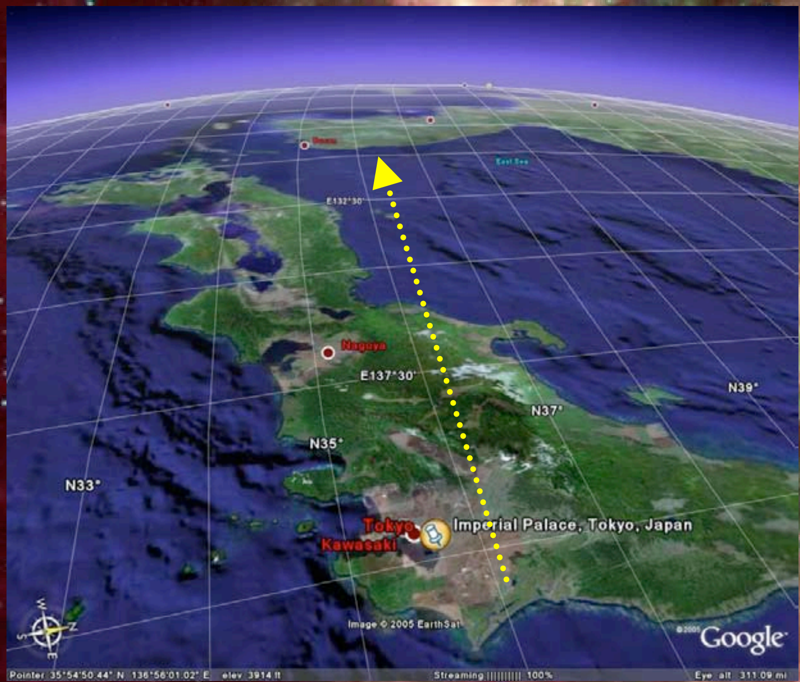
Concepts and R&D for very large liquid Argon Time Projection Chambers



Swiss Institute of Particle Physics

André Rubbia (ETH Zürich)

International Workshop on a Far Detector in Korea for the J-PARC Neutrino Beam
Nov 18 - 19. 2005, International Conference Hall (KIAS), Seoul, Korea

Introduction

- Within the ICARUS program, the concept of large cryogenic detectors based on noble liquids (Argon and Xenon) have been developed for many years. In such detectors, ionisation electrons are used to create an "image" of the tracks of the particles. Scintillation light may be used to trigger the event.

- A series of several modules of different sizes have been operated, in which all the basic features of ionisation, long electron drift and scintillation in liquid Argon (and to some extent also Xenon) have been systematically studied for a variety of incident particles. Applications to neutrino physics, proton decay searches and direct dark matter detection have been considered. The largest detector ever built has a mass of 600 tons to be used in the ICARUS experiment at Gran Sasso.

- In this talk, we report on our investigations regarding possible developments in the liquid Argon TPC technique in order to envisage its use in future neutrino experiments and nucleon decay searches. More details in:

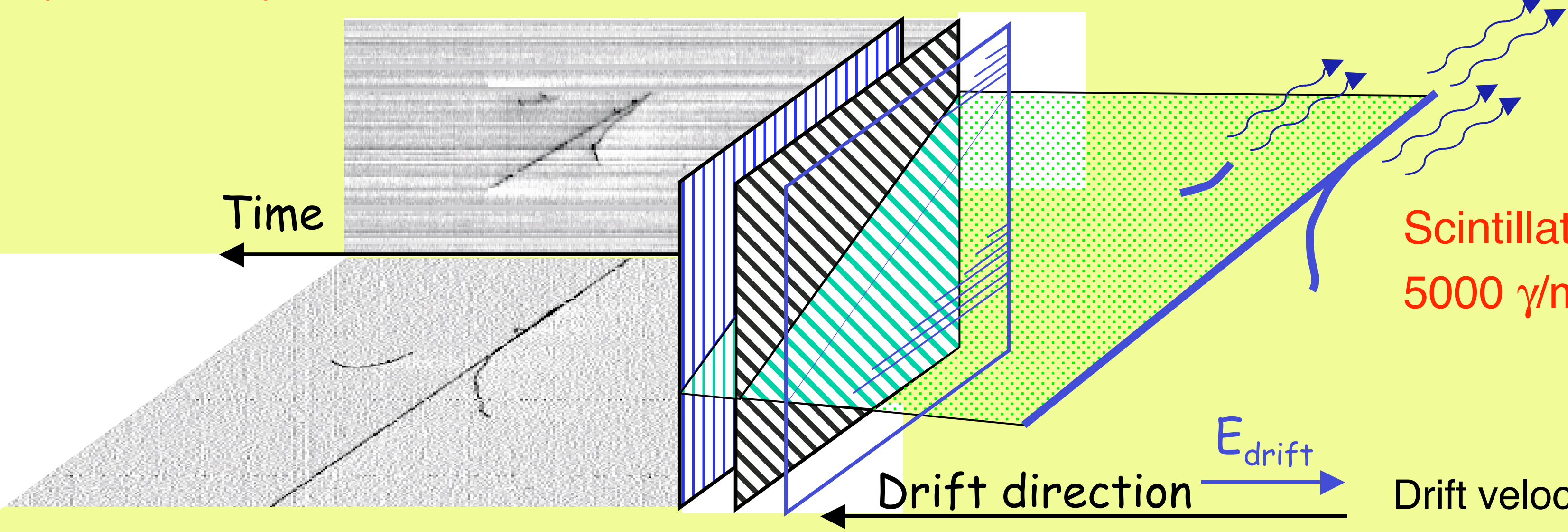
- Experiments for CP violation: a giant liquid Argon scintillation, Cerenkov and charge imaging experiment, A.Rubbia, Proc. II Int. Workshop on Neutrinos in Venice, 2003, Italy, hep-ph/0402110
- Ideas for future liquid Argon detectors, A. Ereditato and A.Rubbia, Proc. Third International Workshop on Neutrino-Nucleus Interactions in the Few GeV Region, NUINT04, March 2004, Gran Sasso, Italy, **Nucl.Phys.Proc.Suppl.139:301-310,2005,** hep-ex/0409034
- Ideas for a next generation liquid Argon TPC detector for neutrino physics and nucleon decay searches, A. Ereditato and A.Rubbia, Proc. Workshop on Physics with a Multi-MW proton source, May 2004, CERN, Switzerland, submitted to SPSC Villars session
- Very massive underground detectors for proton decay searches, A.Rubbia, Proc. XI Int. Conf. on Calorimetry in H.E.P., CALOR04, Perugia, Italy, March 2004, hep-ph/0407297
- Liquid Argon TPC: mid & long term strategy and on-going R&D, A.Rubbia, Proc. Int. Conf. on NF and Superbeam, NUFACT04, Osaka, Japan, July 2004
- Liquid Argon TPC: a powerful detector for future neutrino experiments, A.Ereditato and A. Rubbia, HIF05, La Biodola, Italy, May 2005, hep-ph/0509022
- Neutrino detectors for future experiments, A.Rubbia, Nucl. Phys. B (Proc. Suppl.) 147 (2005) 103.
- Conceptual Design of a scalable milti-kton superconducting magnetized liquid argon TPC, A. Ereditato and A. Rubbia, hep-ph/0510131.

The Liquid Argon TPC principle

Charge yield ~ 6000 electrons/mm
(~ 1 fC/mm)

Charge readout planes: Q

UV Scintillation Light: L



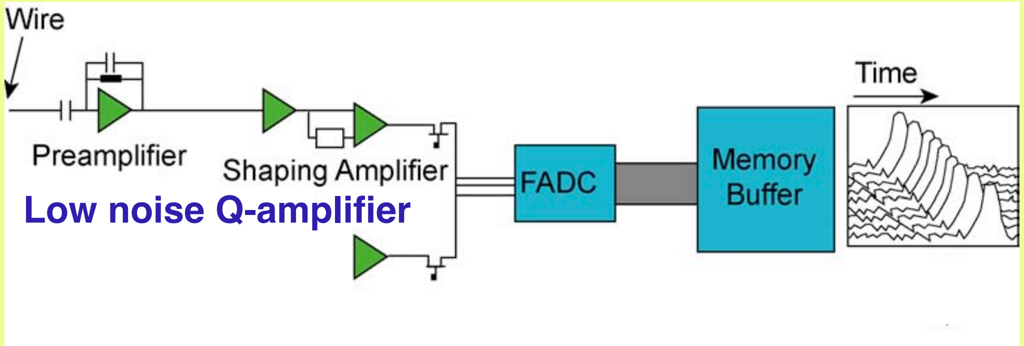
Scintillation light yield ~ 5000 γ/mm @ 128 nm

Drift velocity ≈ 2 mm/μs
@ 1 kV/cm

Drift electron lifetime:

$$\tau \approx 300\mu s \times \frac{1\,ppb}{N(O_2)}$$

Purity < 0.1ppb O_2-equiv.



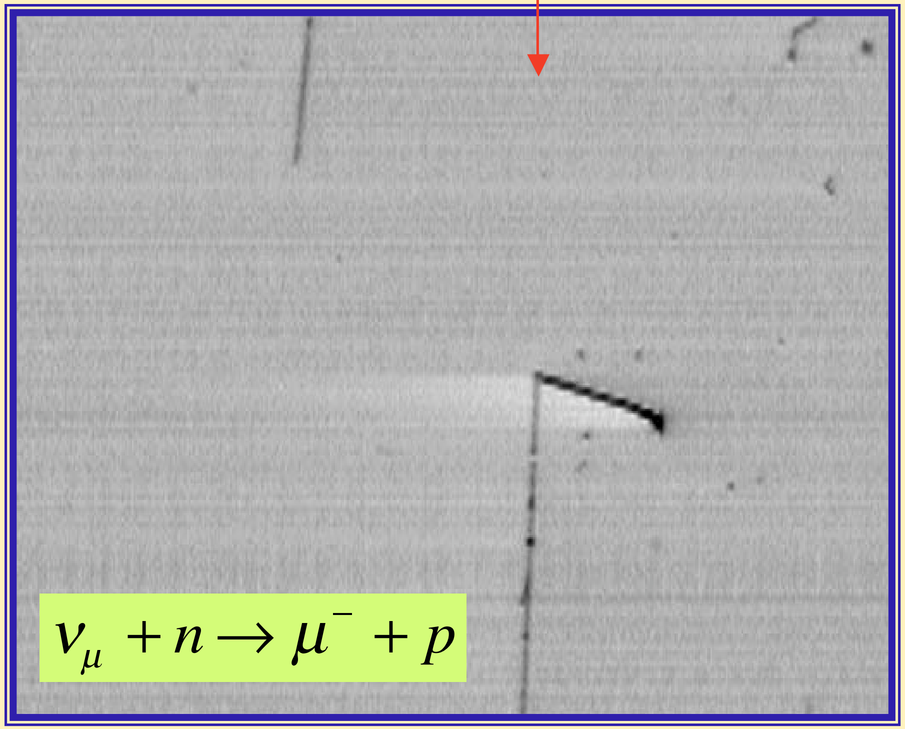
Continuous waveform recording → image

- The Liquid Argon Time Projection Chamber: a new concept for Neutrino Detector, C. Rubbia, CERN-EP/77-08 (1977).
- A study of ionization electrons drifting large distances in liquid and solid Argon, E. Aprile, K.L. Giboni and C. Rubbia, NIM A251 (1985) 62.
- A 3 ton liquid Argon Time Projection Chamber, ICARUS Collab., NIM A332 (1993) 395.
- Performance of a 3 ton liquid Argon Time Projection Chamber, ICARUS Collab., NIM A345 (1994) 230.
- The ICARUS 50 l LAr TPC in the CERN neutrino beam, ICARUS Collab, hep-ex/9812006 (1998).

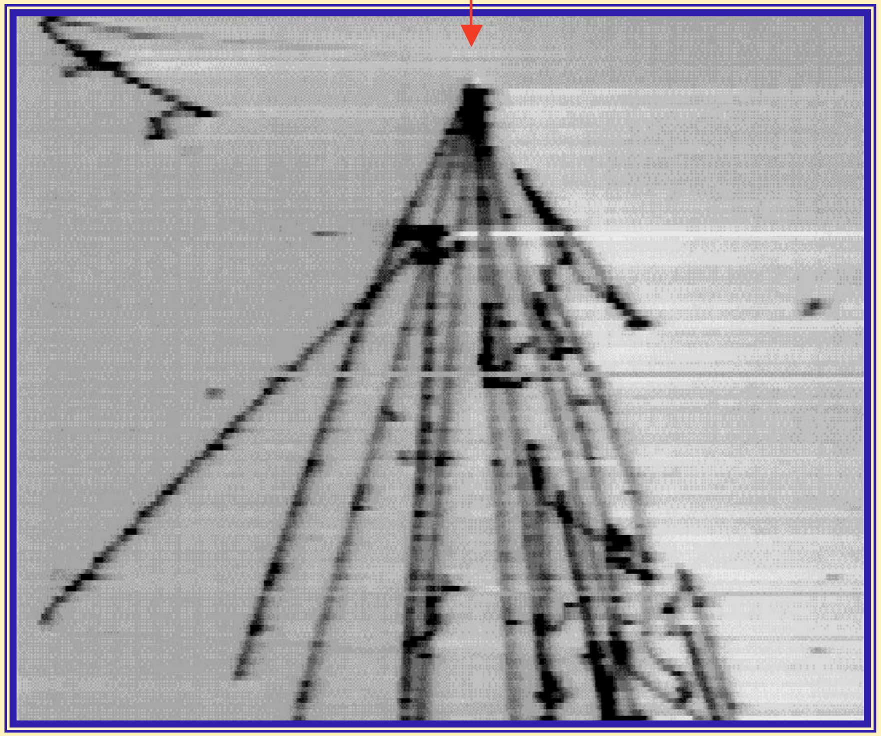
Neutrino interactions in 50 liter exposed to CERN WANF

Several months joint-venture ICARUS+INFN Milano+CERN

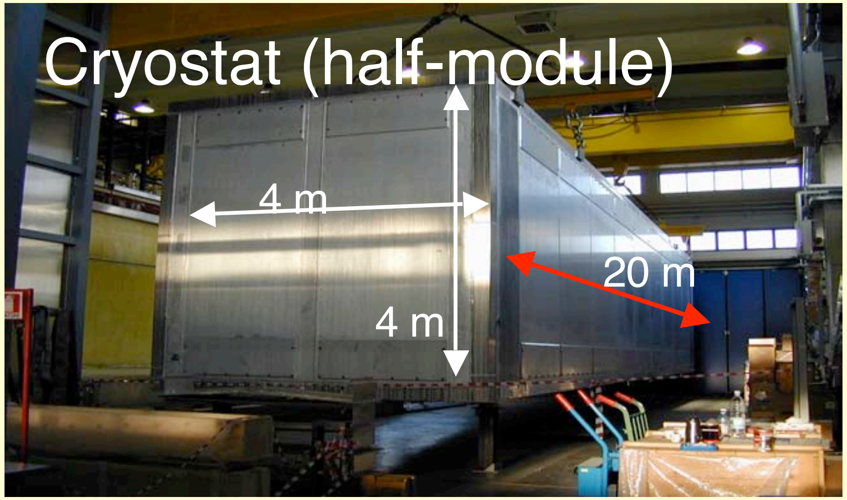
Quasi-elastic

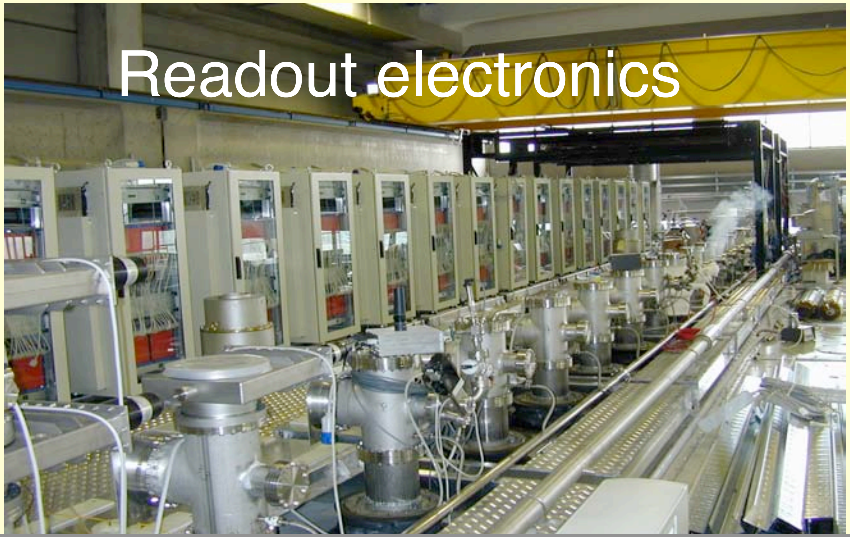


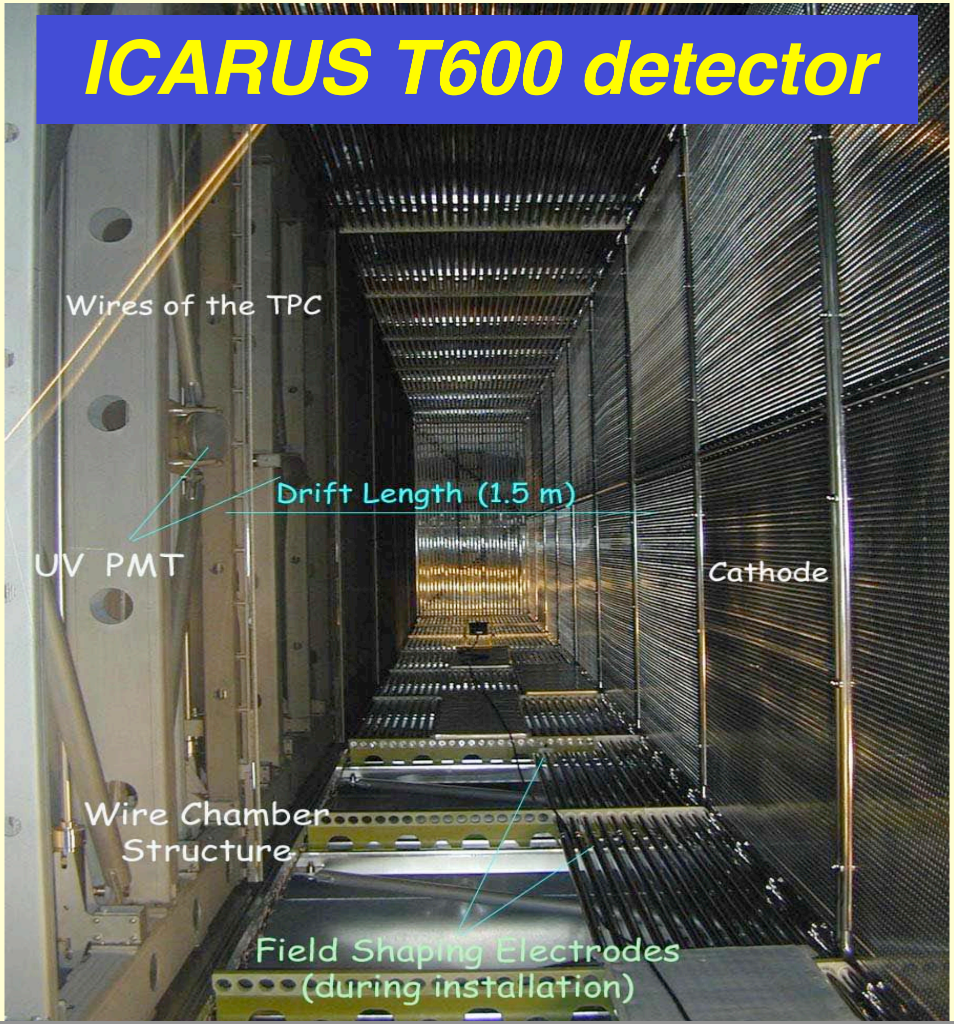
Deeply inelastic



- Possibility to study exclusive final states also in MultiGeV range
- Detector behaves as a very fine-grain “tracking-calorimeter”







- Design, construction and tests of the ICARUS T600 detector, ICARUS Collab, NIM A527 329 (2004).
- Study of electron recombination in liquid Argon with the ICARUS TPC, ICARUS Collab, NIMA523 275-286 (2004).
- Detection of Cerenkov light emission in liquid Argon, ICARUS Collab, NIM A516 348-363 (2004).
- Analysis of the liquid Argon purity in the ICARUS T600 TPC, ICARUS Collab, NIM A516 68-79 (2004).
- Observation of long ionizing tracks with the ICARUS T600 first half module, ICARUS Collab, NIM A508 287 (2003).
- Measurement of the muon decay spectrum with the ICARUS liquid Argon TPC, ICARUS Collab, EPJ C33 233-241 (2004).

A large liquid Argon TPC in the J2K beam?

What for ?

For detailed physics discussions and motivations, see

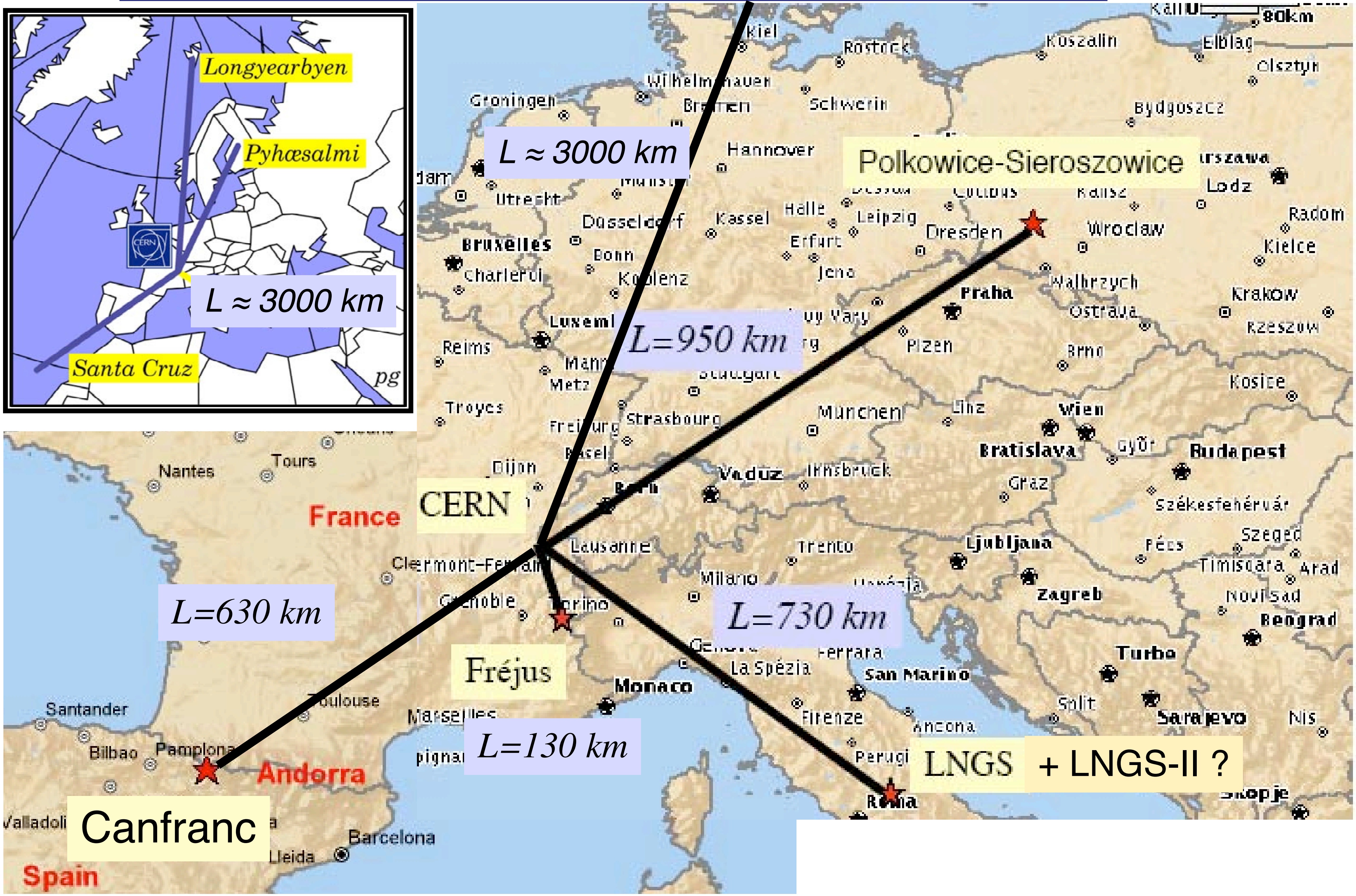
- *M. Aoki et al, Phys. Rev. D67, 093004 (2003)*
- *K. Senda @ NP04*
- *K. Hagiwara, Nucl. Phys. B (Proc. Suppl.) 137 (2004) 84*
- *N. Okamura, hep-ph/0509164*
- *M. Ishitsuka et al., Phys. Rev. D72, 033003 (2005)*
- *… + references therein*

What for?

