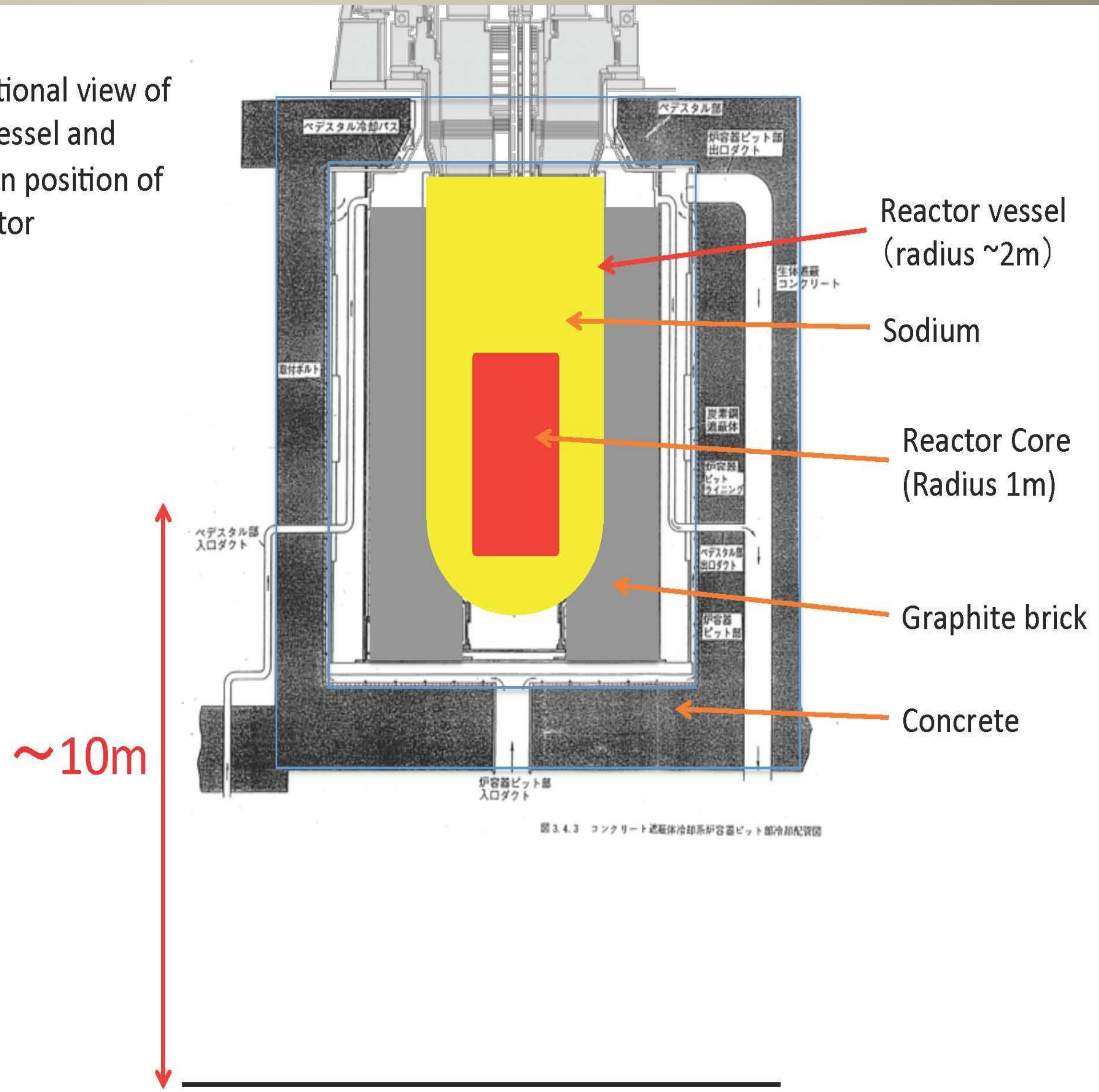
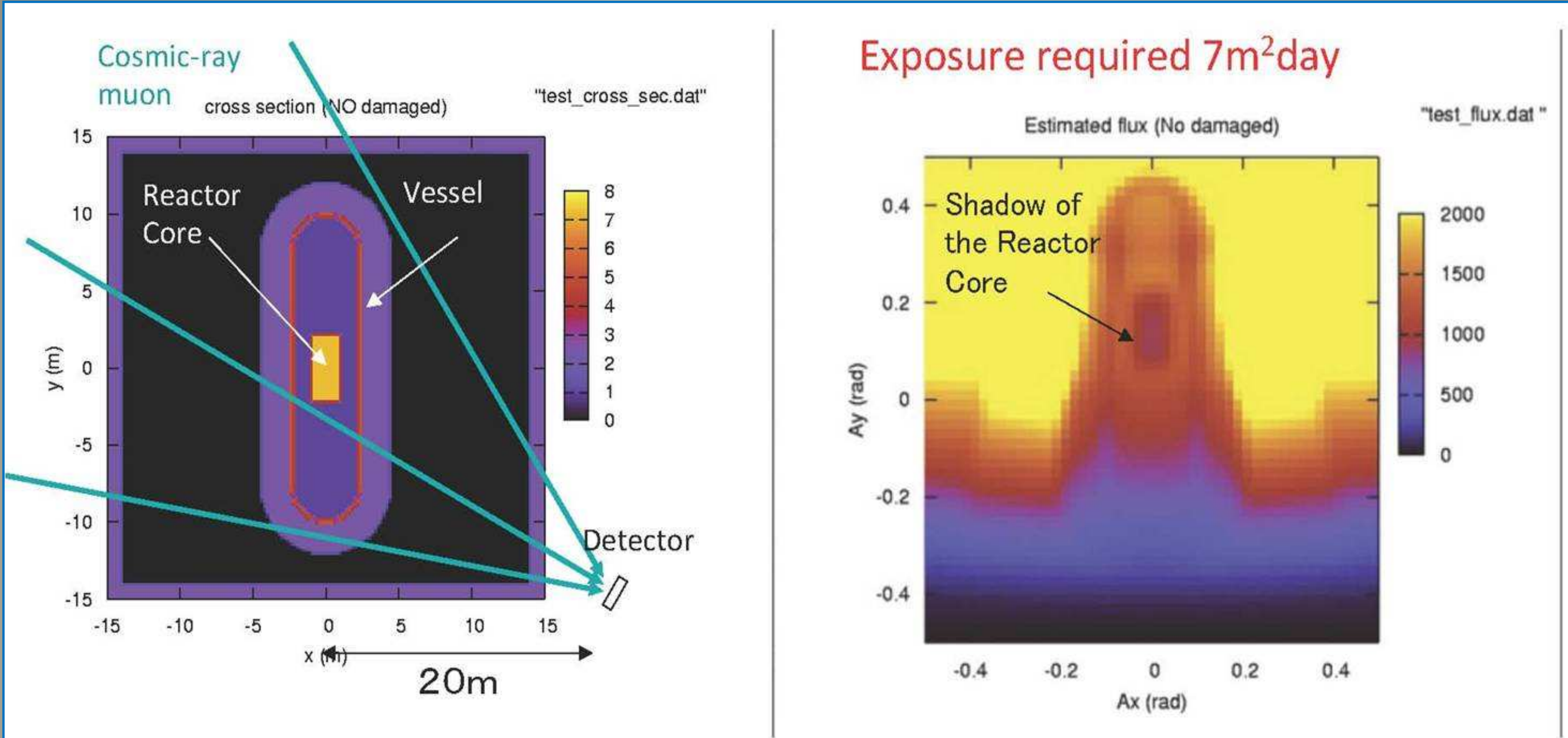
ПЕРЕСЛАВЛЬ-ЗАЛЕССКИЙ
указатель:
поворот налево
"Никитская
Слобода"
Городской
пляж
сразу за мостом
светофор
Ботик Петра
Поляна Ботика
указатель:
поворот налево
"Ботик Петра"
Москва



Muon tomography can be applied for inspection of interrior conditions of **nuclear objects (reactors)** while their malfunction or other impossibility of measurements

