The India based Neutrino Observatory – present status

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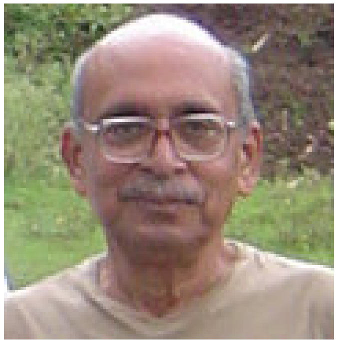
Talk dedicated to my teacher Prof. C.V.K. Baba



INO Collaboration

Spokesperson : N.K. Mondal

Collaborating institutions/universities

AMU, BHU, BARC, CU, DU, HRI, UoH, HPU, IITB, IITKh, IGCAR, IMSc, IOP, LU, NBU, PU, PRL, SINP, SMIT, TIFR, VECC

Plan of talk

1. Introduction

2. Physics goals

3. Choice of detector and site

4. Status of ICAL subsytems and simulations

5. Training for INO – a beginning

6. Estimated cost and schedule

1. Introduction

- Proposed by Pauli (1930)
- first evidence in reactor expt.(Reines & Cowan 1956) $\bar{\nu}_e$
- helicity of ν_e (Goldhaber *et al* 1958) $h = -(1.0 \pm 0.3)$
- ν_μ (1962) and ν_τ (2001) in accelerator expts.
- 3 families of neutrinos ($\Gamma(Z^0)$ at LEP $\Rightarrow N_\nu = 2.994 \pm 0.012$)
- mass of $\nu_e < 2.2$ eV/c^2 via ^{3}H β-spectrum
- Majorana or Dirac ? $\nu = \bar{\nu}$ or $\nu \neq \bar{\nu}$ (verify ^{76}Ge claim)

Why study neutrinos?

- Physics beyond Standard Model (particles & interactions)
- Neutrinos change flavours or *oscillate*

  SuperKamioka (atmos. ν), SNO (solar ν_e), Kamland (reactor $\bar{\nu}_e$)

  What are the mixing angles and Δm^2 ?
- At least 2 non-zero mass eigen-states exist

  $m_3 > m_2 > m_1$ or $m_2 > m_1 > m_3$ with all $m < 2.5$ eV/c^2
- Are neutrinos their own antiparticles? Majorana or Dirac
- Is there CP or CPT violation in neutrino/leptonic sector?

Neutrino oscillations – some basics of 3-flavour mixing

Expand $|\nu_\alpha\rangle$ flavour eigenstates in mass eigenstates basis $|\nu_i\rangle$

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$$ where

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

is the unitary Maki-Nakazawa-Sakata (1962) matrix diagonalizing M_ν^2

Here c_{12}= cos θ_{12} , s_{12}= sin θ_{12} etc., δ is the CP-violating phase

The vacuum $\alpha \to \beta$ flavour changing probability in length L is

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \mathrm{Re}[U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}] \sin^2\left(\frac{\pi L}{\lambda_{ij}}\right) + 2 \sum_{i>j} \mathrm{Im}[U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}] \sin\left(2\frac{\pi L}{\lambda_{ij}}\right)$$

where $\lambda_{ij} \approx 2.5\ (E\ /\mathrm{GeV})\ (\mathrm{eV}^2/\Delta_{ij})$, L in km

Matter effects…

ν_e interacts with matter electrons (neutral current common to all ν_α)

$\Rightarrow$ Change in mixing angle and mass

$$\sin^2 2\theta_m = \frac{\Delta_{21}^2 \sin^2 2\theta}{(\Delta_{21}\cos 2\theta - A)^2 + \Delta_{21}^2 \sin^2 2\theta}$$

$$\Delta_{21}^m = M_2^2 - M_1^2 = \sqrt{(\Delta_{21}\cos 2\theta - A)^2 + {\Delta_{21}}^2 \sin^2 2\theta}$$

ν_e-e interaction $\Rightarrow$ $V \simeq \sqrt{2} G_F n_e$ and $A \simeq 2\sqrt{(2)} G_F n_e E$

where n_e is electron density, G_F is Fermi coupling constant

Best values for neutrino oscillation parameters

Parameter	Exp. value (1σ)
Δ_{21}^2	$(7.9\pm0.4)\times10^{-5}$ eV^2
Δ_{23}^2	$(\pm2.4\pm0.2)\times10^{-3}$ eV^2
θ_{12}	$34.1^\circ\ {}^{+1.6^\circ}_{-1.2^\circ}$
θ_{23}	$41.6^\circ\ {}^{+5.7^\circ}_{-2.9^\circ}$
θ_{13}	$<8^\circ$

Not known : δ_{CP}

$m(\nu_e) = \sqrt{\sum_i |U_{ei}|^2 m_i^2} < 2.2$ eV/c^2 (^{3}H β-decay *Troitsk 2004, Mainz 2005*)

$\langle m(\nu_{ee})\rangle = |\sum U_{ei}^2 m_i| < 0.4$ eV/c^2 (^{76}Ge $0\nu2\beta$ Heidelberg-Moscow)

$= 0.4 \pm 0.2$ eV/c^2 (subset H-M collab, Klapdor)

Mixing matrix (best values)

$$U = \begin{pmatrix} 0.8200 & 0.5552 & 0.1392\ e^{-i\delta} \\ -0.4192 - 0.0765\ e^{i\delta} & 0.6192 - 0.0518\ e^{i\delta} & 0.6575 \\ 0.3722 - 0.0862\ e^{i\delta} & -0.5498 - 0.0583\ e^{i\delta} & 0.7405 \end{pmatrix}$$

Here the maximal allowed (at 1σ level) value of θ_{13} has been used. U_{13}, U_{21b}, U_{31b} and U_{32b} are the upper bounds while U_{11}, U_{12}, U_{23}, U_{33} are the lower bounds *vis a vis* θ_{13}

An Indian first and present initiative…

- Atmospheric neutrinos were first detected in KGF (1965) by a TIFR group ahead of Reines (Nobel laureate 1995)

- The Indian Neutrino Observatory (INO) is an initiative to revive underground experiments in this exciting field (see http://www.imsc.res.in/~ino). An MoU signed by participating DAE institutes on 30th August, 2002 to work towards a proposal for INO.

- Funding by Dept. of Atomic Energy (DAE) for feasibility studies leading to submission of detailed project report

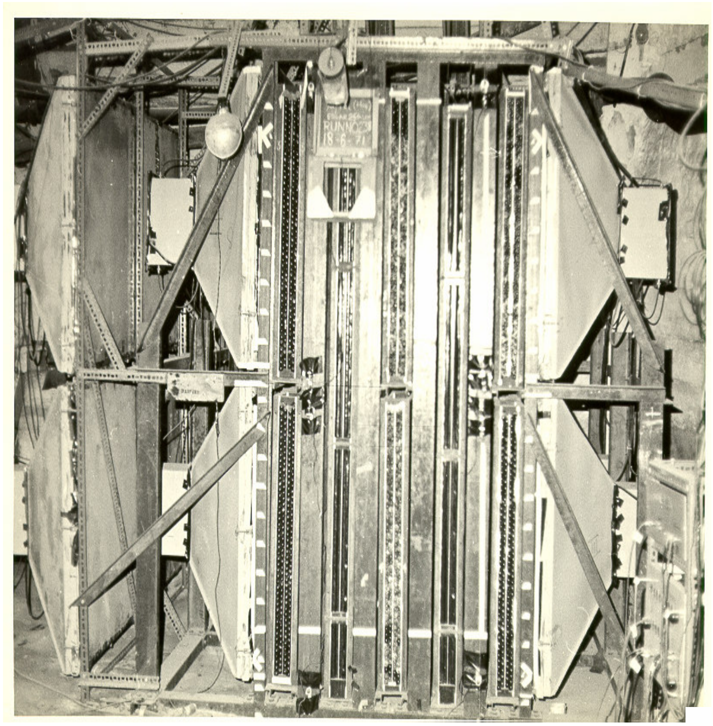
- An interim report was submitted on May 1, 2005 to Chairman, DAE

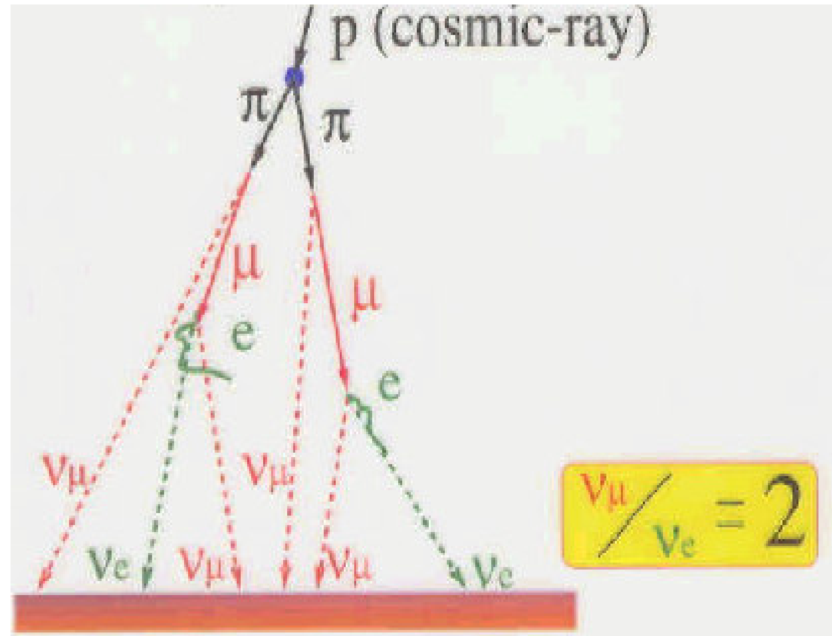
- In 2006 updated report reviewed by 6 international experts

  Responses very positive – ratings A++ to A

Atmospheric Neutrinos

Atmospheric neutrino detector at Kolar Gold Field –1965





DETECTION OF MUONS PRODUCED BY COSMIC RAY DEEP UNDERGROUND

C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMAN, and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLI
University of Durham, Durham, U.K.

Received 12 July 1965

Physics Letters 18, (1965) 196, dated 15th Aug 1965

EVIDENCE FOR HIGH-ENERGY COSMIC-RAY NEUTRINO INTERACTIONS*

F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, and G. R. Smith

Case Institute of Technology, Cleveland, Ohio

and

J. P. F. Sellschop and B. Meyer

University of the Witwatersrand, Johannesburg, Republic of South Africa

(Received 26 July 1965)

Phys. Rev. Lett 15, (1965), 429, dated 30th Aug. 1965

2. Physics goals

Using ICAL with *atmospheric neutrinos* and cosmic muons at INO

- direct observation of oscillation (fall & rise)
- precision measurement of oscillation parameters
- if nature is kind ($\theta_{13} > 5°$), neutrino mass hierarchy
- CP and CPT violation in neutrino sector
- Kolar events (*tracks emerging from long lived particle produced in cosmic ray interaction with rock near proton decay detector*)
- 1-100 TeV cosmic muon flux measurement by pair counting technique

Using accelerator produced neutrinos (J-PARC, CERN, Fermilab)