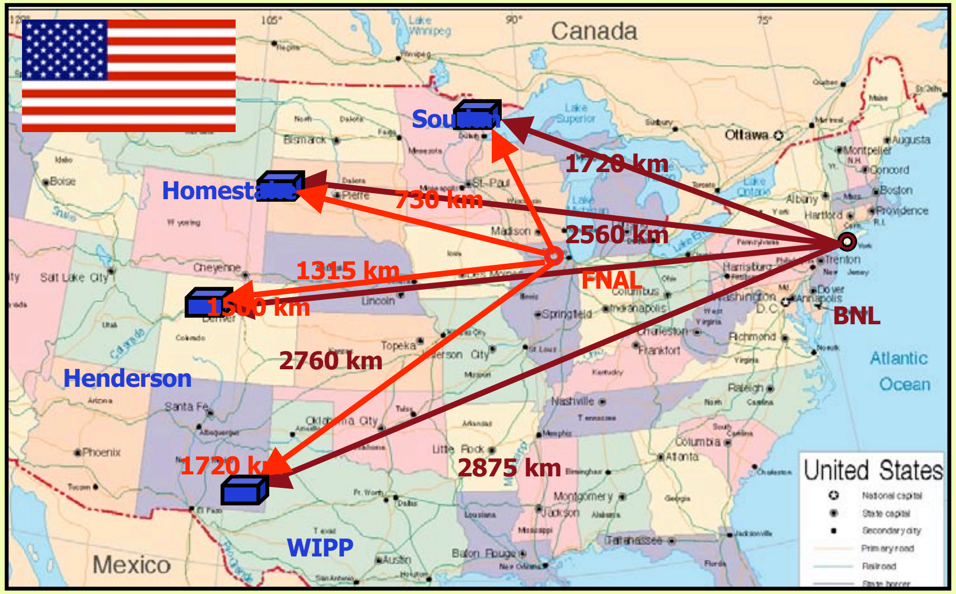
- **The pragmatic approach:**
  - ✓ „Wherever you go, there will always be those liquid Argon guys who will want to put a detector“, Alain Blondel NUFACT 05

- **Other scientific reasons:**
  - ✓ Fully and continuously sensitive
  - ✓ High detection efficiency for multiGeV events
  - ✓ Excellent and „Gaussian“ neutrino energy resolution
  - ✓ Clean event selection and background suppression
  - ✓ Excellent electron identification
  - ✓ Magnetic field possible, useful for neutrino/antineutrino separation
  - ✓ Broad physics program (possibly even at shallow depths)

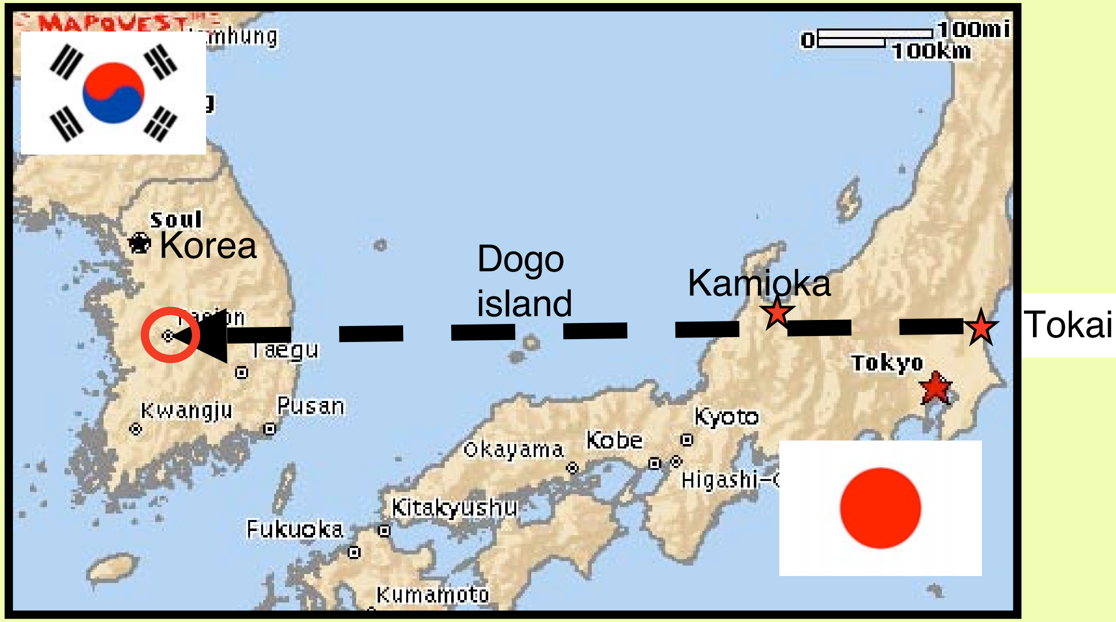
Possible underground sites in Europe ?



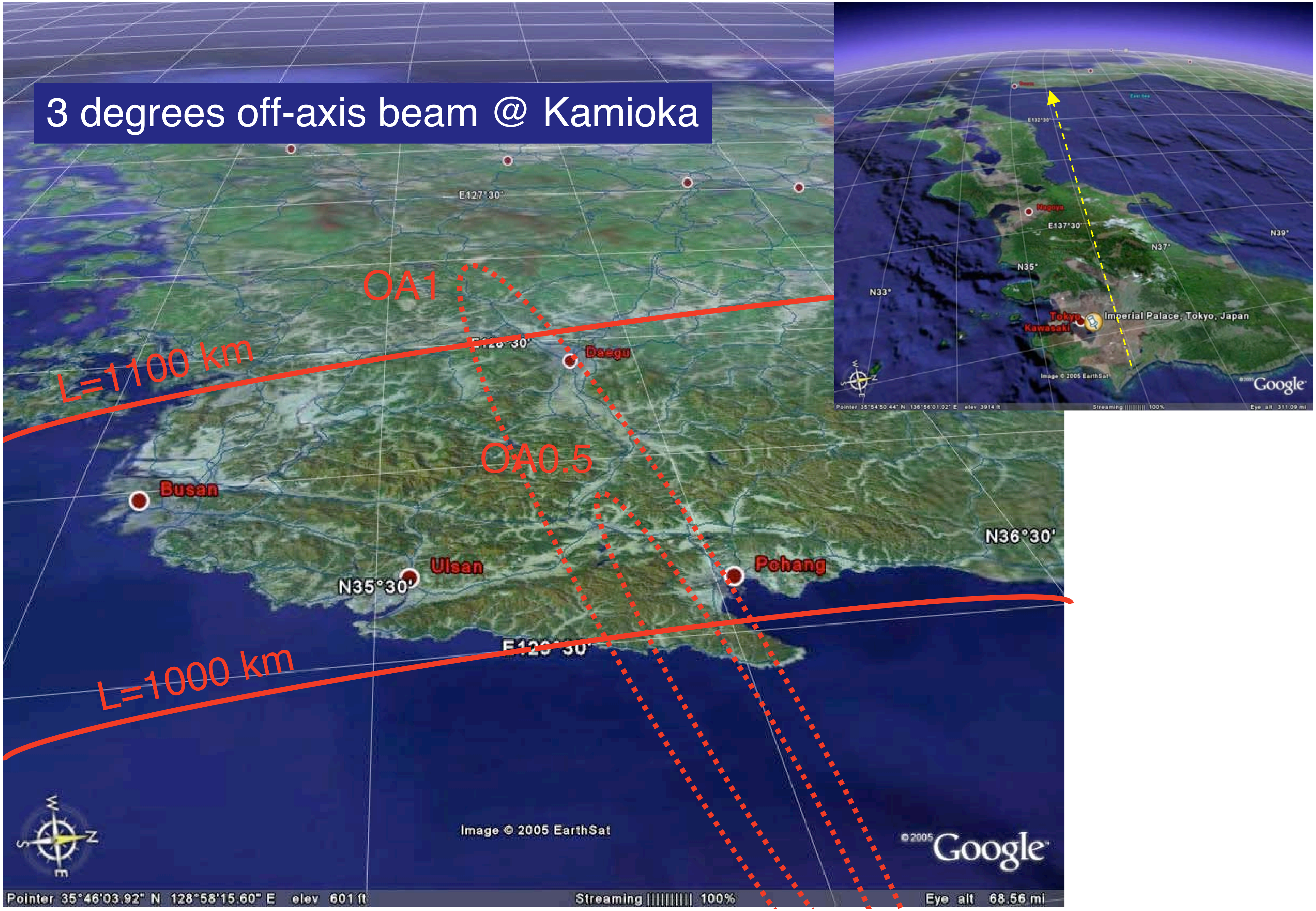
Non-European sites for very large liquid argon TPC



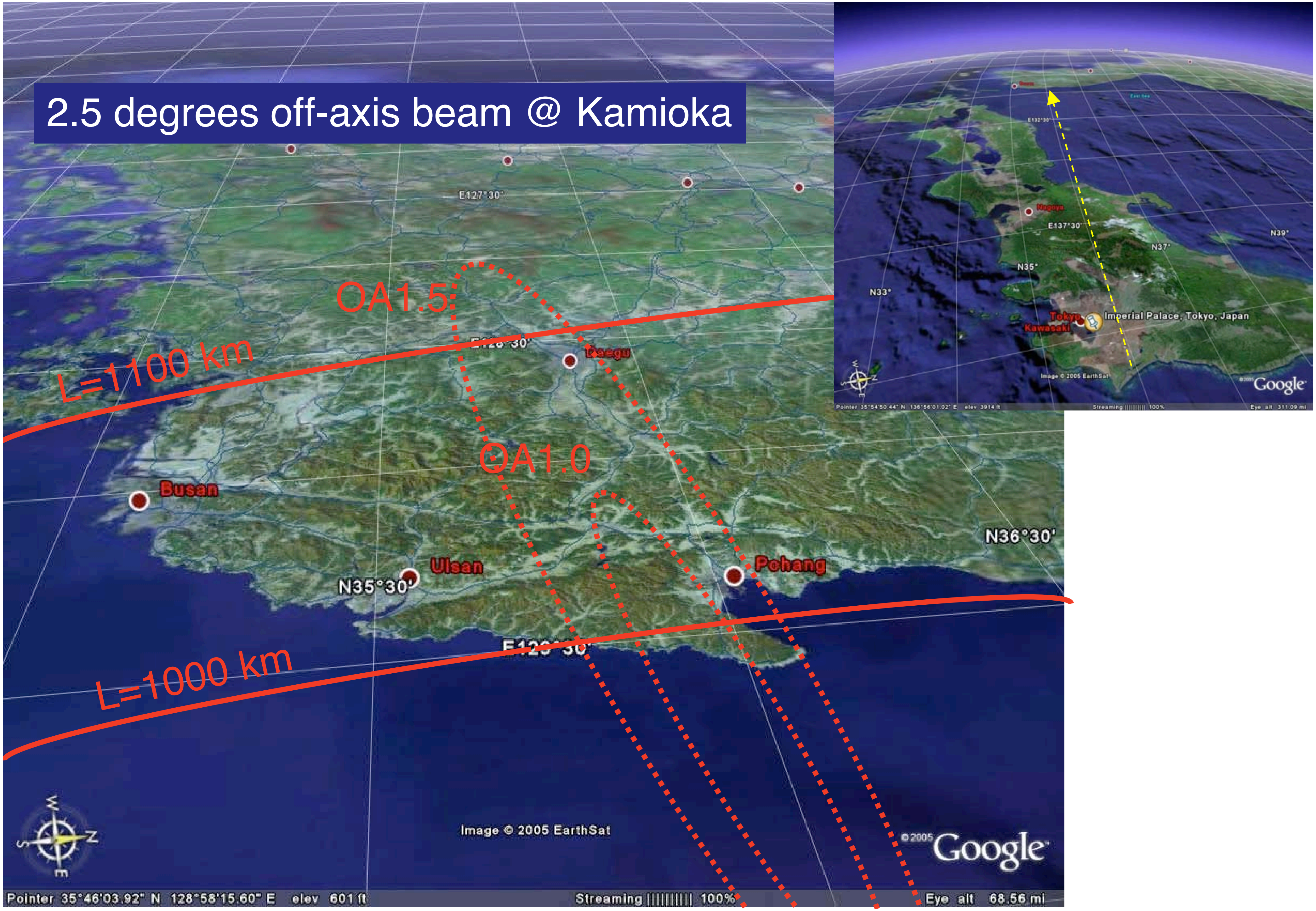
Liquid Argon TPC provides high efficiency for broad energy range: Flexibility in L & E choice



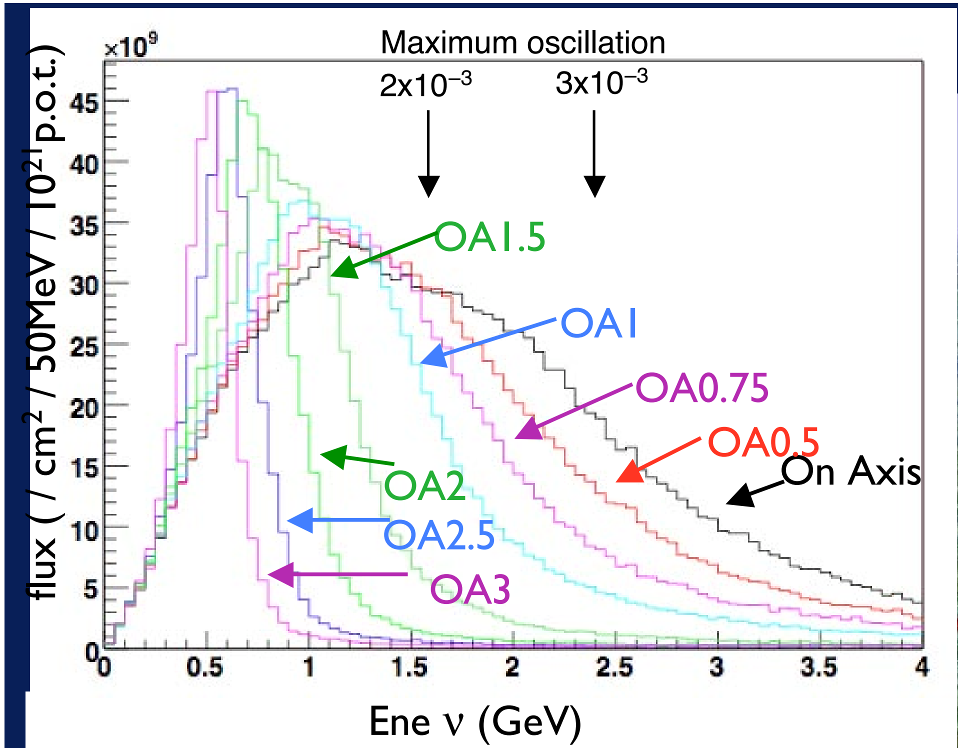
3 degrees off-axis beam @ Kamioka



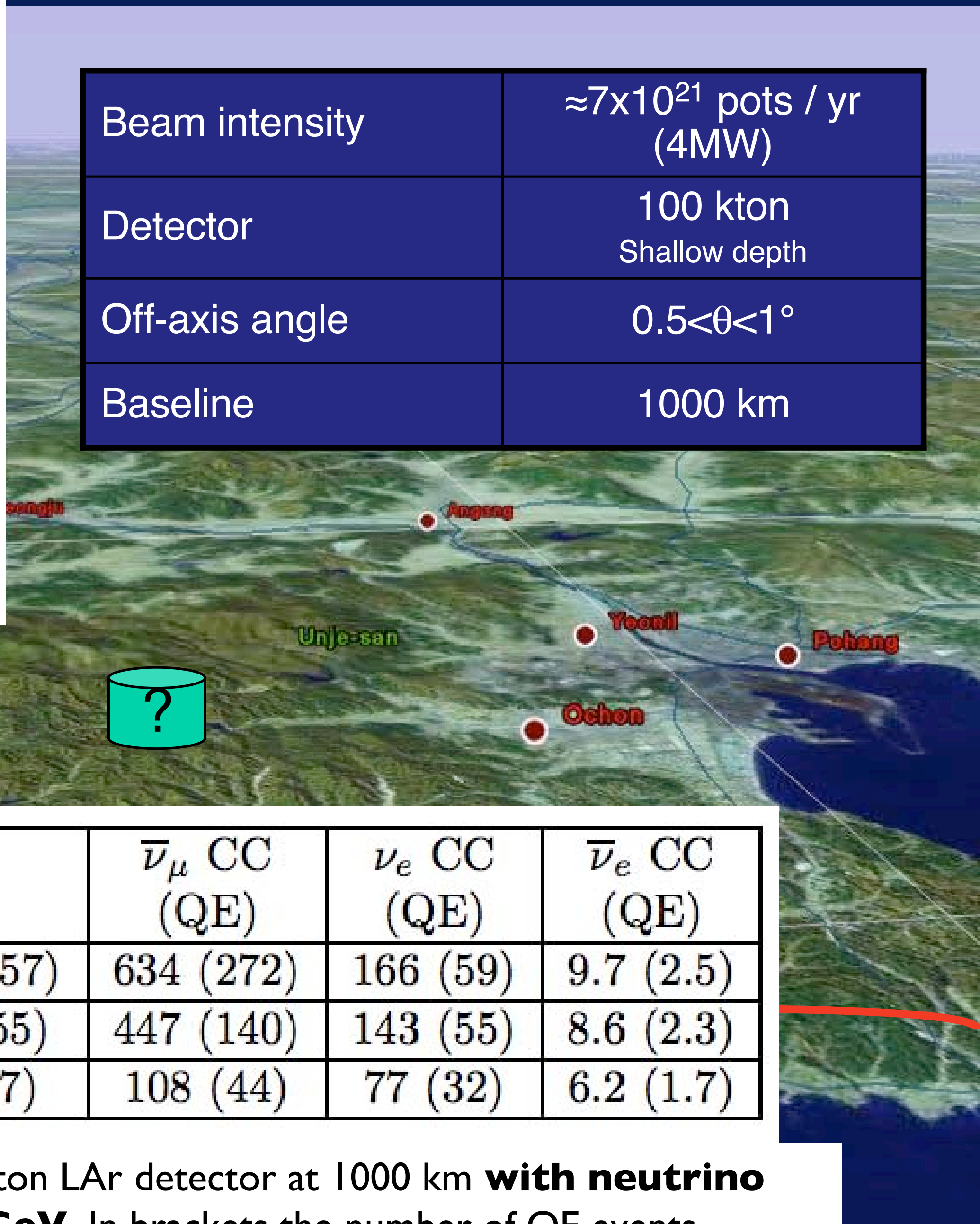
2.5 degrees off-axis beam @ Kamioka



Assumed parameters:



Beam intensity	≈7x10^{21} pots / yr (4MW)
Detector	100 kton Shallow depth
Off-axis angle	0.5<θ<1°
Baseline	1000 km



Off-Axis angle (Deg.)	ν_μ CC (QE)	$\overline{\nu}_\mu$ CC (QE)	ν_e CC (QE)	$\overline{\nu}_e$ CC (QE)
0.5°	26566 (10157)	634 (272)	166 (59)	9.7 (2.5)
1°	17363 (7755)	447 (140)	143 (55)	8.6 (2.3)
2.5°	3851 (2627)	108 (44)	77 (32)	6.2 (1.7)

Rates for 7e+21 p.o.t. on 100 kton LAr detector at 1000 km **with neutrino energy smaller than 4GeV**. In brackets the number of QE events.

Rates & oscillations

Expansion of oscillation formula:

$$P(\nu_e \to \nu_\mu) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2}$$
$$\pm \sin\delta_{CP}\ \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})}$$
$$+ \cos\delta_{CP}\,\alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})}$$
$$+ \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

Lindner

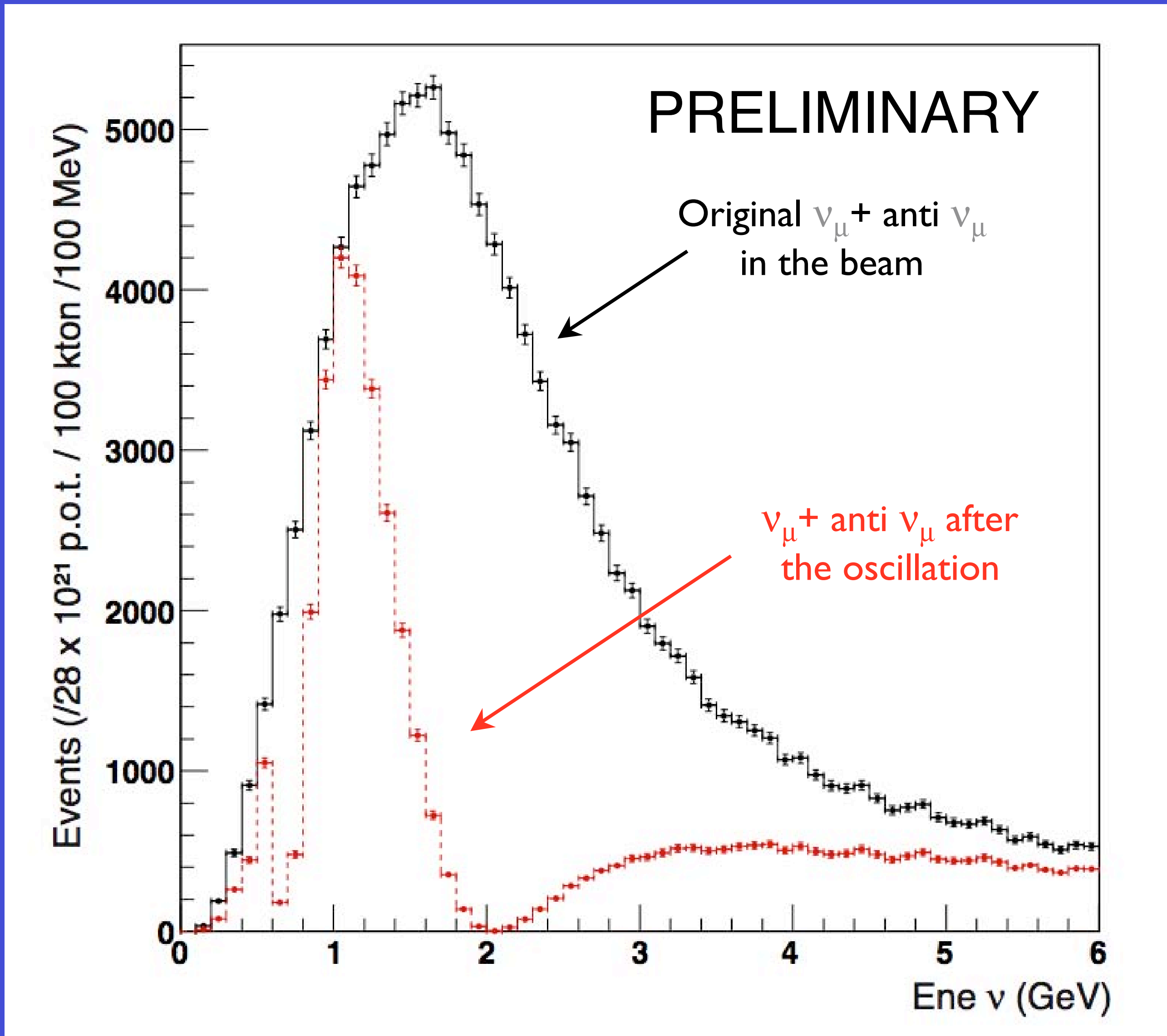
$\alpha = \Delta m^2_{21}/\Delta m^2_{31}$

matter effects $\hat{A} = A/\Delta m^2_{31} = 2VE/\Delta m^2_{31};\ V = \sqrt{2} G_F n_e$

Off-Axis angle (Deg.)	ν_e CC ($\overline{\nu}_e$ CC)	Osc. no solar no matter	Osc. solar no matter	Osc. solar matter
0.5°	166 (9.7)	94 (2.4)	149 (3.6)	167 (3.1)
1°	143 (8.6)	52 (1.7)	101 (2.6)	105 (2.3)
2.5°	77 (6.2)	12 (0.4)	52 (1)	47 (0.9)

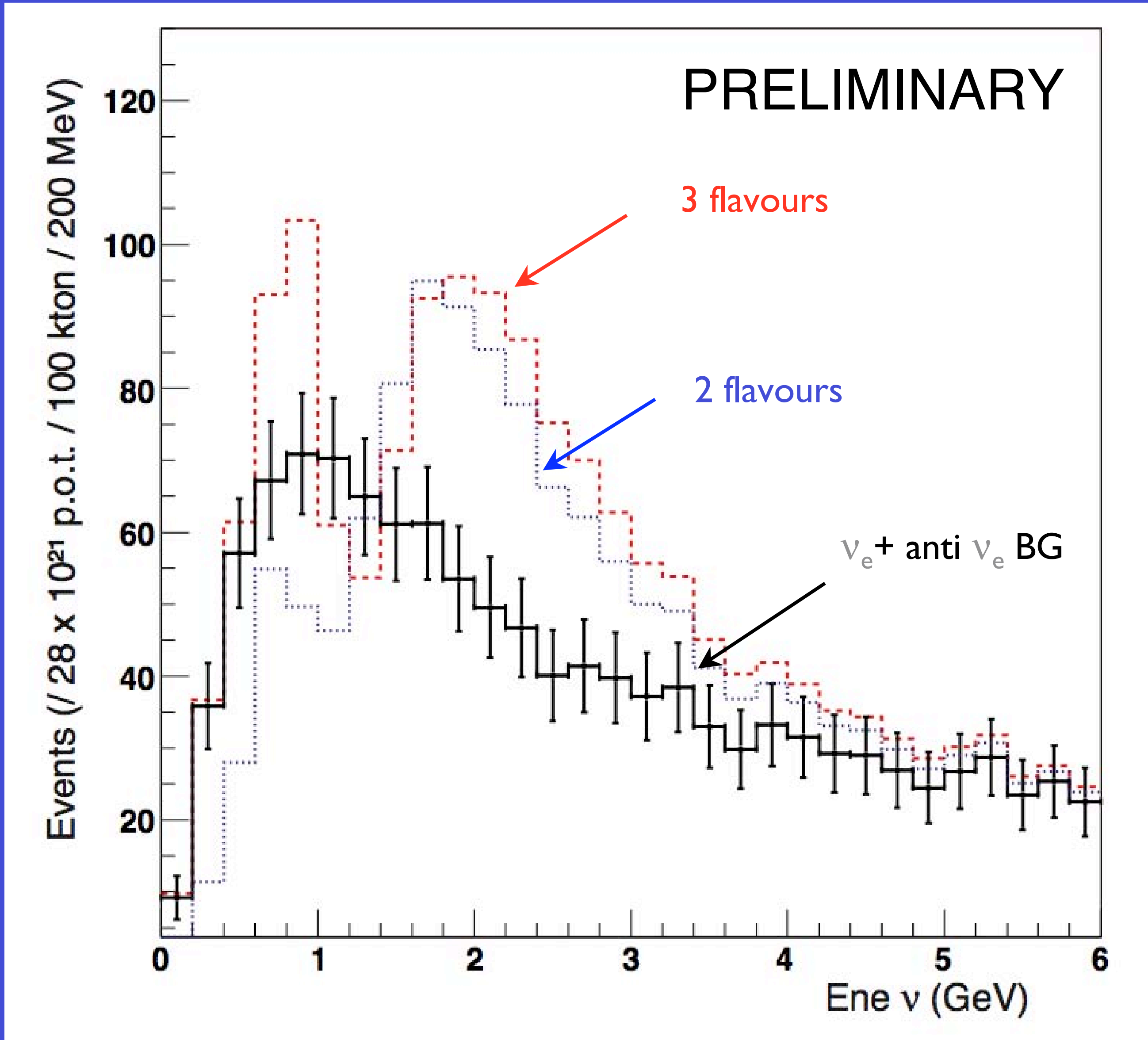
Oscillation $\nu_\mu \to \nu_e$ (anti $\nu_\mu \to$ anti ν_e in brackets) for 7e+21 p.o.t. on 100 kton LAr detector at 1000 km with energy smaller than 4GeV. The parameters used for the oscillation are: $\sin^2(2\theta_{13}) = 0.01$, $\Delta m^2_{23} = 2.5\text{e-}3\ \text{eV}^2$ and $\delta = 0$ degrees and normal mass hierarchy.

