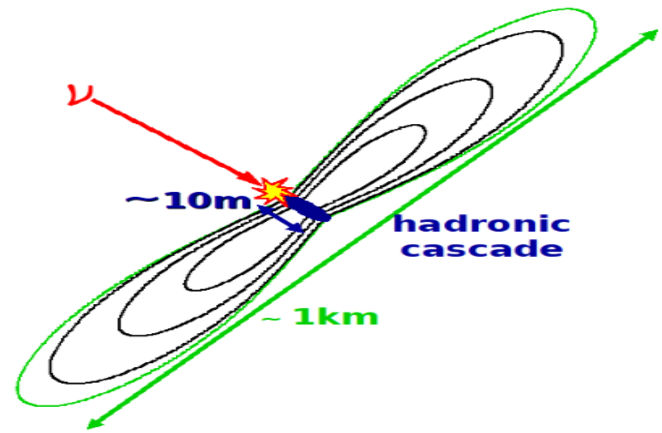
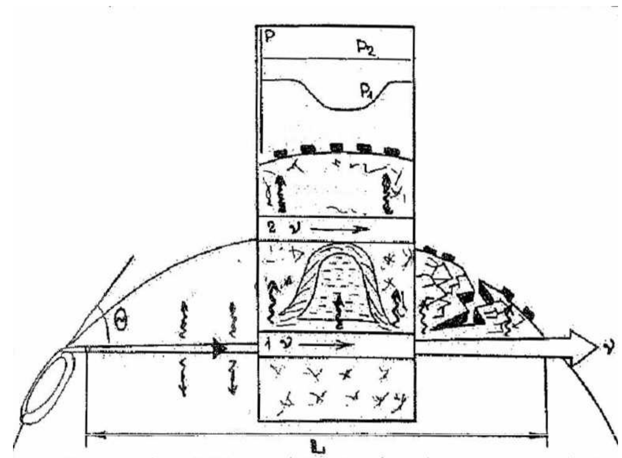
Acoustic Method of Particle Detection and its Applications for Geophysics Studies by Means of a Neutrino Beam

Homage to Boris Analtol'evich Dolgoshein (1930-2010)

- The Thermo-Acoustic Mechanism
  - Basis Theory
  - Beam Test Experiments
- Detection of Ultra High Energy Neutrino
  - Baikal
  - IceCube
- Possibility of Muon Acoustic Calorimetry
- Possibility of Neutrino Exploration of the Earth
  - Neutrino Beam as the Sonic Antenna
  - Perspectives for the Search of Oilfields
  - Acoustic Signal from Muon Beam of U-70
  - Possibility of Forecast of Earthquake
- Summary
- Outlook





Alexander Borissov, Wayne State University , Bari, 14.09.2011

The Thermoacoustic Excitation Mechanism

- Instantaneous deposition of heat through ionization: $t_{deposition} \approx \sigma/c \approx 10^{-7} \div 10^{-8}$ s
  σ - size of the region of energy deposition.

- Energy deposition $\rightarrow$ thermal expansion: $\Delta V/V = \alpha \Delta T = \alpha \frac{\epsilon}{\rho C}$,
  α - thermal expansion coefficient, ρ - density, C - heat capacity of the medium.

- Pressure pulse: $p = K \frac{\Delta V}{V} = \frac{K\alpha}{\rho C}\epsilon = \Gamma \epsilon$,
  K - bulk modulus, $\Gamma = K\alpha/\rho C$ - Grüneisen coefficient of the medium.

- Bipolar pulse due to spherical expansion of point like energy deposition:
  $p(r,t) \propto \frac{\epsilon_0 \alpha v_l^2}{C} \frac{d}{dt} \frac{\delta(t - t/v_l)}{r}$,
  v_l - velocity of longitudinal acoustic wave, and r - distance. Note that $t_{expansion} \propto \sigma/v_l >> t_{deposition}$.

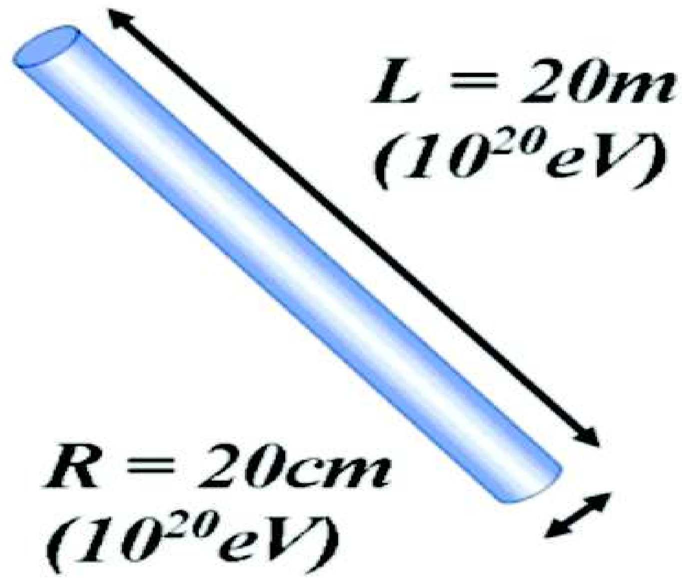
- Wavefront from shower/beam heating a volume of matter as a sum of point-like sources
  $p(r,t) \propto \frac{\alpha v_l^2}{C} \frac{d}{dt} \int \frac{1}{r} \epsilon dV$

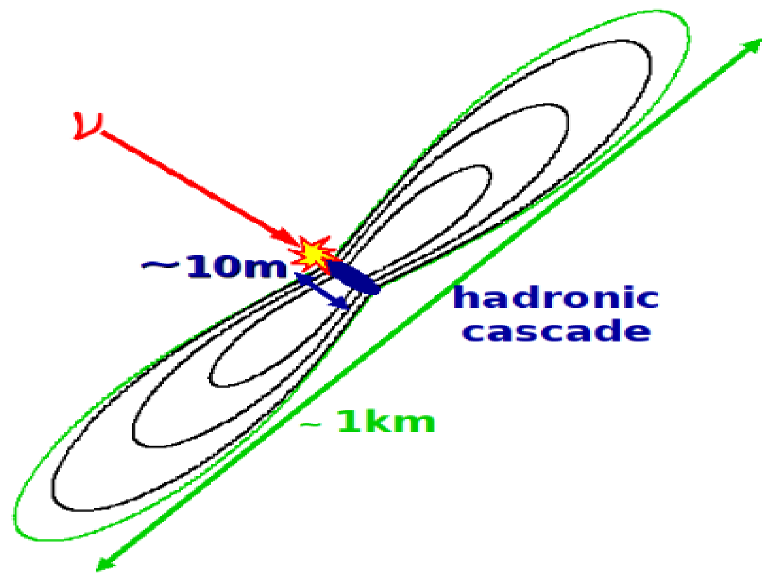
- Wave peak wavelength and frequency : $\lambda \approx 2\sigma$, $f = v_l/2\sigma$

(G.A. Askaryan, Atomnaya Energia 3, 152, 1957.)

Production of Acoustic Signal from ν Cascade

- In water or ice, for $E_\nu = 10^{20}$ ev, 95 % of the cascade energy is contained within a cylinder of length 20 m and radius 20 cm.
- The energy deposition can be considered as a continuous distribution of individual heating centers.
- Radiation is emitted coherently along the cascade axis leading to a confinement of the signal to narrow pancake due to a superposition of waves.
- Sound waves $\sim$ tens kHz.
- Attenuation length $\sim$ 10 km.





(G.A. Askaryan and B.A. Dolgoshein FIAN SSSR Priprint 160, Moskow, 1976.;

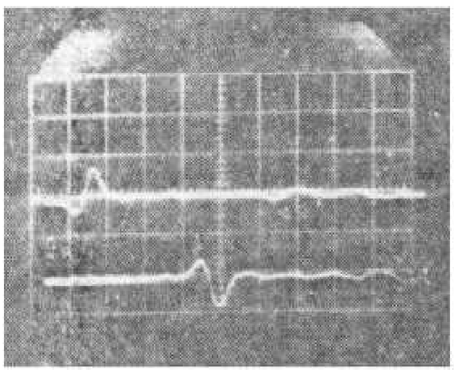
G.A. Askaryan, B.A.Dolgoshein, A.N.Kalinovsky, NIM 164(1979);

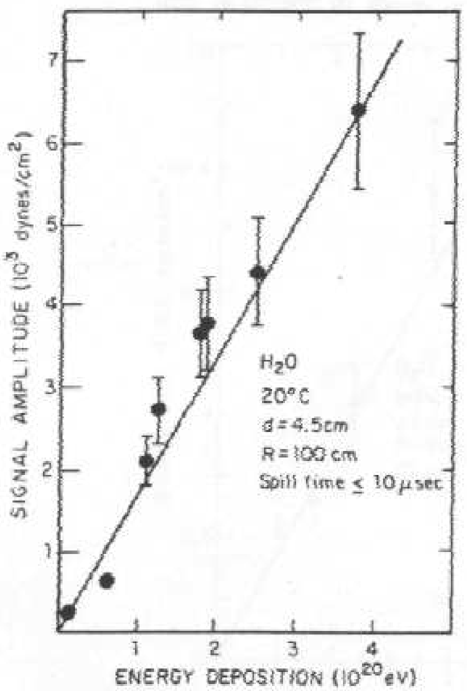
B.A. Dolgoshein "Possibility of acoustic detection of neutrinos in the ocean", 1981 Sov.Phys. Usp. 24, 244.)