Cross-sectional view of Reactor vessel and installation position of the detector





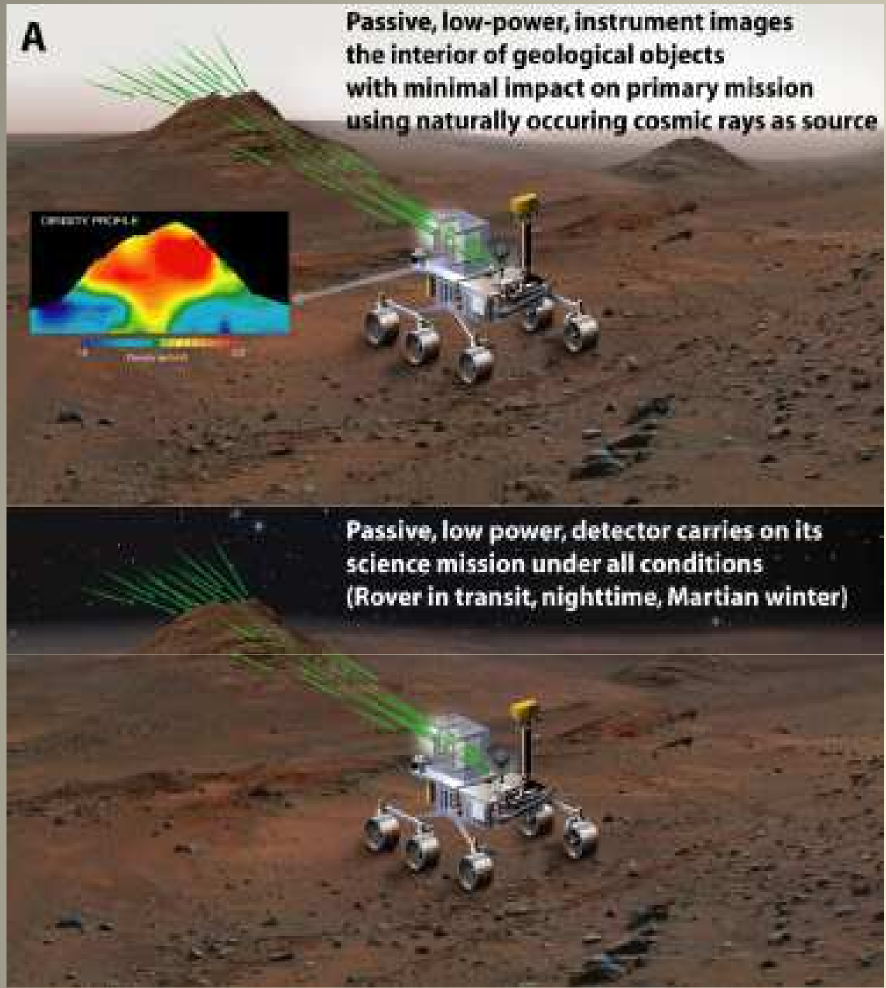
Left — possible detector location while reactor tomography and muon trajectories. Right — angular scan of muon tomography results after exposition 7 m^2·day (the reactor core is distinguished and no big damage is seen).

Muon radiography for exploration of Mars geology

Operational concept. Muons generated by interactions of primary cosmic rays in the planet's atmosphere (green spheres) pass through a geologic object of interest, and are partially absorbed by the object.

A passive muon detector composed of parallel scintillating plates on a lander or a rover records the tracks of the muons. The recorded tracks are analyzed on site to determine the direction from which they entered the detector and the amount of energy absorbed by the target.

The observations are distilled into a density image of the geological target, much like an X-ray radiograph would, except using muons as a passive source of radiation.

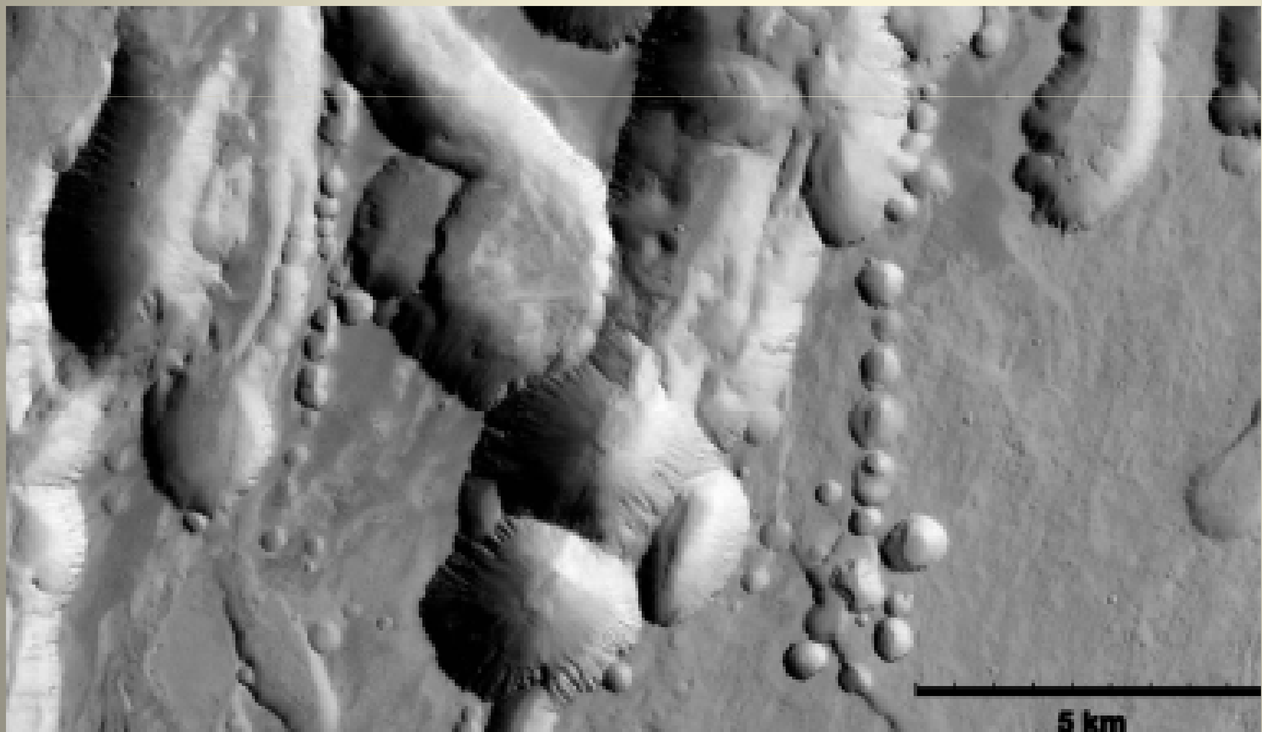


Two concepts are presented:

(A) Muon radiography instru-ment mounted as a secondary instrument on a rover.

(B) The instrument is mounted on a small Phoenix class lander observing multiple targets during the life of the mission.

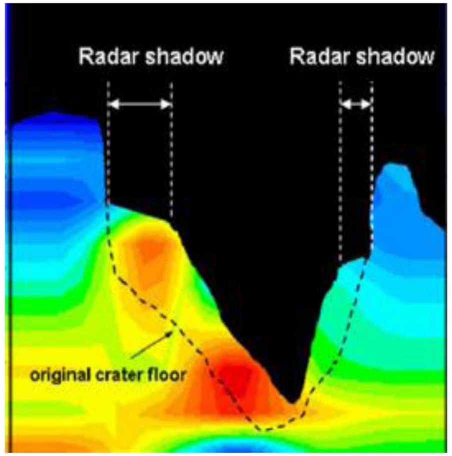
Potential primary target for muon radiography exploration on **Mars**. Complex terrain of collapse structures on the lower flanks of Arsia Mons, Mars likely contains lava tubes and caves in the subsurface. Muon radiography obtained from trough floors could be used to map the void space associated with partially collapsed lava tubes.



Employment of nuclear emulsions as detectors for muon radiography.

Beyond **high space and angular resolution** track detectors on the base of nuclear emulsions are very suitable for muon radiography due to their information capacity, easy transportation and rather simple operation under the conditions of unfavourable environment. Moreover emulsions do not need energy supply and electronic reader device.

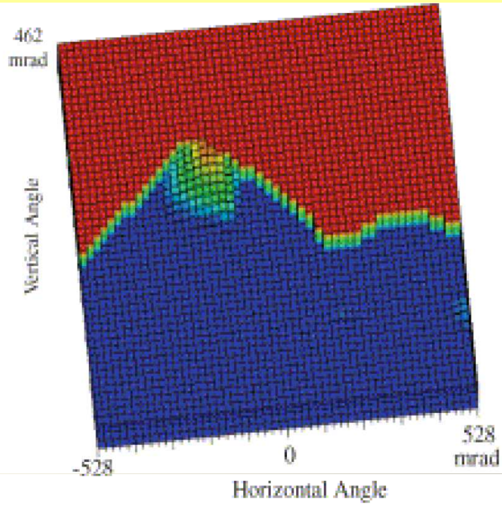
Experimental techniques



Mt. Asama
H.T.M. Tanaka and coll.
Telescope area ~1 m^2

EPS Lett. 263 (2007) 104

Resolution ~ 70 mrad
NIM A507 (2003) 657



NUCLEAR EMULSION

Precise muon tracking
Resolution ~10 mrad (as scattering)
Minimal infrastructure
No electric power
Usable in difficult locations
Unusable in warm season
Area limited by scanning power