ν_μ disappearance



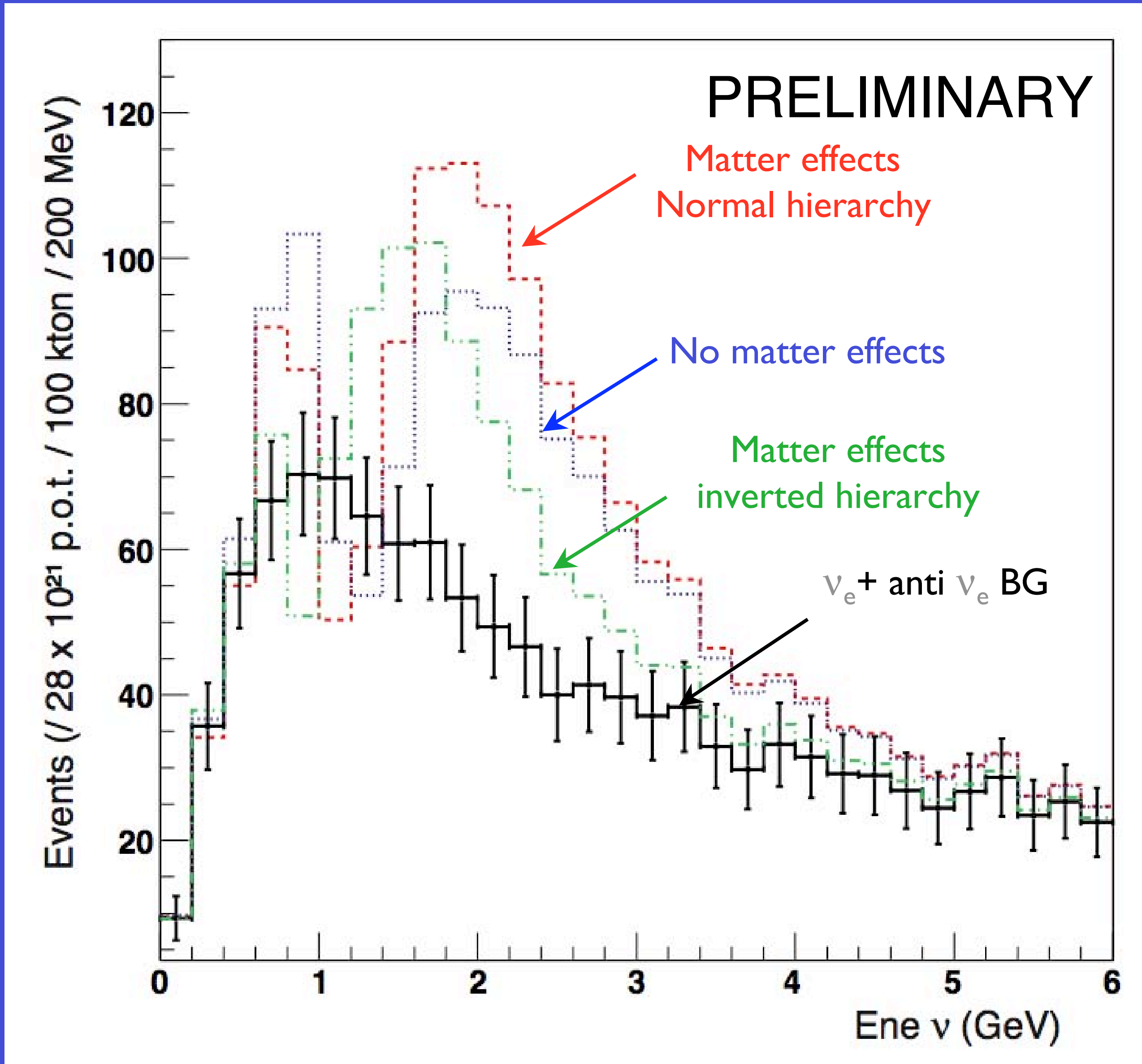
- 28e+21 p.o.t.
- 100 kton LAr detector at 1000 km.
- Beam OA0.5 degrees
- Δm^2_{23} = +2.5e-3 eV^2
- $\sin^2(\theta_{23})$ = 0.5
- No visible energy smearing

ν_e appearance: solar + interference terms contributions



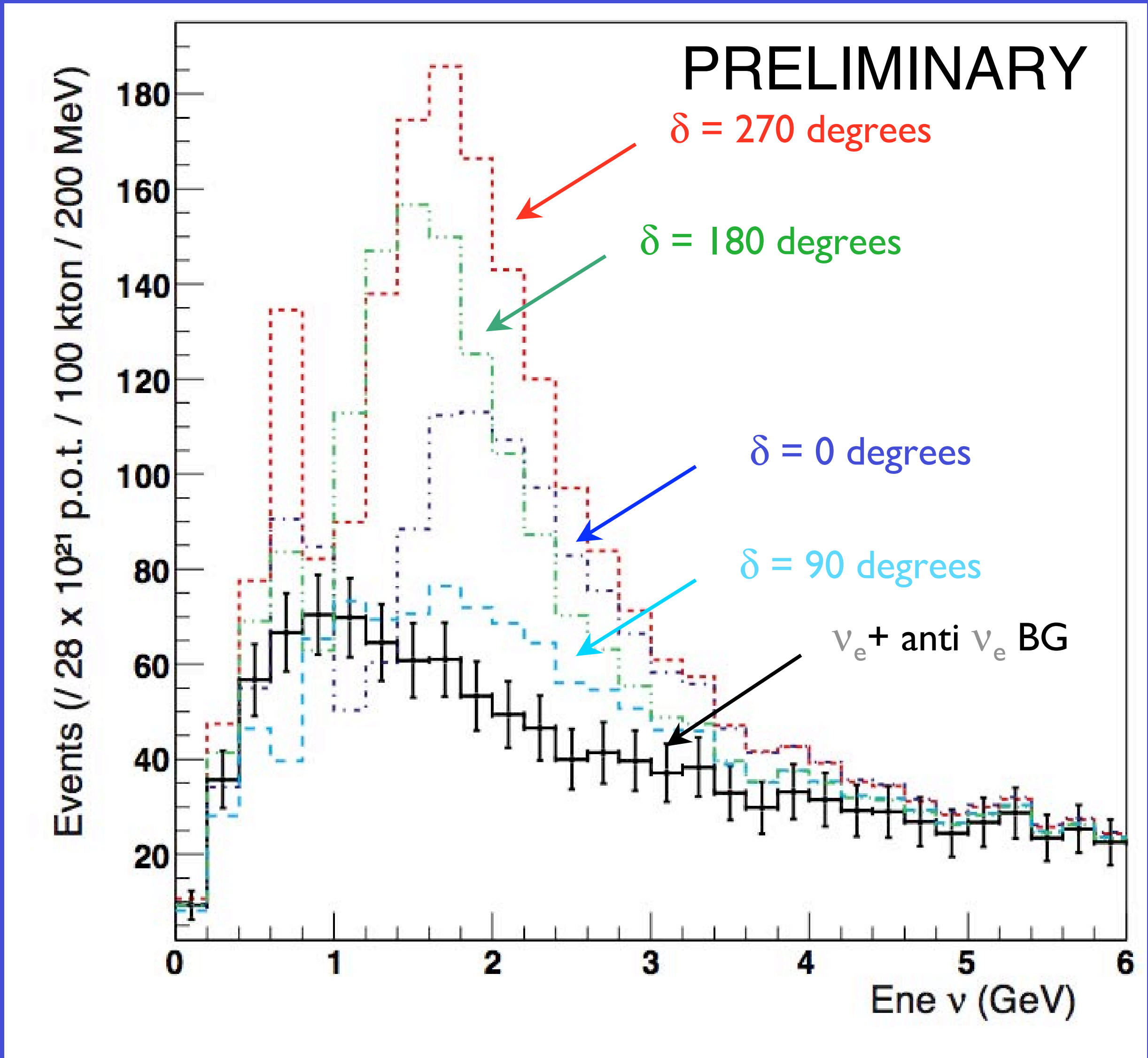
- 28e+21 p.o.t.
- 100 kton LAr detector at 1000 km.
- Beam OA 0.5 degrees.
- $\sin^2(\theta_{23}) = 0.5$
- $\sin^2(2\theta_{13}) = 0.01$
- $\Delta m^2_{23} = +2.5e\text{-}3\ eV^2$
- $\tan^2(\theta_{12}) = 0.45$
- $\Delta m^2_{21} = +7e\text{-}5\ eV^2$
- $\delta = 0$
- No visible energy smearing

ν_e appearance : matter effects



- 28e+21 p.o.t.
- 100 kton LAr detector at 1000 km.
- Beam OA 0.5 degrees.
- $\sin^2(2\theta_{13}) = 0.01$
- $\Delta m^2_{23} = \pm 2.5e\text{-}3\ eV^2$
- $\tan^2(\theta_{12}) = 0.45$
- $\Delta m^2_{21} = +7e\text{-}5\ eV^2$
- $\delta = 0$
- $\rho = 2.8\ g/cm^3$
- No visible energy smearing

ν_e appearance: δ-phase

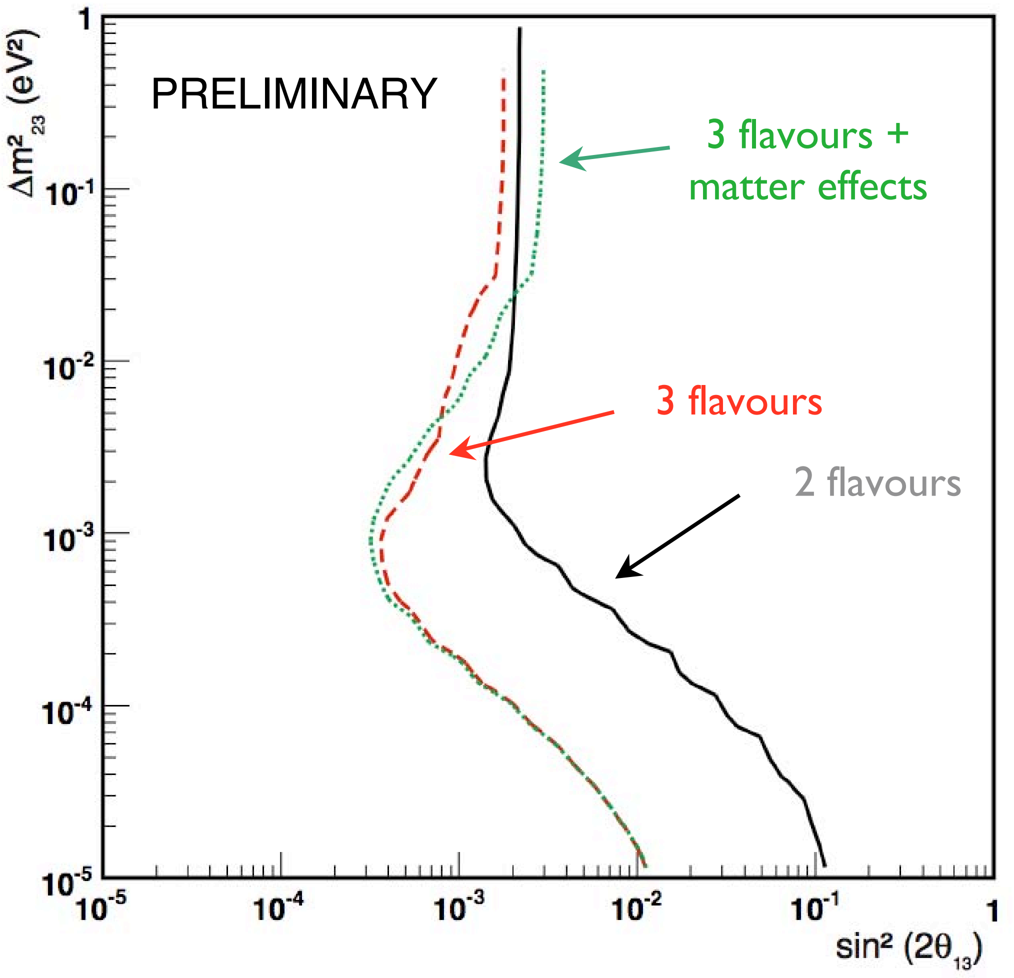


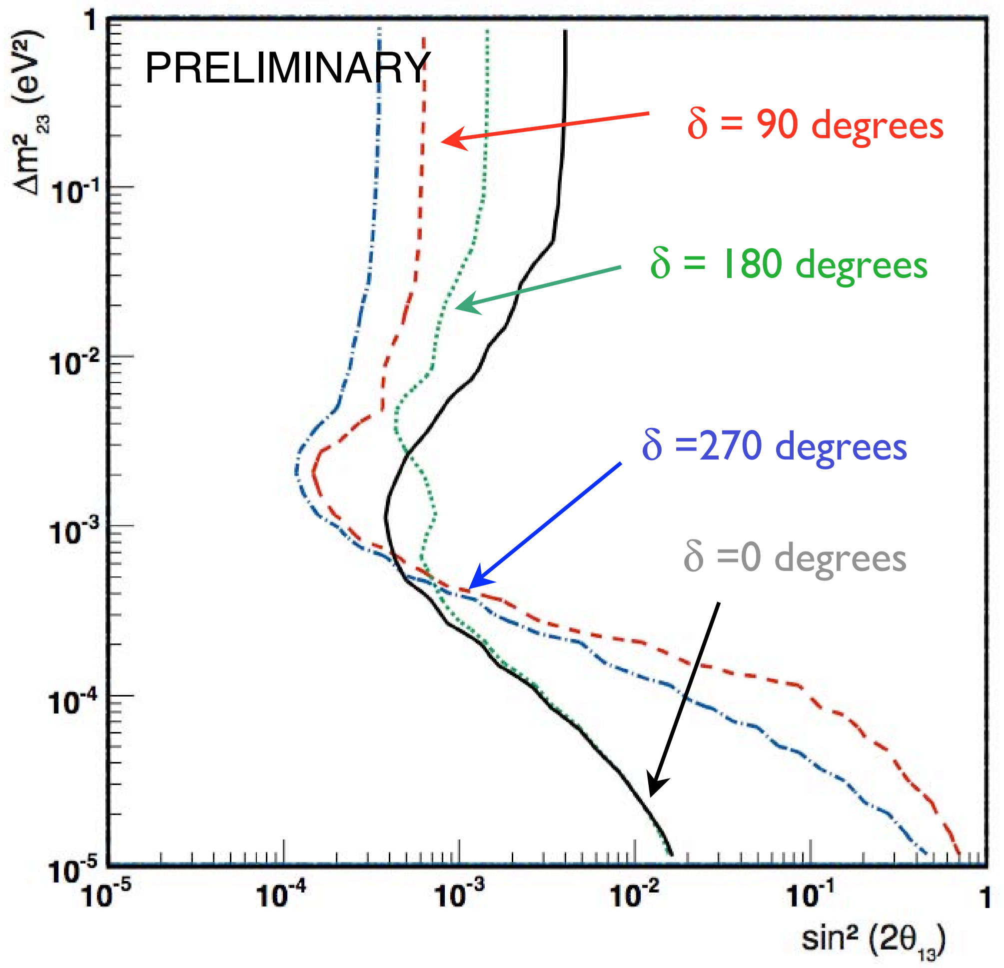
- 28e+21 p.o.t.
- 100 kton LAr detector at 1000 km.
- Beam OA 0.5 degrees.
- $\sin^2(2\theta_{13}) = 0.01$
- $\Delta m^2_{23} = +2.5\text{e-}3\ eV^2$
- $\tan^2(\theta_{12}) = 0.45$
- $\Delta m^2_{21} = +7\text{e-}5\ eV^2$
- $\delta = 0$
- No visible energy smearing

Sensitivity: $\sin^2(2\theta_{13})$ vs Δm^2_{23}

- 28e+21 p.o.t.
- 100 kton LAr detector at 1000 km.
- Beam OA 0.5 degrees.

Statistical errors only





Summarizing

- **Qualitative:**
  - A 100 kton liquid Argon TPC located on the east Korean coast (possibly running at shallow depth) at an off-axis angle of 0.5-1 degree of the T2K 4MW beam after 4 years would have the statistical power to
    - ✓Search for $\sin^2 2\theta_{13} < O(0.001)$
    - ✓Study matter effects (determine mass hierarchy)
    - ✓Look for non-vanishing δ-phase (for $\sin^2 2\theta_{13} \approx 0.01$)

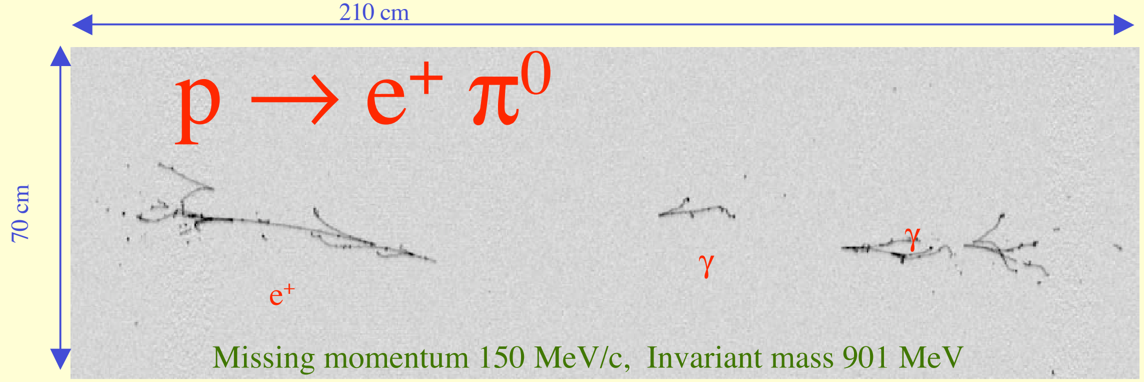
- **Quantitative:**
  - ✓ For quantitative assessment one needs to understand all sources of systematic errors.
  - ✓ Include correlations between parameters, degeneracy,…
  - ✓ Work in progress.

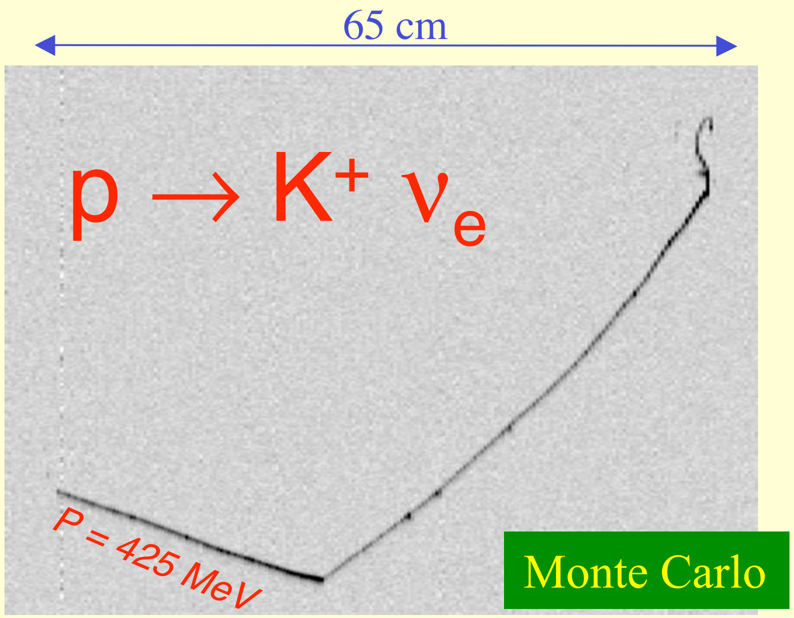
Non-accelerator program

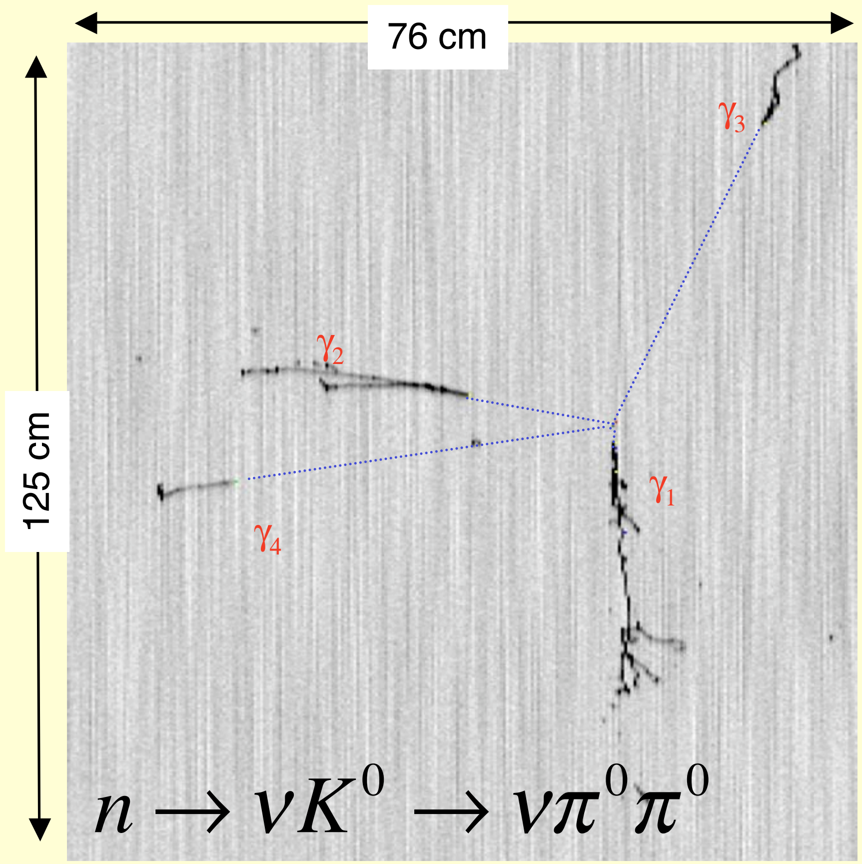
Outstanding non-accelerator physics goals