Test-Beam Experiments

Brookhaven NL (Harvard, SLAC) 1979

200 MeV proton beam (LINAC)
Spill time 3 to 20 us
Beam diameter 4.5 cm
Energy deposited in water $10^{19} \rightarrow 10^{21}$ eV
Bipolar pulses observed
Dependency on C_p, T and on beam diameter confirmed (about 10% uncertainty)



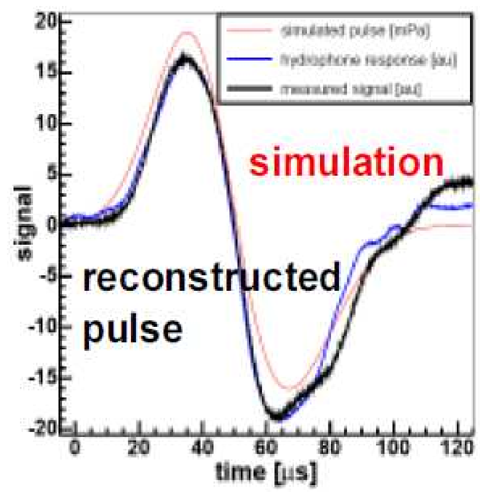


Recent measurements (2000's)

Uppsala: 177 MeV p
E= $10^{16} - 10^{17.5}$ eV
Bipolar pulse observed
Unclear dependence on temperature
Other contibution to observed pulses ?

ITEP Synchrotron: 100, 200 MeV p
E= $10^{15} - 10^{20}$ eV
Measured pressure increses linearly with E