PLASTIC SCINTILLATORS

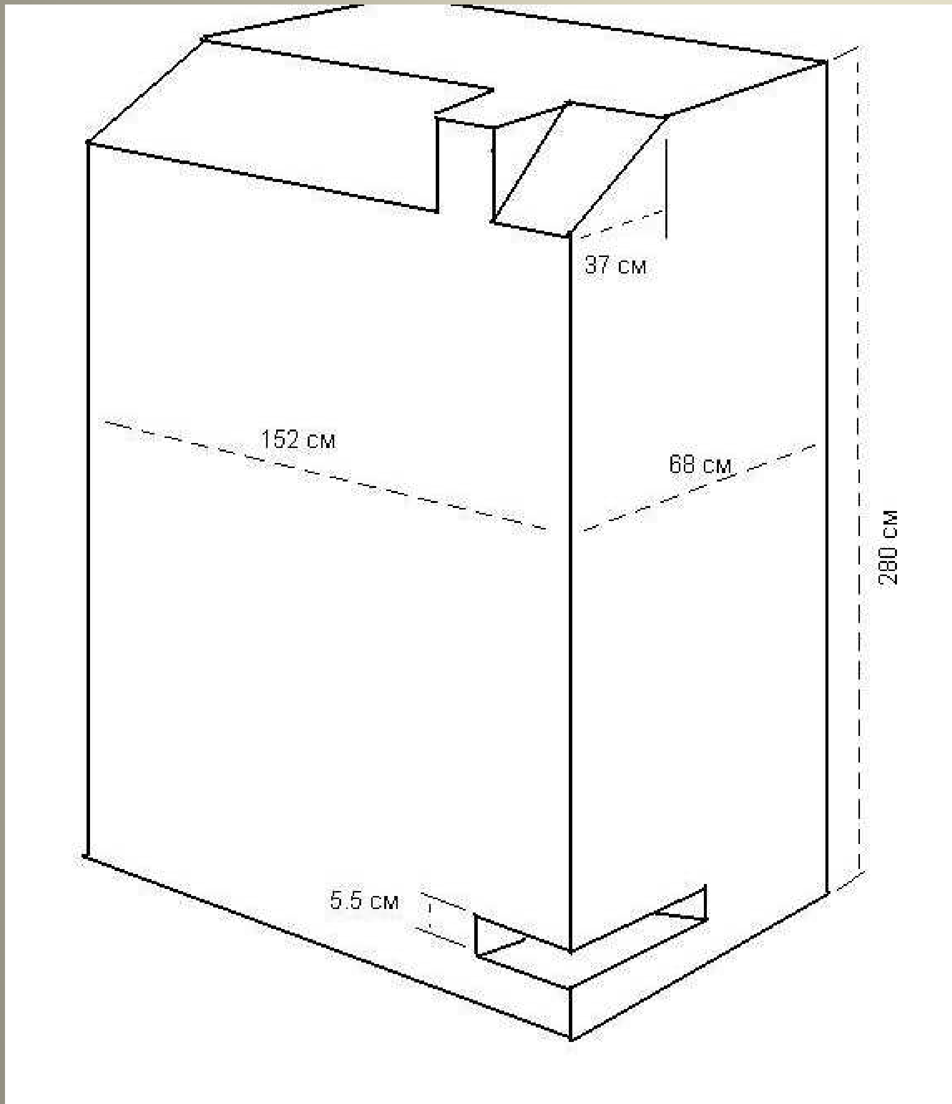
Analysis in real-time
Long exposures possible

Muon radiography test-2012 of nuclear emulsion detector method

(2012, P.N.Lebedev Physical Institute, RAS and D.V.Skobeltsyn Institute of Nuclear Physics, MSU):

Emulsion stacks were inserted within the body of steel metal column (around 3 m height) of SINP MSU accelerator frame and outside

Steel column being the part of accelerator frame

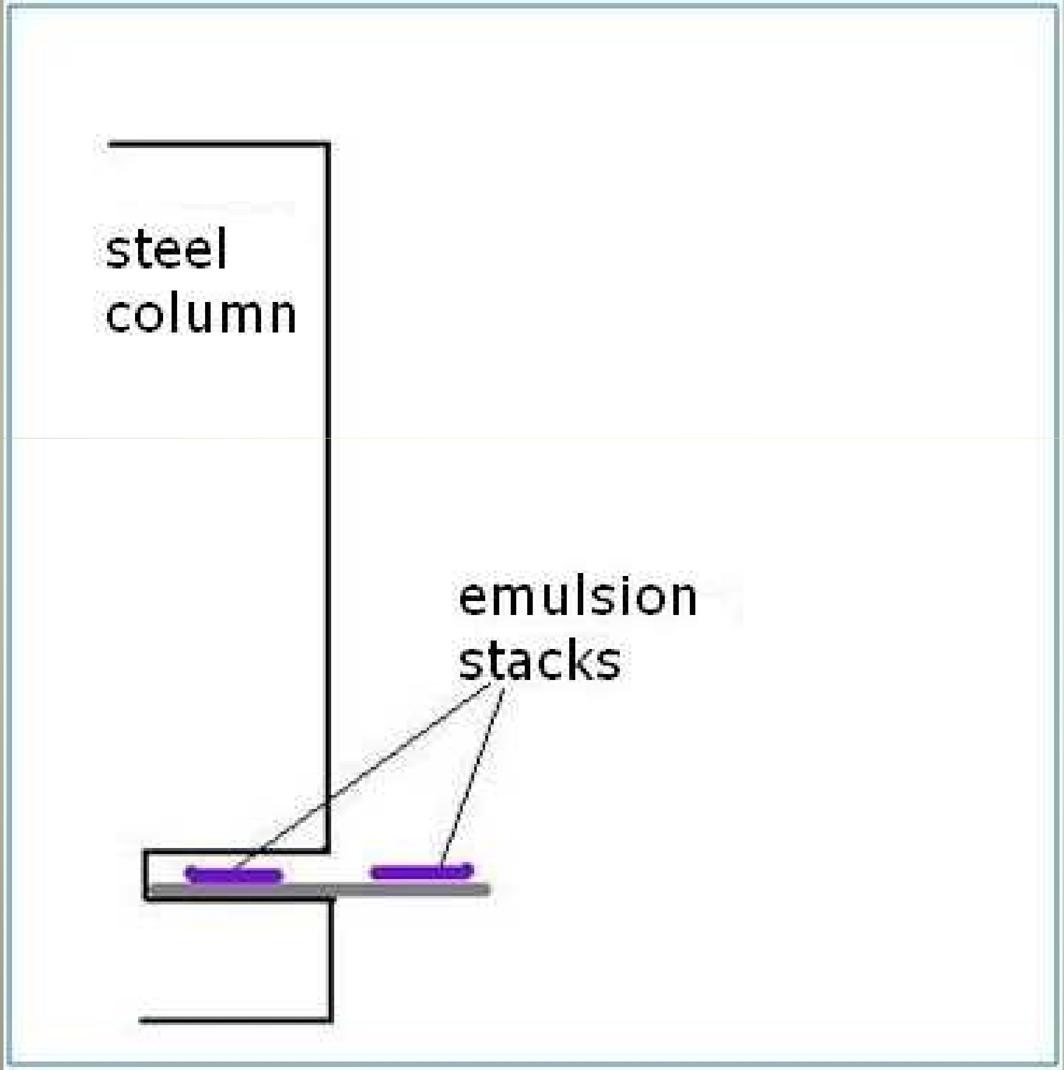


Exposition – 49 days

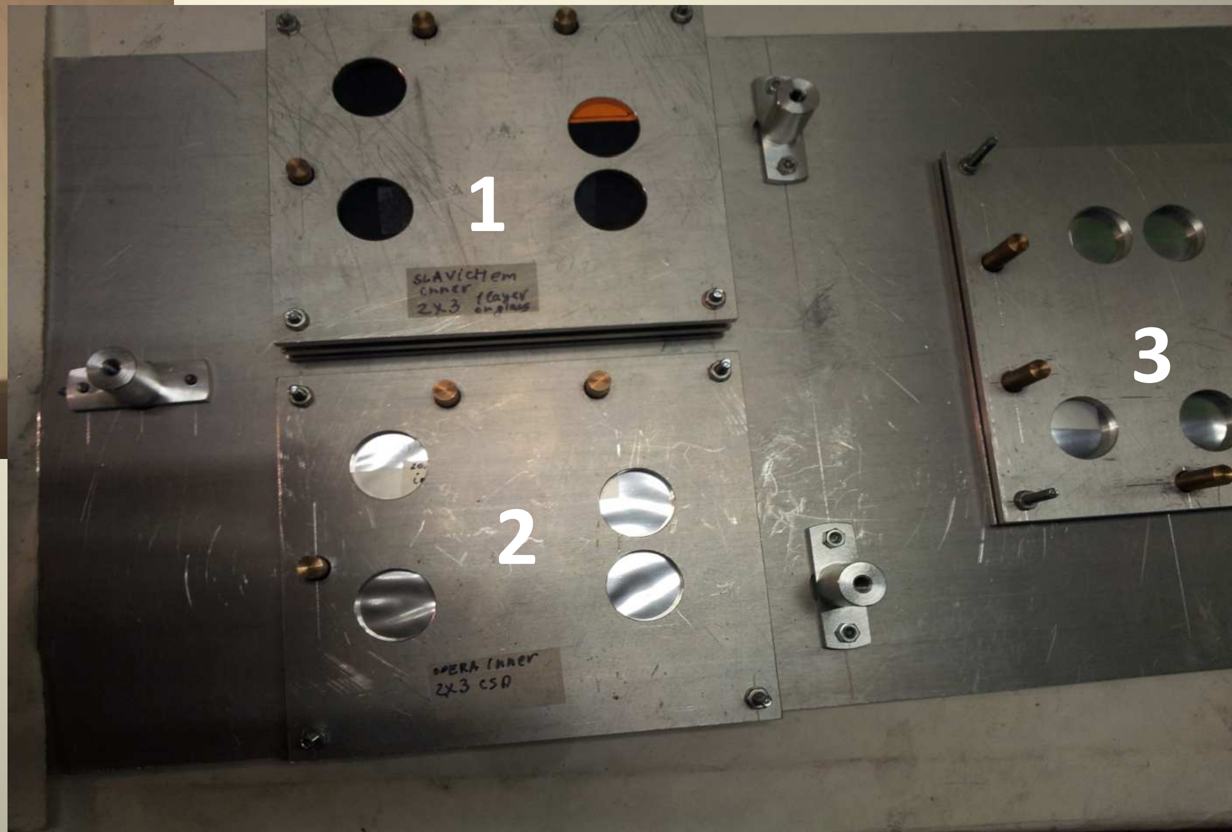
The weight of this steel column is about 23 tonnes