	Water Cerenkov	Liquid Argon TPC
Total mass	650 kton	100 kton
$p \rightarrow e\,\pi^0$ in 10 years	1.6×10^{35} years ε= 17%, ≈ 1 BG event	0.5×10^{35} years ε= 45%, <1 BG event
$p \rightarrow \nu K$ in 10 years	0.2×10^{35} years ε= 8.6%, ≈ 37 BG events	1.1×10^{35} years ε= 97%, <1 BG event
$p \rightarrow \mu \pi K$ in 10 years	No	1.1×10^{35} years ε= 98%, <1 BG event
SN cool off @ 10 kpc	194000 (mostly $\bar{\nu}_e p \rightarrow e^+ n$)	38500 (all flavors) (64000 if NH-L mixing)
SN in Andromeda	40 events	7 (12 if NH-L mixing)
SN burst @ 10 kpc	≈330 ν-e elastic scattering	380 ν_e CC (flavor sensitive)
SN relic	Yes	Yes
Atmospheric neutrinos	60000 events/year	10000 events/year
Solar neutrinos	E_e > 7 MeV (40% coverage)	324000 events/year E_e > 5 MeV

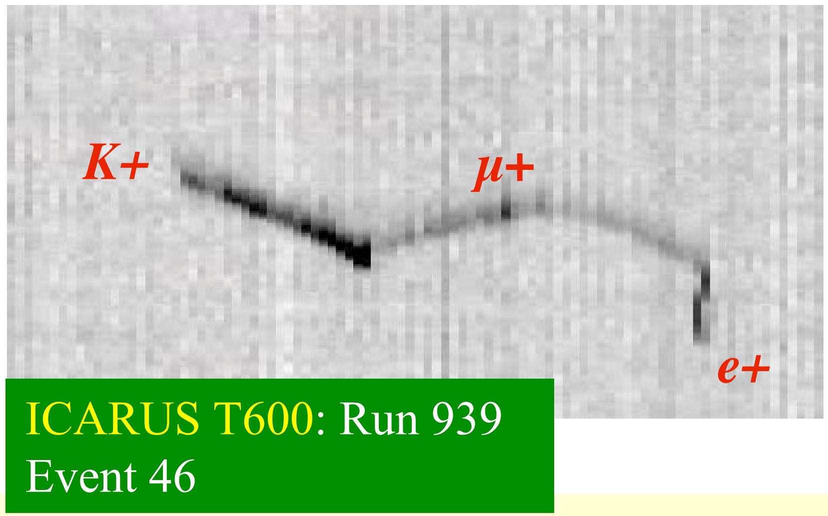
Nucleon decay





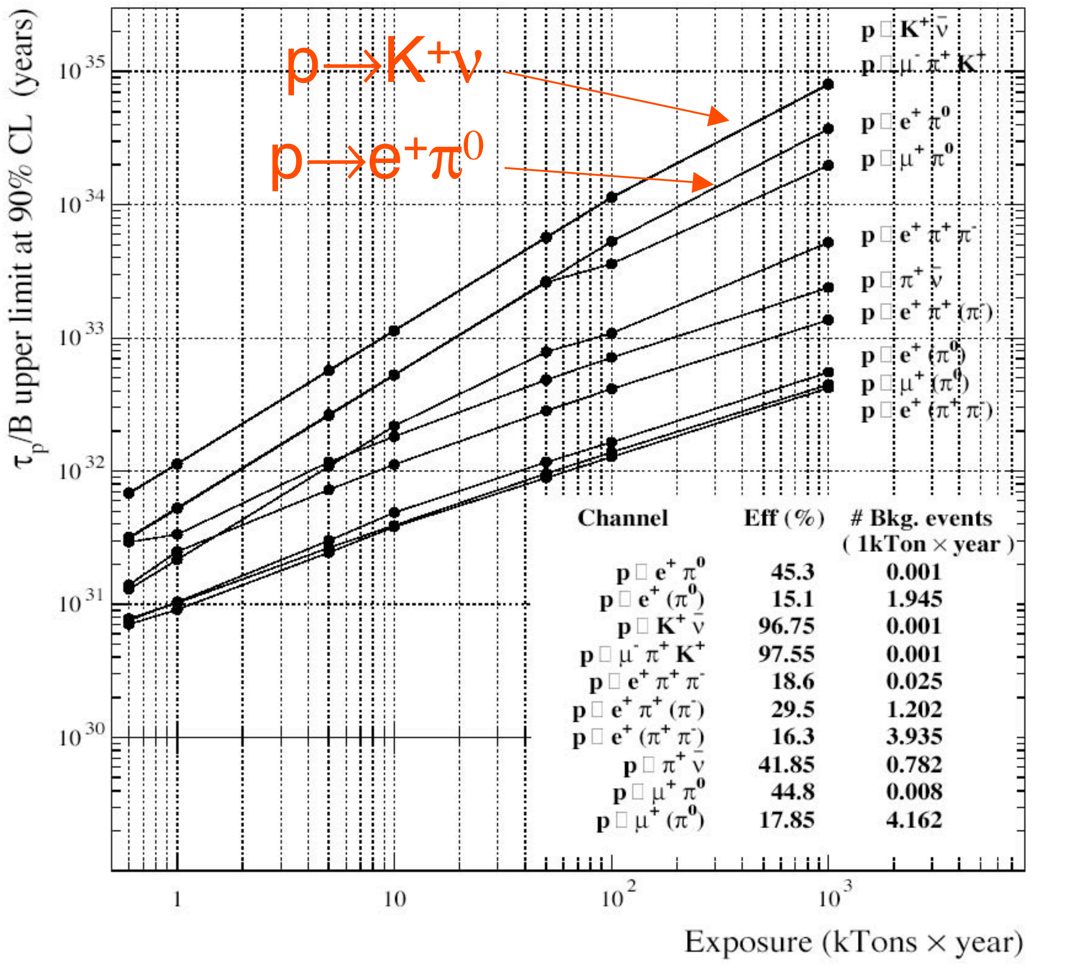


"Single" event detection capability



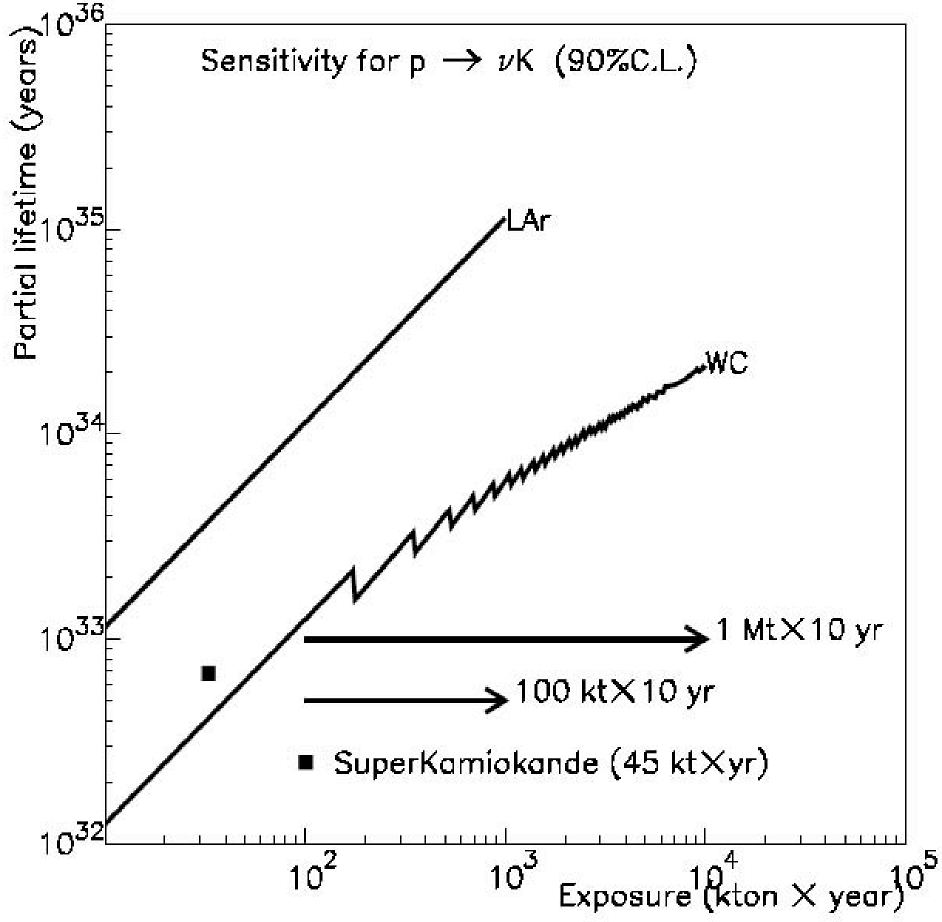
Proton decay sensitivity

Many channels accessible



Channel	Eff (%)	# Bkg. events (1kTon × year)
p □ $e^+ \pi^0$	45.3	0.001
p □ $e^+ (\pi^0)$	15.1	1.945
p □ $K^+ \bar{\nu}$	96.75	0.001
p □ $\mu^- \pi^+ K^+$	97.55	0.001
p □ $e^+ \pi^+ \pi^-$	18.6	0.025
p □ $e^+ \pi^+ (\pi^-)$	29.5	1.202
p □ $e^+ (\pi^+ \pi^-)$	16.3	3.935
p □ $\pi^+ \bar{\nu}$	41.85	0.782
p □ $\mu^+ \pi^0$	44.8	0.008
p □ $\mu^+ (\pi^0)$	17.85	4.162

Complementarity



LAr TPC provides ultimate fine-grain tracking and calorimetry as necessary for proton decay searches

Can such a detector be scaled up to ≈100 kton ?

Can it be magnetized ?

At which depth should it be ?

Can the cost be kept within reasonable limits?

Concept:

The Giant Liquid Argon Charge Imaging ExpeRiment (GLACIER)

GLACIER people (12 groups, ≈25 people)

ETHZ (CH): A. Badertscher, L. Knecht, M. Laffranchi, A. Meregaglia, M. Messina, G. Natterer, P.Otiougova, A. Rubbia, J. Ulbricht
Granada University (Spain): A. Bueno, J. Lozano, S. Navas
INP Krakow (Poland): A. Zalewska
INFN Naples (Italy): A. Ereditato
INR Moscow (Russia): S. Gninenko
IPN Lyon (France): D. Autiero, Y. Déclais, J. Marteau
Sheffield University (UK): N. Spooner
Southampton University (UK): C. Beduz, Y. Yang
US Katowice (Poland): J. Kisiel
UPS Warszawa (Poland): E. Rondio
UW Warszawa (Poland): D. Kielczewska
UW Wroclaw (Poland): J. Sobczyk

Many thanks to:

Technodyne Ltd, Eastleigh, UK

CUPRUM (KGHM group), Wroclaw, Poland

CAEN, Viareggio, Italy

GLACIER in European context for astroparticle physics - ApPEC

- ApPEC is the Astroparticle Physics Coordination in Europe
- Represents large funding agencies for APP in Belgium, France, Germany, Greece, Italy, Netherlands, Spain, Switzerland and UK
- The Steering Committee has mandated the Peer Review Committee to write a Roadmap
- On September 18th 2005, we have submitted the following input for our activities:
  a) R&D: long drift tests, charge extraction and amplification, magnetic field tests, large scale purification, shallow depth operation < 2008
  b) 1 kton prototype: > 2008 ?
  c) 10 kton detector: > 2012 ?
  d) 100 kton facility: > 2020 ?

- First ApPEC "town meeting" in Munich Nov 23-25th 2005.
- Possible submission to EU FP7 end of 2006: 10kton "design study" ?

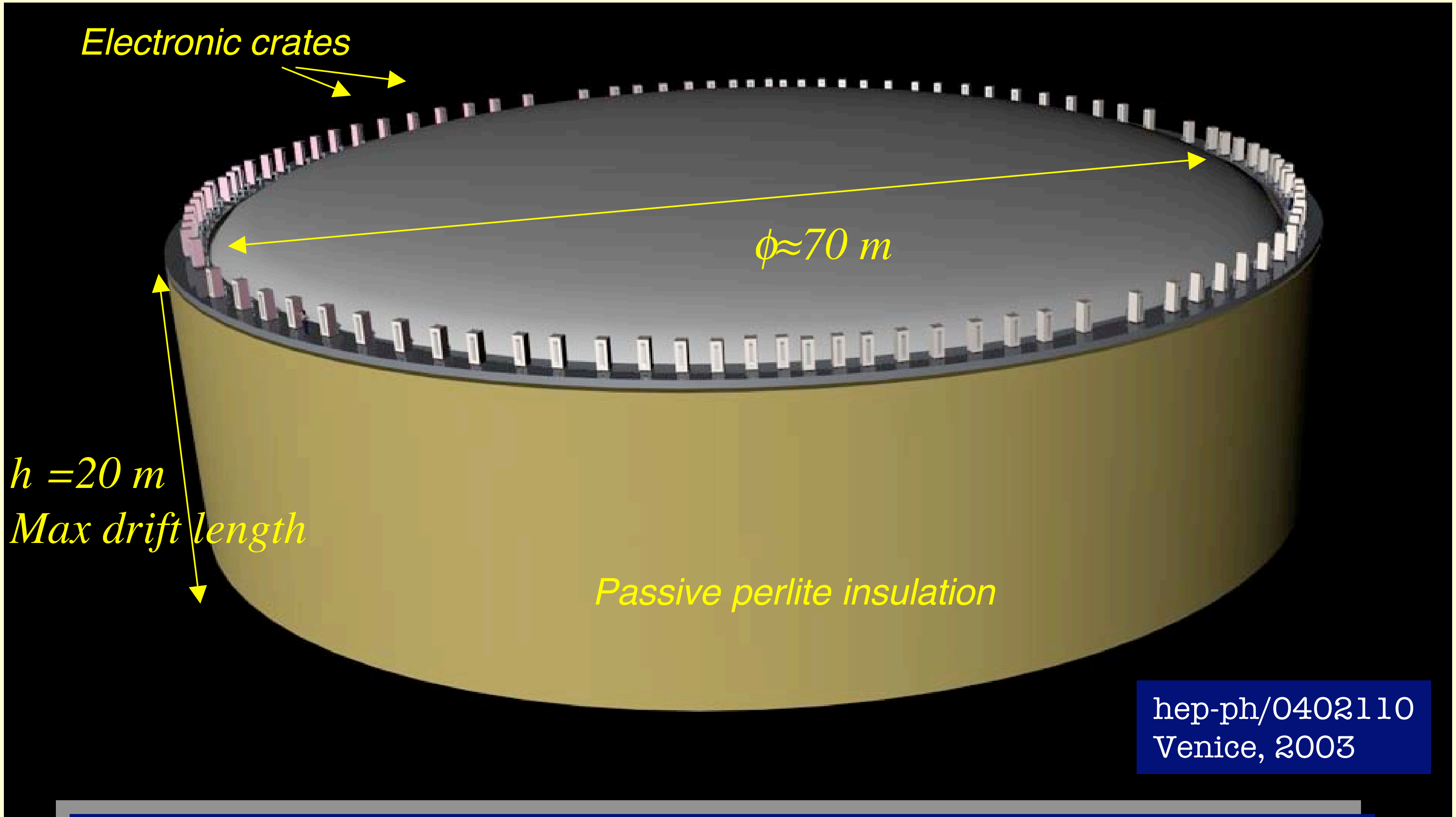
A strategy for long-term application of the liquid Argon TPC

In order to reach the adequate fiducial mass for long-term future physics programs, new concepts are required to extrapolate further the technology.

We consider different mass scales:

- A O(100 kton) liquid Argon TPC will deliver extraordinary physics output. It will be an ideal match for a future Superbeam, Betabeam or Neutrino Factory. This program is very challenging.
- A O(10 kton) prototype (10% full-scale) could be readily envisaged as an engineering design test with a physics program of its own. This step could be detached from a neutrino facility.
- An open issue is the necessity of a magnetic field encompassing the liquid Argon volume (mandatory for the neutrino factory). We have demonstrated the possibility to use magnetic field in a small prototype. We discuss here possible 10-100 kton in magnetic fields (see later).
- A O(1 kton) "shallow-depth" demonstrator could be readily envisaged to demonstrate the technical choices, with a physics program similar to the ICARUS T1800 project.

A 100 kton liquid Argon TPC detector



Single module cryo-tanker based on industrial LNG technology

A “general-purpose” detector for superbeams, beta-beams and neutrino factories with broad non-accelerator physics program (SN ν, p-decay, atm ν, …)

New features and design considerations

•**Single "boiling" cryogenic tanker at atmospheric pressure for a stable and safe equilibrium condition** (temperature is constant while Argon is boiling). The evaporation rate is small (less than 10^{-3} of the total volume per day given by the very favorable area to volume ratio) and is compensated by corresponding refilling of the evaporated Argon volume.

•**Charge imaging, scintillation and Cerenkov light readout for a complete (redundant) event reconstruction**. This represents a clear advantage over large mass, alternative detectors operating with only one of these readout modes. The physics benefit of the complementary charge, scintillation and Cerenkov readout are being assessed.

•**Charge amplification to allow for very long drift paths**. The detector is running in bi-phase mode. In order to allow for drift lengths as long as ≈20 m, which provides an economical way to increase the volume of the detector with a constant number of channels, charge attenuation will occur along the drift due to attachment to the remnant impurities present in the LAr. We intend to compensate this effect with a modest charge amplification near the anodes located in the gas phase.

•**Possibility of magnetic field considered (see below)**. R&D studies for charge imaging in a magnetic field have been successful and results have been published. Physics studies indicate that a magnetic field is mandatory when the detector is coupled to a Neutrino Factory and could be avoided in the context of Superbeams and Betabeams. Non-accelerator physics performance under study.

Tanker

In Collaboration with industry, we have shown that extrapolation from LNG technology to LAr is possible

Cryogenic storage tankers for LNG

LNG = Liquefied Natural Gas

About 2000 cryogenic tankers exist in the world, with volume up to ≈ 200000 m^3

Process, design and safety issues already solved by petrochemical industry

Cooling by "auto-refrigeration"

Expertise in ships : efficient thermal shield, safety, …

Washington post (Sept 23rd 2005)

- **S.Korean shipbuilders enjoy boom.**
  By Jong-Heon Lee **UPI Business Correspondent**

  Seoul, South Korea, Sep. 23 (UPI) -- **South Korea is expected to maintain its status as the world's biggest shipbuilder for the next decade mainly on the back of bumper orders for lucrative liquefied natural gas (LNG) carriers**, industry analysts say.Soaring demand for LNG, driven by rising gas consumption and higher crude oil prices, has come as a boon to the shipbuilding sector in South Korea, which has more than 72 percent of the global LNG tanker market. South Korean shipbuilders sucked more than 90 percent of global orders for new LNG tankers this year until July, according to the Korean Shipbuilders' Association.**The country's three major shipbuilders -- Daewoo Shipbuilding and Marine Engineering Co., Hyundai Heavy Industry Co., and Samsung Heavy Industries Co. -- have been awarded orders of 29 LNG carriers for the seven months.** Daewoo Shipbuilding, the world's largest LNG shipbuilder, has won $2.2 billion worth of orders to build 13 LNG tankers so far this year.The shipbuilder now has a total of 26 LNG carries in its order book, the largest among shipbuilders worldwide, a company spokesman said. The carriers are mostly 150,000-cubic-meter tankers (…) It usually takes 28-29 months to build one 150,000-cubic-meter LNG carrier. (…) Thanks to the LNG tankers boom, South Korean shipbuilders grabbed 43.8 percent of global orders for new vessels this year until July, **widening the gap with the world second biggest shipbuilder, Japan**.

Study of large underground storage tank

	Project: Large Underground Argon Storage Tank
Issued By: JMH	Document Title
Date:	

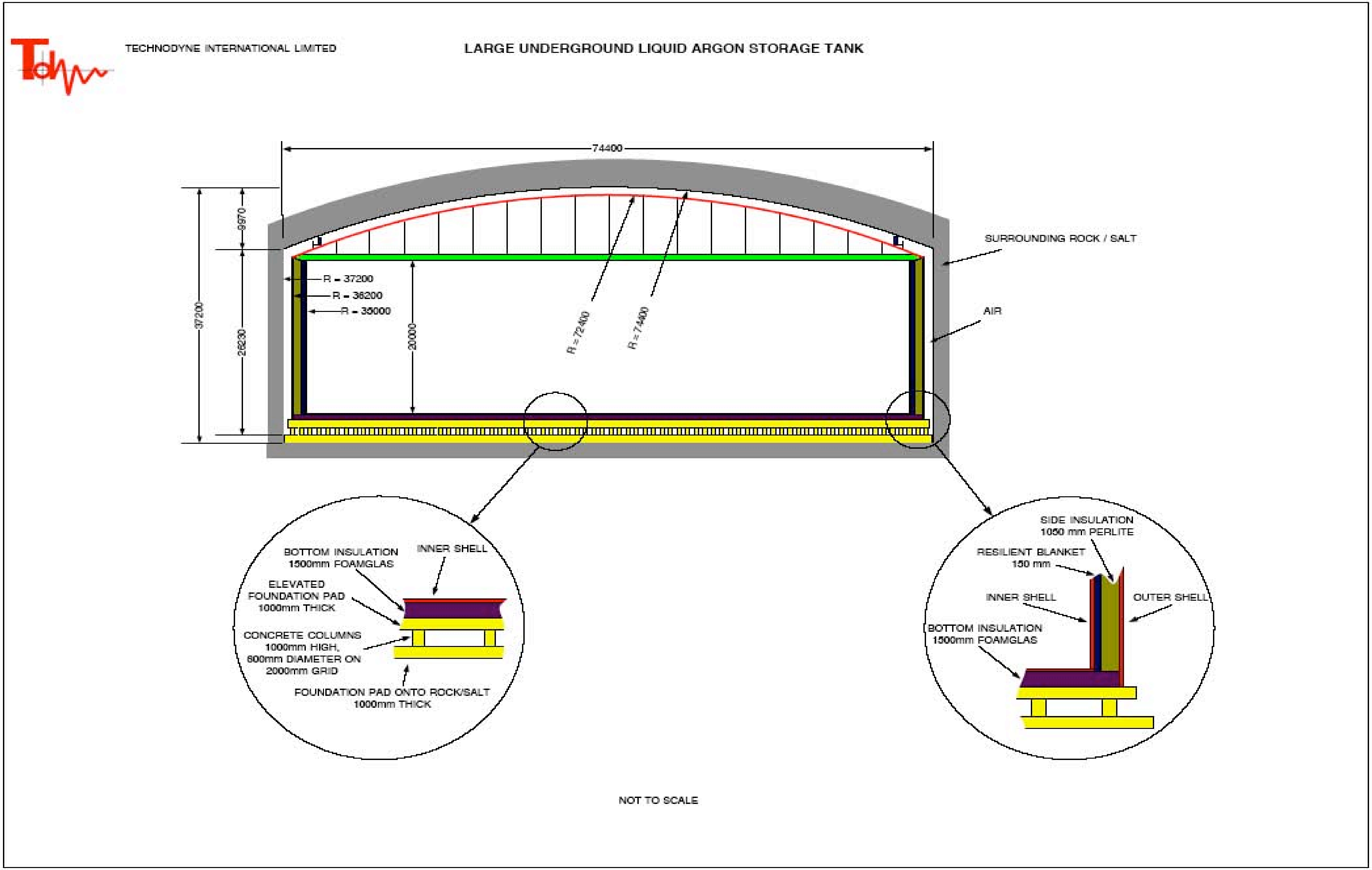
A feasibility study mandated to Technodyne LtD (UK)

Study duration:

February - December 2004

Funded by ETHZ

Technodyne baseline design

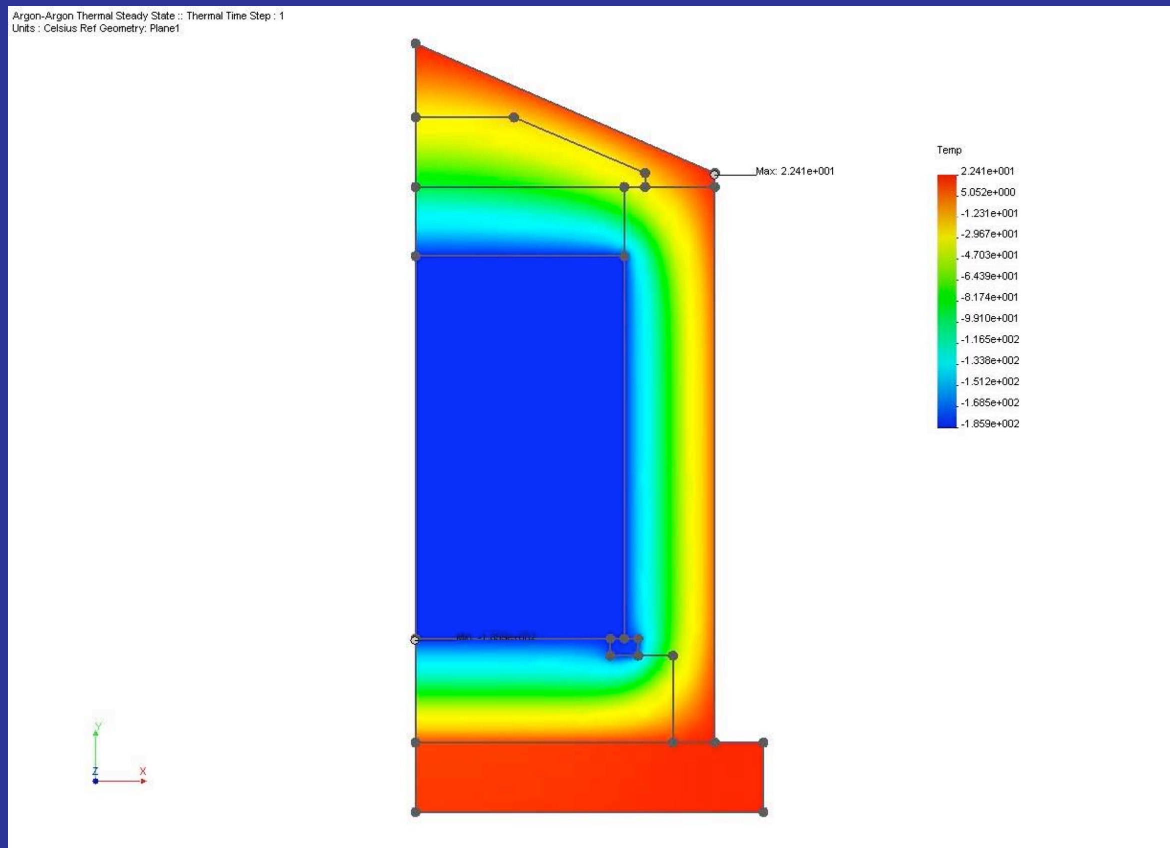


Technodyne baseline design

- The tank consists of the following principal components:
  1. A 1m thick reinforced concrete base platform
  2. Approximately one thousand 600mm diameter 1m high support pillars arranged on a 2m grid. Also included in the support pillar would be a seismic / thermal break.
  3. A 1m thick reinforced concrete tank support sub-base.
  4. An outer tank made from stainless steel, diameter 72.4m. The base of which would be approximately 6mm thick. The sides would range from 48mm thick at the bottom to 8mm thick at the top.
  5. 1500mm of base insulation made from layers of felt and foamglas blocks.
  6. A reinforced concrete ring beam to spread the load of the inner tank walls.
  7. An inner tank made from stainless steel, diameter 70m. The base of which would be approximately 6mm thick and the sides would range from 48mm thick at the bottom to 8mm thick at the top.
  8. A domed roof with a construction radius of 72.4m attached to the outer tank
  9. A suspended deck over the inner tank to support the top-level instrumentation and insulation. This suspended deck will be slightly stronger than the standard designs to accommodate the physics instrumentation. This in turn will apply greater loads to the roof, which may have to be strengthened, however this is mitigated to some extent by the absence of wind loading that would be experienced in the above ground case.
  10. Side insulation consisting of a resilient layer and perlite fill, total thickness 1.2m.
  11. Top insulation consisting of layers of fibreglass to a thickness of approximately 1.2m.