Erlangen Laser Nd-YaG
E= $10^{17} - 10^{19}$ eV
Dependence on C_p confirmed

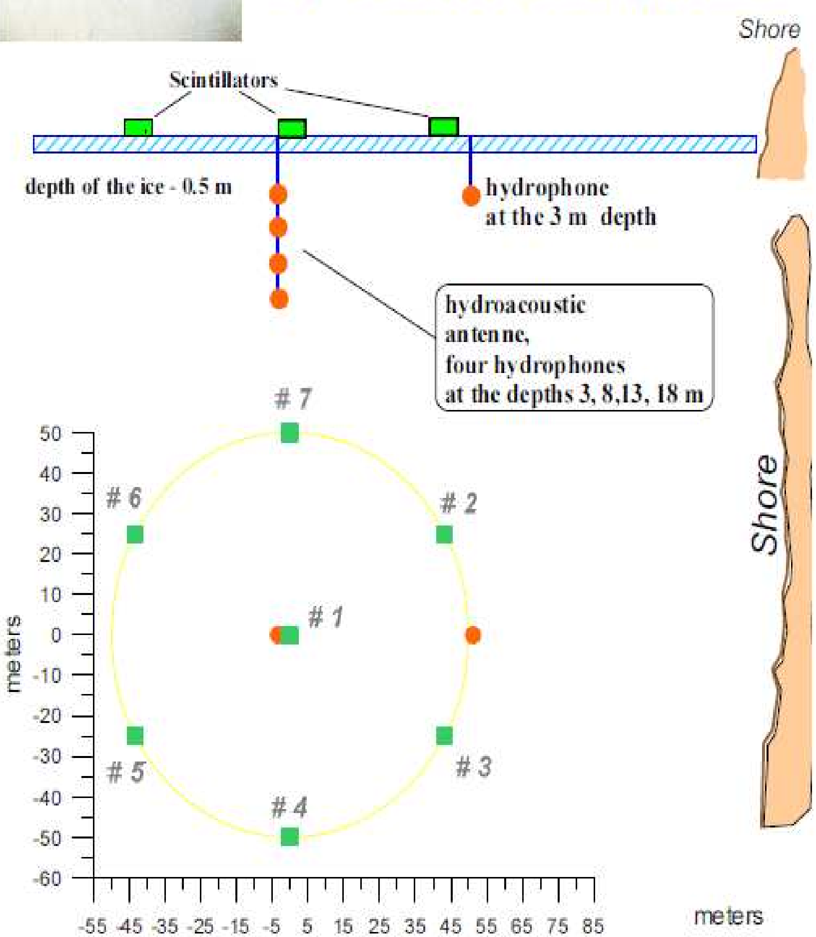


Baikal

ITEP antenna / surface EAS array

Sensitivity -135 dB re V/ μPa

Events sample dominated by surface Background

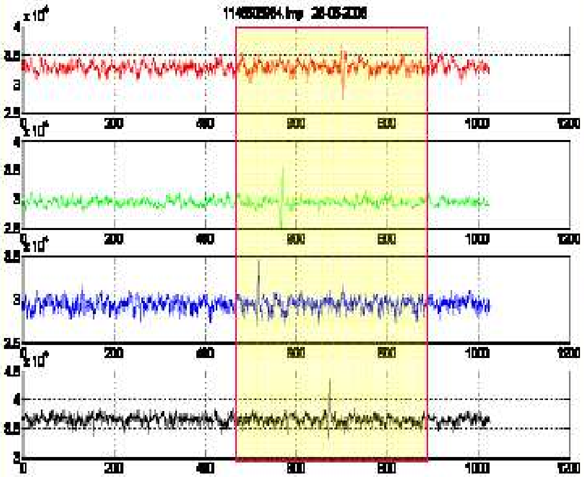


Thetrahedral antenna / NT200+

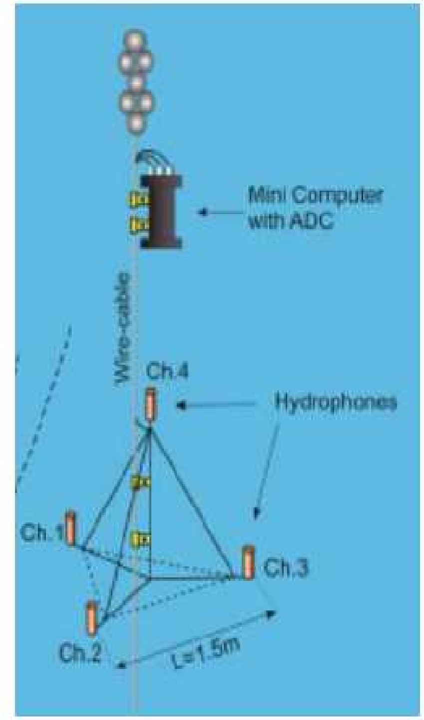
Deployed at 100m

Noise studies

Event search

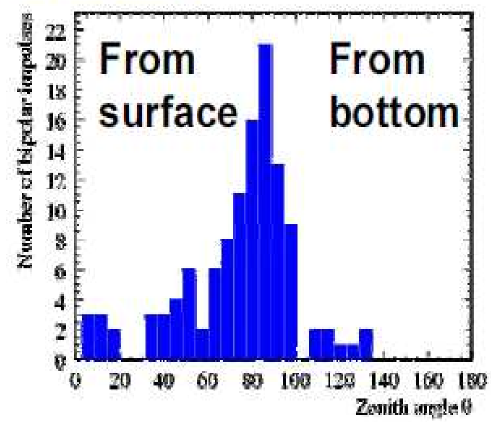


1 msec



Bipolar pulse on 4 hydrophones

Angular distribution of bipolar pulses for 2 months data acquisition



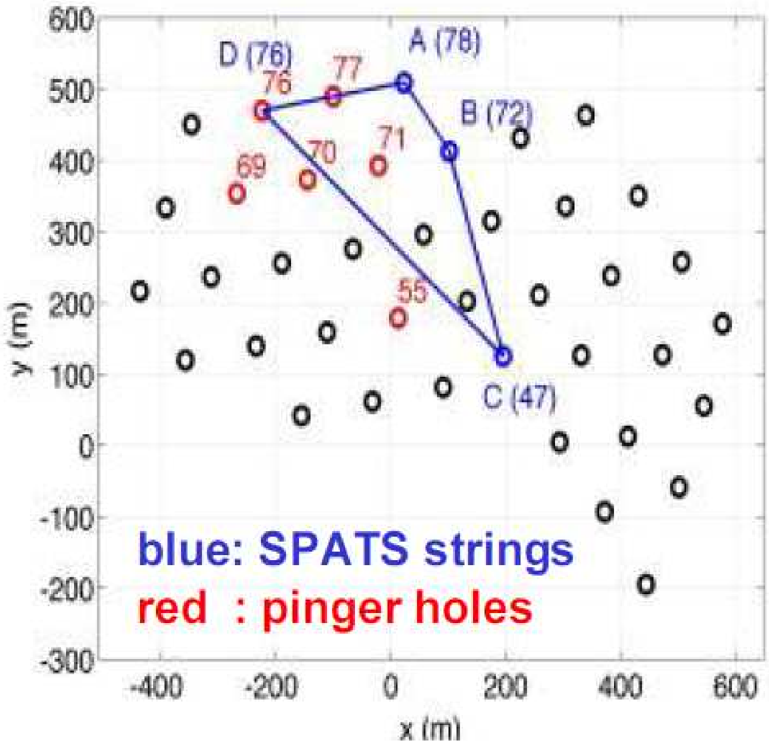
(G.Riccobene, Neutrino 2008)

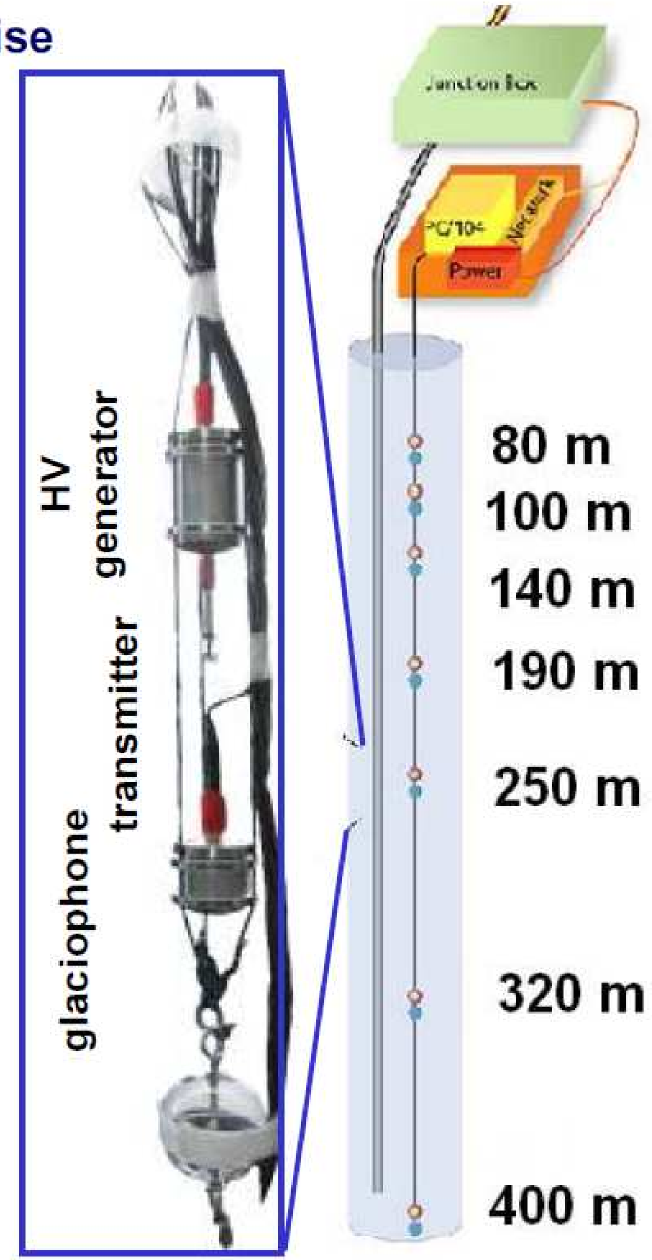
South-Pole-Acoustic-Test-Setup in IceCube

Measure ice properties :
attenuation length, wave refraction, noise

3 strings in IceCube holes 72, 78 47
7 stages per string
stage = 1 transmitter + 1 sensor

surface digitization (200 / 400 kHz)
GPS phased array





String-D
100 m longer

Improved glaciophones

Improved transmitters

New HADES glaciophone

Pinger tests: movable transmitter used in 6 holes (water filled)

AAL to meausre sound velocity (Aachen)

(G.Riccobene, Neutrino 2008)

Activities at Many Sites:

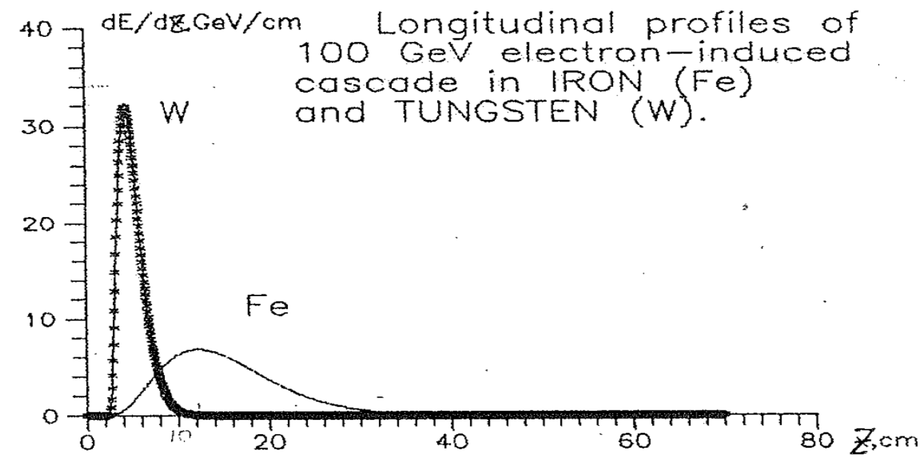
group	experiment	activities
Stanford	SAUND	data taking, signal processing, calibration , simulation
INR1	AGAM, MP10	signal processing, calibration , simulation
INR2, Irkutsk	Baikal	signal processing, noise studies, in-situ tests at Baikal
ITEP	Baikal,Antares	detector R&D, accel. tests, in-situ tests at Baikal, signal proc., noise st.
Marseille	Antares	detector and installation R&D, calibration, noise studies, simulation,
Erlangen	Antares, KM3NET	detector R&D, accel. tests, calibration, simulation, noise studies, in-situ test measurements
Pisa, Firenze, Genua	KM3NET	detector R&D
Rom, Catania	NEMO	installation R&D, noise studies, simulation
Sheffield, Newcastle	Rona, KM3NET	simulation, signal processing , calibration
U. Texas	Salt Dome	detector R&D, attenuation studies, material studies
Berkeley, DESY, Stockholm, Uppsala	IceCube	detector R&D, accel. tests, material studies, simulation, noise studies, in- situ test measurements (SPATS)