Metal column of the accelerator frame

Test experiment on muon registartion - 2012
Scheme of detector location



Prepared stacks of emulsions and aluminium plate with fixed stacks

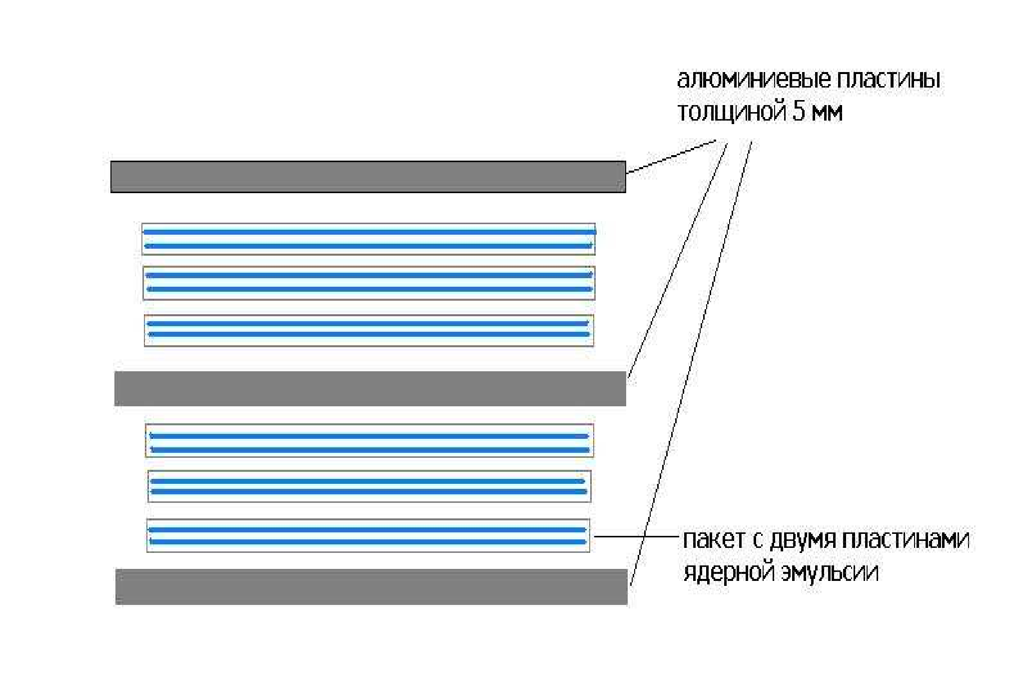


Structure of emulsion stacks:

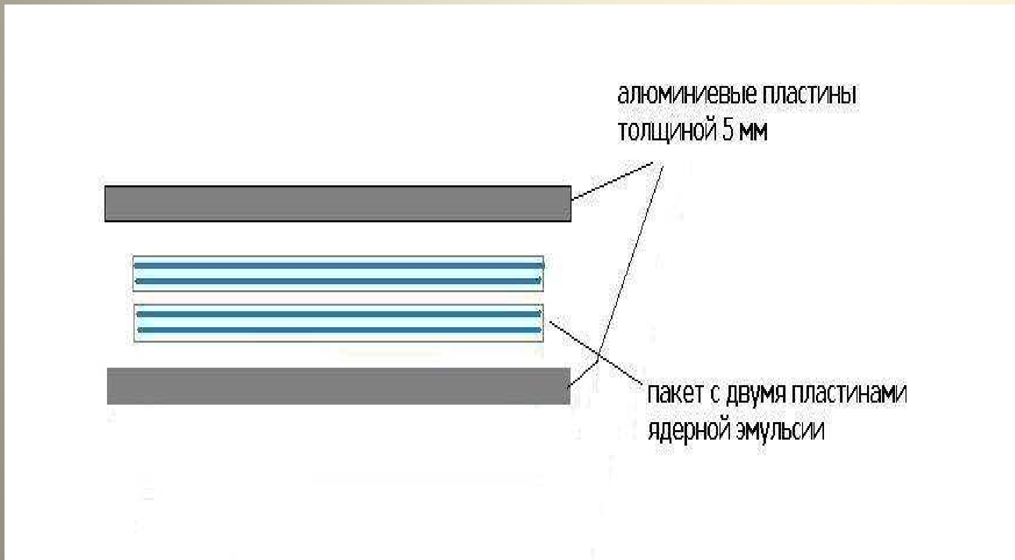
1. **“Slavich”** emulsion — 3 single layer emulsion plates + metal plate + 3 single layer emulsion plates.

2. **Fuji-OPERA** emulsion — Changeable sheet stack + metal plate + Changeable sheet stack (12 layers in total).

3. **Fuji-OPERA** emulsion — 4 emulsion layers.

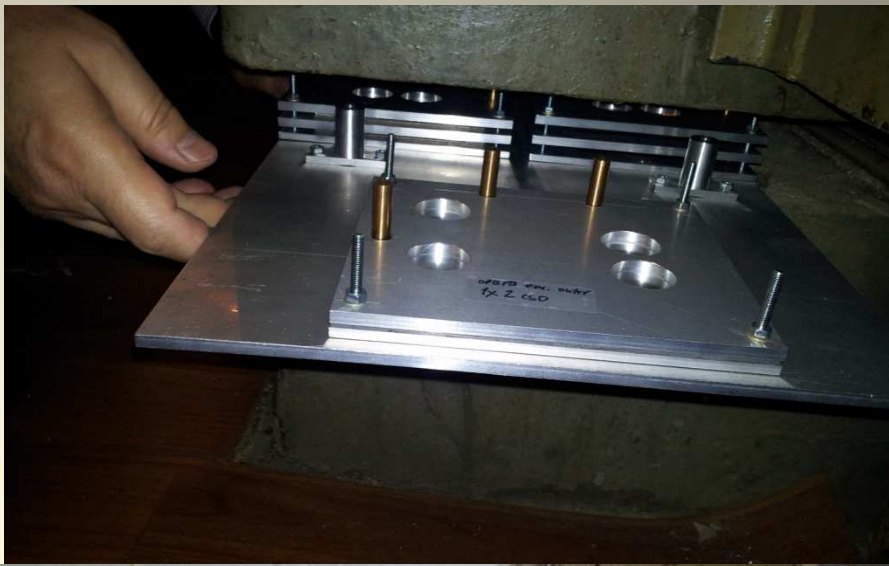


А) *Схема эмульсионной стопки, размещенной в теле стальной колонны*



Б) *Схема эмульсионной стопки, размещенной сбоку от стальной колонны.*

Arrangement of emulsion stacks into metal column



Estimations and expected results of the test

Assumptions:

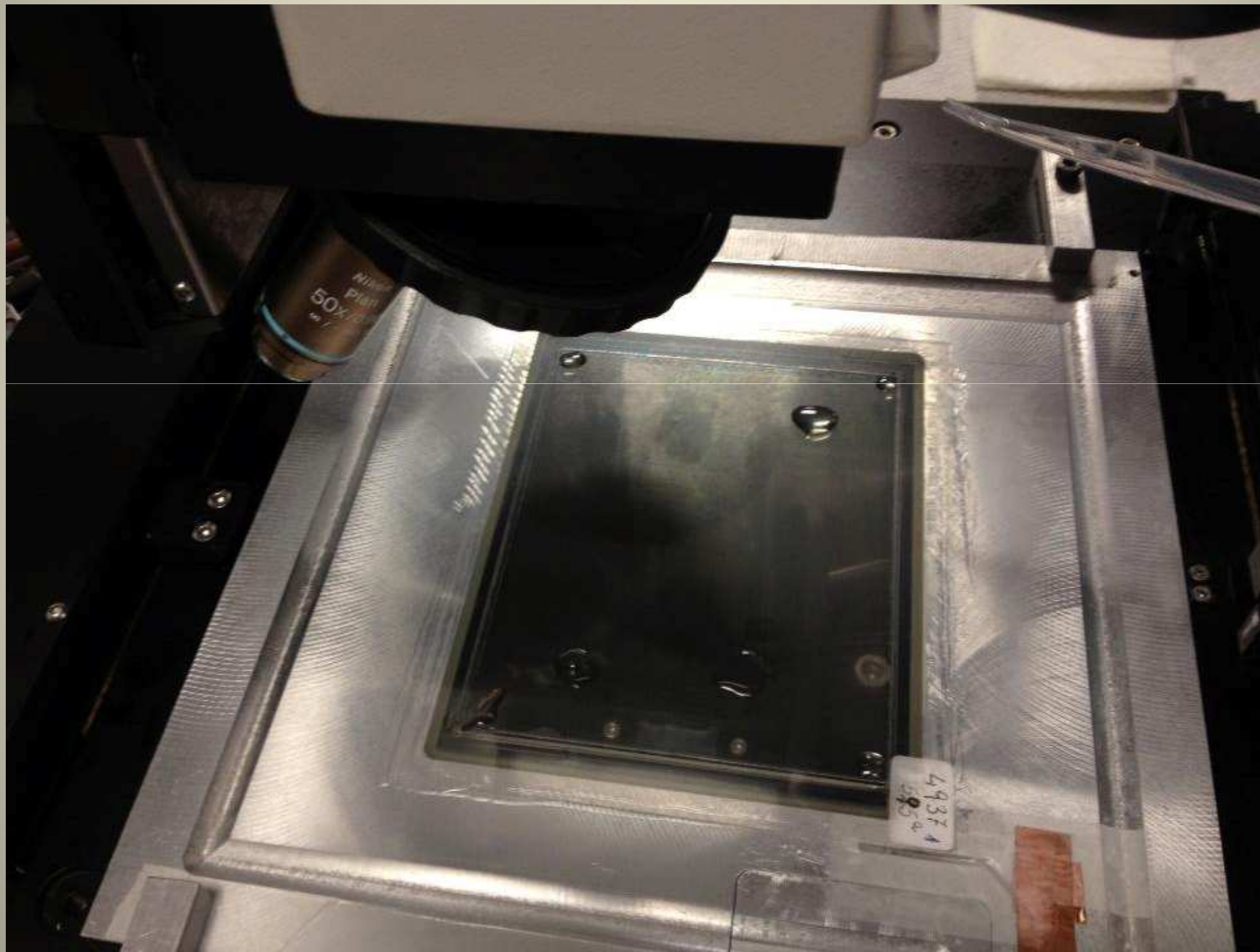
$I(E > 0.3\ GeV) \approx 7 \cdot 10^{-3}\ cm^{-2} sec^{-1} sr^{-1}$