Insulation considerations

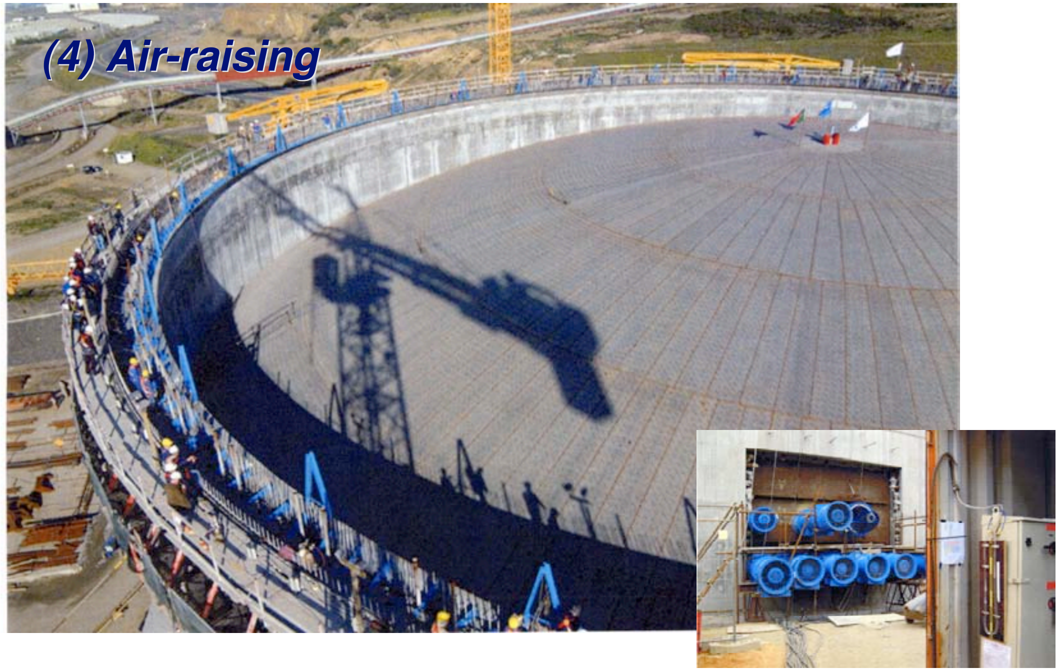
- Based upon current industry LNG tank technology, Technodyne have designed the tank with 1.5 m thick load bearing Foamglas under the bottom of the tank, 1.2 m thick perlite/resilient blanket on the sides and 1.2m thick fibreglass on the suspended deck. Assuming that the air space is supplied with forced air at 35 degrees centigrade then the boil off would be in the order of 29m^3 LAr per day. This corresponds to 0.039% of total volume per day.



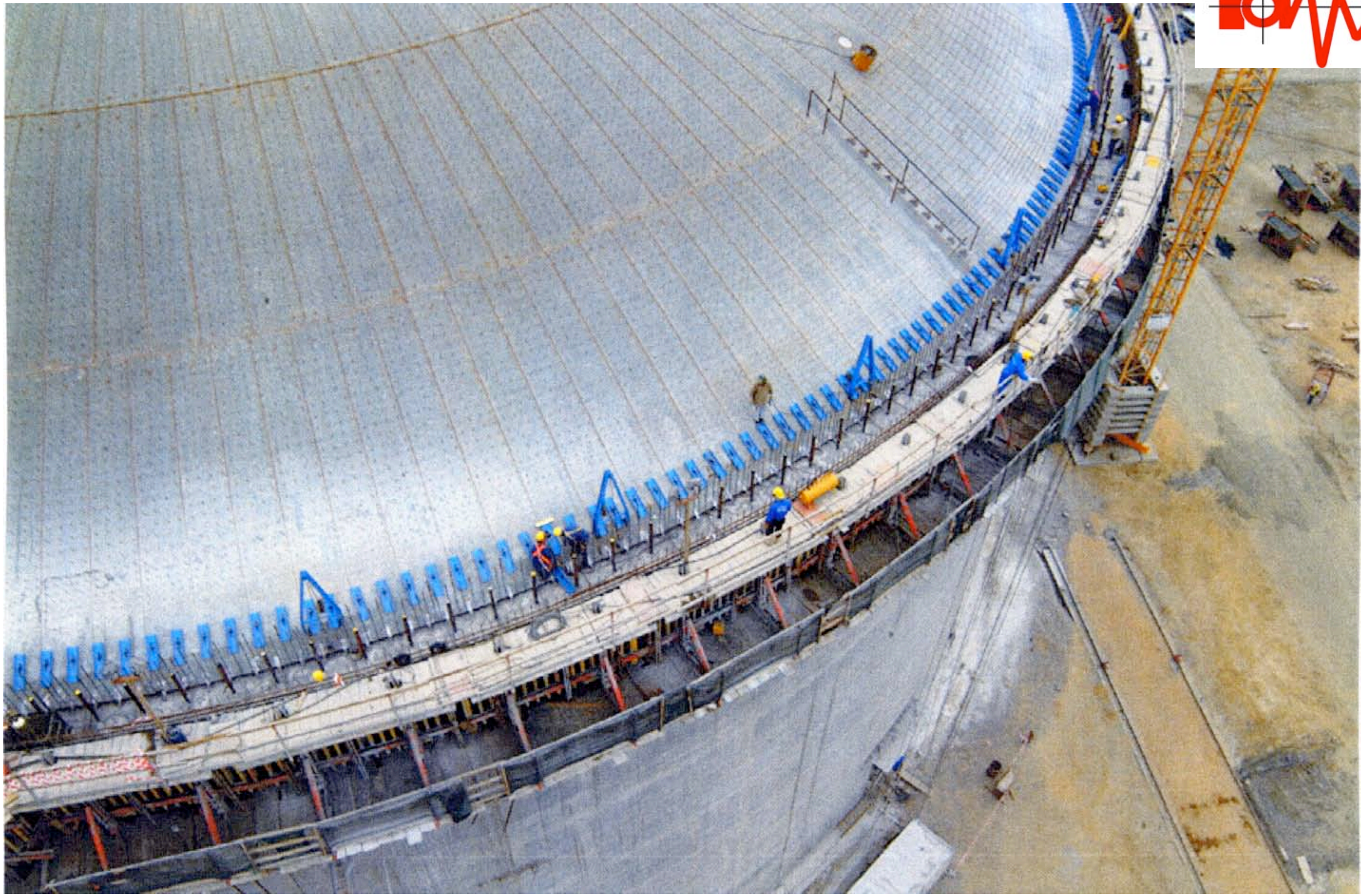
Tank safety issues

- *1.1 Stability of cavern*
  - The assessment of the stability of a large cavern must be considered. When designing cryogenic tanks for above ground factors such as wind loading and seismic effects are taken into account, however large rock falls are not. The structure in a working mine are well understood by the mining engineers.
- *1.2 Seismic events*
  - Consideration of seismic events must be given to both the cavern and the tank. The tank design codes require an assessment of performance at two levels of seismic event corresponding to a 500 year and a 10,000 year return period. The design procedure will require a geo-technical Seismic Hazard Assessment study which will establish design ground accelerations. The tanks can normally be successfully designed to withstand quite severe seismic events.
- *1.3 Catastrophic failure of inner tank*
  - In spite of the recent large rise in LNG tank population, there has been no failure of an LNG tank built to recent codes, materials and quality standards. Catastrophic failure is now discounted as a mode of failure.
- *1.4 Argon gas leaks*
  - According to the most complete source of refrigerated tank failures, there have been 16 leaks from refrigerated storage tanks during the period 1965 to 1995. Using this value, an overall leak frequency can be calculated to be 2.0×10^{-4} per tank year. Measures must be put in place to mitigate the effects of an Argon Gas leak. The force ventilation system required for the insulation system will do this.

A dream come true?



(5) Roof welding



Tank budgetary costing

- The estimated costs tabulated below are for an inner tank of radius 35m and height 20m, an outer tank of radius 36.2m and height 22.5m. The product height is assumed to be 19m giving a product mass of 101.8 k tonnes.

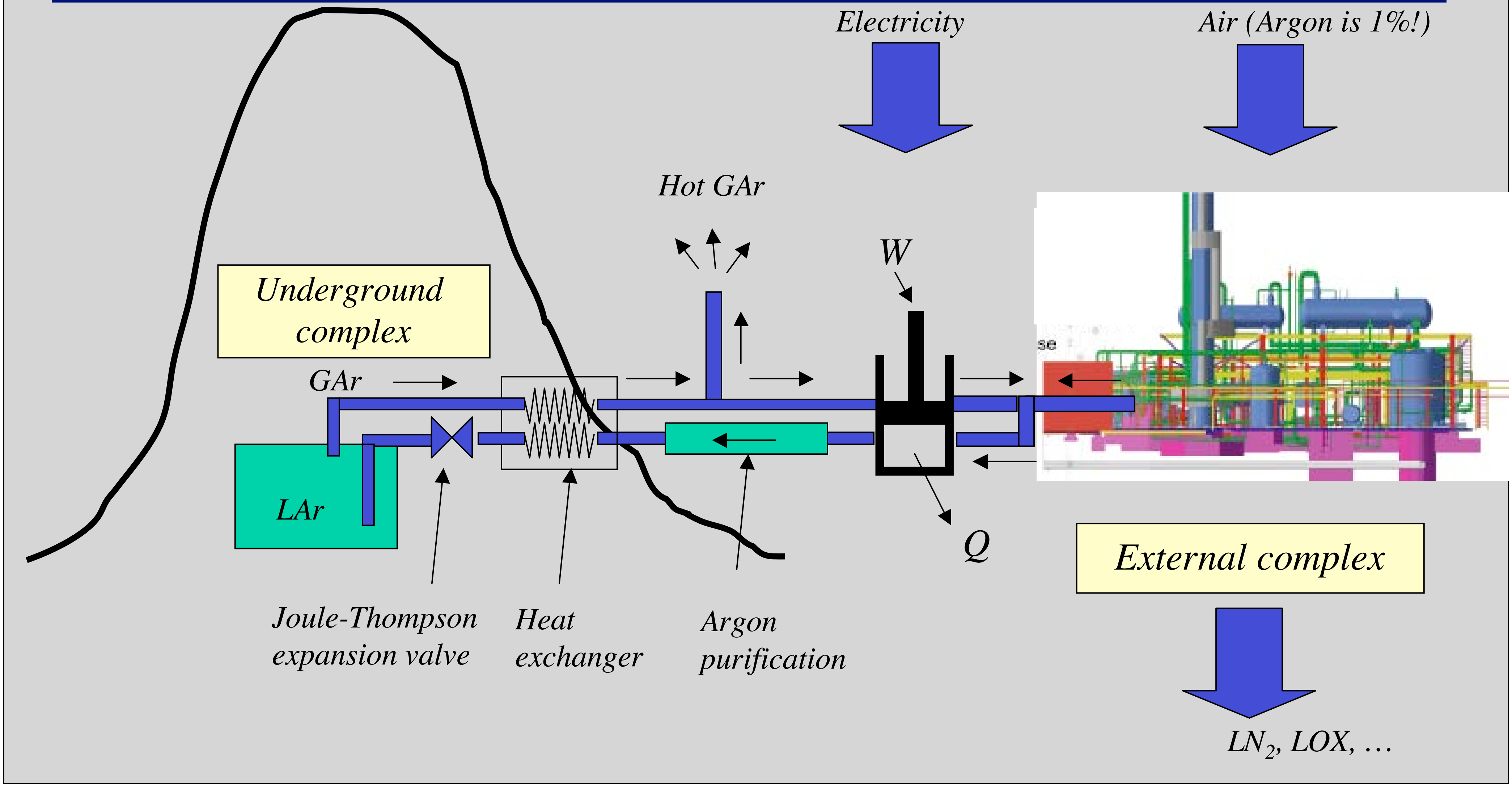
Item	Description	Size	Million Euros
1	Steel	3400 tonnes	11.6 (*)
2	Insulation	16200 m^3	2.6
3	Concrete	9000 m^3	2.7
4	Electro-polishing	38000 m^2 Plate 20.5 km weld	8.2
5	Construction design / labour		18.8
6	Site equipment / infrastructure		9.8
	Total		**53.7**
6	Underground factor		2.0
	Underground tank cost		107.4

Estimate based on existing data for mine operations

(*) includes the recent increase of steel cost (was 6.2 MEuro in 03/2004)

Process system & equipment

- Filling speed (100 kton): 150 ton/day → 2 years to fill
- Initial LAr filling: decide most convenient approach: transport LAr and/or in situ cryogenic plant
- Tanker 5 W/m^2 heat input, continuous re-circulation (purity)
- Boiling-off volume at regime: ≈45 ton/day (≈10 years to evaporate entire volume)



Process considerations

- There are three major items required for generating and maintaining the Liquid Argon needed in the tank. These are:
  - ➥ Filling the tank with the initial Liquid Argon bulk
  - ➥ Re- liquefaction of the gaseous Argon boil-off.
  - ➥ Continuous purification of the Liquid Argon.
- *1.1 Initial fill*
  - ➥ The requirements for the initial fill are large, corresponding to 150 tonnes of Liquid Argon per day over two years. Argon is a by product of the air separation plant which is usually aimed at a certain amount of oxygen production per day. The amount required is a significant proportion of the current European capacity. Hence new investment will be required by the industry to meet the project requirement. This could either be a specific plant located for the project or increases in capacity to several plants in the area. British Oxygen's largest air separation plant in Poland has the capability to produce 50 Tonnes of Liquid Argon per day. However, this is nearly all supplied to industry and therefore the available excess for a project of this size would be relatively small.
  - ➥ A typical air separation plant producing 2000 tonnes per day of Oxygen would produce 90 tonnes per day of Liquid Argon. This facility would have a 50-60 metre high column, would need approximately 30m x 40m of real-estate, would need 30-35MW of power and cost 45 million euros. Energy to fill would cost ≈25MEuro.
  - ➥ Purchasing LAr costs would be in the region of 500 euros per tonne. Transportation costs are mainly dependant upon the cost of fuel and the number of kilometres between supply and site. To fill the tank would require 4500 trips of 25 tons trucks and would cost ≈30 million euros for transport.

Process considerations

- *1.2 Cooldown*
  - ➥ Assuming a start temperature of 35 degrees C and using Liquid Argon to perform the cool-down then the amount of liquid Argon required for the cool-down process would be ≈1000 tonnes LAr. Assuming that the liquefaction plant can produce 150 tonnes / day of liquid argon then the cool-down process would take 7 days.
- *1.3 Re-Liquefaction of the boil-off*
  - ➥ The Technodyne design of the tank assumes that an adequate supply of air is circulated around the tank to prevent the local rock / salt from freezing, thereby reducing the risk of rock movement or fracture. For an air temperature of 35 degrees (constant throughout a 24 hour period) the boil off of Liquid argon would be in the region of 29000 litres per day. This would require ≈10 MW of power.
  - ➥ Alternatively a compression system can take the boil off gas and re-compress, filter and then re-supply to the tank. The power is likely to be a similar order of magnitude of 8 MW.
- *1.4 Purification of the Liquid Argon*
  - ➥ The Liquid Argon should be as pure as possible, the required target impurities being less than 0.1 ppb. To achieve this argon must be re-circulated through a filter system to remove impurities. The requirement is to re-circulate all the LAr in a period of 3 months. This equates to 33m^3 / hour. The use of Messer- Griesheim filters suggests that a flow of 500 l / hour is possible through a standard hydrosorb / oxysorb filter. This would equate to a requirement for a minimum of 67 filters to achieve the required flow rate.

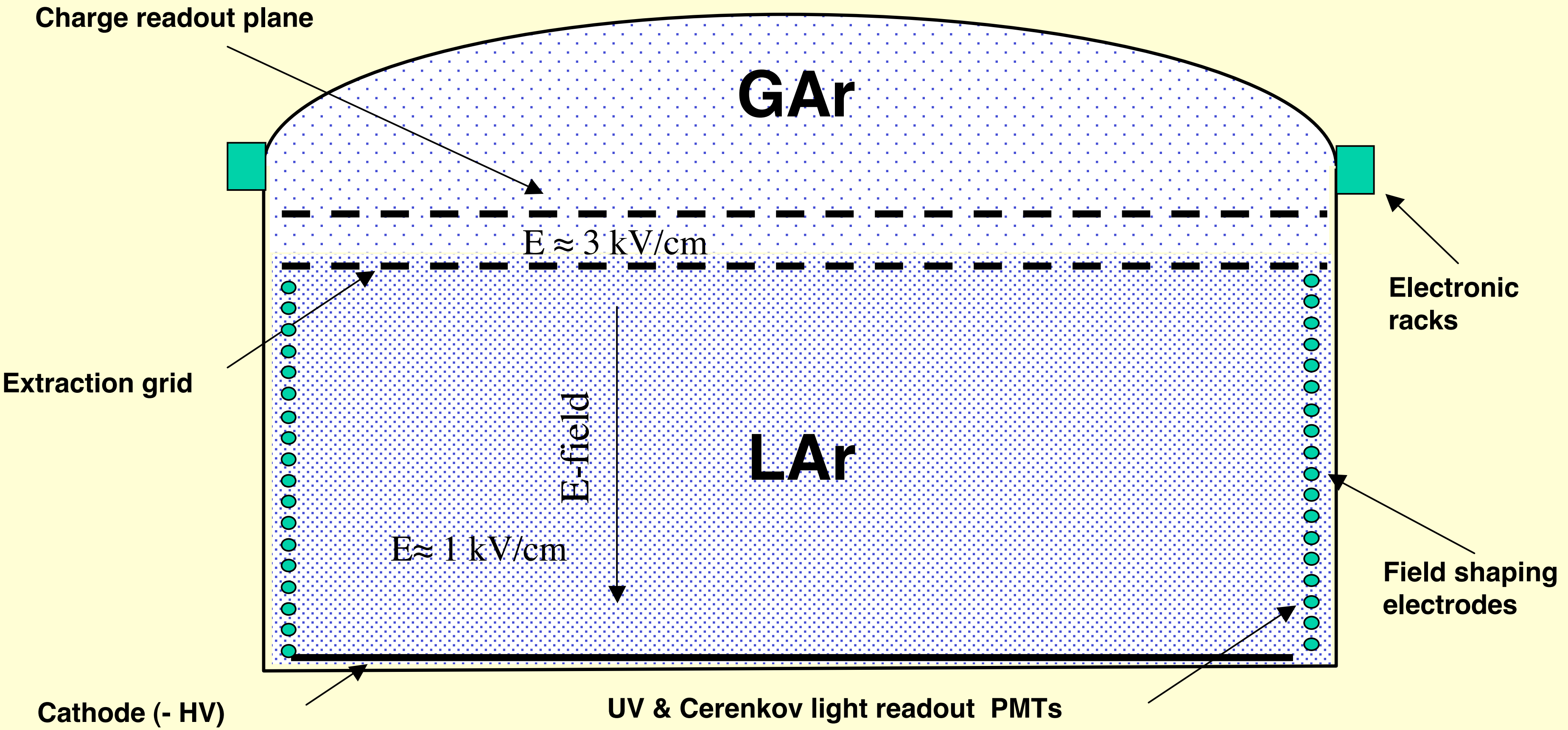
Detector layout

A “simple” scalable detector layout

A tentative detector layout

Single detector: charge imaging, scintillation, possibly Cerenkov light

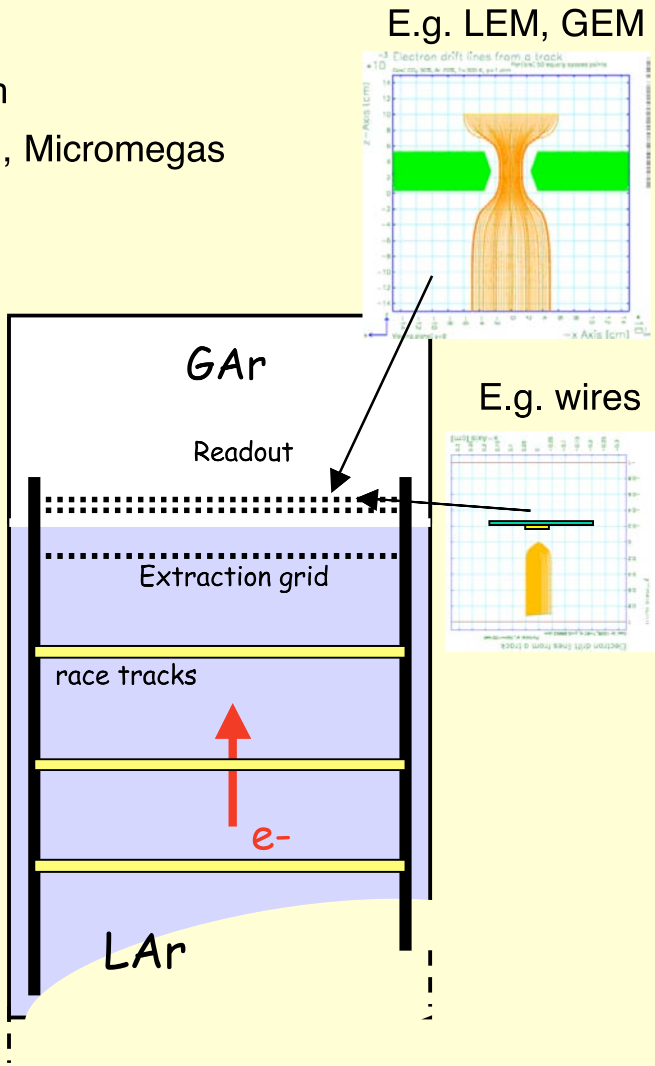
Dewar	$\phi \approx 70$ m, height ≈ 20 m, perlite insulated, heat input ≈ 5 W/m^2
Argon storage	Boiling Argon, low pressure (<100 mbar overpressure)
Argon total volume	73000 m^3, ratio area/volume $\approx 15\%$
Argon total mass	102000 tons
Hydrostatic pressure at bottom	3 atmospheres
Inner detector dimensions	Disc $\phi \approx 70$ m located in gas phase above liquid phase
Charge readout electronics	100000 channels, 100 racks on top of the dewar
Scintillation light readout	Yes (also for triggering), 1000 immersed 8" PMTs with WLS
Visible light readout	Yes (Cerenkov light), 27000 immersed 8" PMTs of 20% coverage, single γ counting capability



Charge extraction, amplification, readout

Detector is running in bi-phase mode TO ALLOW FOR A VERY LONG DRIFT PATH

- Long drift (≈ 20 m) ⇒ charge attenuation to be compensated by charge amplification near anodes located in gas phase (18000 e^- / 3 mm for a MIP in LAr)
- Amplification operates in proportional mode
- After maximum drift of 20 m @ 1 kV/cm ⇒ diffusion ≈ readout pitch ≈ 3 mm
- Amplification can be implemented in different ways: wires+pad, GEM, LEM, Micromegas