- long baseline experiment – (6560, 7150, 11300 km)

  compared to CERN-Gran Sasso 730 km, K2K 250 km,

  Fermilab-MINOS 735 km

  $\Rightarrow$ increased sensitivity & precision to smaller mixing angle

  θ_{13} and Δ_{23} , 2 distances (e.g.3000 & 7000 km) for δ_{CP}

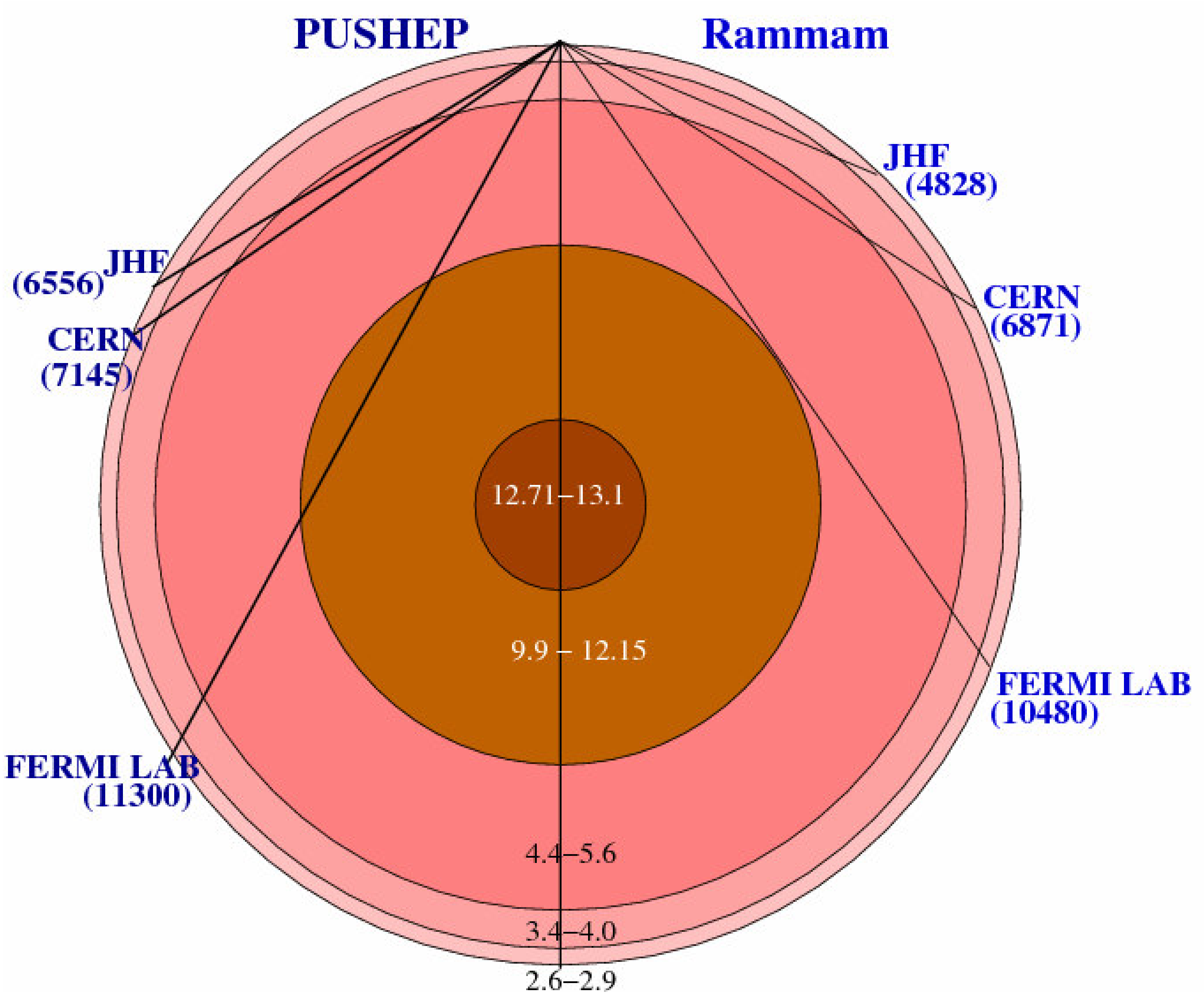
- Beta beams ($\bar{\nu}_e$ from ultra-relativistic, circulating beta

  decaying RIBs such as ^{6}He) 6×10^{18} $\bar{\nu}_e$ /yr for ν_μ appearance

  experiments

- Neutrino factories using accelerated, stored muon beams

  10^{20} ν /yr /straight section


PUSHEP
Rammam
JHF
(4828)
JHF
(6556)
CERN
(6871)
CERN
(7145)
12.71−13.1
9.9 − 12.15
FERMI LAB
(10480)
FERMI LAB
(11300)
4.4−5.6
3.4−4.0
2.6−2.9

Other experiments at INO

- search for $0\nu2\beta$ in ^{124}Sn via cryogenic bolometer (*feasibility ongoing*)
- nuclear cross sections of astrophysical interest using 500 kV accelerator

3. Choice of detector and site

Existing detectors worldwide

- water Cerenkov (50 kT SuperKamioka)
- Fermilab-MINOS (5 kT Fe calorimetric detector)
- CERN- OPERA at Gran Sasso

Our choice

- Detector – physics reach, our capabilities & limitations ⇒

  INO Collab. chose a 50-100 kT Iron Calorimeter (ICAL)

- Site requirement – 1 km rock cover all round detector

  Preferred site : Pushep (near Ooty)

Why is the neutrino detector so big ?

Typical σ (ν_μ N$\rightarrow \mu^-$ X) ~ 10^{-38} cm^2 at E_ν ~ 1 GeV

So λ_ν (Fe) ~ A / (ρ NA σ) ≈ 1.2×10^{13} m

For $\Phi_\nu \sim 6 \times 10^4$ m^{-2} sec^{-1}

Count rate of about 1000/year ≈ 3/day ⇒

$\Phi_\nu L^2 \cdot L / \lambda_\nu \approx 3.2 \times 10^{-5} \Rightarrow L^3 \approx 6.2 \times 10^3$ m^3

⇒ L ≈ 18 m

⇒ Mass of Fe detector ~ 49 kton

Requirements of active detector

- Position resolution ~ 2 cm, time resolution ~ 1 nsec

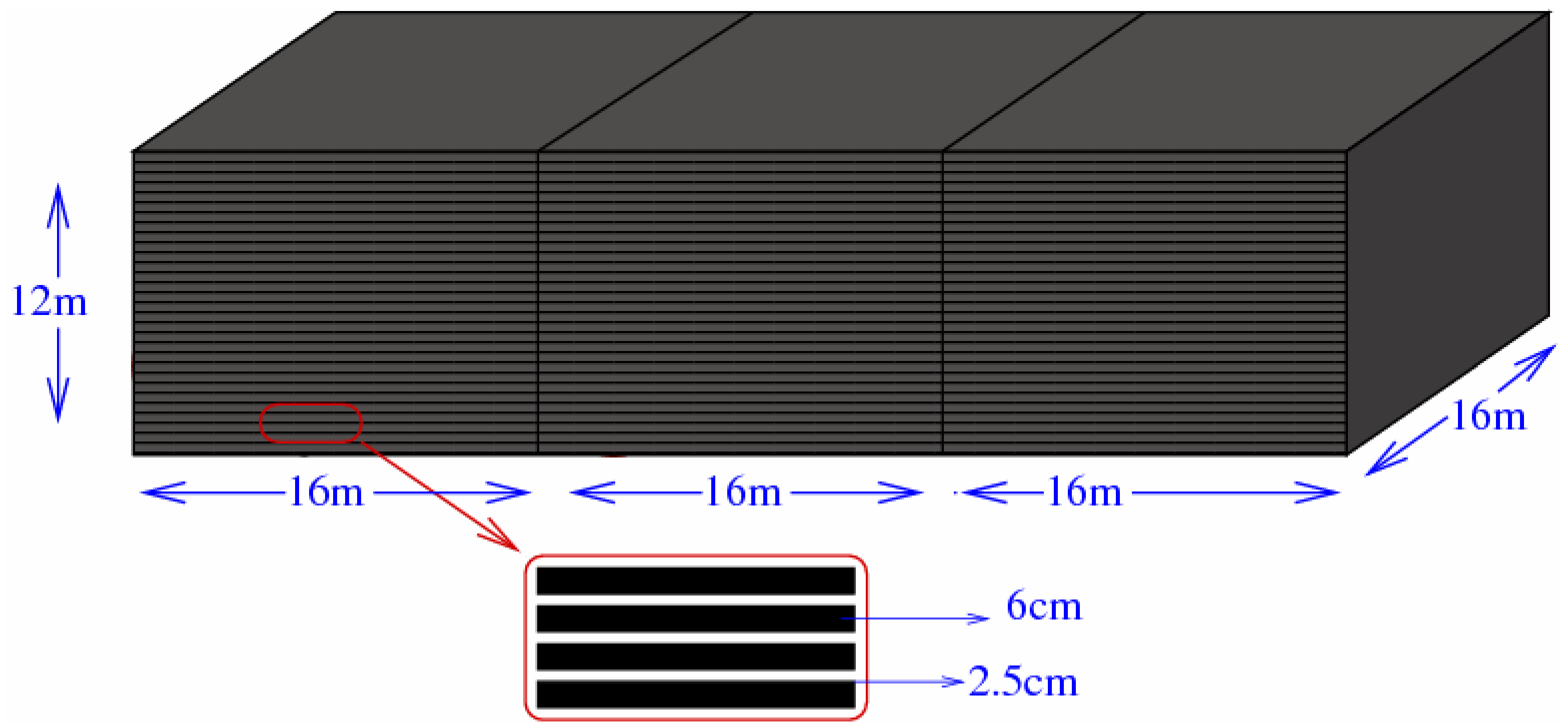
  curvature of track ⇒ ***p***, fast timing ⇒ up-down

  both of these ⇒ charge identification (μ^+ or μ^-)
- Modular design
- Large size (total area for 50 kT detector ~ 10^5 m^2)
- Large numbers so should be cheap, rugged, reliable

Options :

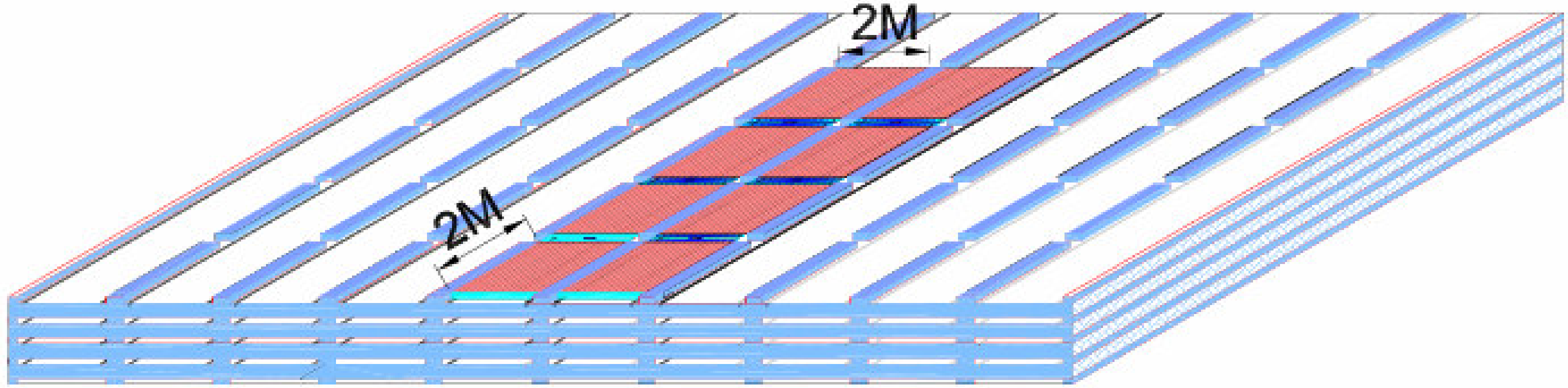
Plastic scintillator tiles, large area gas detectors

Schematic of 50 kton Iron Calorimeter (ICAL)



- Magnetic field using low carbon steel (B ~ 1.3 Tesla)
- nsec timing (from RPC) $\Rightarrow$ up/down discrimination of muons
- X-Y-Z tracking by RPC $\Rightarrow$ $\boldsymbol{p}/q$ $\Rightarrow$ L/E for μ^+ and μ^- events