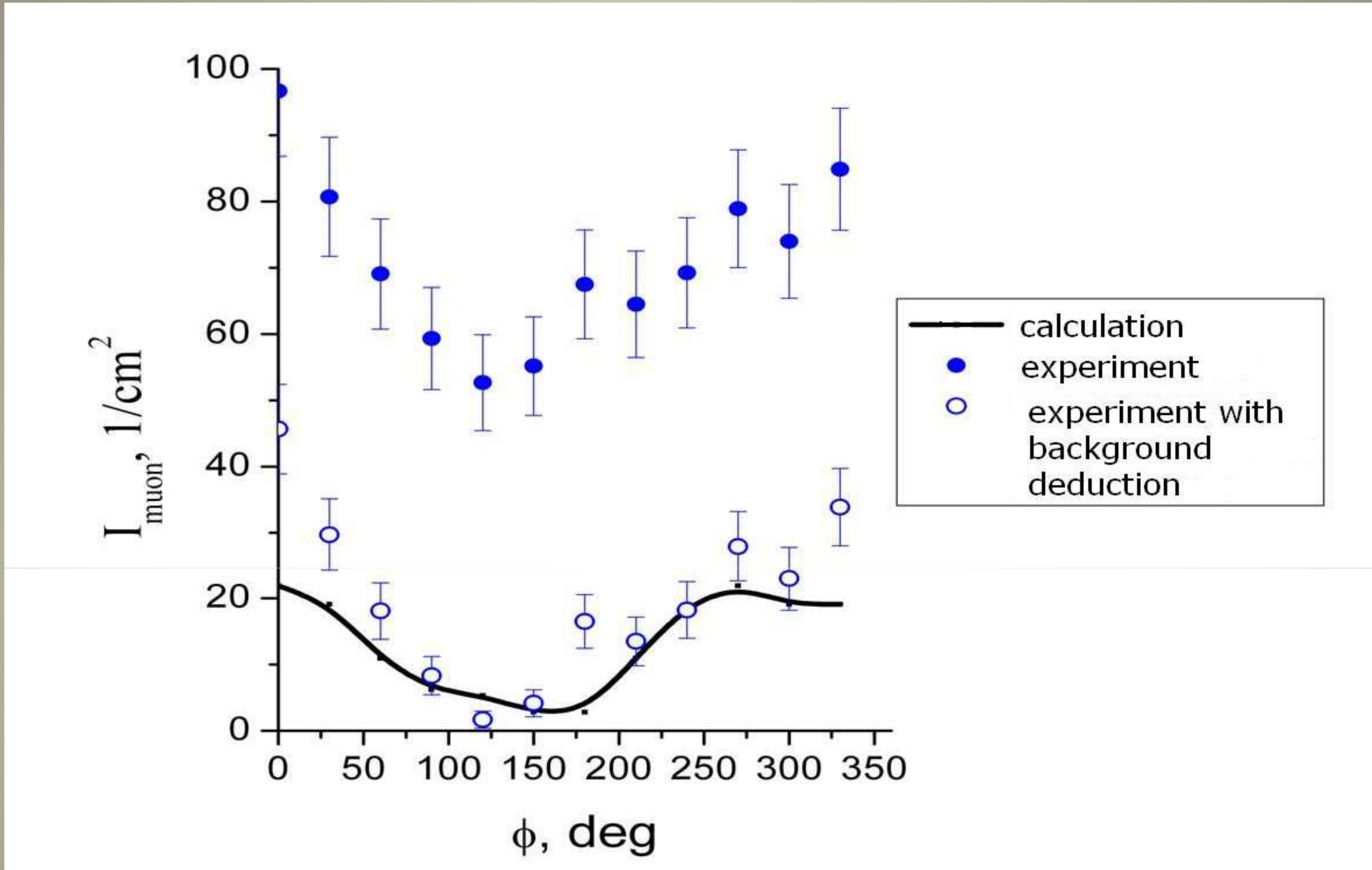
Effective zenith angle range — 30°

Exposition duration — 49 days

Then $I_{local\ outside} / I_{local\ underFe} \approx 10$

Microscopic stage in MSU with nuclear emulsion plate





Comparison of muon angular distributions at various azimuth angles ***φ*** *and fixed zenith angle θ = 21.6^o in model calculation and in the test experiment itself,* O *presents experiment results with background deduction for 2 months assumption.*

TEST-2012 RESULTS

Spatial distribution of muon fluxes measured in this test experiment and calculated nonuniformity caused by huge solid absorber (column) agree rather satisfactory. That shows muon radiography capability. It is necessary to take into account, that some procedure corrections in experiment realization are required.

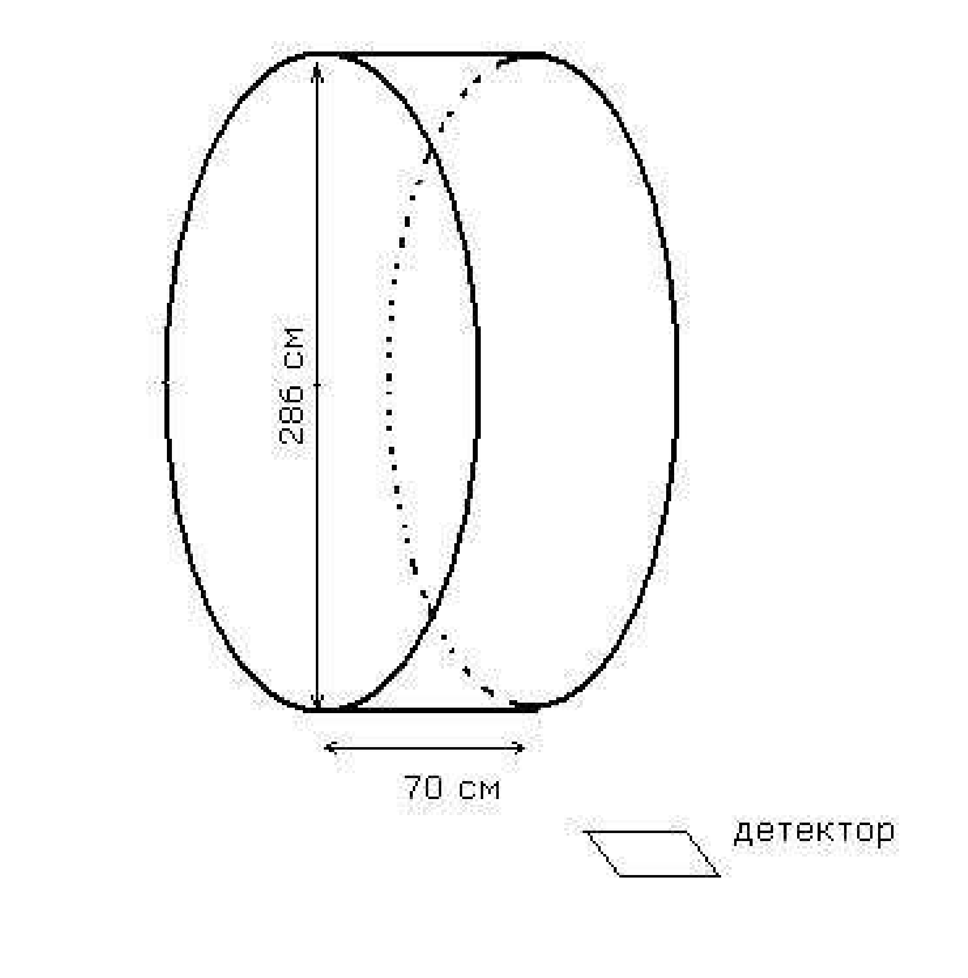
Muon radiography test – 2013 of nuclear emulsion detector method

(2013, P.N.Lebedev Physical Institute, RAS and D.V.Skobeltsyn Institute of Nuclear Physics, MSU):

Emulsion stacks were placed near two huge steel disks in the building of industrial plant in Moscow.