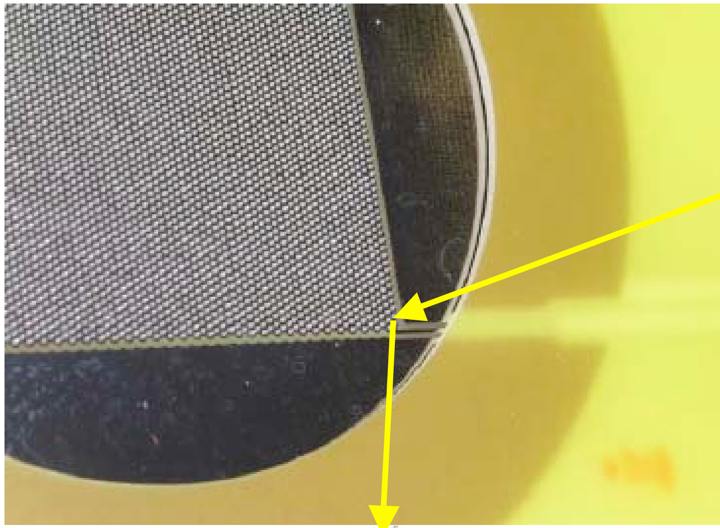
Electron drift in liquid	**20 m maximum drift, HV = 2 MV for E = 1 kV/cm, v_d ≈ 2 mm/μs, max drift time ≈ 10 ms**
Charge readout view	**2 perpendicular views, 3 mm pitch, 100000 readout channels**
Maximum charge diffusion	**$\sigma \approx$ 2.8 mm ($\sqrt{2Dt_{max}}$ for D = 4 cm²/s)**
Maximum charge attenuation	**$e^{-(t_{max}/\tau)} \approx$ 1/150 for τ = 2 ms electron lifetime**
Needed charge amplification	**From 100 to 1000**
Methods for amplification	**Extraction to and amplification in gas phase**
Possible solutions	**Thin wires ($\phi \approx$ 30 μm) + pad readout, GEM, LEM, Micromegas… Total area ≈ 3850 m²**

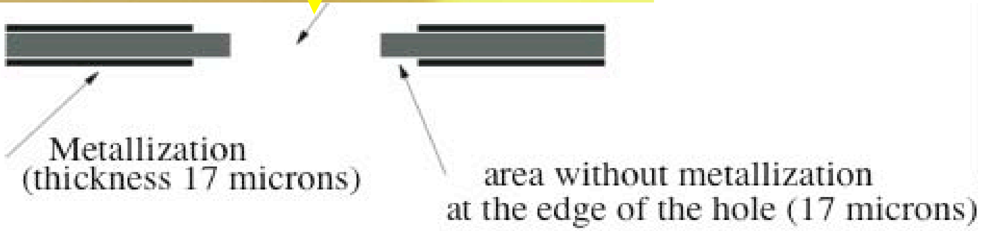
(1) Thick Large Electron Multiplier (LEM)

Thick-LEM (vetronite Cu coated + holes)

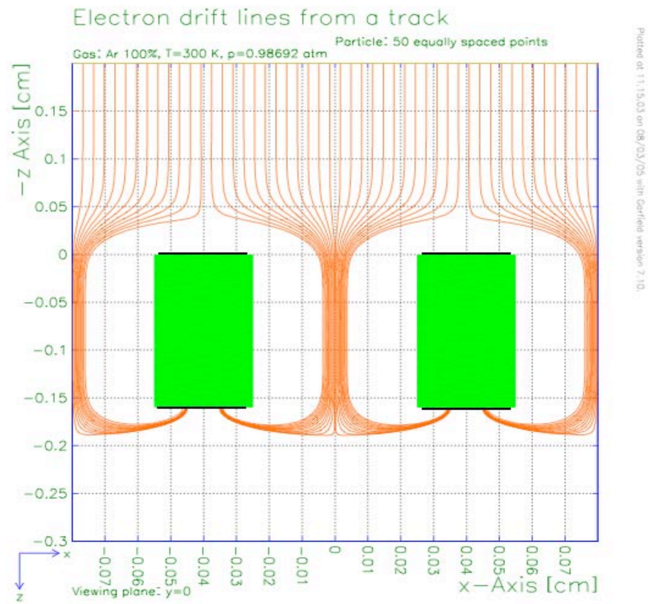
Sort of macroscopic GEM. Easier to operate at cryogenic temperature.

On application of a difference of potential between the two electrodes, electrons on one side of the structure drift into the holes, multiply and transfer to a collection region.



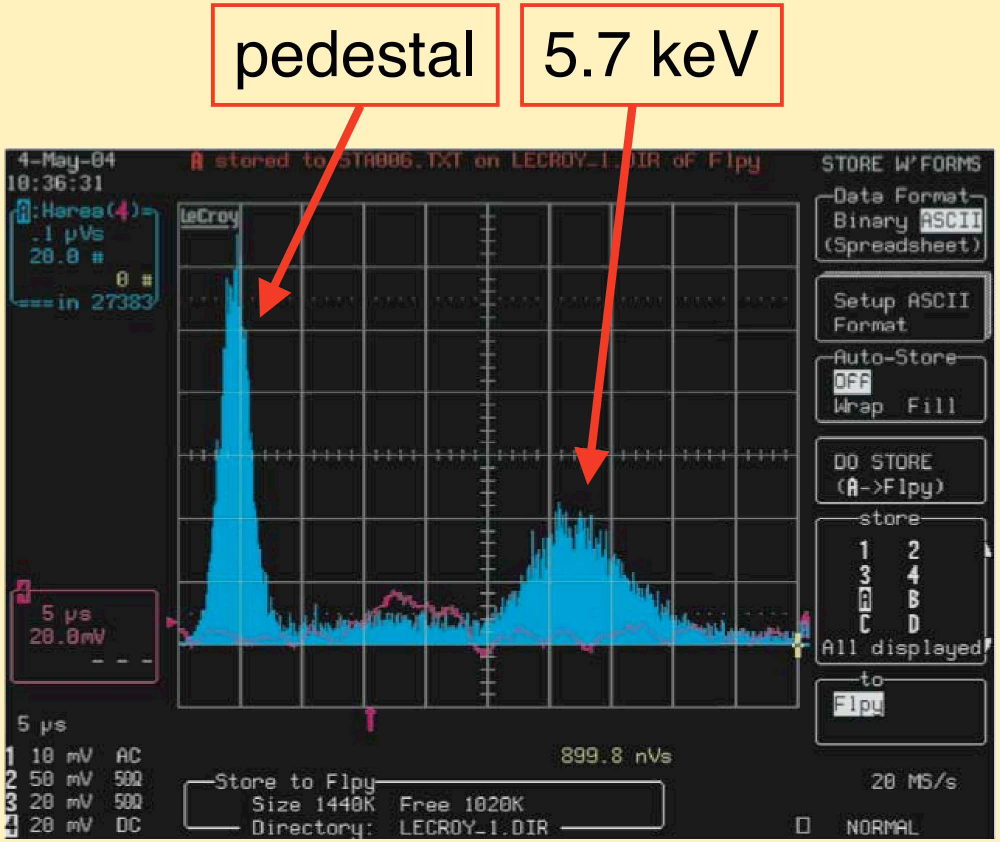


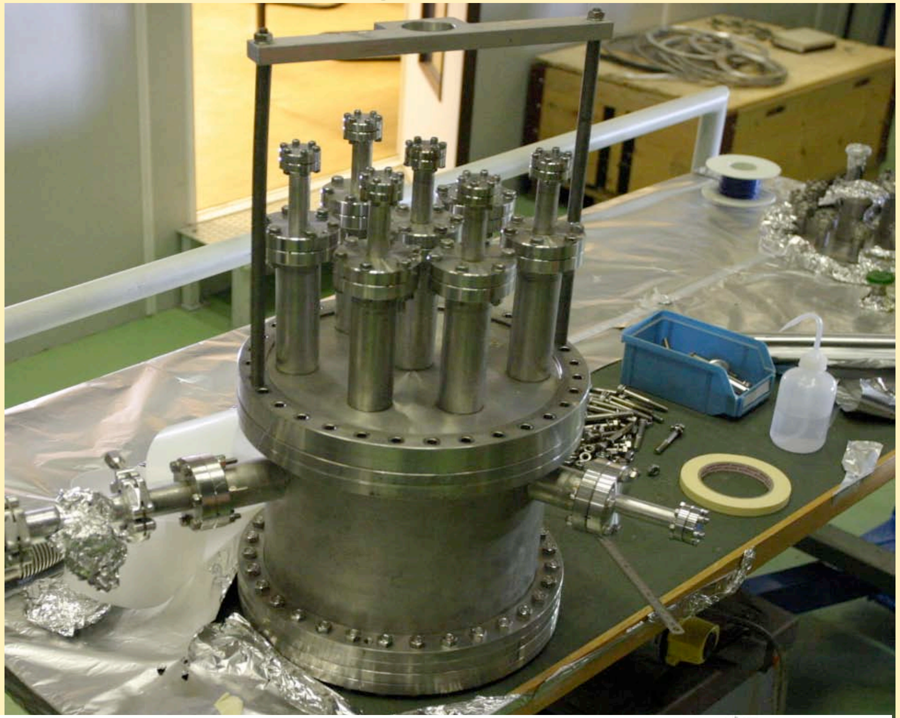
- Three thicknesses: 1, 1.6 and 2.4 mm
- Amplification hole diameter = 500 μm

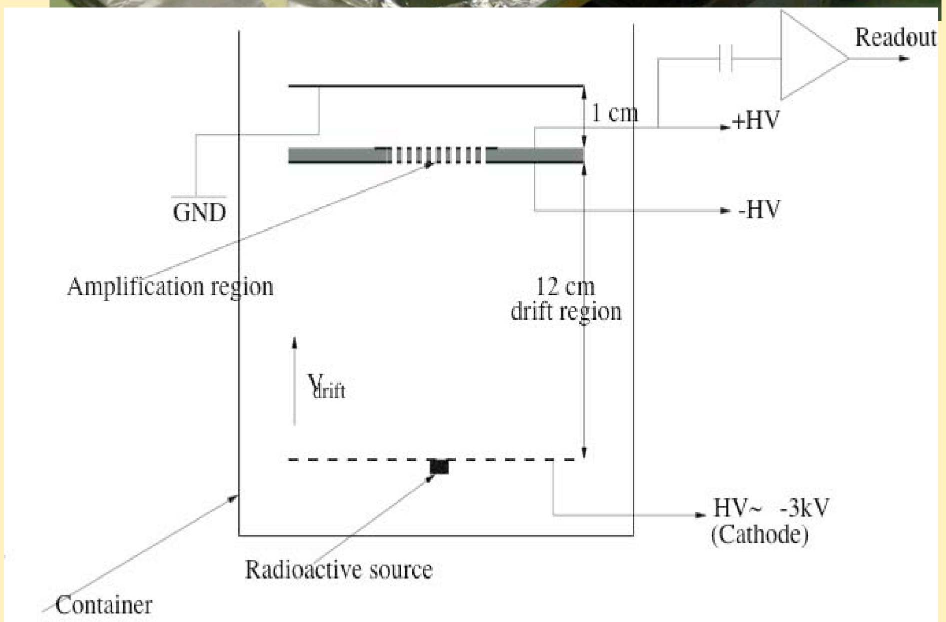


High gain operation of LEM in pure Ar at high pressure

- Fe-55 & Cd-109 sources, Argon 100%
- Varying pressures (from 1 bar up to 3.5 bar)
- Room temperature
- Drift field ≈100V/cm (100% transparency)

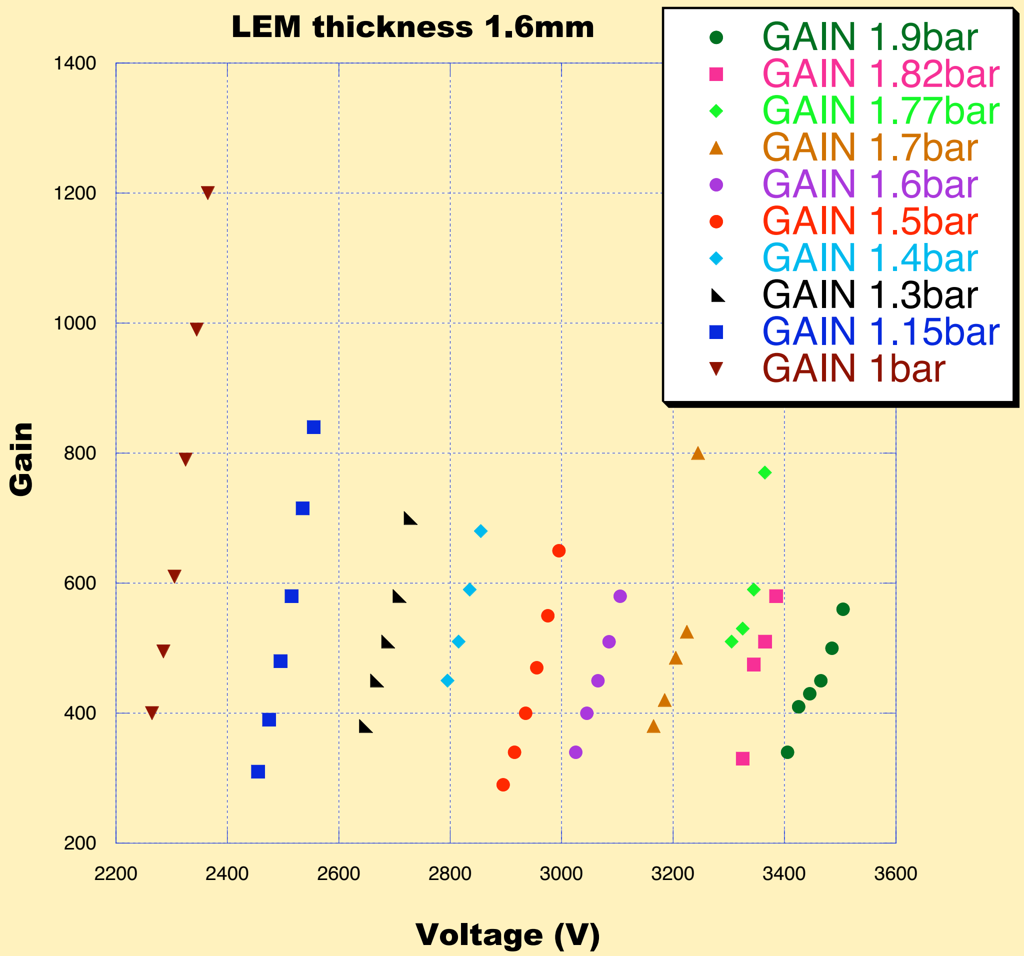


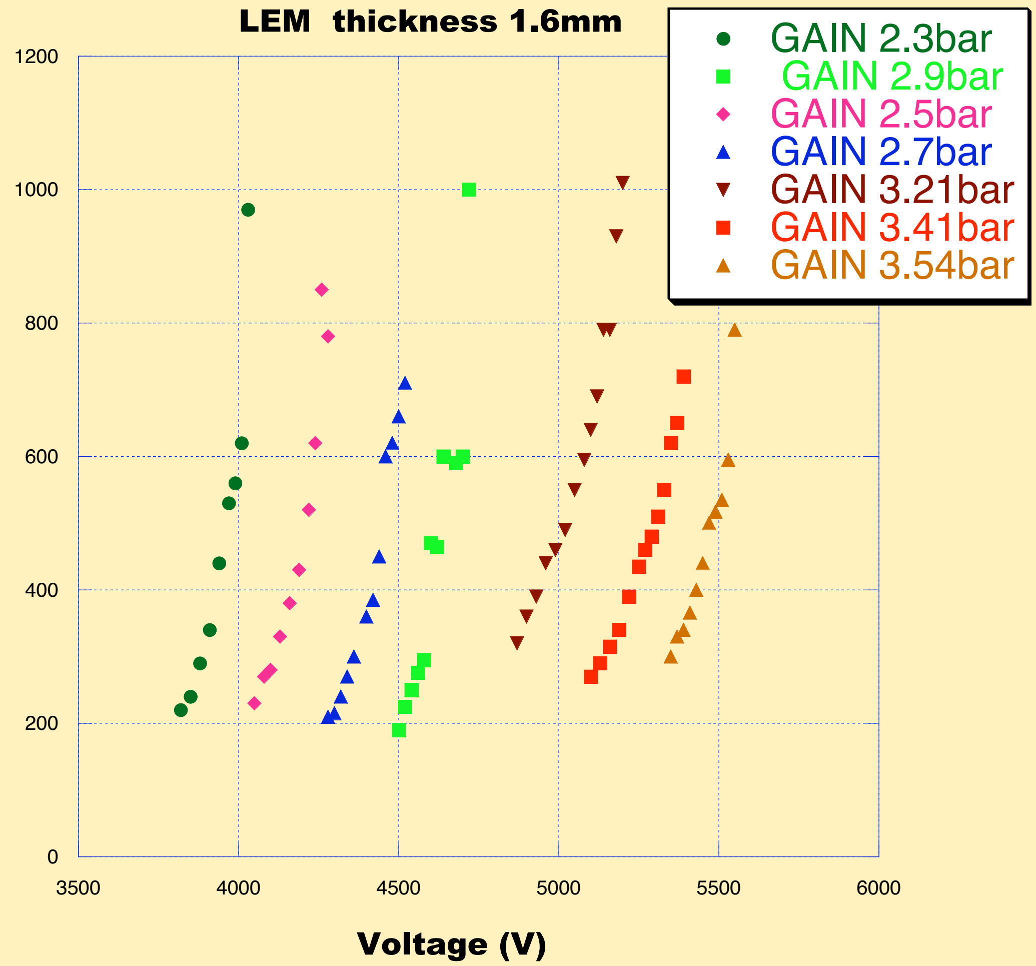




High gain operation of LEM in pure Ar at high pressure

- Fe-55 & Cd-109 sources, Argon 100%, Room temperature





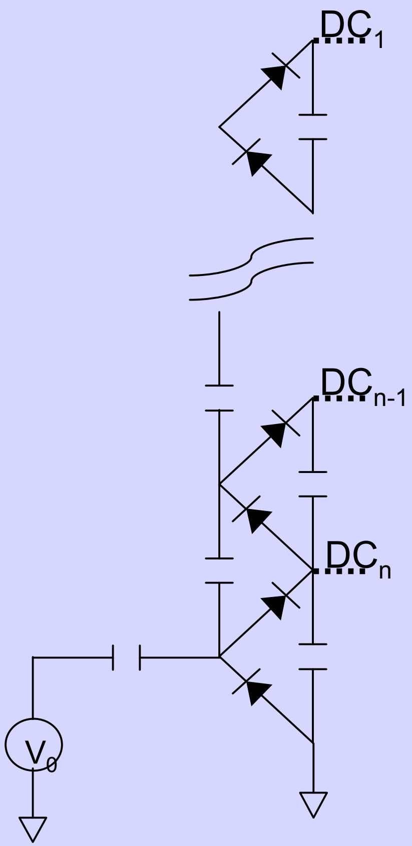
Gain up to ≈800 possible even at high pressure (good prospects for operation in cold)

Resolution ≈ 28% FWHM for Fe-55 source

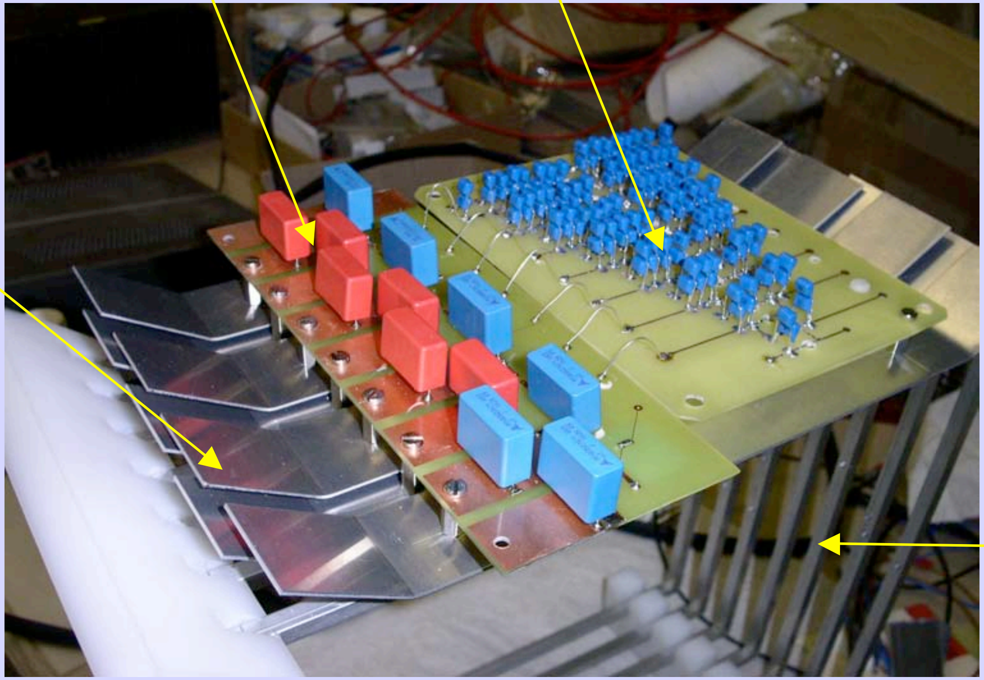
Good agreement with GARFIELD simulations (confirm shower confinement)

(2) Drift very high voltage: Greinacher circuit

- No load to avoid resistive ripple
- Low frequency (50-500 Hz) to induce noise with a spectrum far from the bandwidth of the preamplifiers used to read out the wires or strips
- Possibility to stop feeding circuit during an event trigger

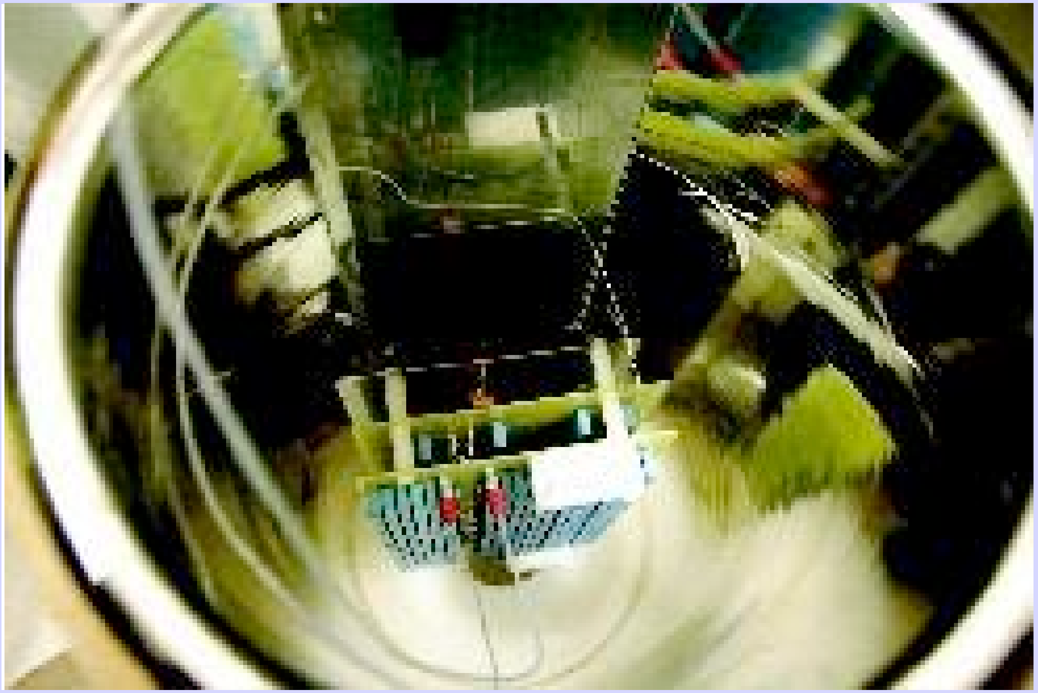


Greinacher or Cockroft/Walton voltage multiplier



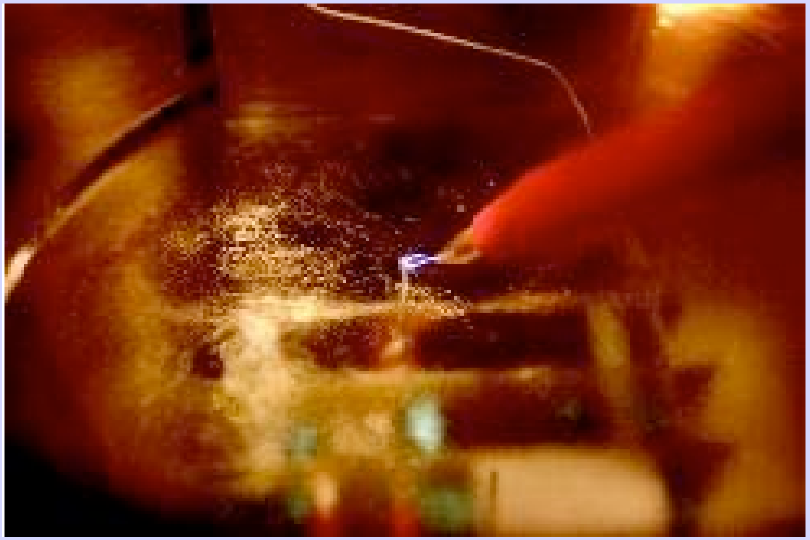
Prototype connected to actual electrodes of 50 liter TPC (ripple noise test)
Successfully tested up to ≈20kV