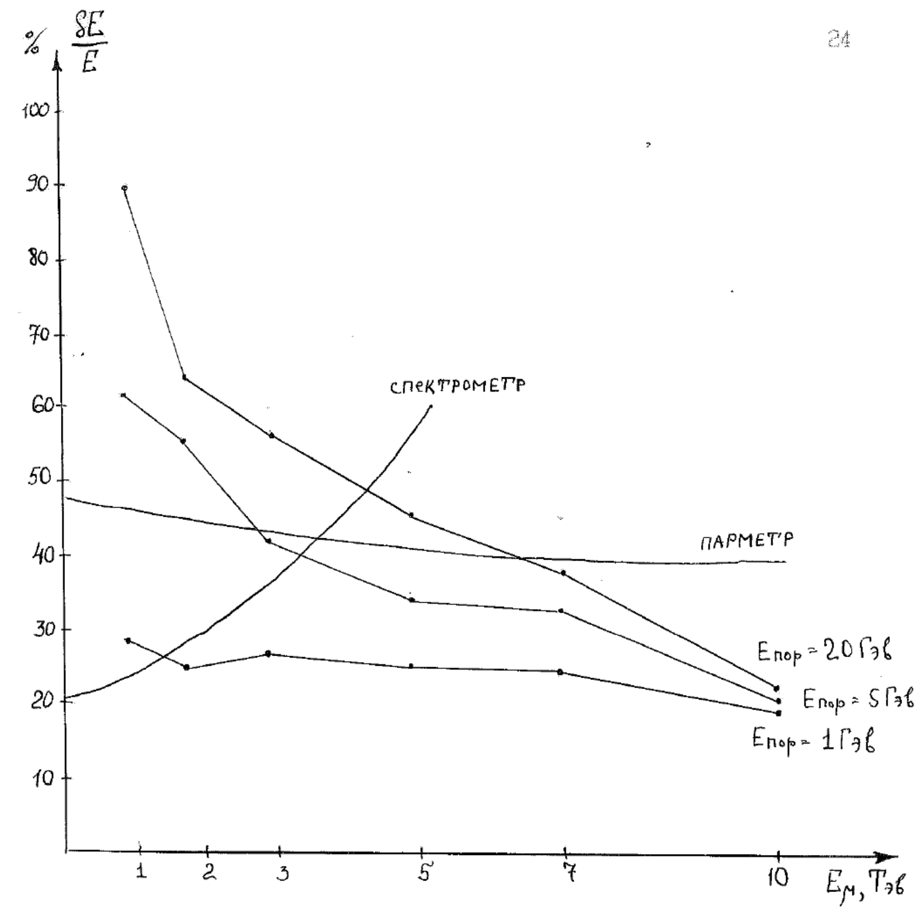
(R.Nahnhauer, DESY, www-zeuthen.desy.de/arena)

Possibility of Muon Acoustic Calorimetry

- Sound signal from electromagnetic showers simulated in dense medium (iron and tungsten) by GEANT. Approach is somehow analogous to neutrino hadron cascades in water or ice.
- Showers were originated from from muon energy losses (B_2 term) in dense medium by means of e^+e^- pair production and bremstrahlung photons.
- Muon energy loss: $\frac{dE_\mu}{dz} = B_1(1 + B_2 E_\mu)$, where $B_1 = 0.424\rho Z/A$, GeV/m and $B_2 = 1.25 \cdot 10^{-4} Z$, 1/GeV.
- Signal/noise ratio was calculated as function of E_μ. Thermal noise estimate: $N = \sqrt{2kT\Delta F \rho v_l / S_{det}}$.
- $\delta E_\mu / E_\mu \sim 0.3$ at $S/N = 1$, $E_\mu = 1 \div 10 TeV$, $E_{thresh} = 1 \div 20$ GeV in 2000 X_0 of W. Could be continued...

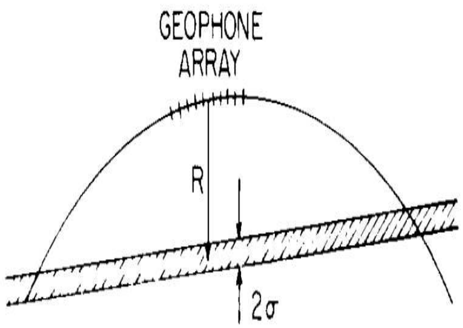
(A.Borissov, grant MASCA 1992-1995, Russian Academy of Science; A.B.Borissov, Yu.S.Gangnus, D.A.Catalumov Acoustical calorimetry of high energy muons, The Problems of Theoretical and Nuclear Physics, Saratov State University, 1992, 14p.)





Possibility of Neutrino Exploration of the Earth

(1): "Neutrino Exploration of the Earth", A. De Rujula, S.L. Glashow, R.R. Wilson, G. Charpak, Physics Reports (Review Section of Physics Letters) 99, No 6 (1983) 341-396.: "...how the neutrinos produced by a multi-TeV proton synchrotron may be used for purposes of geological research. Project GENIUS (geological exploration by neutrino-induced underground sound) is designed to search for deposits of oil and gas at large distances from the accelerator. It depends upon the coherent sound signal produced at depth by millions of neutrino interactions along the underground neutrino beam."



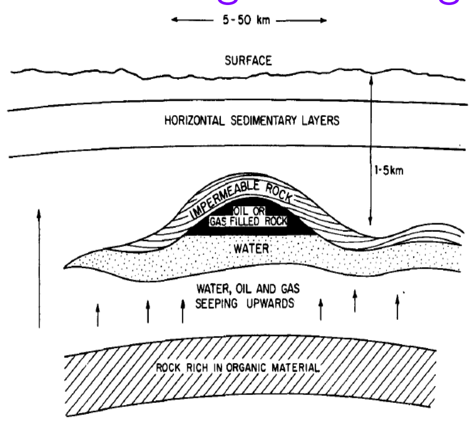


Fig. 6.1. Typical oil or gas deposit.

A. De Rújula et al., Neutrino exploration of the Earth

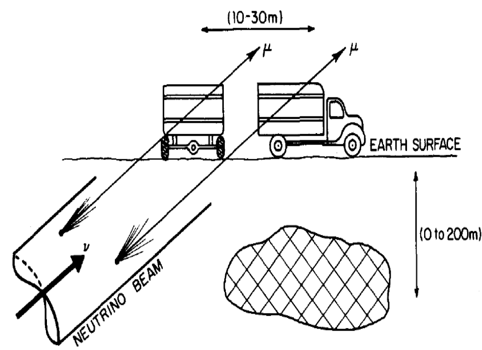


Fig. 7.1. GEMINI's truck-mounted muon detectors.

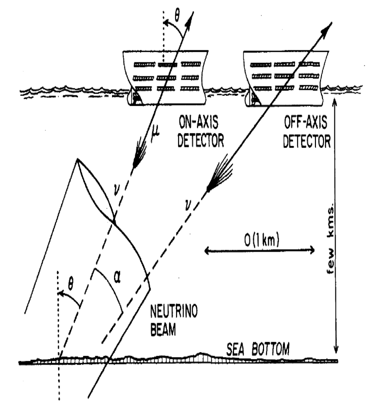


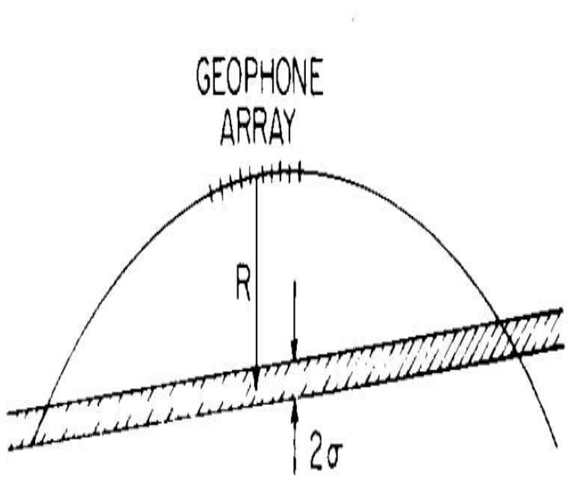
Fig. 8.4. Deployment of GEOSCAN detectors. The angle θ is that of emergence of the neutrino beam axis. The angle α is that of on-axis to off-axis neutrinos.

For the development of GEMINI and GEOSCAN projects see talk of A.Vaniachine.

Dedicated grants were started by B.A.Dolgoshein in MEPhI in 1983, main results published:

- *A.B.Borissov, B.A.Dolgoshein Determination of the ground density by high energy neutrino beams by the method of delayed muons, Nucl. Phys. 6, 1993, 12p; Yad. Fiz. USSR, 6, 1993.*
- *A.B.Borissov, B.A.Dolgoshein, A.N.Kalinovsky Method of determination of the ground density, Patent 1547509 USSR, 5G01N9/24, N4270833/24-25, 15.05.1987.*
- *A.B.Borissov " Methods of Utilization of High Energy Neutrino Beams in Geology and Geophysics" Ph.D. Thesis, Moscow Physical Engineering Institute, 1988, adviser Prof. B.A.Dolgoshein, it was used for grant reports.*
- *A.B.Borissov, B.A.Dolgoshein, A.N.Kalinovsky Direct method for determination of differential distribution of the Earth density by means of high energy neutrino scattering, , Yad. Fiz. (USSR), 1986, v.44 3(9), 681-689; Sov. J. Nucl. Phys. 44, 442 (1986); Preprint MEPhY 23-85, 1985, 21p.*

Estimates for Neutrino Beam from Proton Accelerator



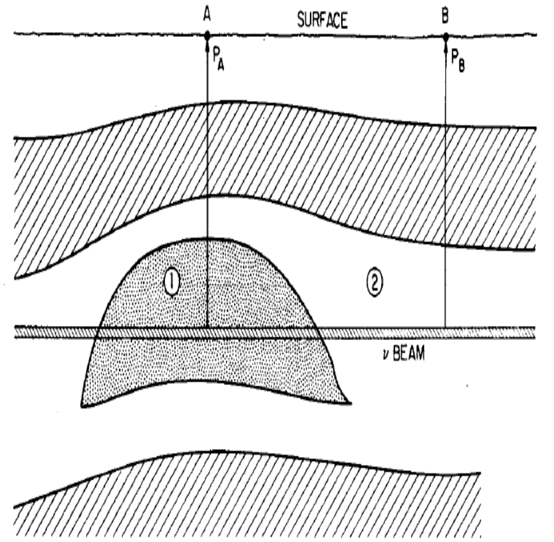


Fig. 6.3. A profile of the neutrino beam in GENIUS, relevant to a mapping in terms of relative pressure signals.