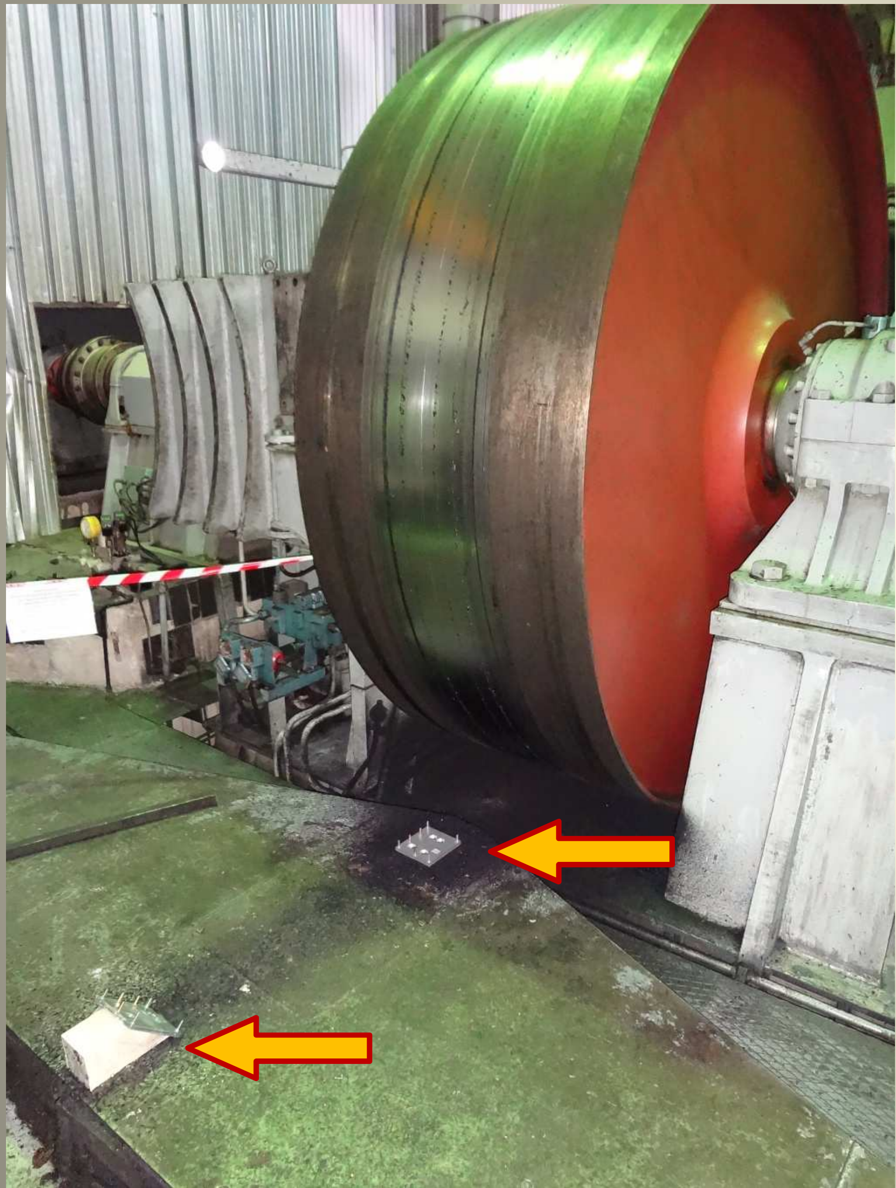
Two huge solid steel disks for tyre trial in industrial factory

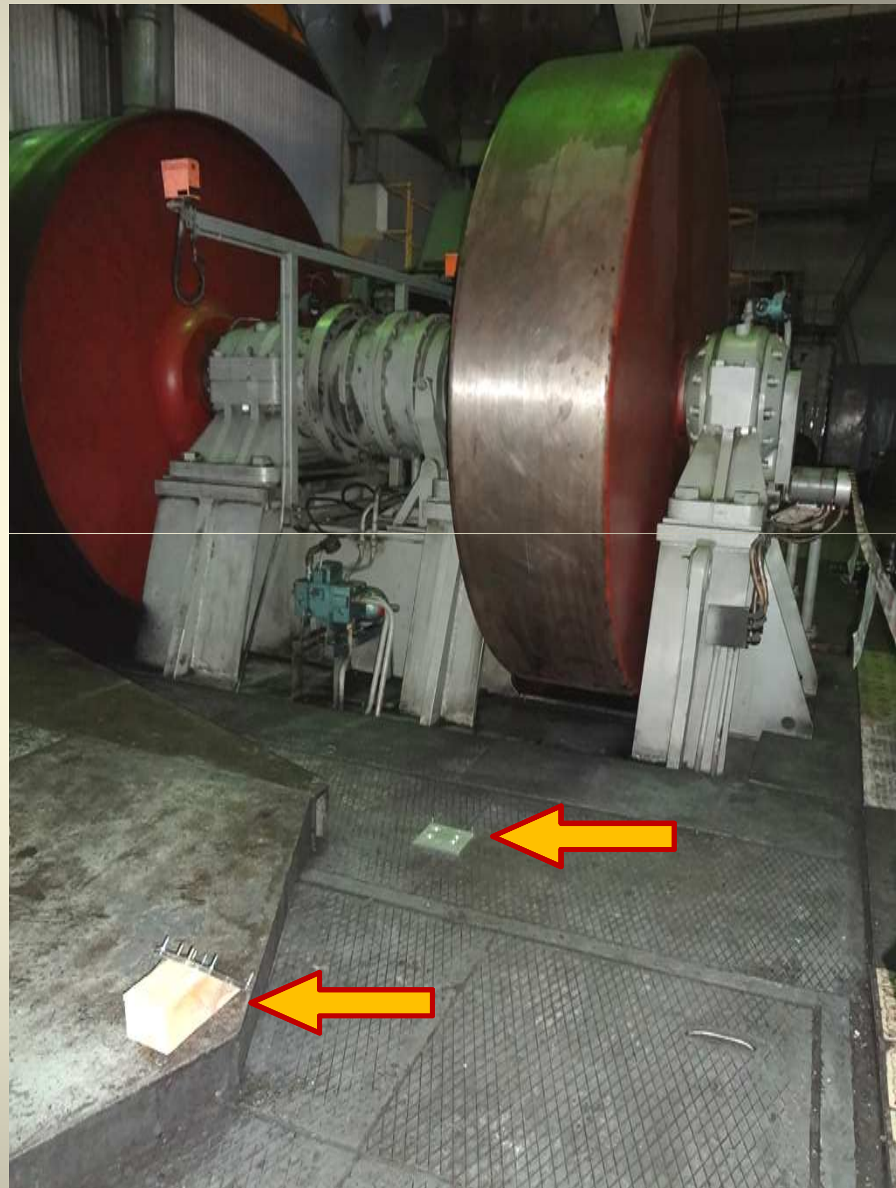
Test-2013 experiment scheme



The weight of such steel disk is about 40 000 kg

Location of emulsion stacks in Test-2013





In this test-2013

2 emulsion stacks were disposed **horizontally**

and

2 emulsion stacks were disposed **with slope 45º**

at some distance from massive objects.

Exposition will be continuing longer

than **4 months.**

We hope to elaborate procedures of such data treatment and extraction of the object image.

Thank you for regard

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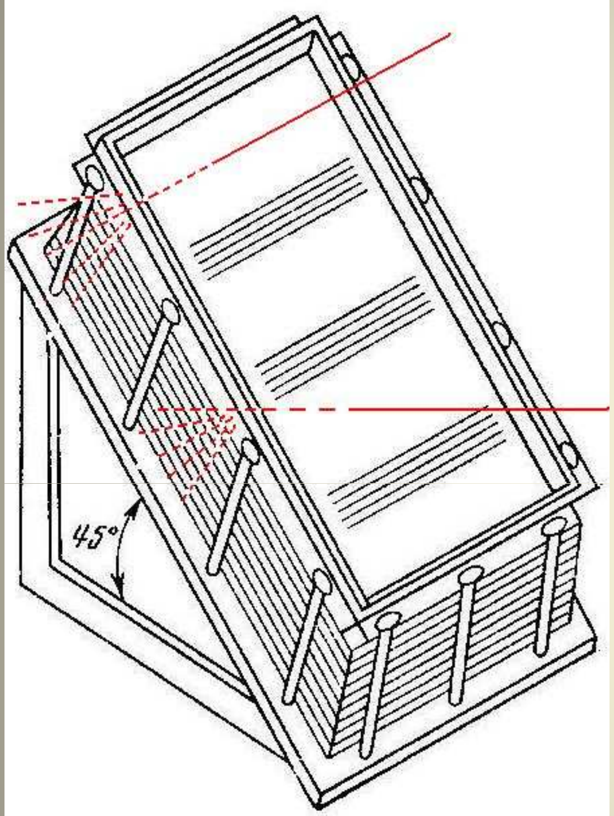
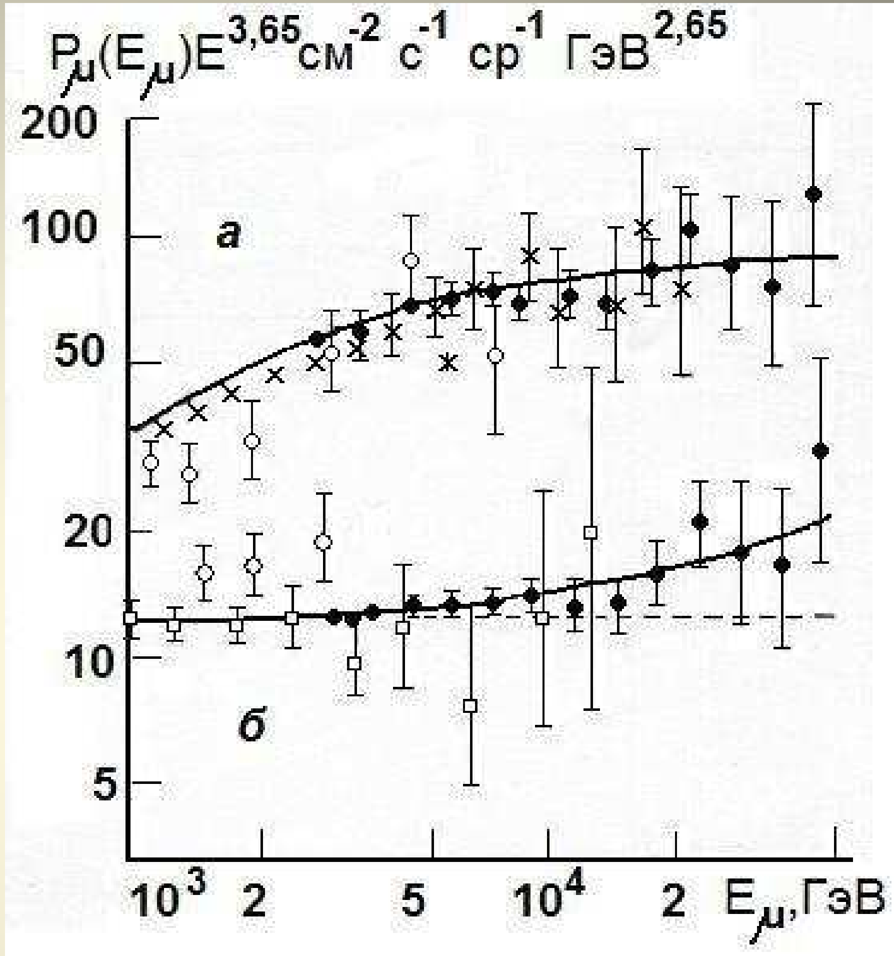
Muon spectrum measurement