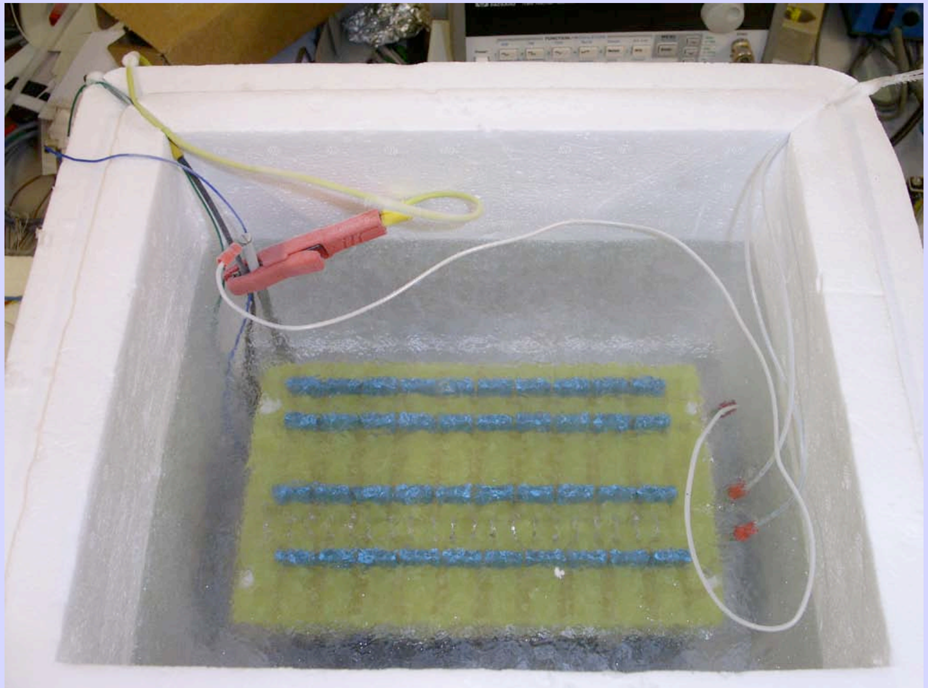
Drift very high voltage: 40 kV multiplier in LAr



- NOVACAP(USA) NP0 dielectric capacitors, stable in temperature and against discharge. Tested successfully in our lab

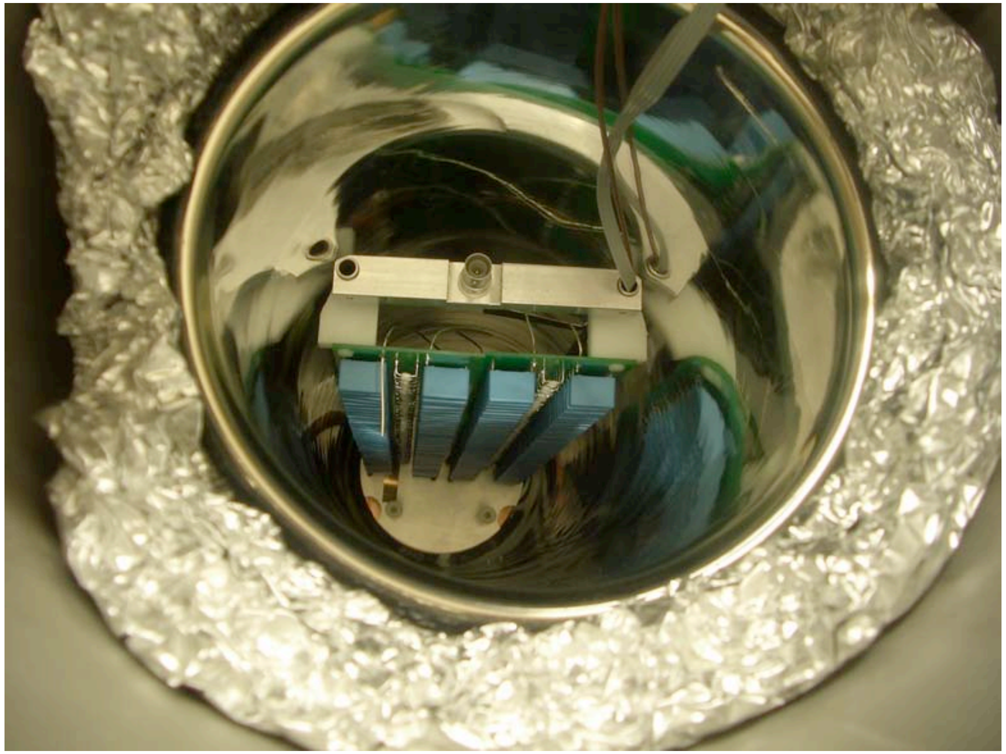
- HV diodes from Vishay/Phillips

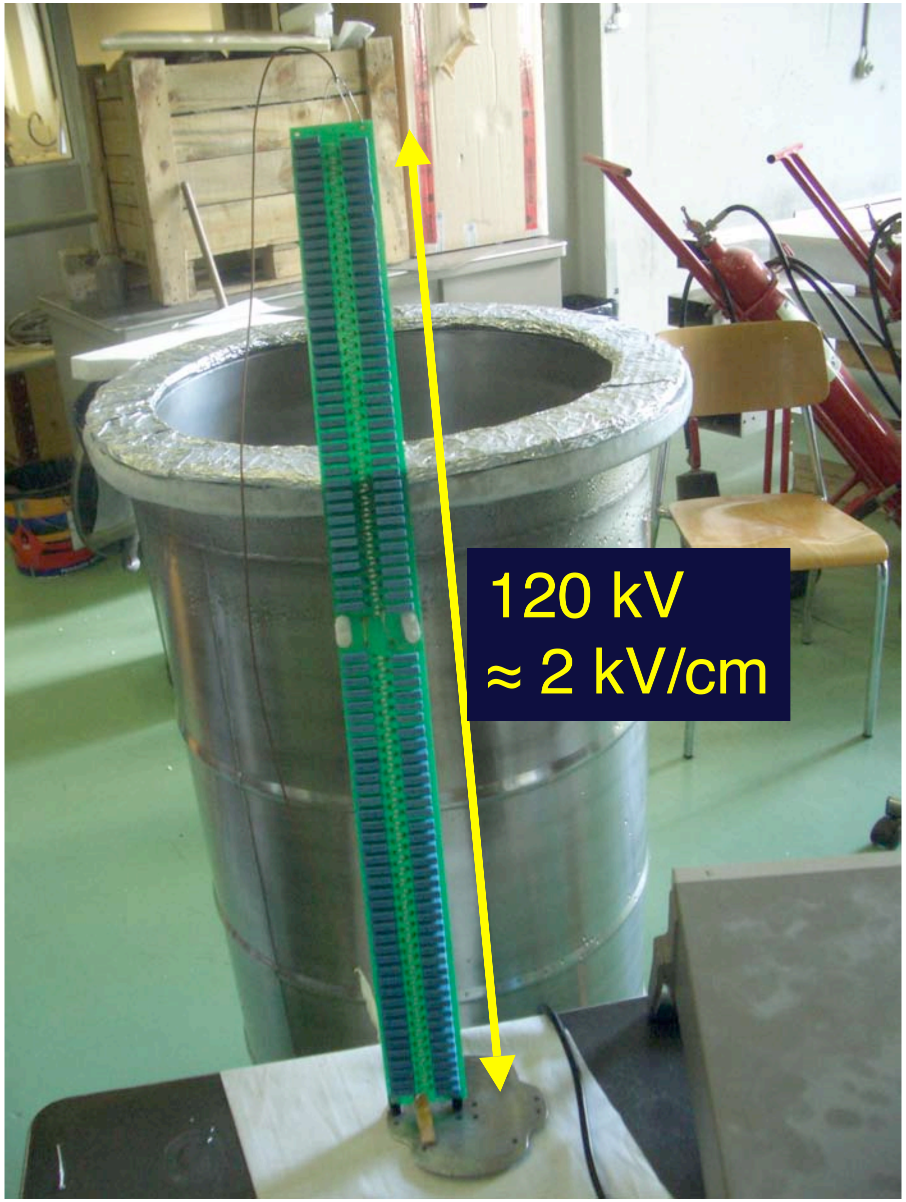




Results from HV tests in cold

- A large number of tests in cold have been performed in order to assess component choice and stability.
- The largest system successfully operated consisted of 80 stages and reached stable operation up to 120 kV.
- Test to 240 kV (≈4kV/cm) in preparation.





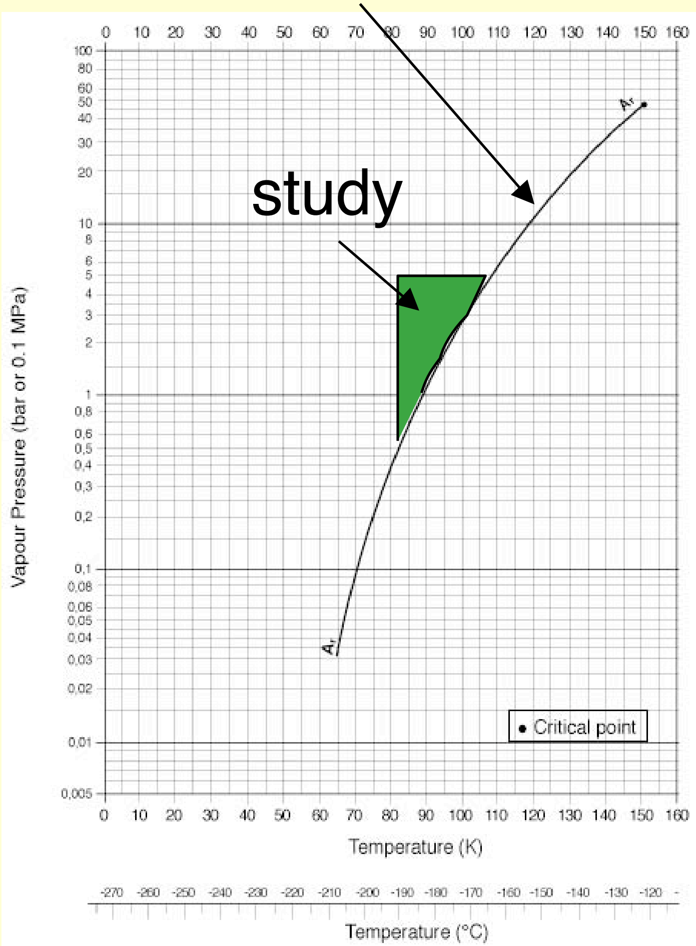
(3) High-pressure drift properties in liquid Argon

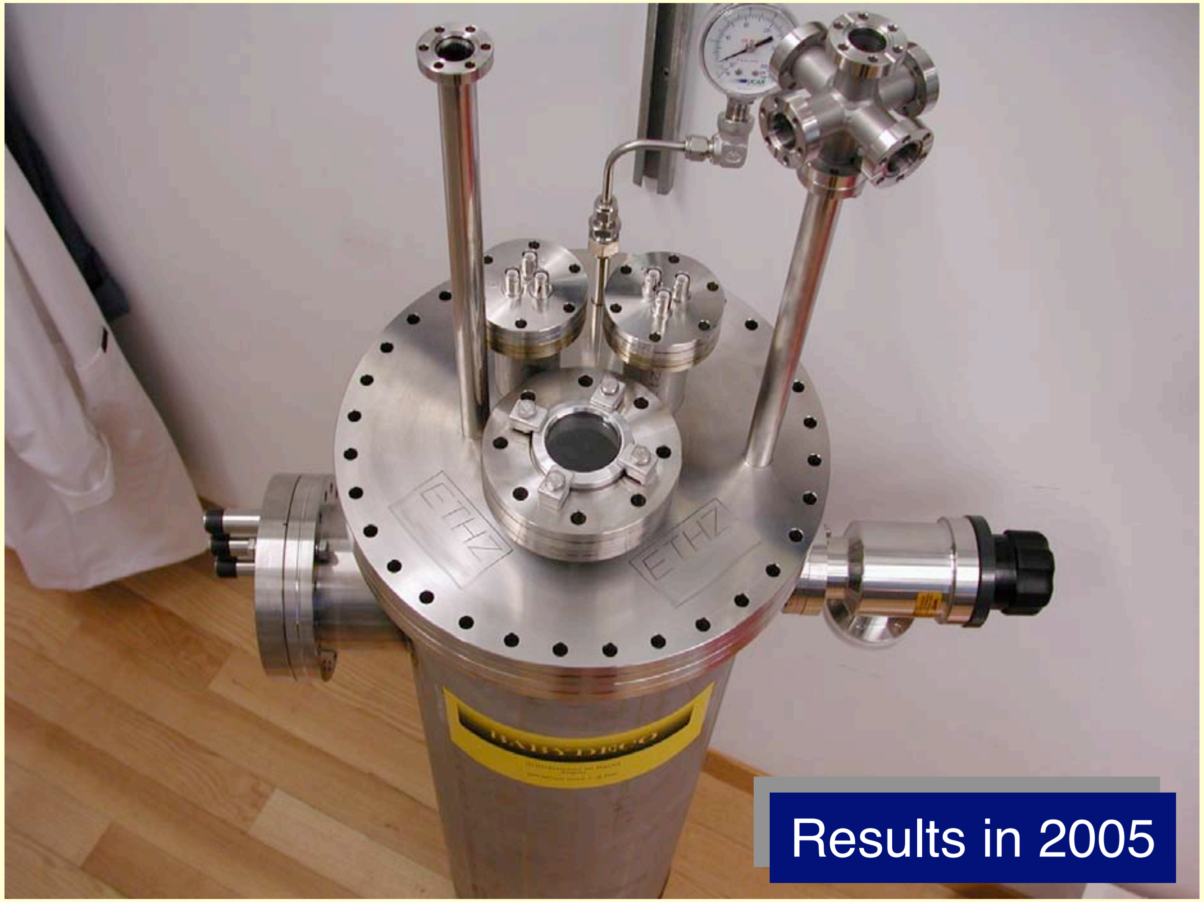
- **At the bottom of the large tankers:**

  Hydrostatic pressure could be quite significant (up to 3-4 atmosphere)

- **Test of electron drift properties in high pressure liquid Argon**

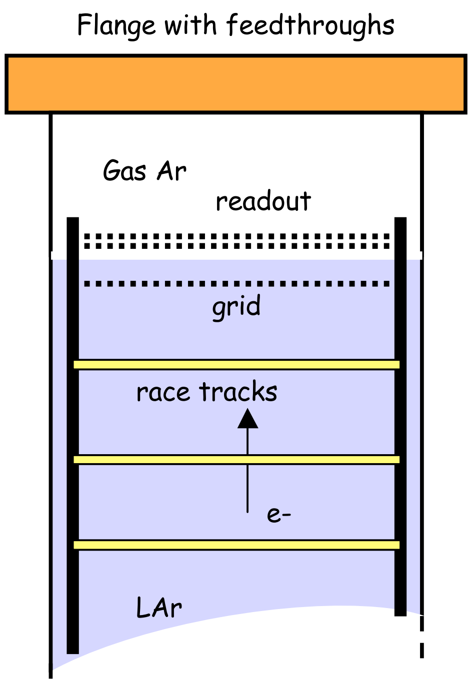
  Important to understand the electron drift properties and imaging under pressure above equilibrium vapor pressure

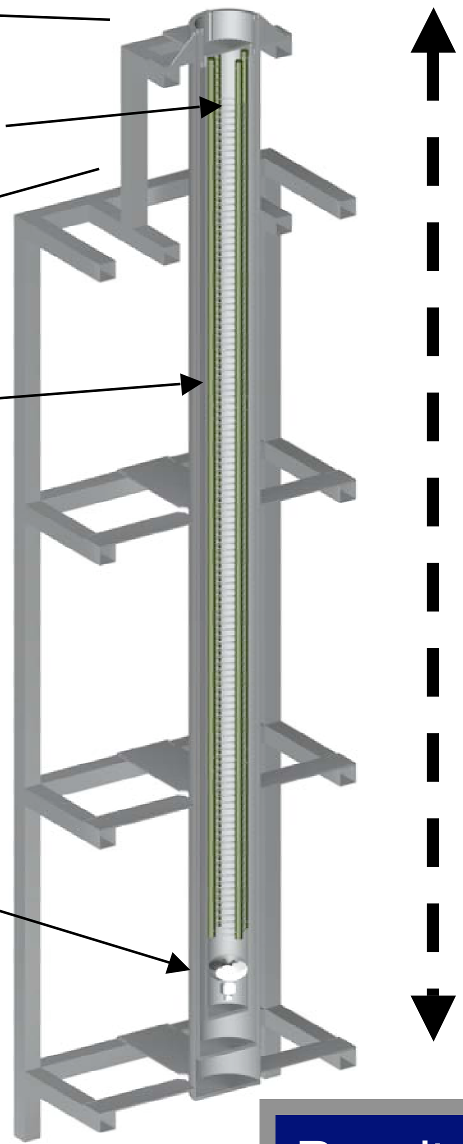




Results in 2005

(4) Long drift, extraction, amplification: “ARGONTUBE”





- Full scale measurement of long drift (5 m), signal attenuation and multiplication
- Simulate ‘very long’ drift (10-20 m) by reduced E field & LAr purity
- High voltage test (up to 500 kV)
- Design & assembly:

completed: external dewar, detector container

in progress: inner detector, readout system, …

Results in 2006

Detector in the support structure
(horizontal garage position)

Front view

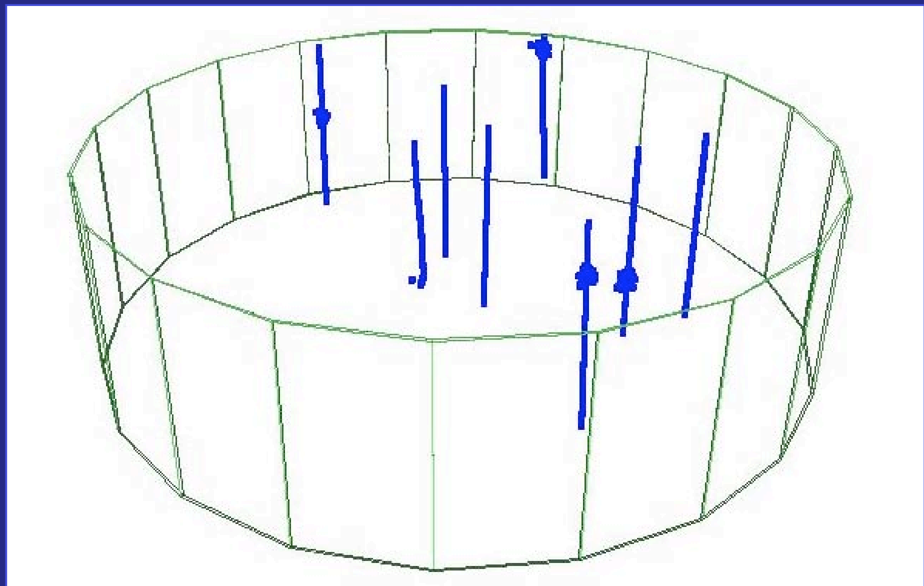
Arrived at ETHZ on September 21st, 2005

Shallow depth

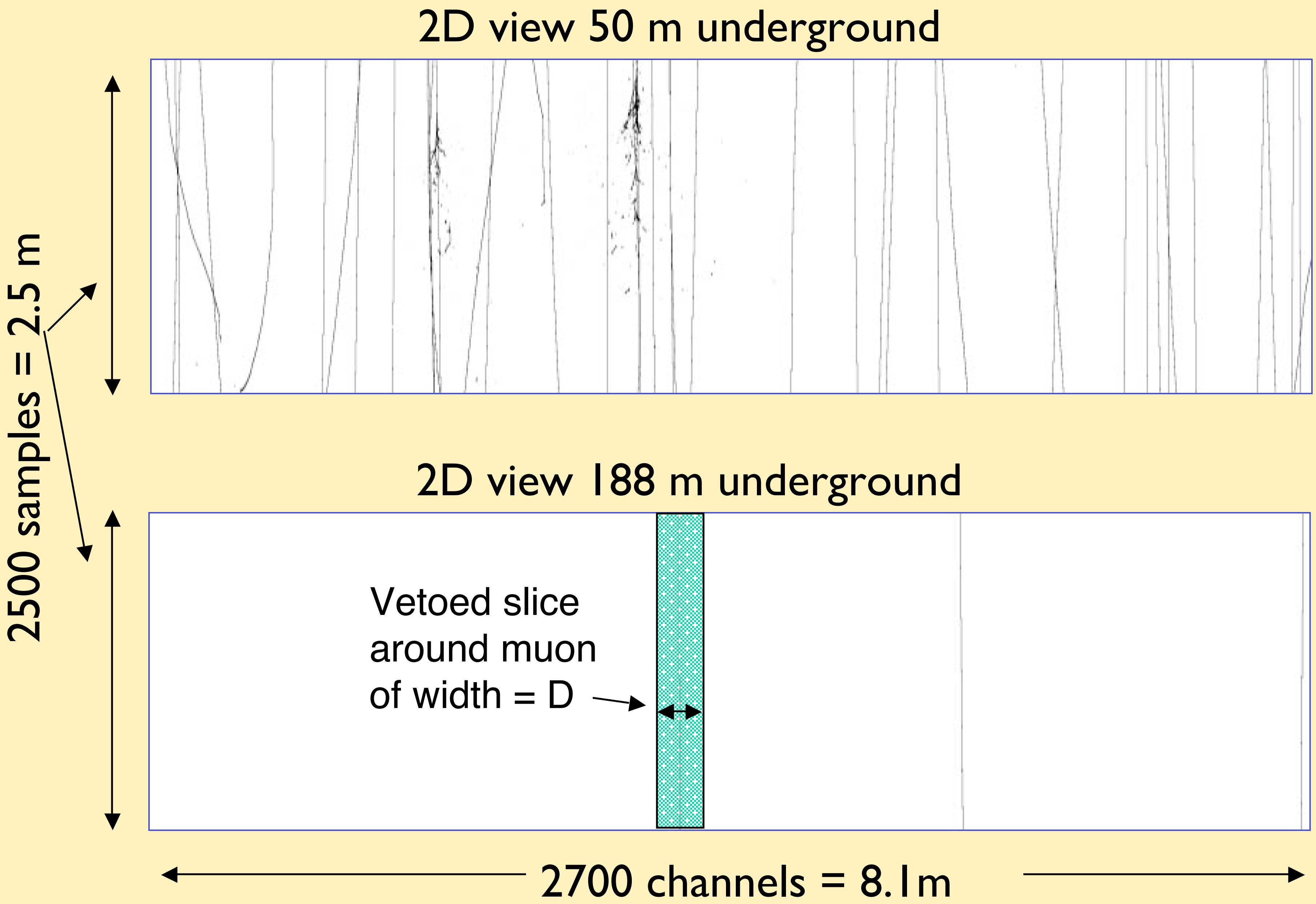
Detector depth

- It is generally assumed that the detector will be located deep underground in order to shield it from cosmic rays.
  - ➥ **Is a shallow depth operation possible?**
- This is not a trivial question. We have started to perform detailed simulations to understand operation at a shallow depth (At a minimum of 50 meter underground and below)
- Preliminary results on (a) crossing muons rates which are important to design detector readout system and fiducial volume definition (b) background to proton decay searches associated to cosmogenic backgrounds

Underground muons are essentially vertical and in our drift configuration point along the drift direction to minimize impact on number of touched channels.
When a muon cross the detector, we "veto" a slice around it of width = D



Example for 50m vs 188m rock overburden



Crossing muon rates at different detector depths

Muon flux on surface = 70 m^{-2} s^{-1} sr^{-1} with E_{μ} > 1GeV

Depth rock	**Total crossing muons (E> 1GeV) per 10ms**	**Fiducial mass after slice of size D around each muon is vetoed**		
		D=10 cm	D=20 cm	D=30 cm
Surface	**13000**	…	…	…
50 m	**100**	50 kton	25 kton	10 kton
188 m	**3.2**	98 kton	96 kton	94 kton
377 m (1 km w.e)	**0.65**	100 kton	100 kton	100 kton
755 m (2 km w.e)	**0.062**	100 kton	100 kton	100 kton
1.13 km (3 km w.e)	**0.010**	100 kton	100 kton	100 kton

Cosmogenic background

High energy hadrons are produced by hard photonuclear reactions of cosmic muons

Results from full FLUKA simulation (courtesy of P. Sala) and GEANT4 cross-checks

Depth rock	Particles entering 100 kton detector per year				
	Neutron (T>1.5 GeV)		K^0_L		Λ^0
50 m	3300000	59000	17000000	42000	≈2% of K^0_L
188 m	270000	1100	2500000	4500	≈2% of K^0_L
377 m (1 km w.e)	100000	430	700000	1300	≈3% of K^0_L
755 m (2 km w.e)	13000	35	76000	140	≈3% of K^0_L
1.13 km (3 km w.e)	2600	13	14000	25	≈4% of K^0_L

Only those produced by a muon contained in rock (not seen in LAr)

Magnetic field

New: A superconducting magnetized LAr TPC detector

- The presence of magnetic field is required for the application in the context of the NF. We can consider two fields: B=0.1 T for the measurement of the muon charge (CP-violation), and B=1 T for the measurement of the muon/electron charges (T-violation).