From (1) and dedicated grants:

- Number of protons per cycle: $N_p = 10^{15}(E_p/10TeV)$, E_p - energy of protons
- Cycle of accelerator: $T = 1min(E_p/10TeV)$
- Length of neutrino decay channel: $l_{dc} = 7.5km(E_p/10TeV)$
- For grants, ν spectra have been simulated, $E_\nu^{max} = 0.43(0.95)E_{\pi(K)}$
- Estimated in (1) mean energy of neutrino beam: $E_\nu \approx E_P/18$
- Cross section of neutrino interaction: $\sigma^{\nu tot} = 0.5(\sigma^{\nu n}+\sigma^{\nu p}) = 0.84\cdot 10^{-38}cm^2/GeV\cdot E_\nu$
- Range of neutrino: $R_\nu = 1/N_A\rho\sigma^{\nu tot} = 2.*10^9 km/(\rho/1g|cm^3)(E_\nu/1GeV)$
- Energy deposition of the beam: $dW/dz = W_i(\rho/1g|cm^3)(E_p/10TeV)^3$,
  $W_{\pi,K} = 60, 170$ erg/cm
- Transverse size of the region of energy deposition: $\sigma = \sigma_i(L/1000km)(10TeV/E_p)$,
  $\sigma_{\pi,K,charm} = 22, 56, 200$ m, L - distance from accelerator

Generation of Sound by Neutrino Beam

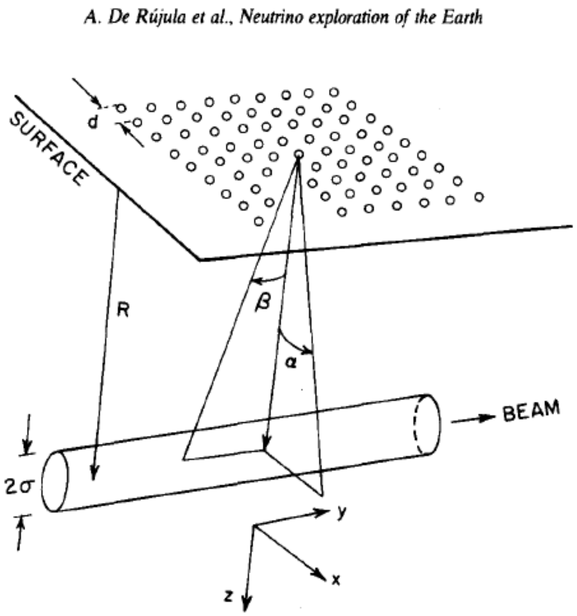


Fig. 5.2. Microphone array contemplated in the GENIUS Project.

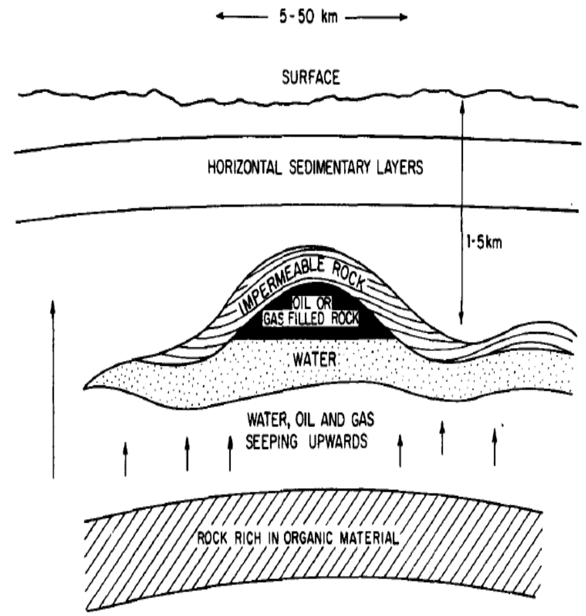
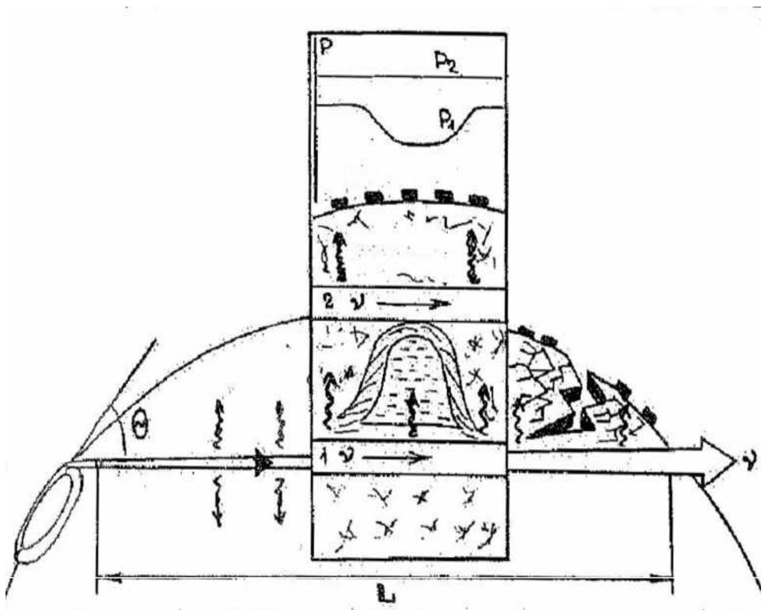


Fig. 6.1. Typical oil or gas deposit.

From dedicated grants:

- Amplitude of acoustic signal: $P(din/cm^2) = |P_{max} - P_{min}|$ $= 2.2 \cdot 10^{-6} \cdot A \cdot (\rho/1g|cm^3)(E_p/10TeV)^{4.5} \cdot (1000km/L) \cdot (1km/R)^{0.5}$, R - depth of ν-beam
- Mean frequency: $f(Hz) = 1.5v_l/2\pi\sigma = 12.4(v_l/1km/s)(1000km/L)(E_p/10TeV)$
- Seismic noise was estimated from (1).
- $S/N = 2.4 \cdot 10^{-4} A(1km/s/v_l)(E_p/10TeV)^{5.2}(1000km/L)^{2.2} \cdot (1km/R)^{0.5} \approx 10^{-5}$ for $E_p = 10TeV$, $R = 1$ km, $L = 1000$ km
- Accumulation of signal/noise: $S_{acc}/N = S/N\sqrt{n_{pulses}N_{det}}$

Possibility of Search of Oilfield



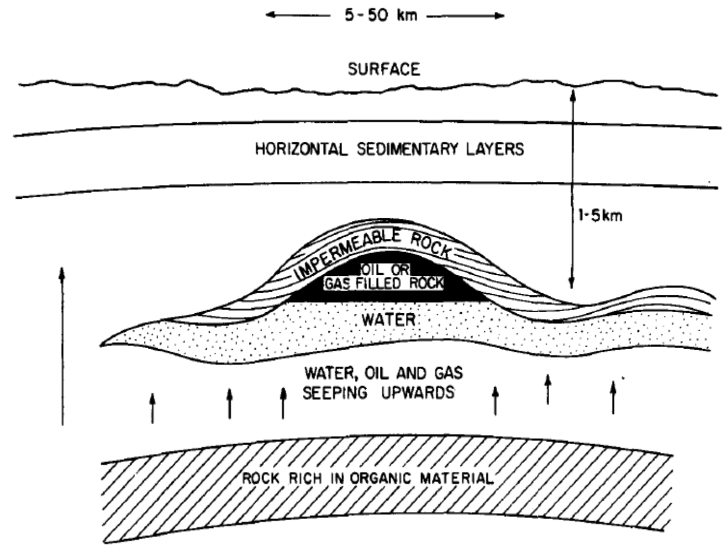


Fig. 6.1. Typical oil or gas deposit.