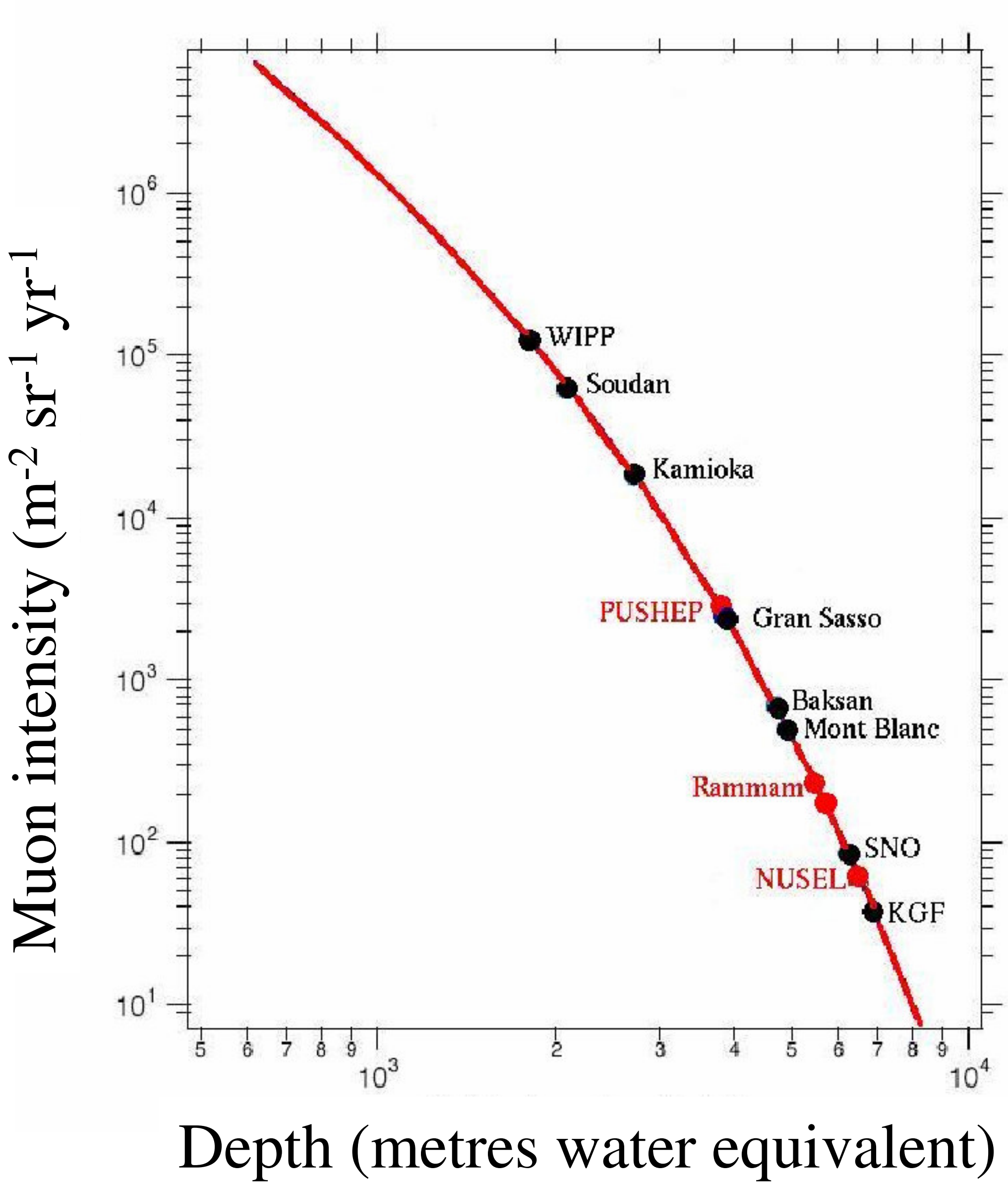
Schematic of RPC layer sandwiched between soft iron plates



Soft iron plate (6 cm thick)

RPC (2.5 cm thick)

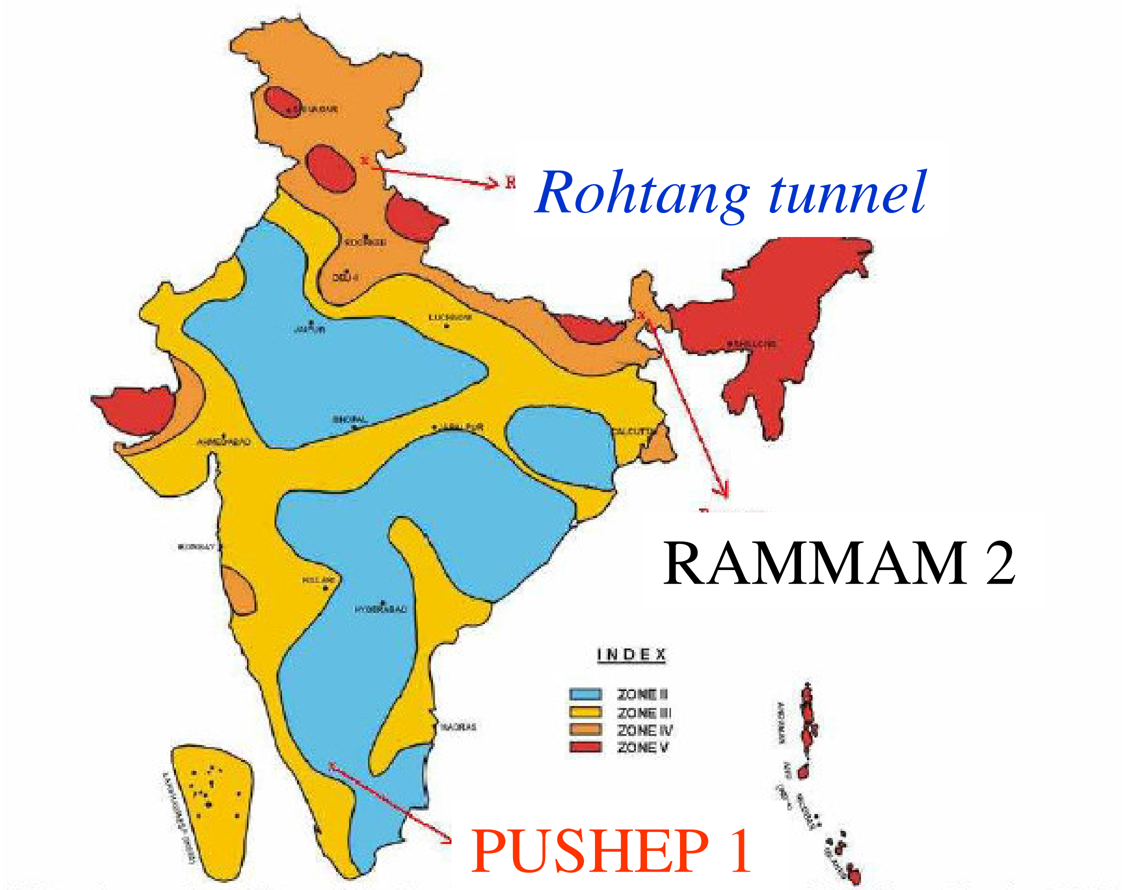
Muon flux as a function of depth



Why go deep underground ?

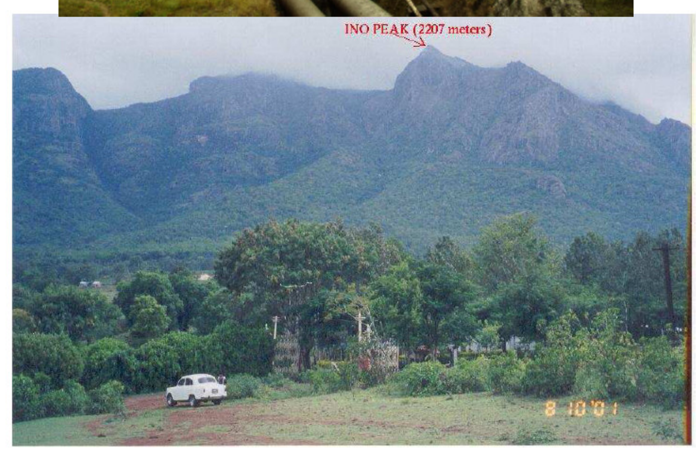
Due to low ν event rates *cosmic ray muons* are most important background. Can be reduced to manageable levels by locating the ν detector deep underground (depth ≥ 1 km) in mines or tunnels

Location of possible sites for INO



Seismic zoning Map of India- issued by Bereau of Indian Standards, 2000

PUSHEP : 11.5°N 76.6°E, 6.5 km from Masinagudi, 96.5 km from Mysore, 5 hrs from Bangalore, Coimbatore, Calicut



4. Status of simulations and ICAL subsytems

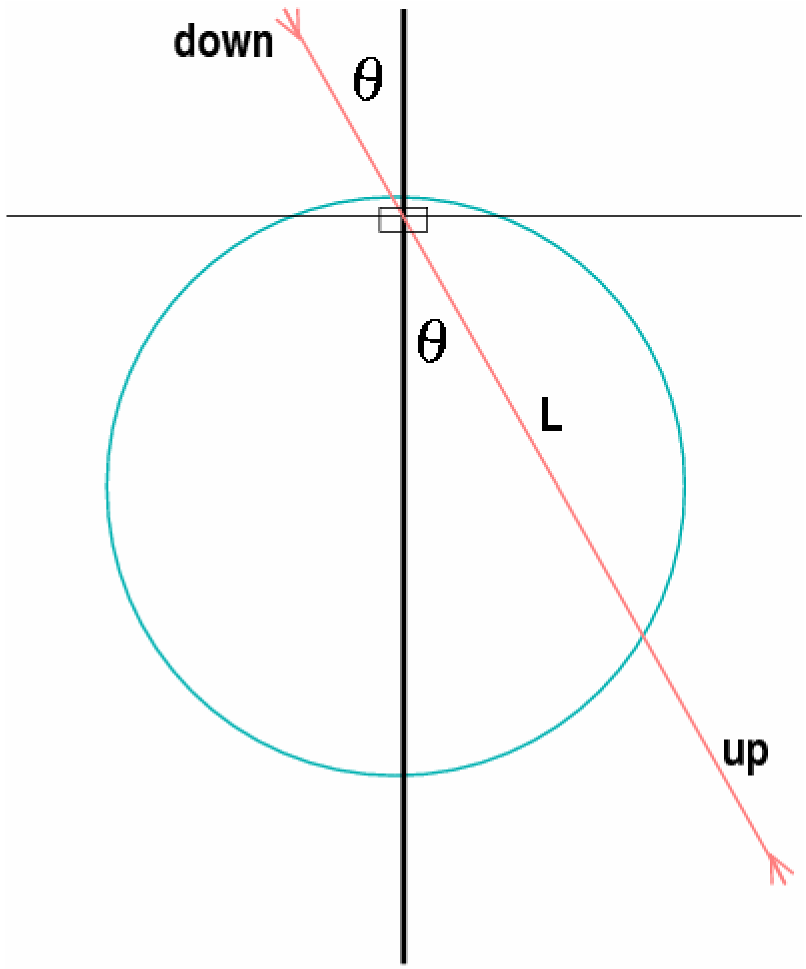
- Detector geometry and materials – GEANT
- Neutrino event generator – NUANCE

  flux – HONDA or any other
- simulation output digitized and input to analysis software

  to reconstruct (E, ***p***) and then $N_{\mu}(L/E)$
- Physics plots such as $\Delta m_{23} - \sin^2 \theta_{23}$

What is yet to be done …

- Optimization of Fe plate thickness, strip readout width, B field strength
- Module (thinner Fe) for ν_e ?