Appearance and structure of multilayer X-emulsion lead chamber in MSU experiment



Differential energy spectra of muons:

а — for horizontal flux of muons, **б** — for vertical flux.

• — MSU experimental data (1994),

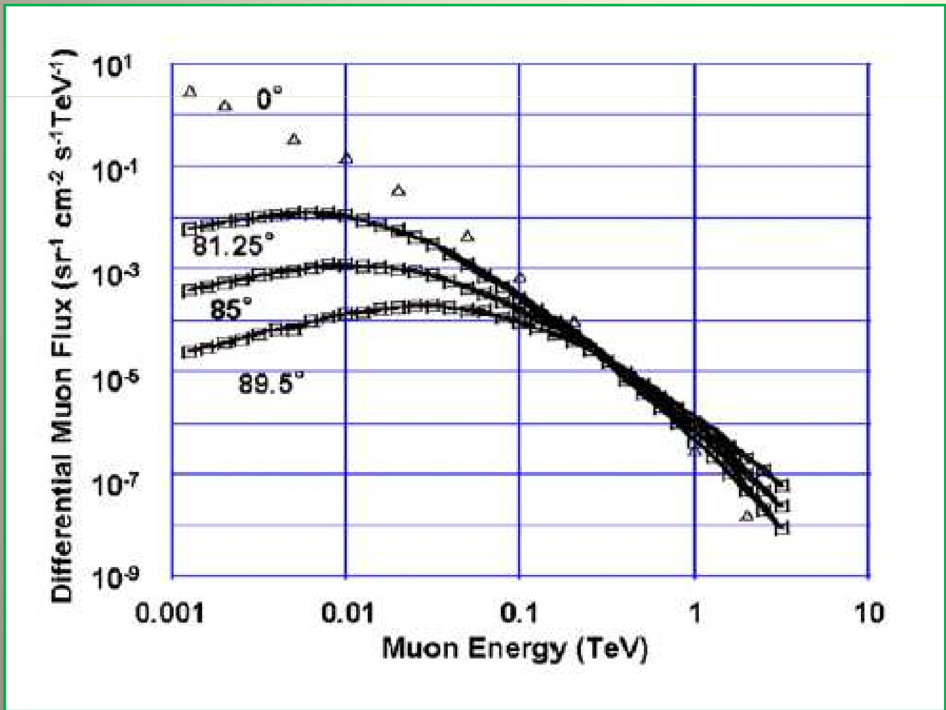
○, ×, □ — results of other authors 1984-1985);

Solid line — calculation of muon flux with charm generation, dashed line — calculation without charm generation.

<u>Предпосылки использования мюонной радиографии.</u>

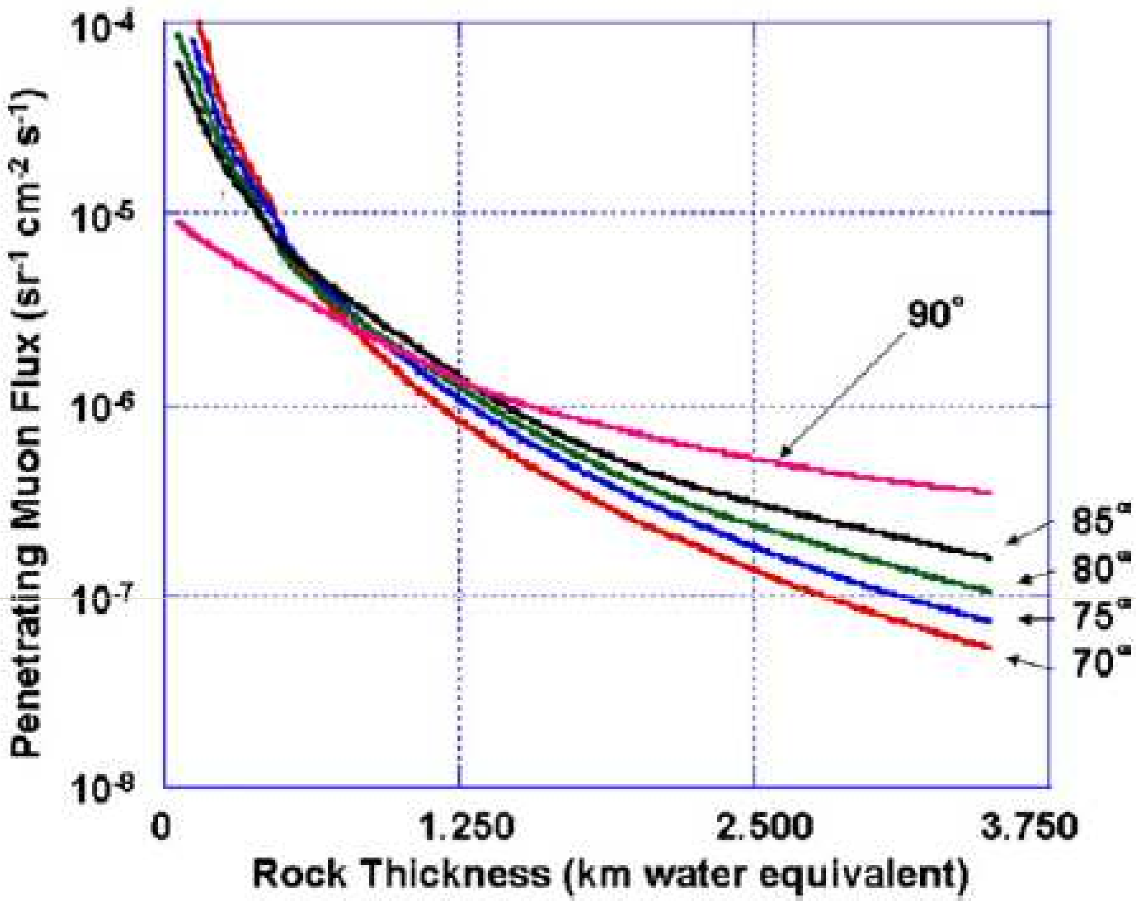
Мюонная радиография базируется на хорошо известном **спектре** мюонов космических лучей, приходящих под различными **зенитными углами**, а также на разработанной **модели** прохождения мюонов через вещество.

При этом освоена **методика** работы **детекторов** мюонов.



Энергетический спектр мюонов космических лучей, приходящих под разными углами.

Эксперимент DEIS (Allkofer et al., 1981) и модельные расчеты для больших углов θ.