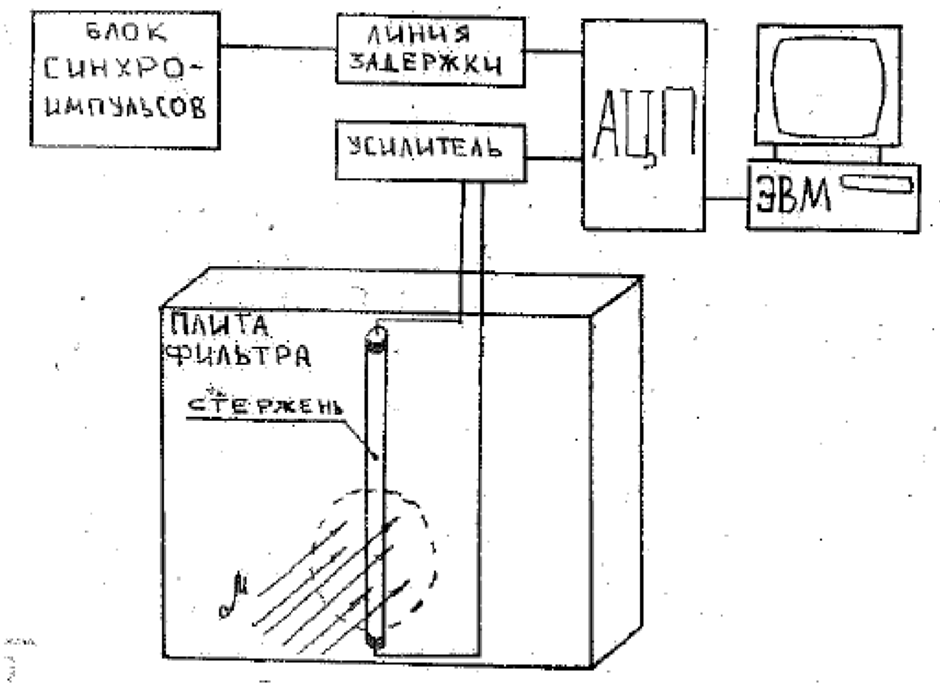
For grants, after consultations with geologists, acoustic signals have been calculated in different rocks with real parameters.

- Sound attenuation length of oil collector or oil is more than 10 times smaller than for oil-free standard rocks.
- Vertical profile of density of oil deposit has a certain structure, but in average, density of deposit is smaller than the density of standard rock.

$\Longrightarrow$ **Expected acoustic signal from neutrino beam passing oil-reached geological layers (or below them) is expected to be more than 10 times smaller relative to signal from neighboring layers.**

Generation of Sound by Muon Beam Simulating Neutrino Beam

(A.B.Borisov et al, Zh.Eksp.Teor.Fiz., 100, 1121-1128, 1991; A.B.Borisov et al, preprint IHEP 92-66, 1992.)



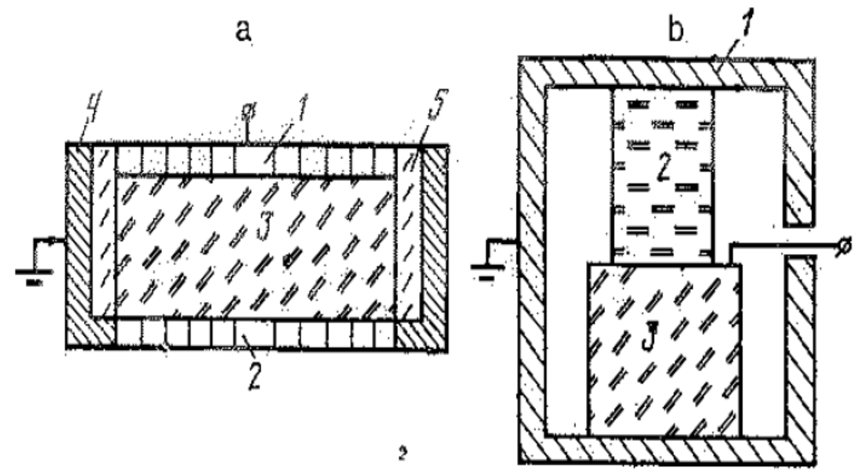
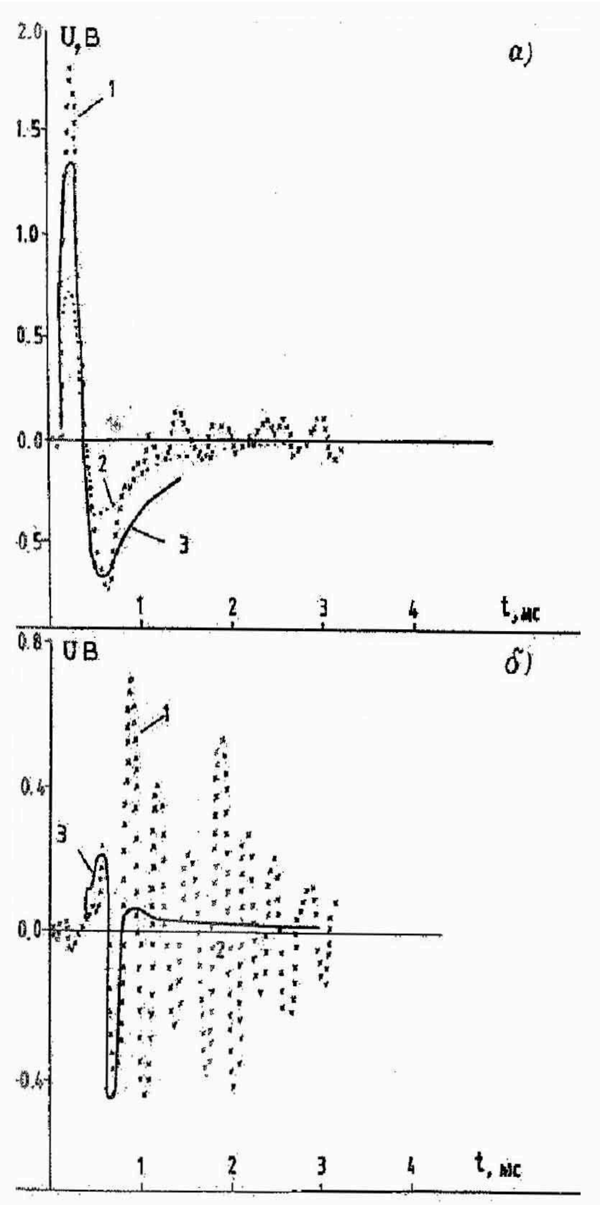


FIG. 5. Acoustic pulse detector. A: 1—Upper electrode; 2—lower electrode; 3—ceramic piezoelectric plate; 4—metal ring; 5—epoxy cement. B: 1—Metal cup; 2—cork cylinder; 3—ceramic piezoelectric plate.

Reasons:

- Monitoring of muon (and neutrino) beam by a new remote method. Acoustic signals have been measured in steel stack of muon filter (Zh.Eksp.Teor.Fiz) and hanged up steel rod (l=274 cm, d=4.5 cm), to reduce seismic noise (preprint IHEP 92-66).
- Signals from U-70 μ-beam simulate ones from ν-beam of multi-TeV accelerators, e.g., the UNK. Planned at UNK neutrino beam was directed on lake Baikal.
- Method of detecting of ultraweak signals from ν-beam would naturally begin with large energy evolution. Proposals for grants were submitted in 1992, 1993.
- Study of effects of the excitation and propagation of waves induced by a μ-beam.

Acoustic Signal from Muon Beam of U-70



a,b - signals from top and bottom acoustic transducers on the steel rod. 1 - data, 2,3 - calculations without/with accounting of amplification.