down
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θ
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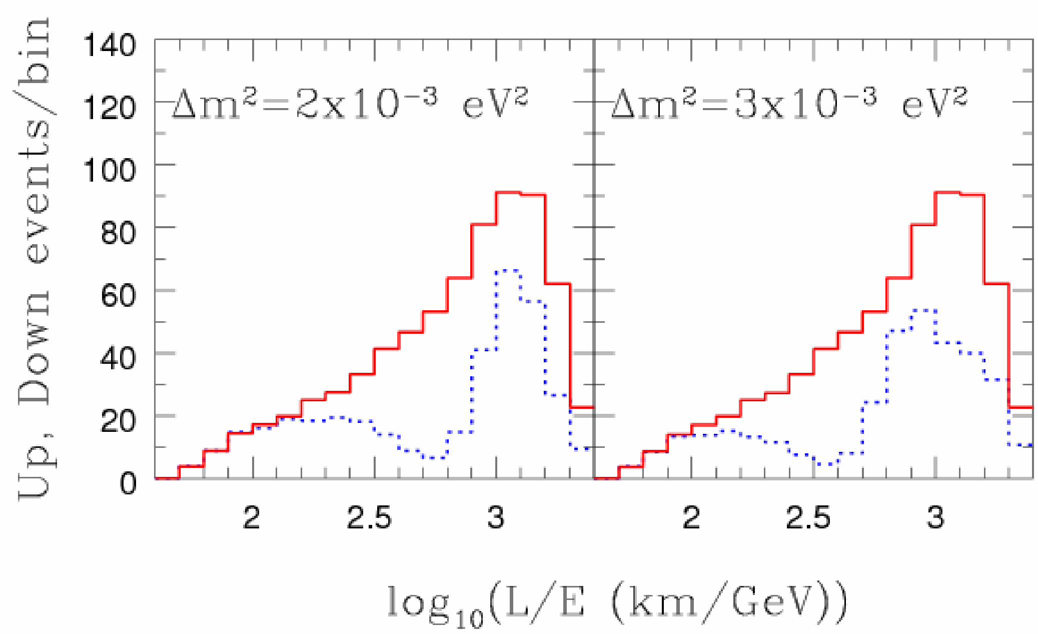
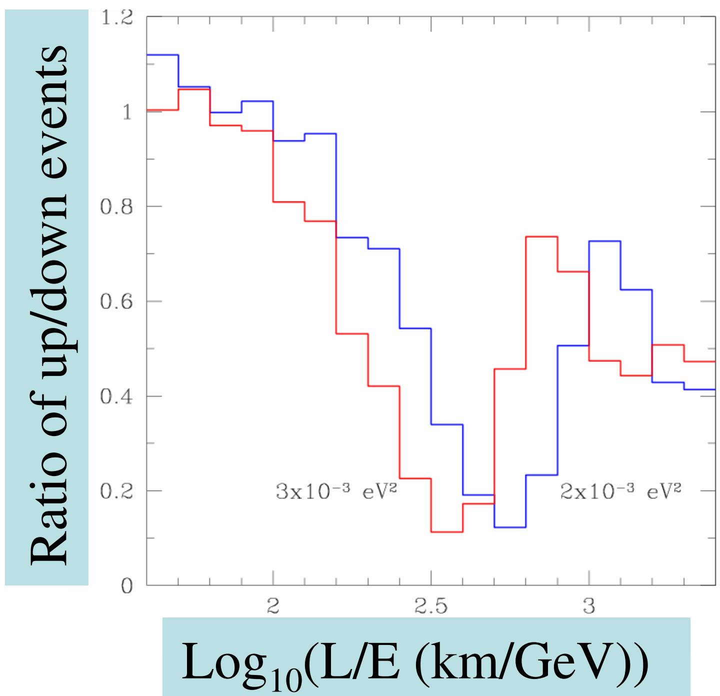
up



Observing fall and rise of ν_μ

Precise Δm^2_{23}



Simulated up & down going muons from CC μ interactions

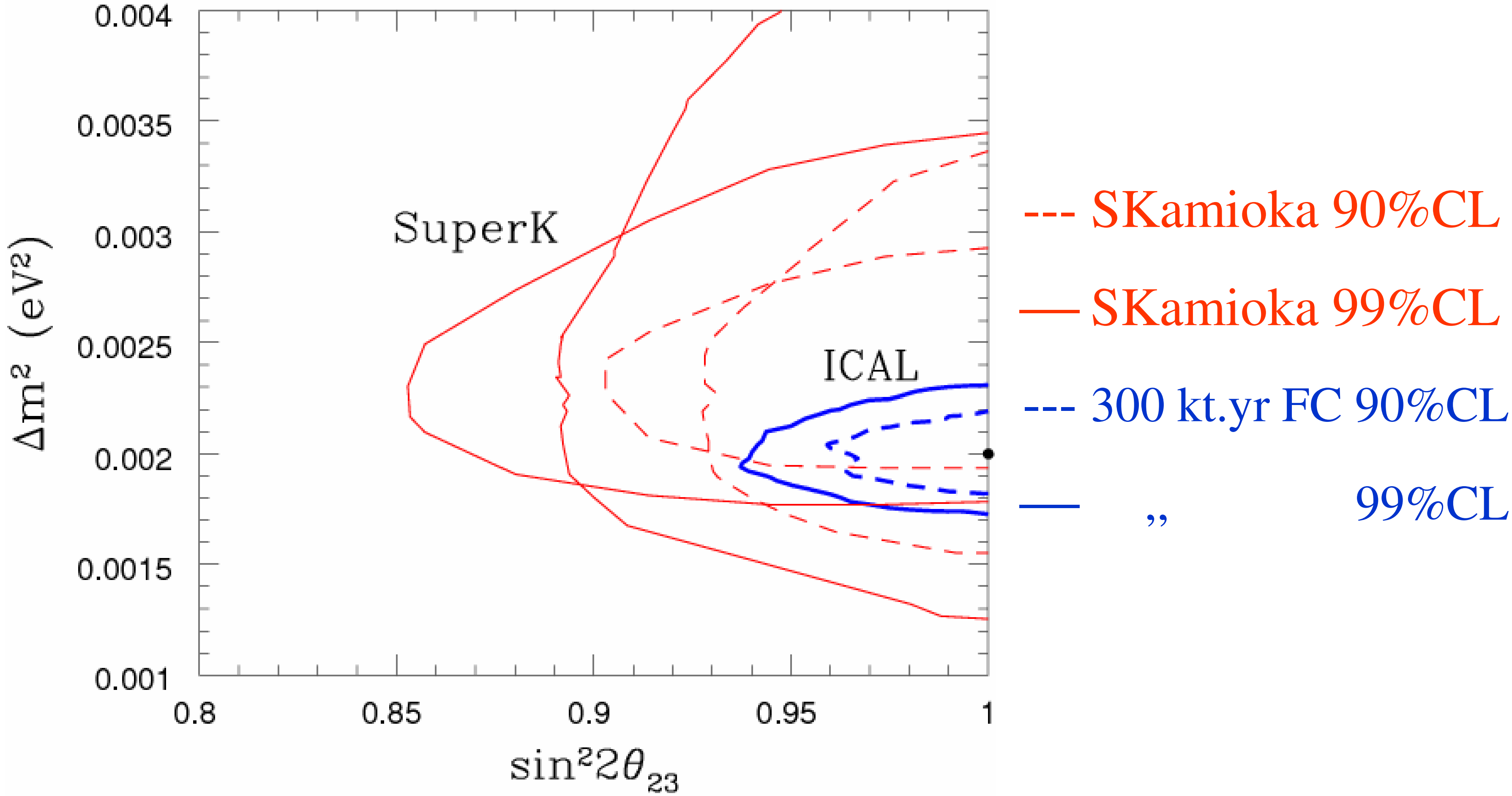
$\sin^2\theta_{23} = 0.5$,

exposure = 250 kt.yr

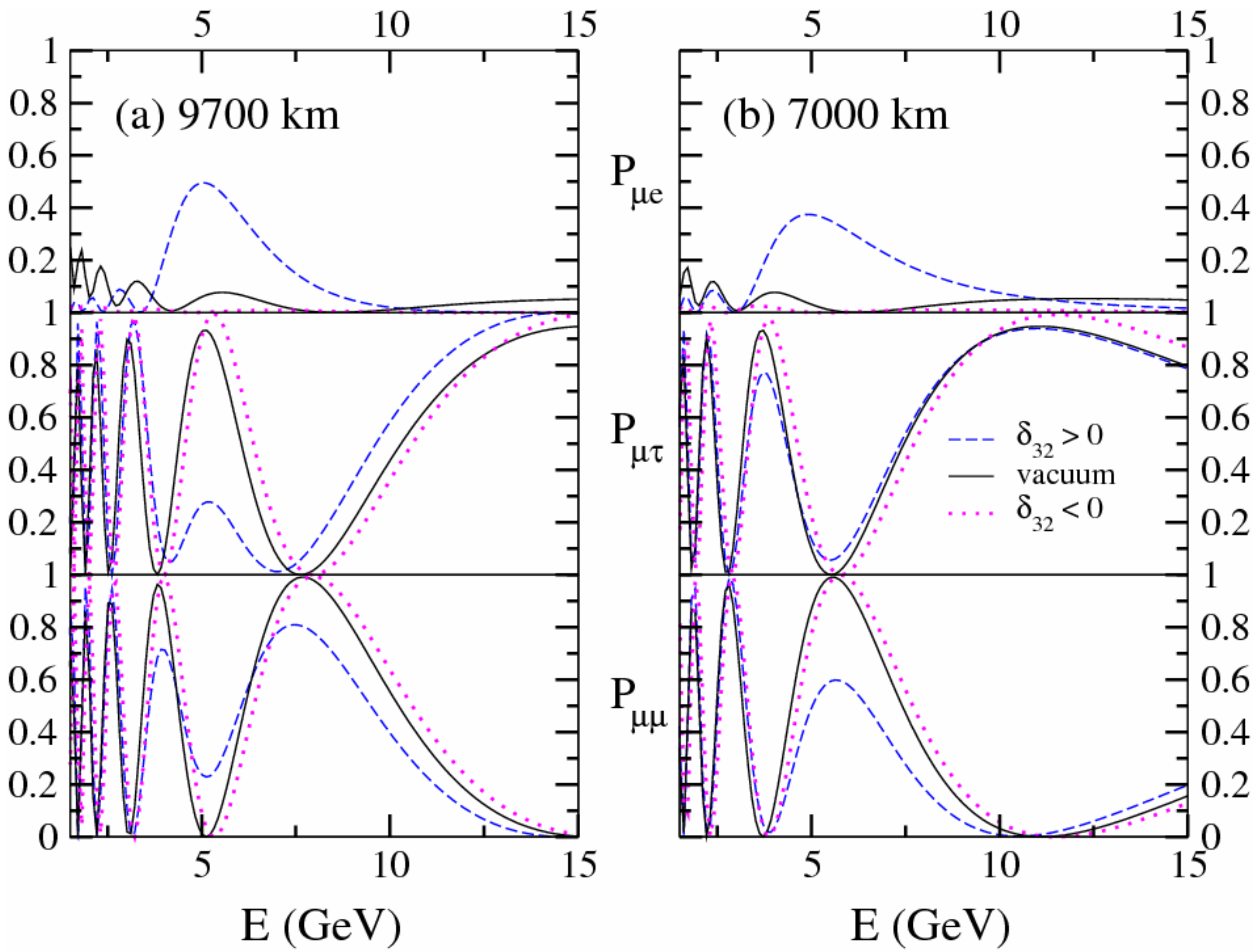
Red : downward μ

Blue : upward μ

Exclusion plot from simulated ICAL data for $\Delta m^2 - \sin^2 2\theta_{23}$



Appearance & survival probabilities for $\nu_\mu \rightarrow \nu_e$, ν_τ and ν_μ in vacuum and matter for normal and inverted hierarchies