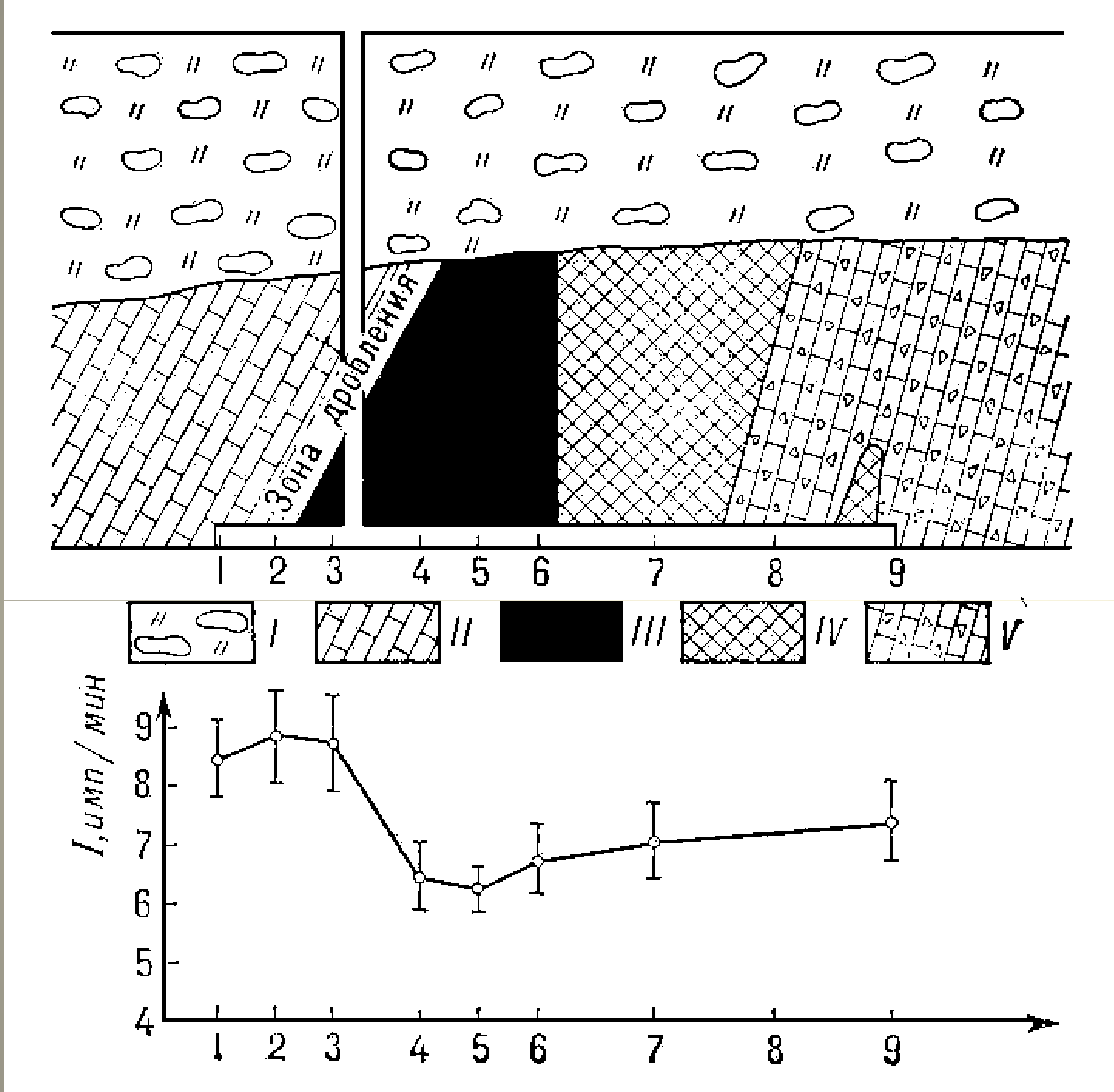
Поток мюонов КЛ при разных зенитных углах, проникающий через толщу скалы с плотностью 2.5 г/см^3.

Facilities of geological exploration

Measurement of CR intensity by detectors in a tunnel and comparison of obtained data with conventional dependence of CR absorption in water or in ground can give information about ore layers and interstices or enable to determine weight load upon ground from installations above.

Progress in muon radiography was enabled by **progress in measurement methods**: introduction of electron stripped detectors and ultraspeed scanning microscope for emulsion handling.

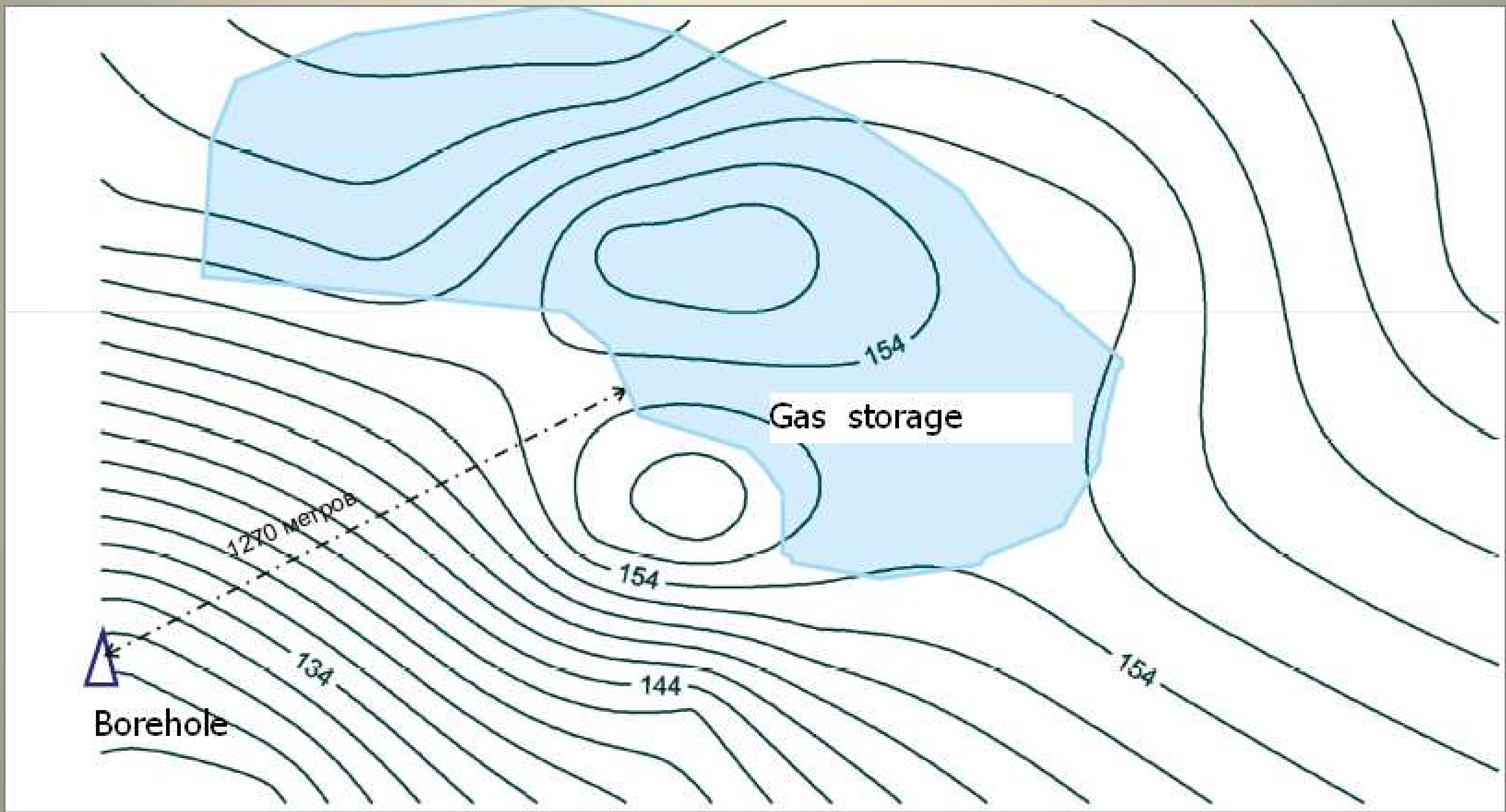
Emulsion technique has **advantage** in cost, does not need electric supply, and the application of fine-grained nano-emulsion provides higher angular resolution.



The example of minerals exploration with measurement of muon CR copmponent.

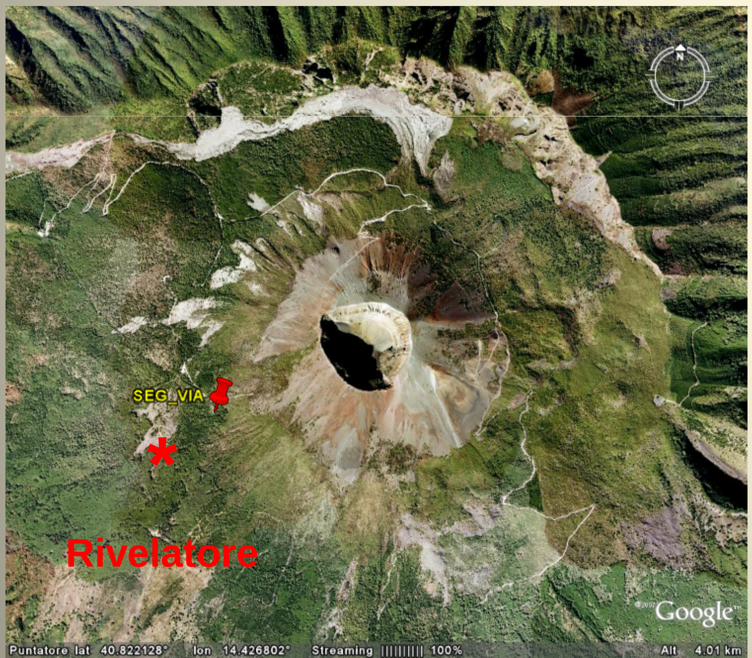
a — profile of polimetalic field (I — alluviums, II — limestone, III — rich ore, IV — poor ore, V — impregnated ore);
b — cosmic ray intensity I measured by detector telescope.

Расположение газохранилища и изолинии топографии местности



The Vesuvio muon telescope site

Telescope location



What we aspect to see