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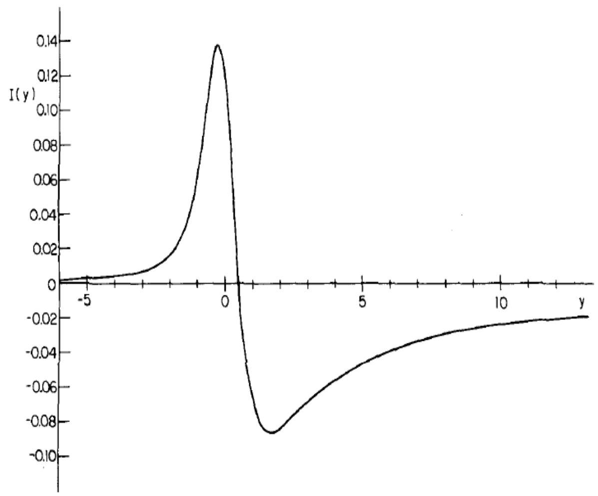
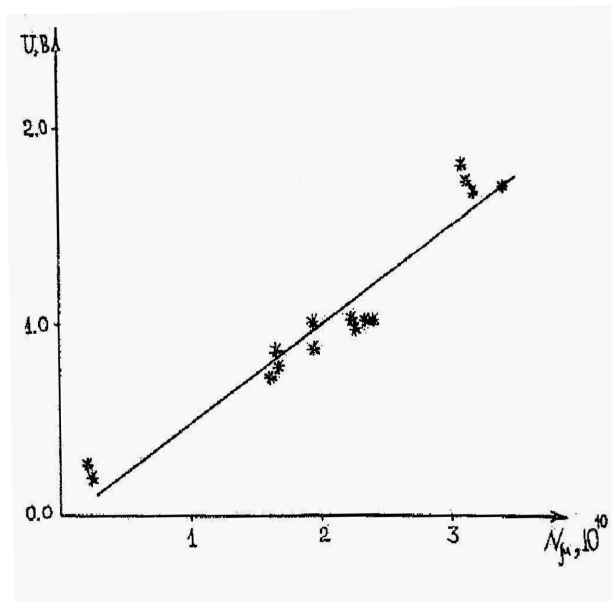


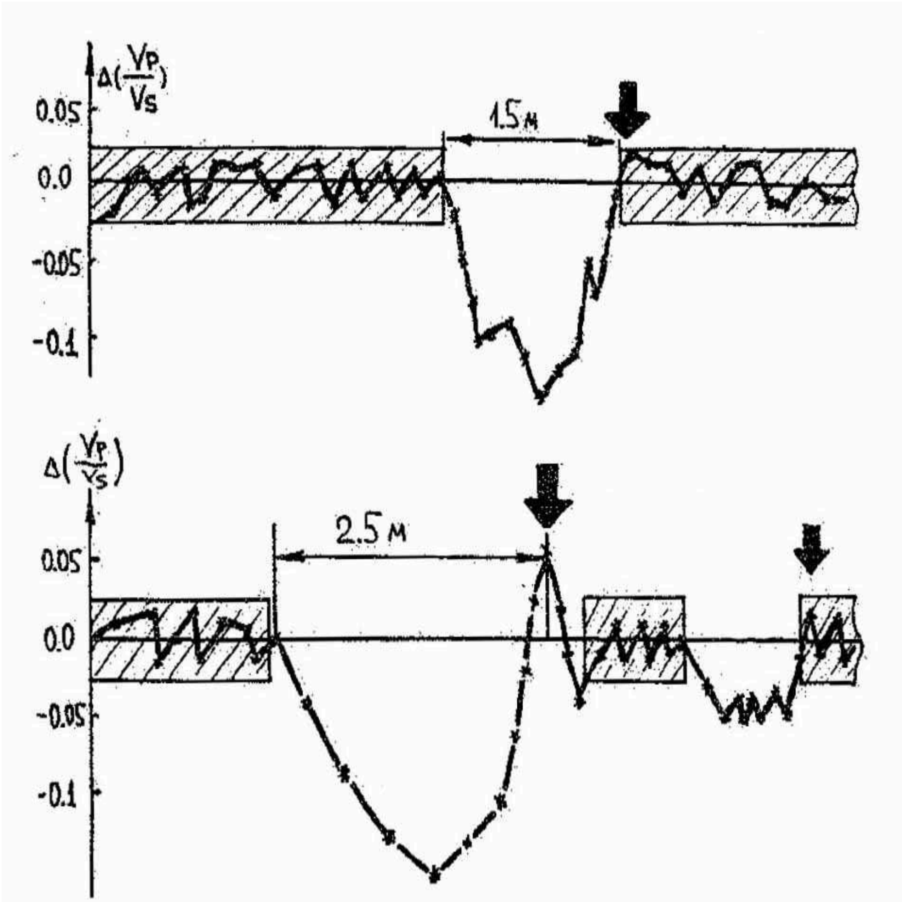
Fig. 4.2. The time dependence of the pressure pulse as given by eq. (4.20) with $y = (ct - R)/\sigma$.



Dependence of amplitude of signal from the intensity of muon beam.

- Agreement of calculated signal ($v_l^{tab} = 5.8$ km/s, $\Gamma = 0.1$) with measured (left plots) supports the thermoacoustic excitation as the predominant mechanism for iron.
- Observed bipolar pulse corresponds in shape to calculated in (1) pulse from ν beam (top-right).
- Linear dependence of measured signal with intensity of muon (neutrino) beam (bottom-right) supports continuous distribution of energy deposition.
- Measured from the fronts of acoustic signals velocity of longitudinal acoustic wave ($v_l = 5.7$ km/s) is in agreement with tabulated values ($v_l^{tab} = 5.8 \div 6.1$ km/s).

Possibility of Forecast of Earthquakes



Variation of v_l/v_t with time (month) measured in Garma, USSR. Arrows show the moments of earthquake. Dashed regions correspond to the uncorrelated with the earthquakes variations.

- Variation of v_l/v_t in the region of earthquake occurs shortly before the earthquake. Velocity of transverse wave (v_t) is almost the same. (D.Rais "Mechanics of Earthquake" 1983; M.A.Sadovski "Deformation of geophysical medium and seismic process", Moscow, Science 1987, in Russian).
- Maximum variation of v_l/v_t is proportional to the magnitude of the earthquake. The struck occurs after ∼10% of the time of the variation period. (T. Rikitake "Earthquake Prediction Reserarch", 1985; Geophysical conditions in the regions of strong earthquakes, Moscow, Science 1983, in Russian).
- It is hard to analyze waves from the explosions on the surface due to many reflections (K. Kasahara "Earthquake Mechanics", 1985).

$\Longrightarrow$ Usage of neutrino beam as an underground source of longitudinal acoustic waves allows to:

- determine v_l in the region of earthquake by means of the registration of the time of signal,
- apply already existing systems for measurement of seismic noise,
- use stable decay channel for observation of time dependence of the variation of v_l.

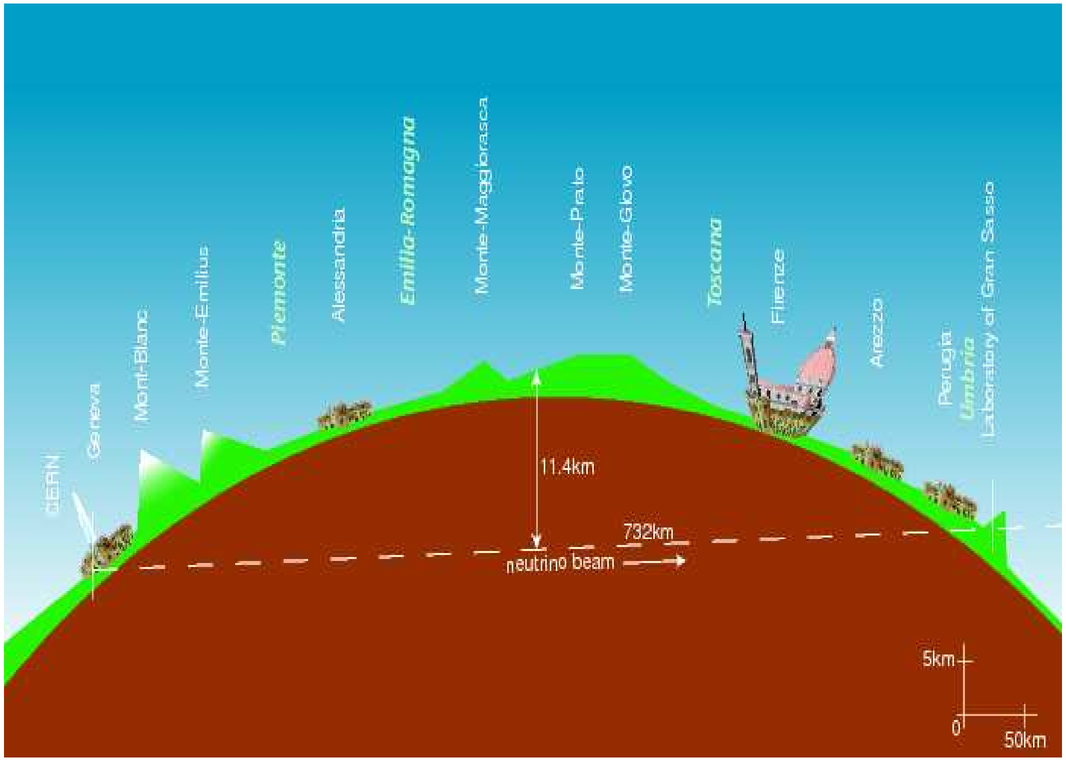
(A.B.Borisov et al, preprint IHEP 92-66, 1992.)