$\sin^2 2\theta_{13} = 0.1$ assumed

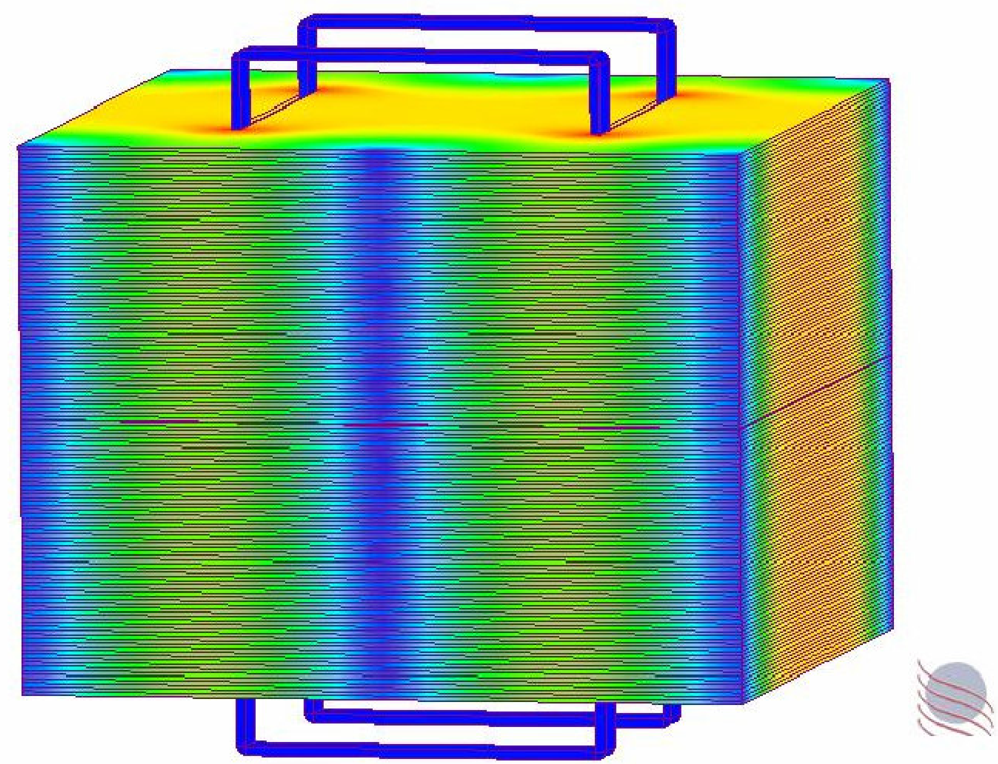
ICAL subsystems - Magnet

B large enough to enable ***p*** measurement (> 1 Tesla)

- Magnetic steel/soft iron should be reasonably cheap (50 ktons!)
- Piecewise uniformity
- Modularity, access for maintainance of RPC & electronics
- Optimum copper to steel ratio
- Mechanical stability

Commercial finite element EM software Magnet 6.0 used on Xeon Pentium with 2 GB RAM

Field map of ICAL magnet module



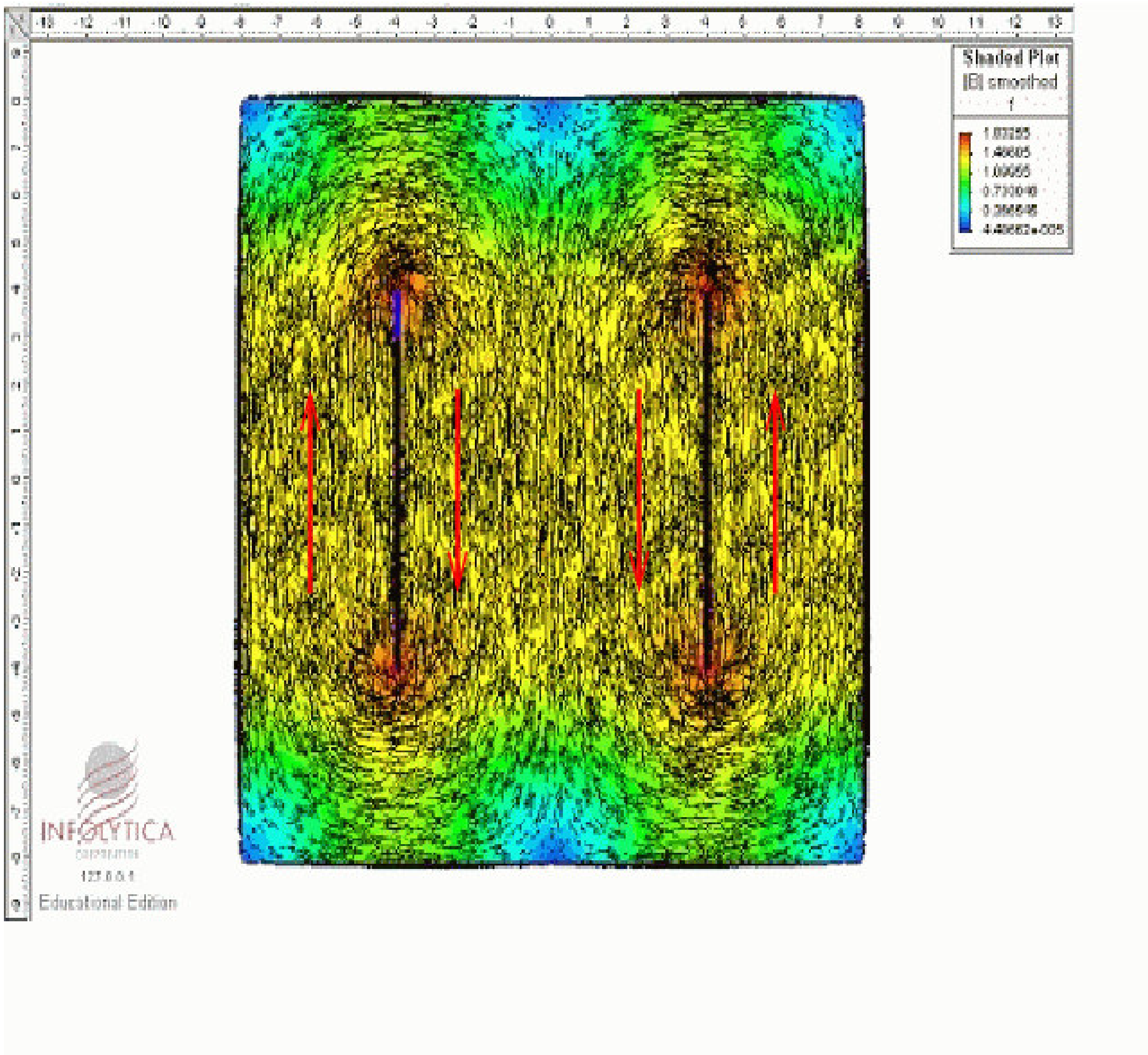
Orange – high B

Yellow – medium B

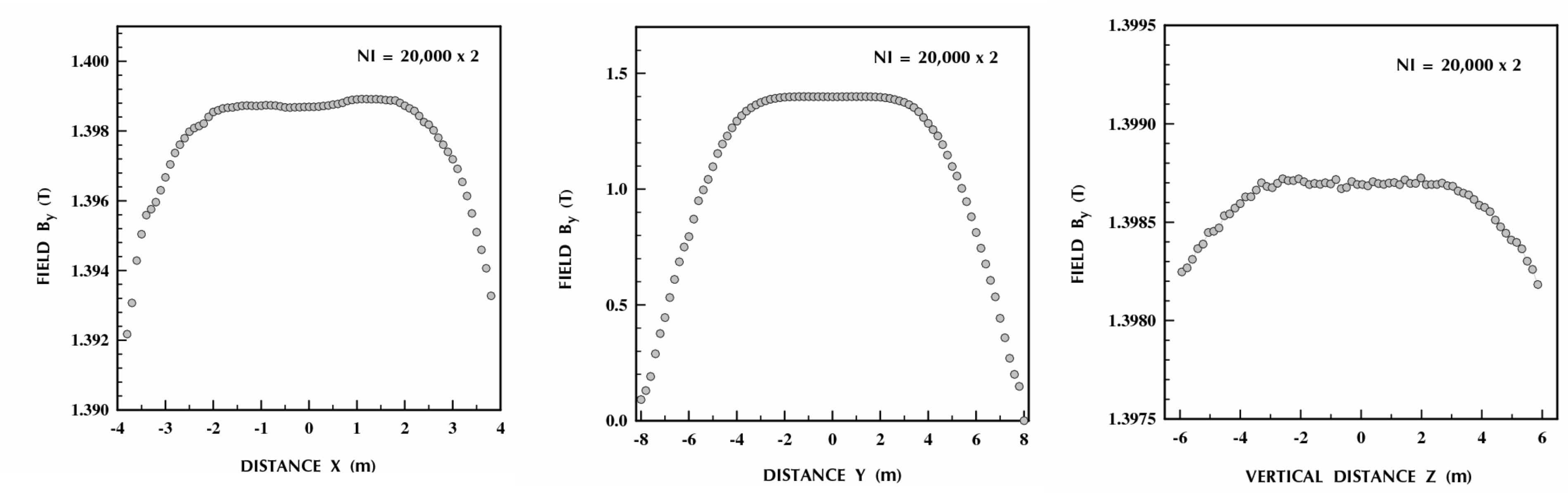
Green – lower B

Blue – lowest B

Magnetic field map in plate (for 2 coils)



Field along & normal the plane of the steel plates in 16 kton module

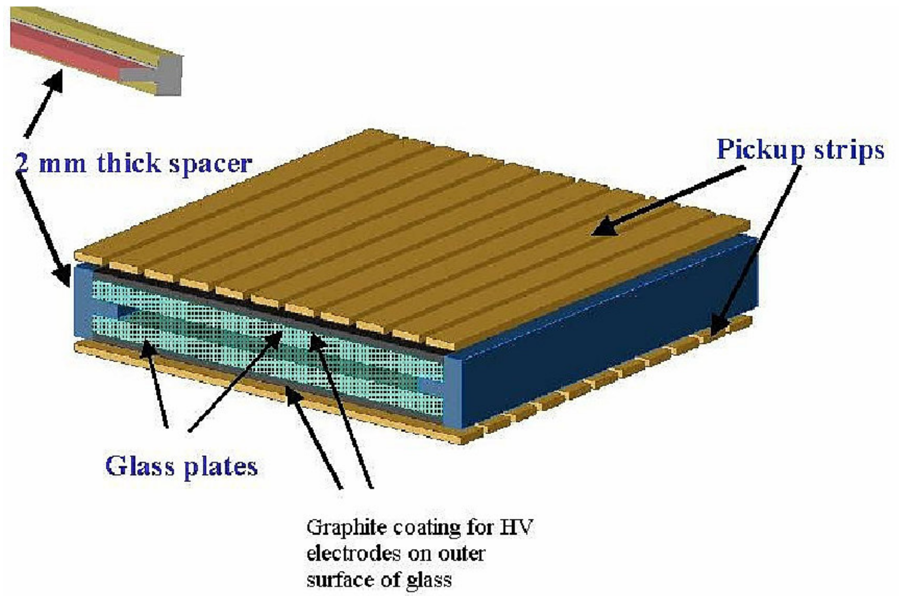


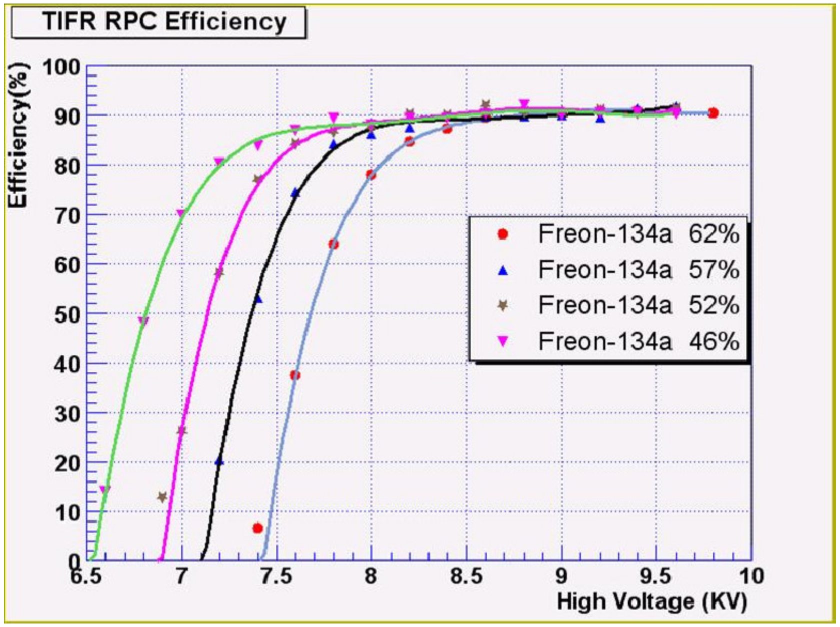
Effect of gap in steel plates 0 mm:2 mm:10 mm

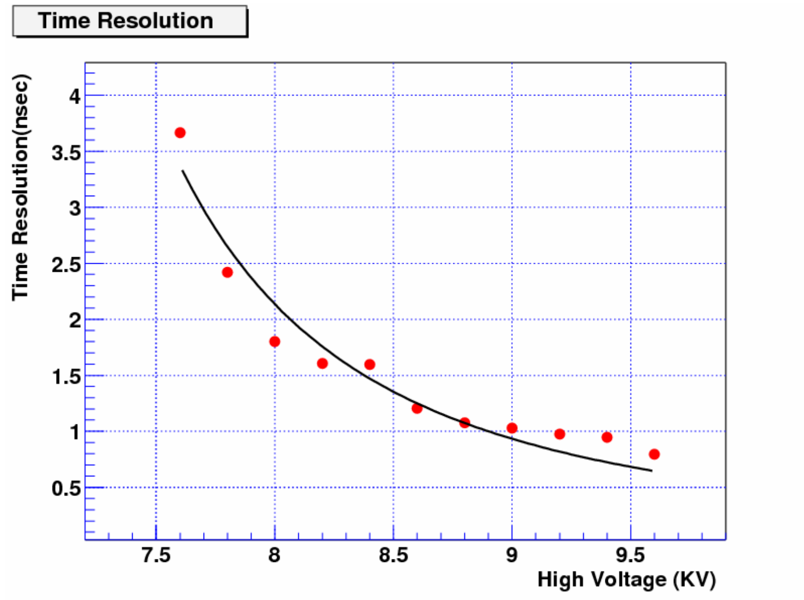
1.0 : 0.97 : 0.70

More studies necessary – assembly scheme, mechanical stability, transient and error analysis

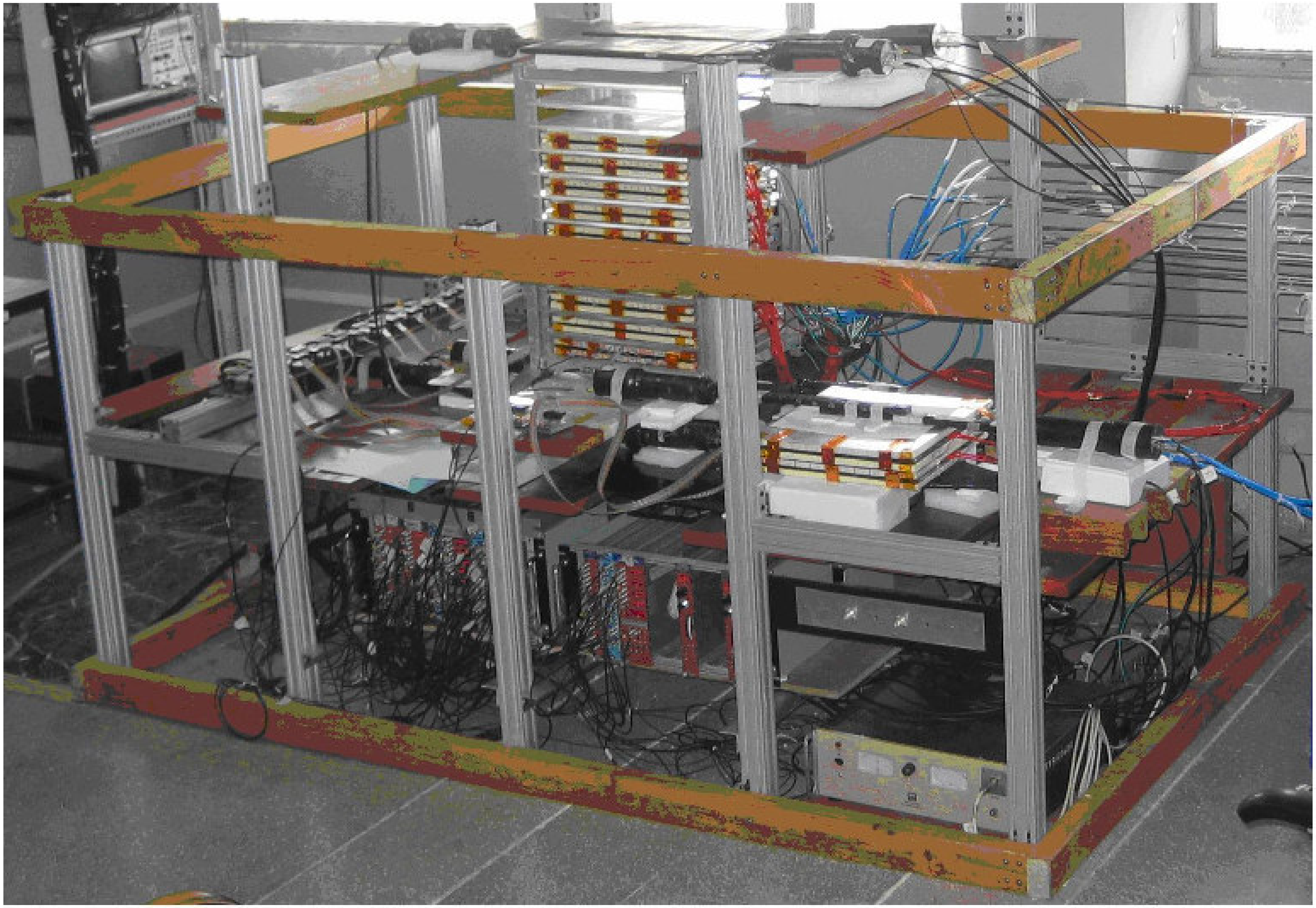
Schematic of Resistive Plate Chamber (RPC) & performance



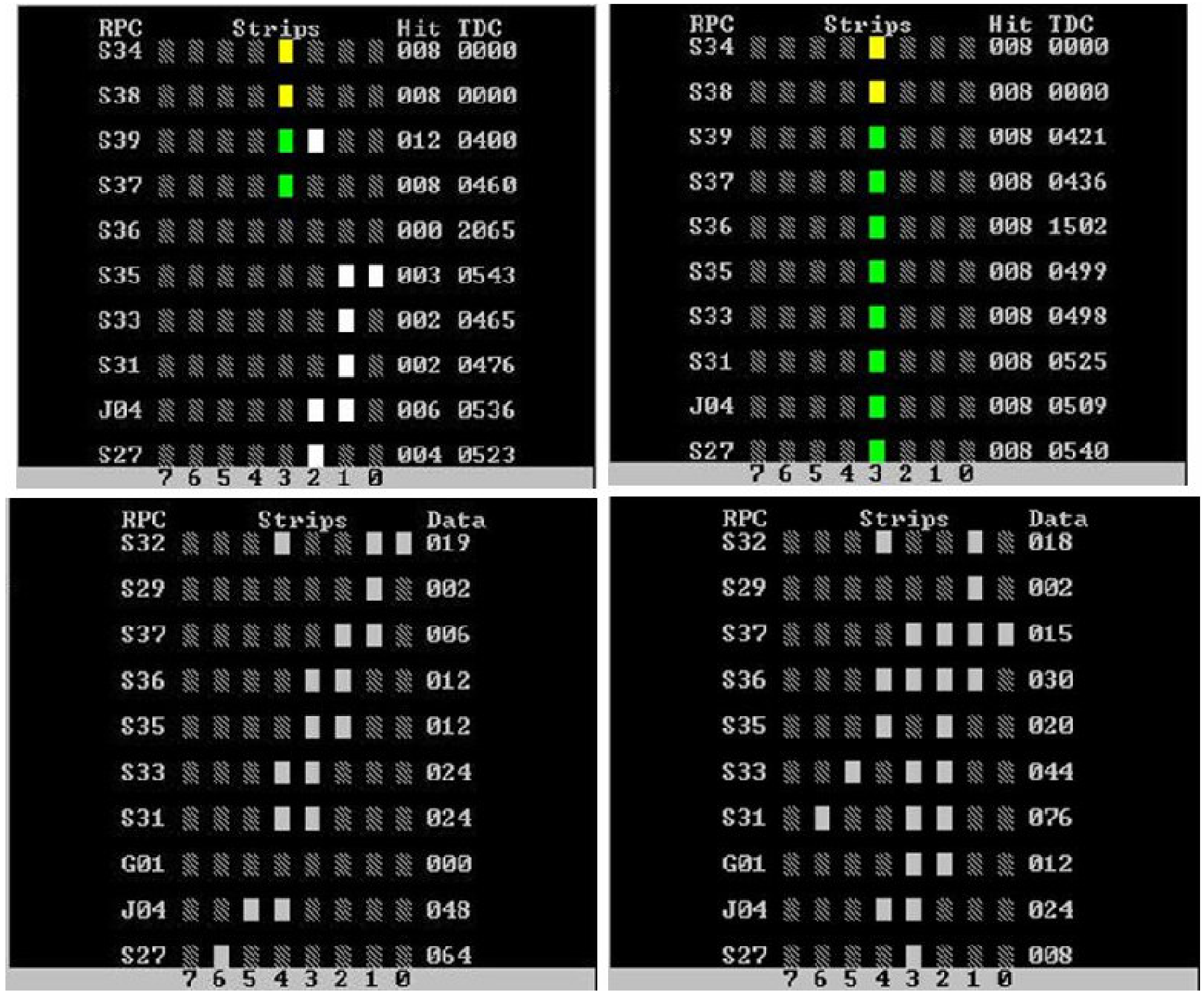




- 2 RPCs 30×40 cm^2 (Osaka glass) in avalanche mode for > 14 months
- aging problem still not solved RPC lifetime (streamer mode) few-20 days
- vendors for electrodes, spacers found



Tracks of cosmic muons triggered by narrow plastic telescope



Gas mixing and distribution system

Features:

- 4 gas mixing possible
- Gas purifier columns for each gas for oil, moisture, other contaminants
- 2 μm dust filters
- Mass flow controllers/gas line
- Moisture, temperature, pressure sensors + data logging
- Safety and isolation bubblers

	hf134a	A	isobutane (%)
Streamer	62	30	8
Avalanche	95.5	-	4.5

Electronics and Data Acquisition System

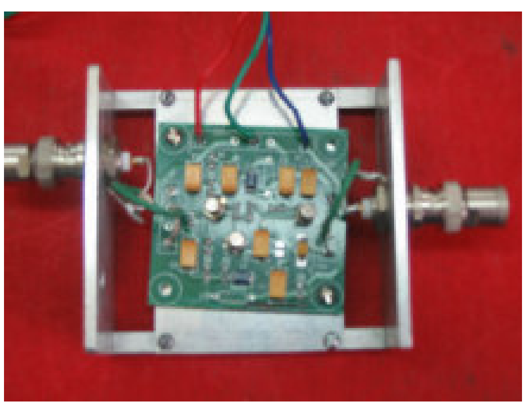
- Electronic signal from minimum ionizing particle induced on X- and Y-pickup strips (~ 3 cm wide, length of detector)
- Impedance matched to input of timing discriminator or preamp
- For *streamer* mode signal ~ 100 - 300 mV across 50Ω

  and *avalanche* mode ~ 1 - 5 mV across 50Ω ⇒ fast current preamplifiers (risetime ~ 1 nsec) with gain ~ 10 - 30 needed. Prototypes designed by Electronics Divn, BARC and fabricated in BEL, Bangalore tested.