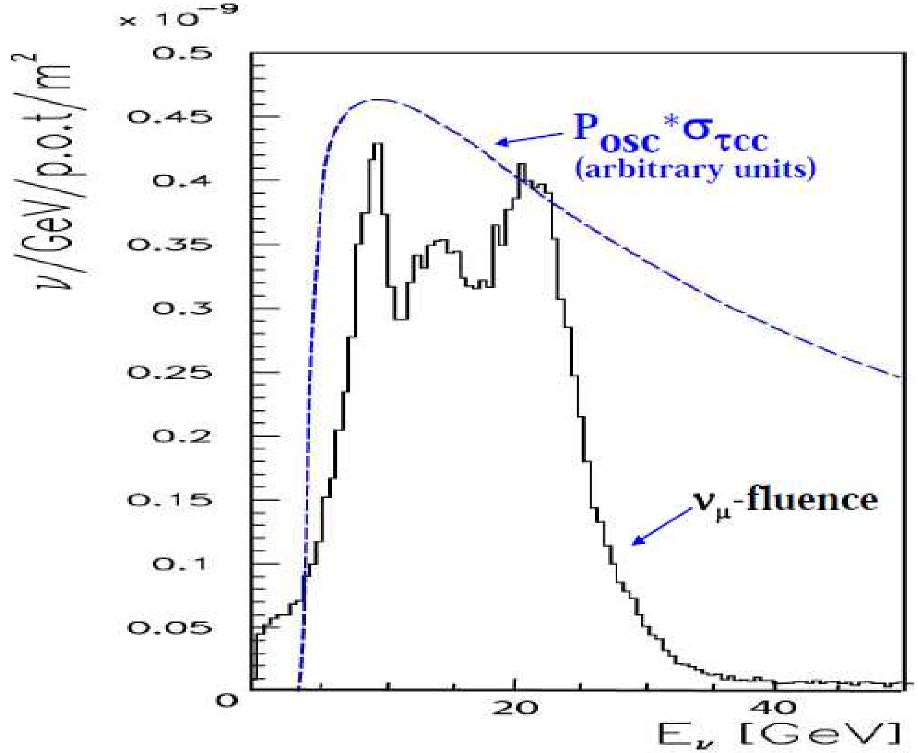
Summary: Timelines

B.A. Dolgoshein (“Possibility of acoustic detection of neutrinos in the ocean”, 1981, Sov.Phys. Usp. 24, 244.):

- **1957** “...It is possible to detect ionizing radiations in water by using an acoustic signal.” *(G.A. Askaryan, Atomnaya Energia 3, 152 (1957).)*
- **1976** “The most interesting application of this technique is in detection of hadron cascades triggered by high-energy cosmic neutrinos deep in the ocean” *(G.A. Askaryan and B.A. Dolgoshein FIAN SSSR Priprint 160, Moskow, 1976.)*
- **1979** “Accelerator-beam experiments sound-radiation mechanism appears to rest largely on thermal expansion of the water.” *(L. Sulak et al, Nucl. Instr. and Methods 161, 203 (1979).)*
- **1981** “Possible to consider the possibility of building a neutrino telescope with an angular accuracy of $\sim 1^o$. Using this technique in the neutrino astronomy of superhigh energies ($\leq 10^{15}$ to 10^{16} eV) requires the development of $\sim 10^{11}$ tons (10 km $\times$ 10 km $\times$ 1 km) of ocean water.”
- **1983** Possibility of “Neutrino Exploration of the Earth”. *(A. De Rujula, S.L. Glashow, R.R. Wilson, G. Charpak, Physics Reports (Review Section of Physics Letters) 99, No 6 (1983) 341-396.)*
- **1981÷2000** Development of Nevod, Baikal, DUMAND neutrino telescopes.
- **1983÷1993** Studies of neutrino usage for geology and geophysics, acoustic signals from muon beam on U-70. *(B.A.Dolgoshein et.al. papers)*
- **2000÷2010** Development of ANTARES, IceCube projects. Operational neutrino beam from CERN to Gran Sasso.
- **2010** LHC is operational with 3.5 TeV proton beam.

Outlook: Operational Neutrino Beam from CERN to Gran Sasso





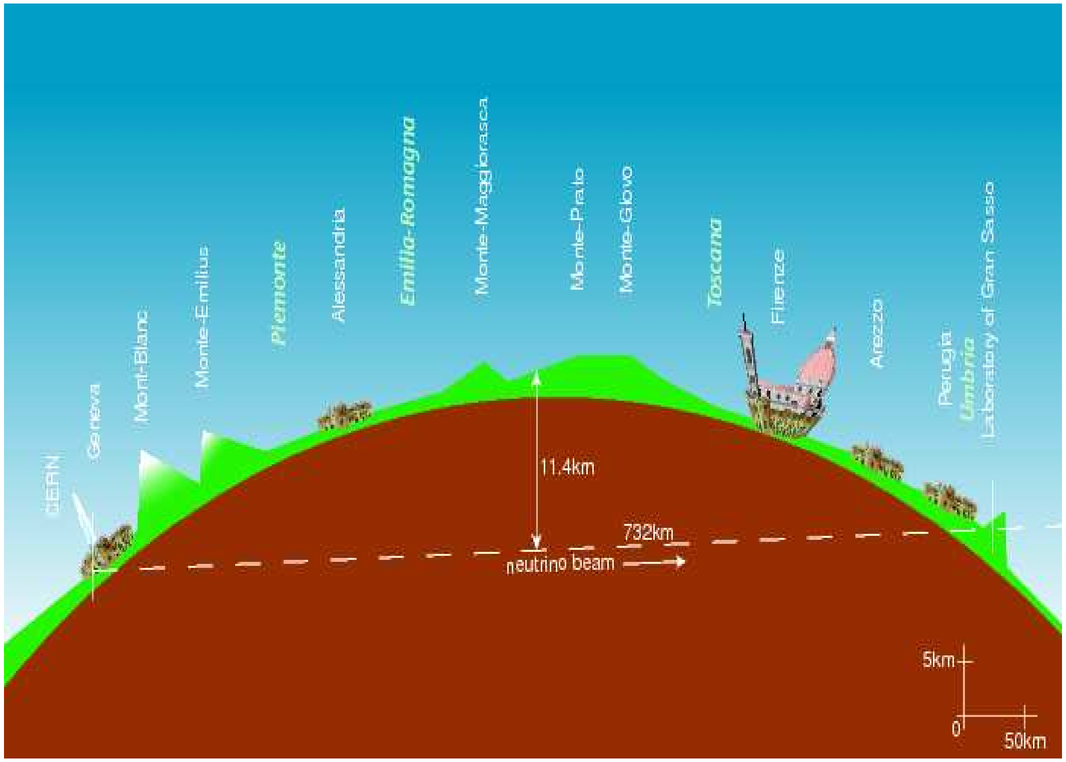
- Experiment OPERA (Oscillation Project with Emulsion-tRacking Apparatus) to test of the phenomenon of neutrino oscillations: $\nu_\mu \longrightarrow \nu_\tau$.

  (http://operaweb.lngs.infn.it/, and http://en.wikipedia.org/wiki/OPERA_experiment)

- Intense and energetic beam of muon neutrinos travels 732 km kilometers. A beam is generated by collisions of accelerated protons with a graphite target after focusing pions and kaons in the desired direction.
- The facility CNGS (CERN Neutrinos to Gran Sasso) has been built at CERN between 2000 and 2005 and it started operation in summer 2006.
- OPERA is collecting data since 2008.

$\Longrightarrow$ **It looks like a prerequisites to study ultraweak acoustic signals from the neutrino/muon beam at CERN...**

Outlook: BBC News 6 April 2009



- **The 6.3-magnitude quake struck at 0330 (0130 GMT) very close to L'Aquila and Gran Sasso.**

- **About 100 people were dead, about 1,500 people were injured.**

- **Altogether, 26 cities and towns have been damaged. In L'Aquila, 95km (60 miles) north-east of Rome, about 10,000 buildings have been damaged.**