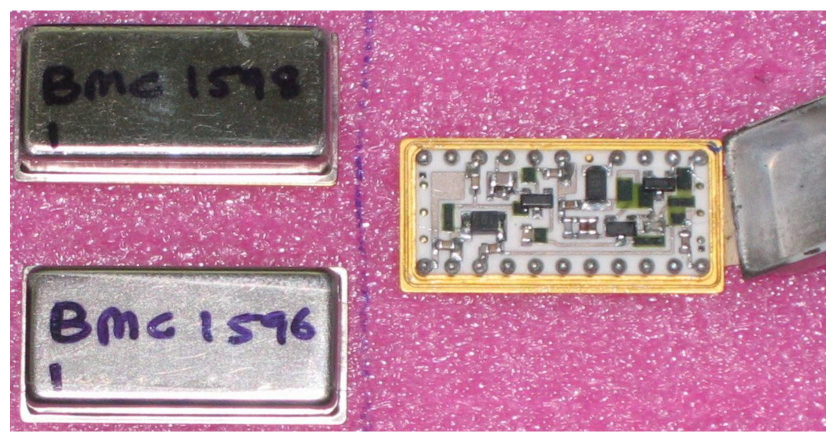
- Anode, cathode pickup signals to timing discriminators
- Feeds latch and multiplexed TDC
- Event trigger generated by FPGA based home built module

  Physics based choice of trigger initiates DAQ
- VME based DAQ coupled to PCs with Linux OS

Discrete component preamp

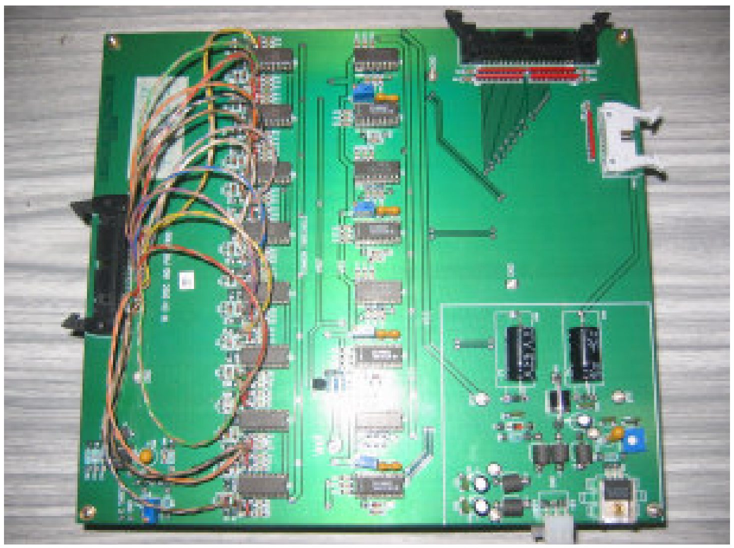


Hybrid versions (BEL-ED/BARC

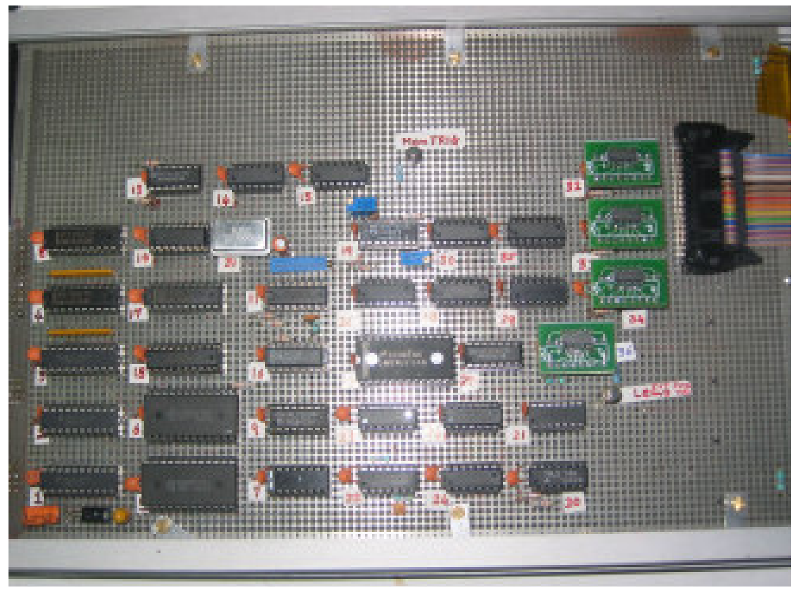


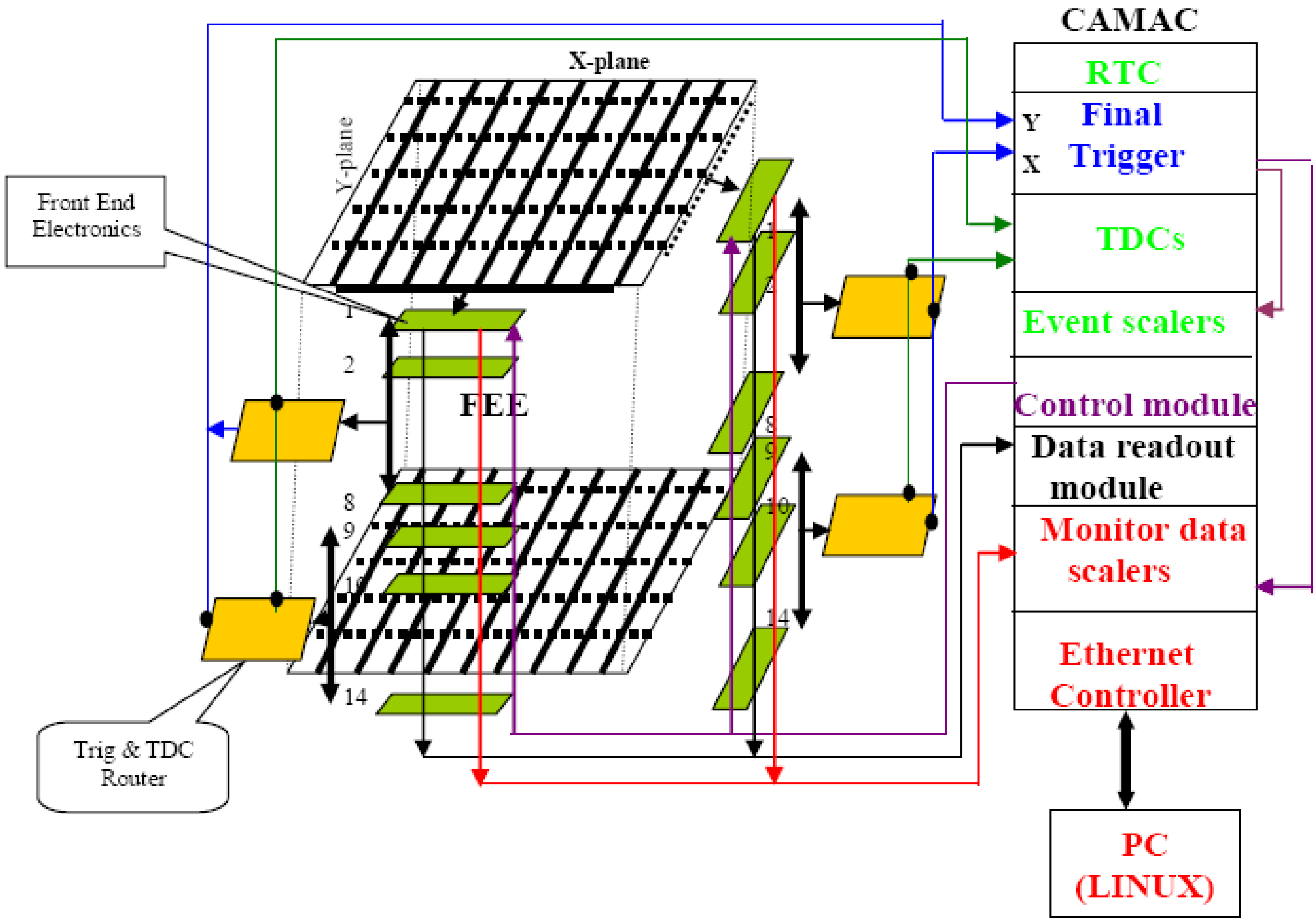
In-house electronics development (TIFR group)

16-ch analog front end



DAQ control module




CAMAC
RTC
Y
X
Final Trigger
TDCs
Event scalers
Control module
Data readout module
Monitor data scalers
Ethernet Controller
PC (LINUX)
X-plane
Y-plane
Front End Electronics
FEE
Trig & TDC Router
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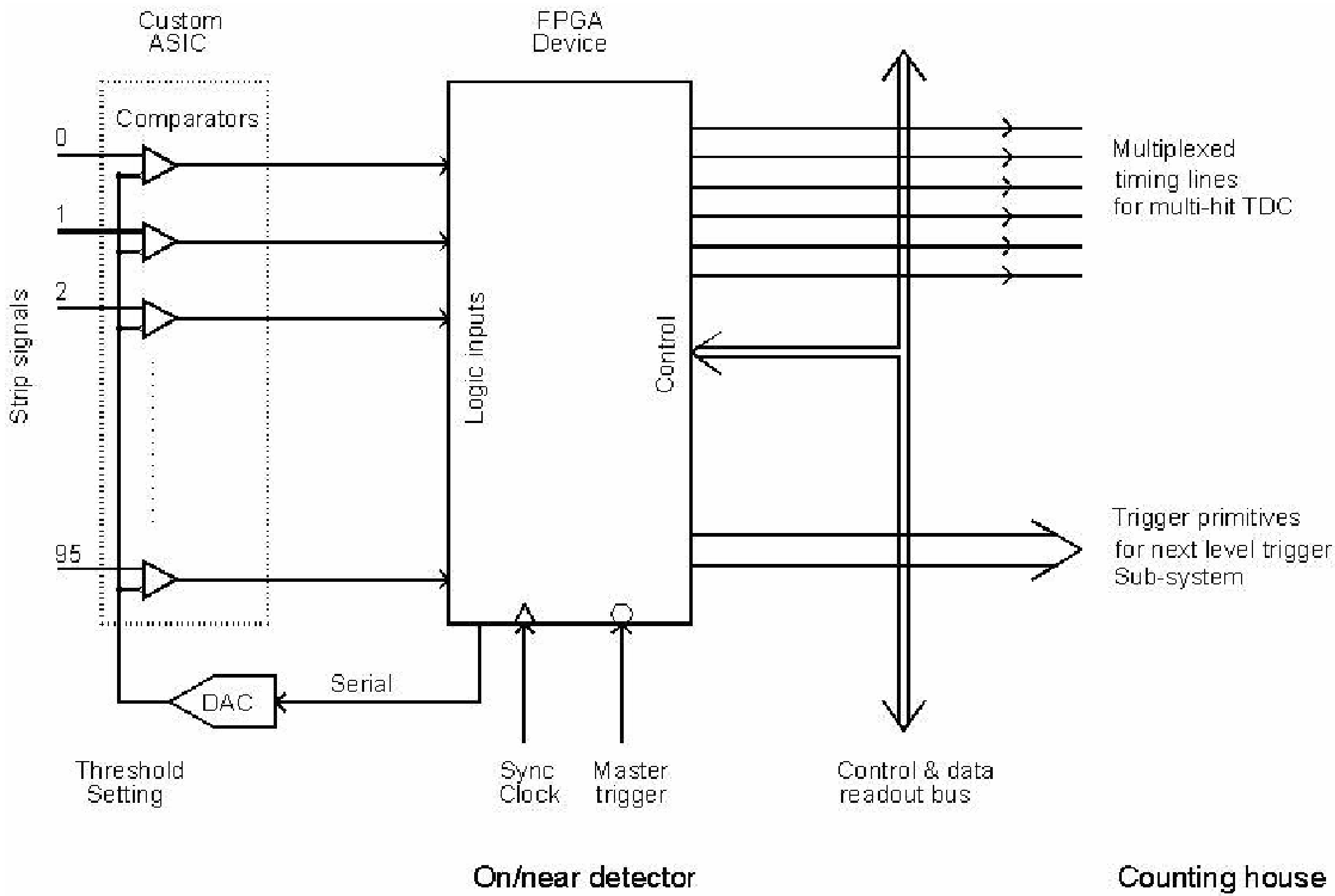
Custom
ASIC
Comparators
FPGA
Device
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1
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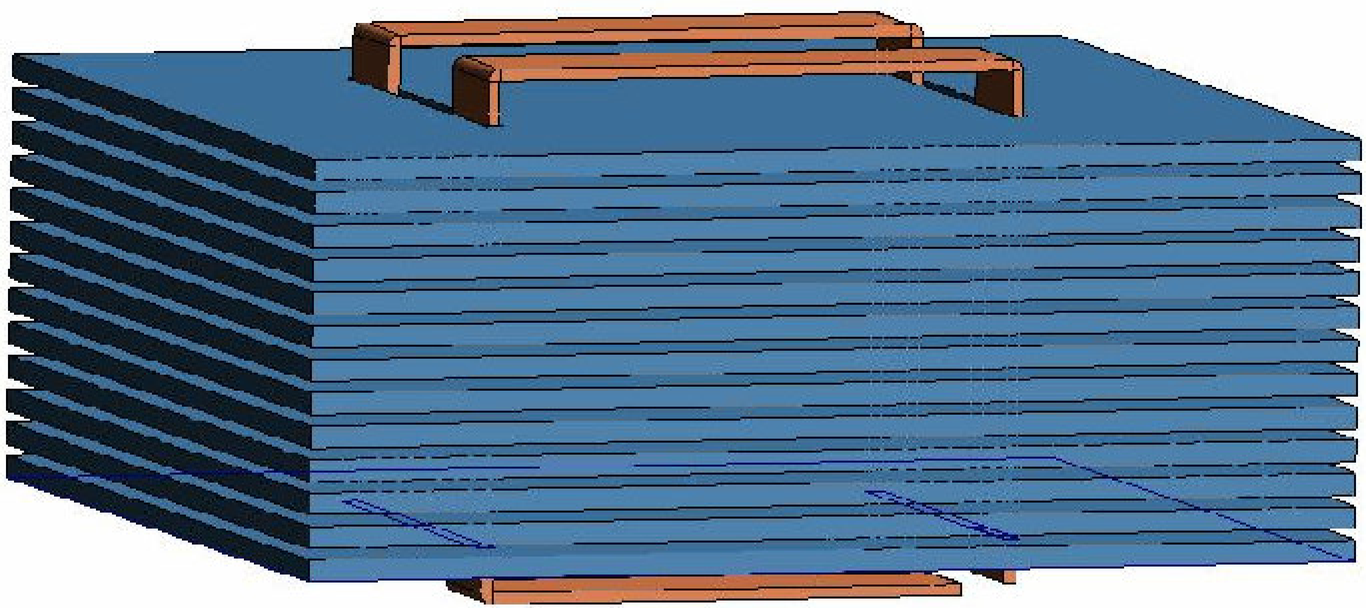
Strip signals
Logic inputs
Control
Multiplexed
timing lines
for multi-hit TDC
Trigger primitives
for next level trigger
Sub-system
DAC
Serial
Threshold
Setting
Sync
Clock
Master
trigger
Control & data
readout bus
On/near detector
Counting house

Status of electronics

- Design and fabrication of analog & timing dicriminator board complete
- DAQ card prototype fabricated
- Fast preamp (4 varieties, gain 10) prototypes fabricated at BEL, Bangalore
- Purchase order for 2000 pieces placed with BEL

Schematic of prototype magnet



Weight 40 tons

B_{max} ~ 2 T

- 13 layers of 5 cm thick soft iron, 12 layers of 1 m × 1 m RPCs
- ~ 800 channels of preamp, timing discriminators
- to be set up at VECC, Kolkata

Status of prototype magnet

- Tata A-grade low carbon steel scavenged from dismantled 330 ton MHD magnet (BARC-BHEL) at Trichy
- Fabrication order placed with Pune vendor (Milman) includes assembly, testing with power supply and field measurement Hall probes
- Fabrication of 40 ton magnet in progress, delivery expected ~ middle of March, 2007

Initiative for DBD experiment in India

DBD Workshops at
IIT Kharagpur (March 05) & Univ. of Lucknow (Nov. 05)

isotopic abundance, availability of the material, purity etc. considered and ^{124}Sn bolometer chosen

^{124}Sn $0\nu2\beta$: $T_{1/2} > 2.4 \times 10^{18}$ yrs *Phys. Lett. B* ***195****, 126 (1987)*

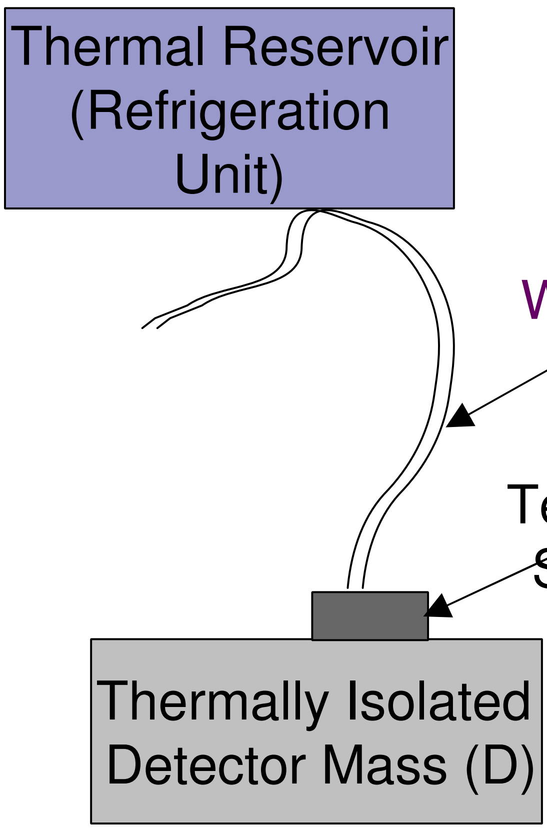
T_c (Sn) = 3.7° K so *electronic* contribution to C_v negligible at <100mK

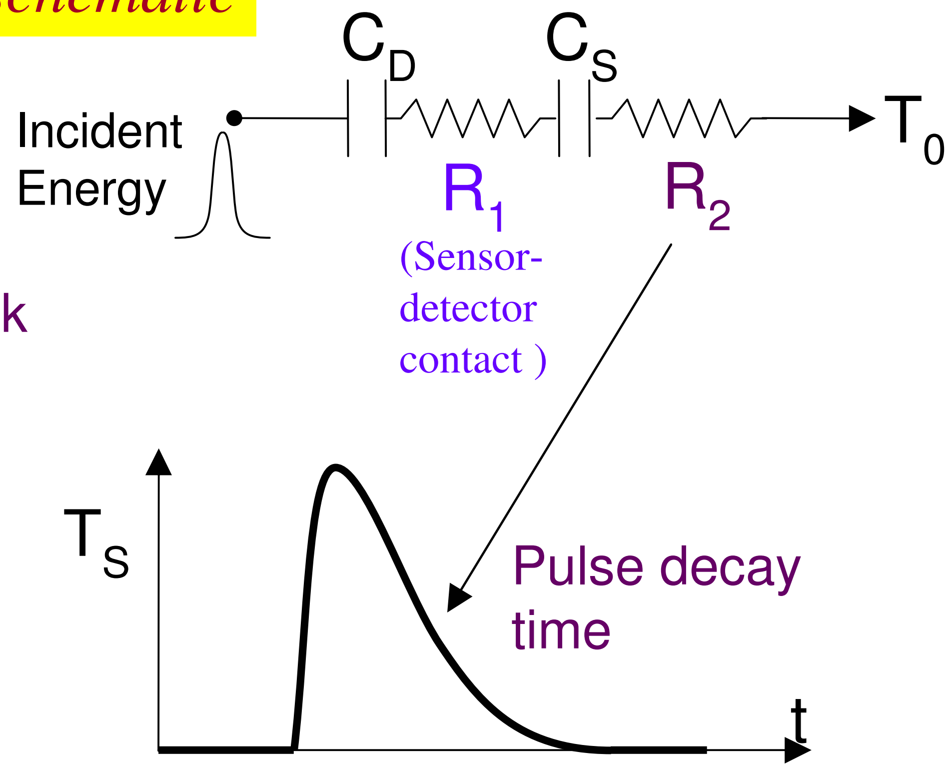
Low temperature Bolometry

Bolometer is a calorimetric detector

Energy of particle → Thermal energy of detector → measurable temperature rise if heat capacity is very low

Bolometer schematic





Work plan for DBD experiment

Make a prototype bolometric detector of ^{124}Sn

I a) Make a natural Sn bolometric detector ~ 0.5–1 kg (TIFR, BARC)

Refurbish an old refrigerator (Cooling power ~20μW at 30 mK)

will serve as a test bench for optimizing the various aspects of milli-Kelvin bolometry. *expected energy resolution ~ 0.5%*

b) Radiation background studies: measurements & simulations

(IIT-KGP, SINP, VECC)

c) Reliable NTME calculations (Univ. of Lucknow, IIT-KGP, IOP, PRL)

II a) Enrichment of ^{124}Sn (> 50%) (BARC & IIT- KGP)

b) Sensor development

c) Build ~ 1 kg enriched ^{124}Sn detector (TIFR, BARC)

III Preparation of DPR

Nuclear cross sections of astrophysical interest

- 11^{th} plan proposal from SINP, Kolkata for one *overground* and one underground (at INO lab) accelerator
- Gran Sasso pioneered such measurements using the low background environment at large depth
- 500 kV DC accelerator for stable light ions (upto ~ A=12)

A few potentially interesting measurements at **Gamow peak** energies

$^{12}C(\alpha,\gamma)^{16}O$, $^{13}C(p,\gamma)^{14}N$, $^{14}N((p,\gamma)^{15}O$, $^{15}N(p,\gamma)^{16}O$, $^{15}N(p,\alpha)^{12}C$

environmental effects on nuclear processes

5. Training people for INO – a beginning

First small step taken in April-May 2006

- 2 weeks (HEP foundation course) at HRI, Allahabad +

  2 weeks (Experimental aspects) at VECC, Kolkata

- About 15 students attended

- Faculty from HRI, TIFR, BARC, VECC, SINP

A much stronger interaction with, and involvement of, University colleagues is essential for the success of INO. Mechanisms for participation in detector building and simulation apart from ν*-physics issues need to be worked out quickly.*

6. Estimated cost and schedule

Rs. 4 crores allotted by Dept. of Atomic Energy for R&D (10th plan)

	Rs (crores)	
	11th plan	12th plan
Infrastructure (*underground lab, services, etc)*	100	
Soft iron 50 kton @Rs 60/kg	100	200
Detector (RPC, electronics, DAQ)	75	130
Salaries	15	
Contingencies	30	20
TOTAL	320 +	350 = 670

- Financial sanction expected ~ 3rd quarter 2007
- Phase 1 – 12-18 months: Details planning of infrastructure, permissions, detector design (engg)
- Phase 2 – 22 months: Tunnel excavation, procurement of detector components and start of fabrication
- Phase 3 – 12-18 months: Assembly of detector modules ½

People required:

50 physicists + 35 technical & scientific + 15 adminstrative

Summary of present status of INO

- Interim Project Report sent for review to 7 experts
  - generally very positive and encouraging
- Site and infrastructure related Detailed Project Report (DPR) being prepared by ETF & TNEB
- ICAL prototype being assembled at VECC, Kolkata
- Design of 16 kT ICAL magnet module in progress
- R&D on glass RPC for longer lifespan in progress
- Vendor development (RPC related, gas recirculation & purification, electronics, magnet related…) is an ongoing activity
- INO proposal with Planning Commission for approval

In summary…

- Significant progress made in detector and simulation, however stepping up of gears imperative
- Infrastructure and site related DPR work in progress
- We are beginning to learn to manage large collaboration

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Thank you

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