- At Nufact01 a design with a magnetic field was presented by Cline et al. However, the presence of long wires in their design disfavours the possibility to use magnetic field. In addition, they proposed a warm coil which would dissipate 17 MW @ 0.2 T (88 MW @ 1T) and assumed a heat input for the LAr of 1 W/m^2.

- We have demonstrated the possibility to use a LAr TPC in magnetic field (see New J.Phys.7:63 (2005) and physics/0505151, accepted in NIMA). This encouraging result now allows use to further consider a design with magnetic field.

- Hence, we propose to magnetize the very large LAr volume **by immersing a superconducting solenoid directly into the LAr tank to create a magnetic field, parallel to the drift-field**.

- For a B=0.1T (resp. 1T) the stored energy in the B-field is 280 MJ (resp. 30 GJ). In case of quenching of the coil, the LAr would absorb the dissipated heat which would produce a boil-off of 2 tons (resp. 200 tons) of LAr. This corresponds to 0.001% (resp. 0.1%) of the total LAr contained in the tank and hence favours once again our approach.

- In the superconducting phase, there is no heat dissipation and the current in the coil flows forever even when disconnected from the power supply.

A possible improvement of the LAr TPC technique ?

Operation of the LAr TPC embedded in a magnetic field

Nucl. Phys. B 631 239;
Nucl. Phys. B 589 577;
hep-ph/0402110;
hep-ph/0106088

The possibility to complement the features of the LAr TPC with those provided by a magnetic field has been considered and would open new possibilities (a) charge discrimination, (b) momentum measurement of particles escaping the detector (e.g. high energy muons), (c) very precise kinematics, since the measurement precision is limited by multiple scattering. These features are mandatory at a NF.

Momentum measurement:

$$\frac{\Delta p}{p} \approx \frac{0.14}{B(Tesla)\sqrt{(x(m))}\ \cos\lambda}$$

x=track length

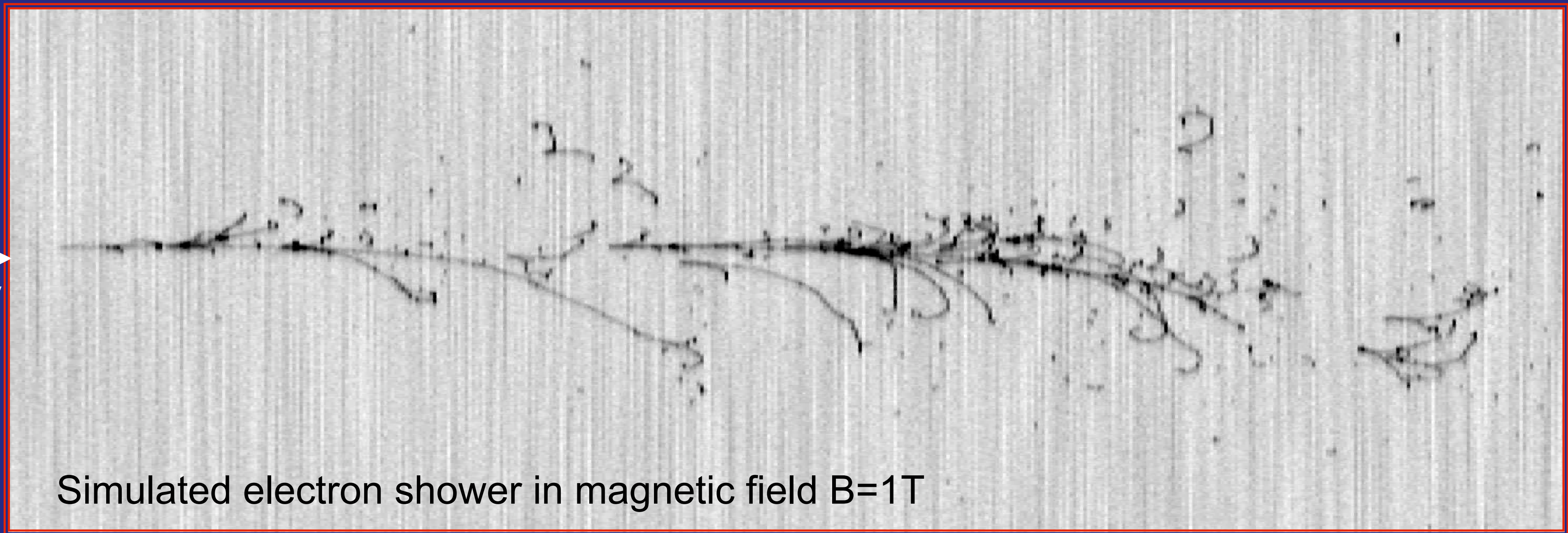
λ=pitch angle

Required field for 3σ charge discrimination:

$$B \geq \frac{0.2\,(Tesla)}{\sqrt{x(m)\ \cos^3\lambda}}$$

e⁻

2.5 GeV

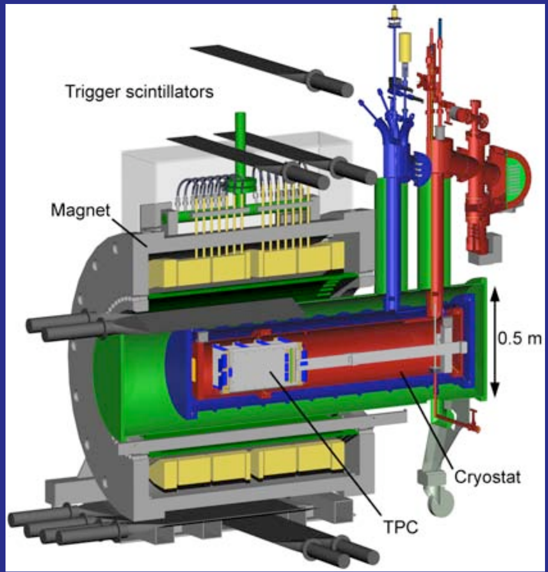


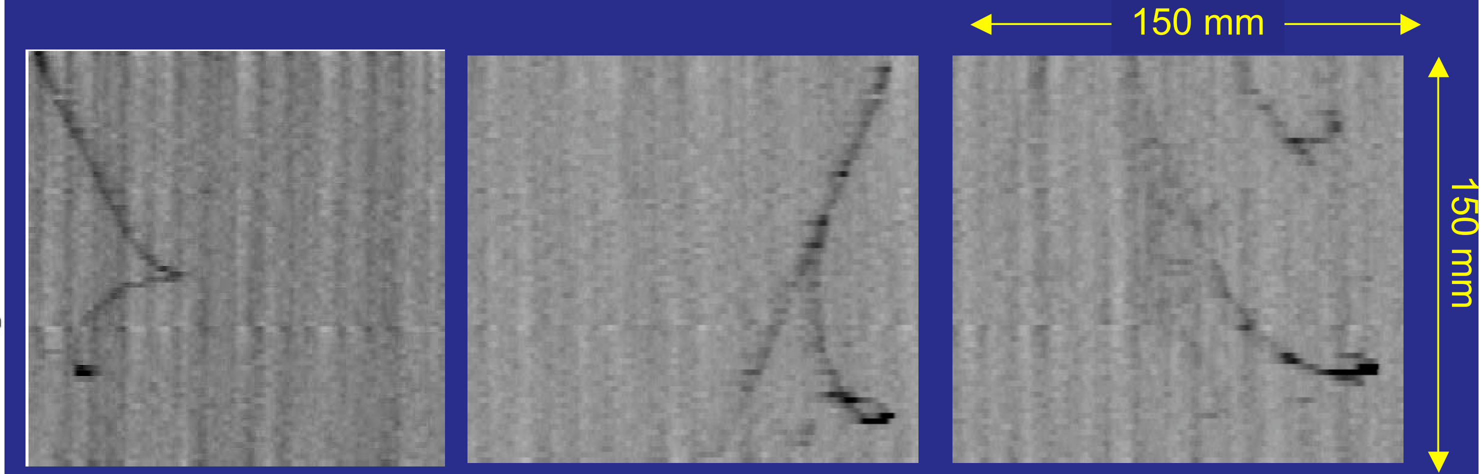
Simulated electron shower in magnetic field B=1T

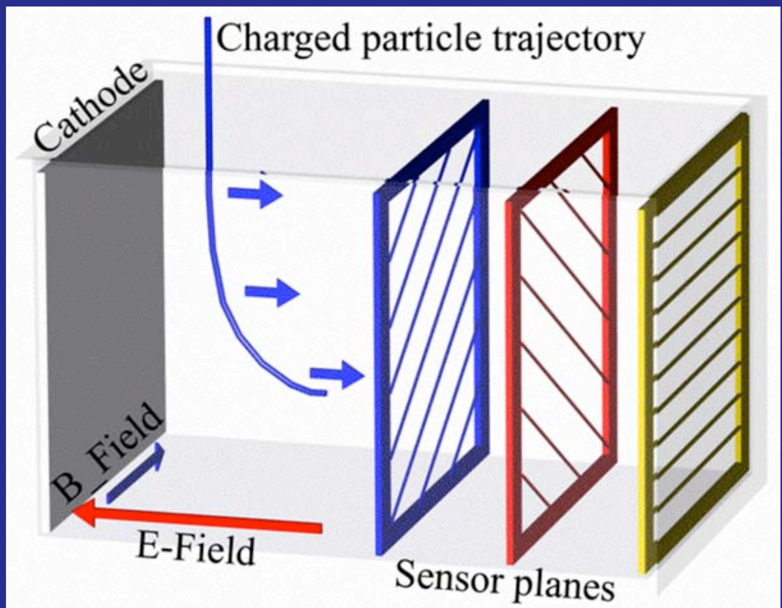
First operation of a 10 lt LAr TPC embedded in a B-field

New J. Phys. 7 (2005) 63

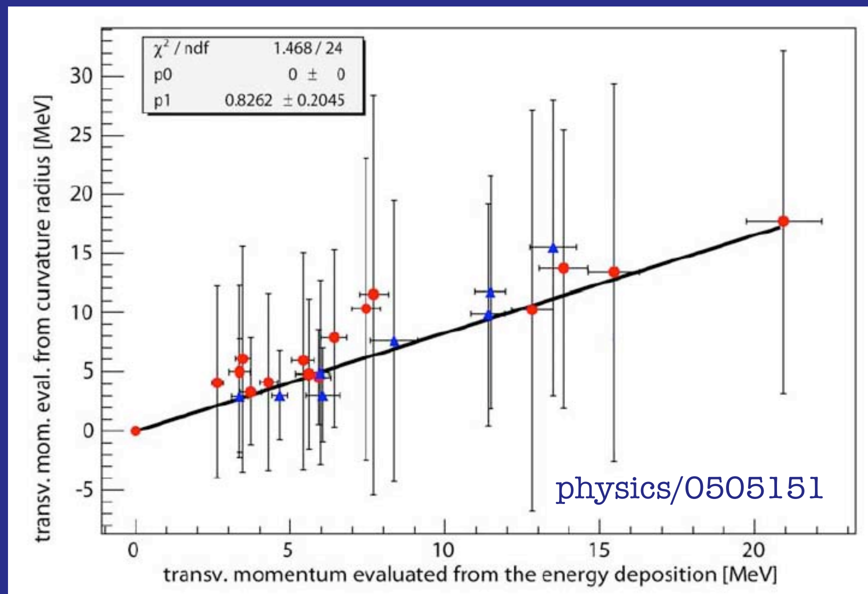
First real events in B-field (B=0.55T):

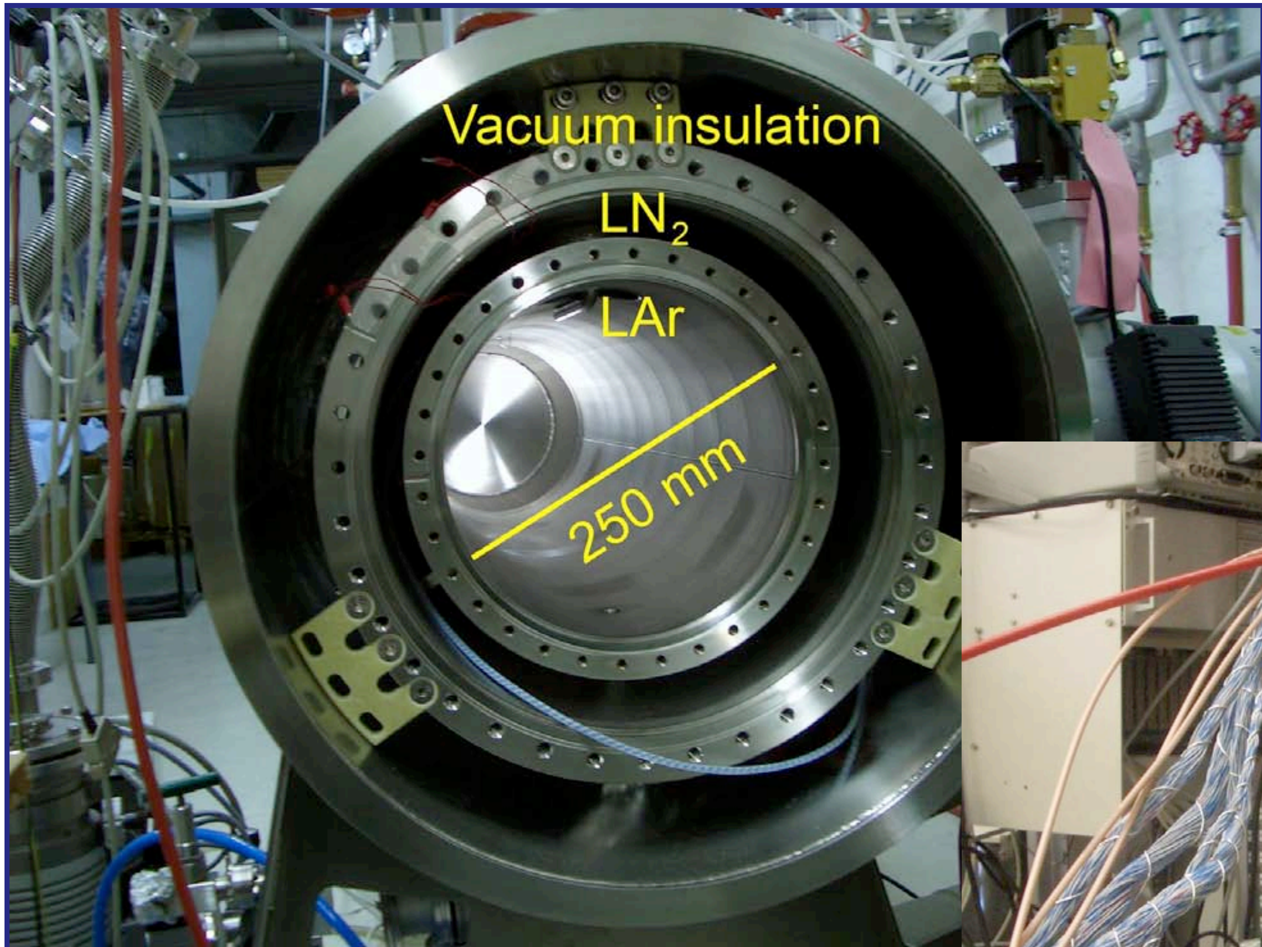




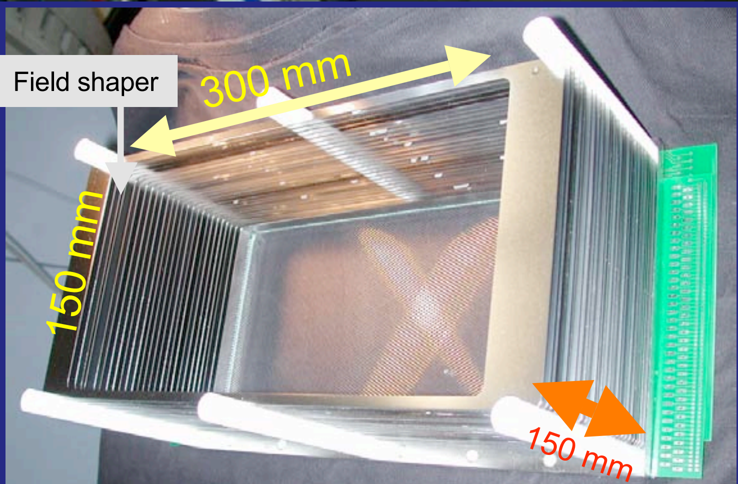


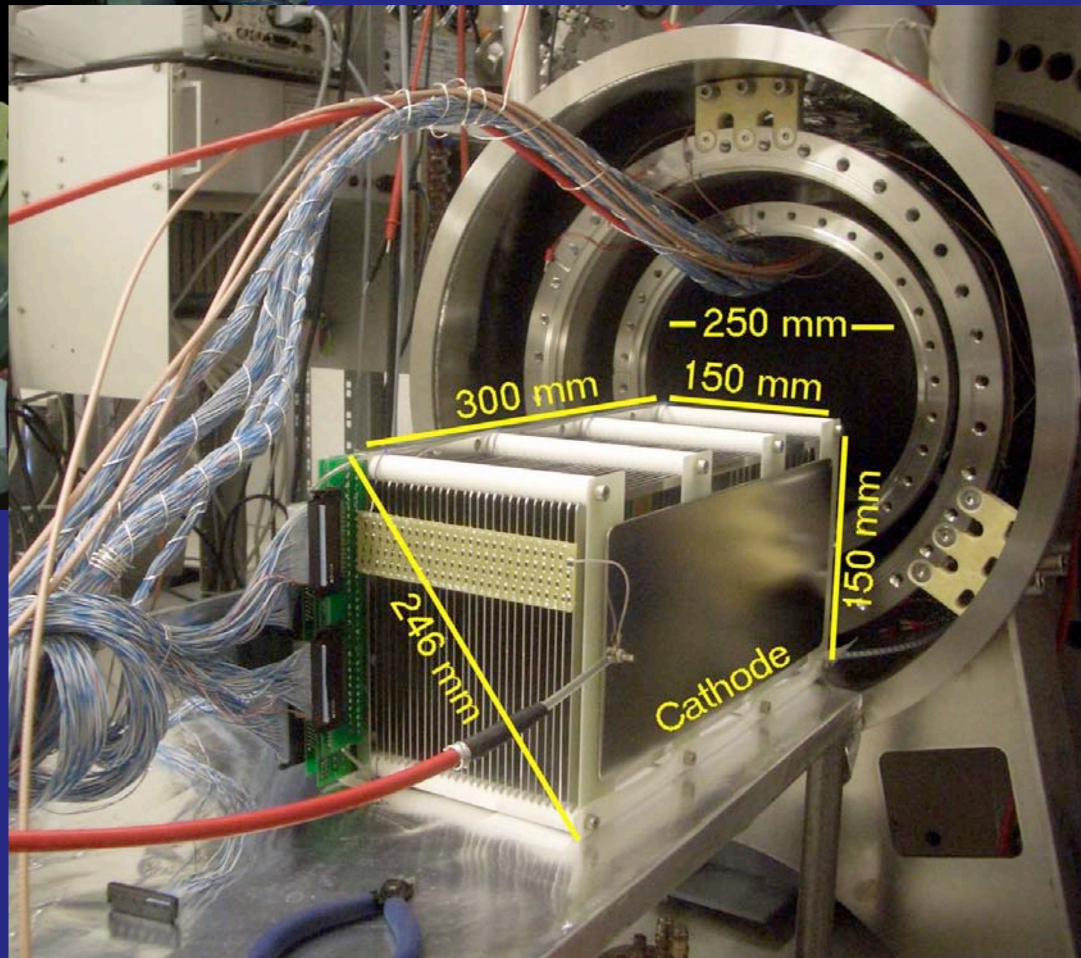
Correlation between calorimetry and magnetic measurement for contained tracks:





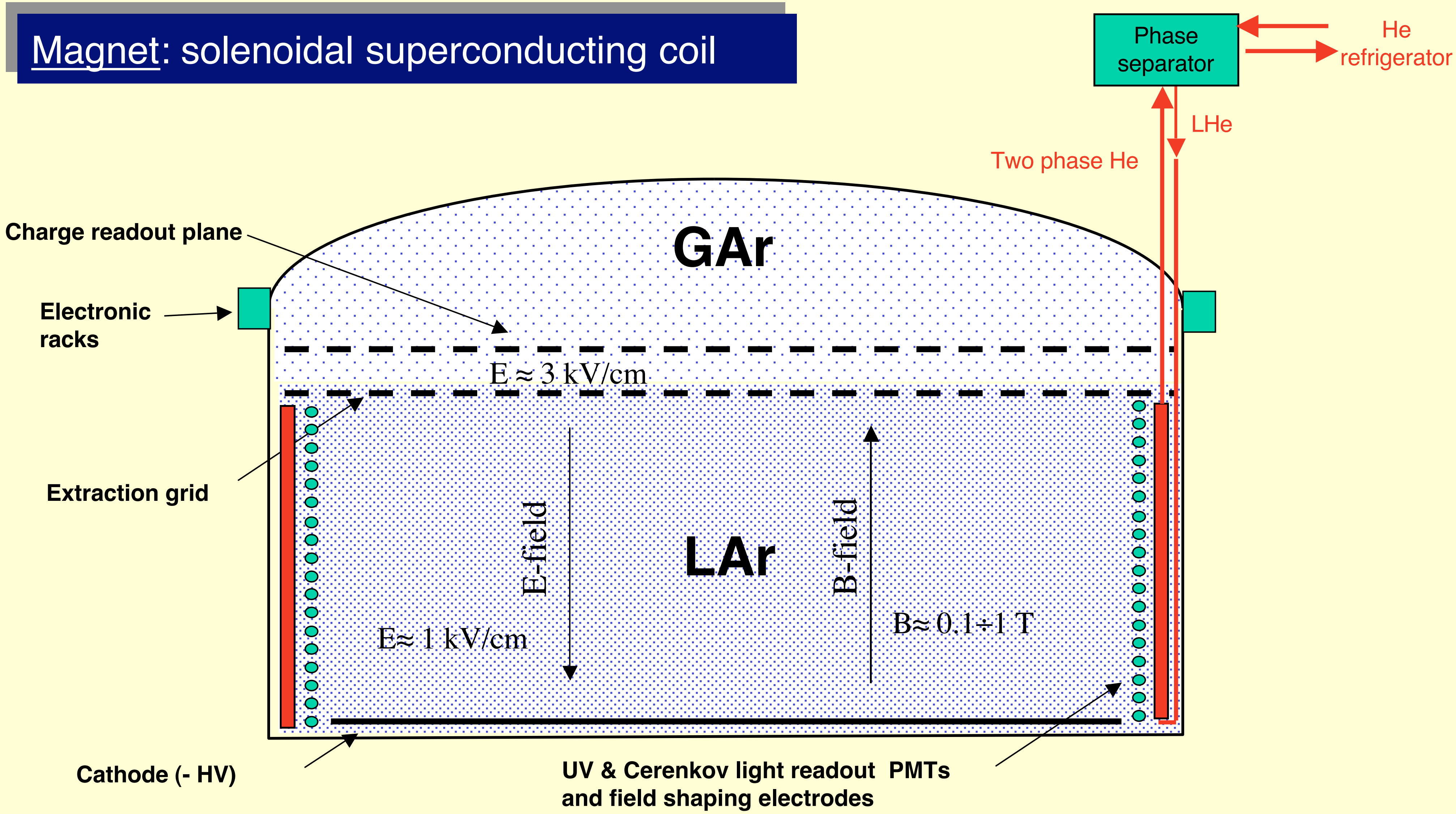
See
physics/0505151,
NIMA in press.





Tentative layout of a large magnetized GLACIER

<u>Magnet</u>: solenoidal superconducting coil



<u>LHe Cooling</u>: Thermosiphon principle + thermal shield=LAr

Tentative coil parameters

Other examples: ALEPH, CDF, ATLAS Toroids, AMS-II

	10 kton LAr			100 kton LAr			ATLAS solenoid	CMS
Magnetic induction (T)	0.1	0.4	1.0	0.1	0.4	1.0	2.0	4.0
Solenoid diameter (m)	30			70			2.4	6
Solenoid length (m)	10			20			5.3	12.5
Magnetic volume (m^3)	7700			77000			21	400
Stored magnetic energy (GJ)	0.03	0.5	3	0.3	5	30	0.04	2.7
Magnetomotive force (MAt)	0.8	3.2	8	1.6	6.4	16	9.3	42
Radial magnetic pressure (kPa)	4	64	400	4	64	400	1600	6500
Coil current (kA)	30 (I/I_c=50%)						8	20
Total length conductor (km)	2.5	10	25	12	57	117	5.6	45
Conductor type	NbTi/Cu normal superconductor, T=4.4K							

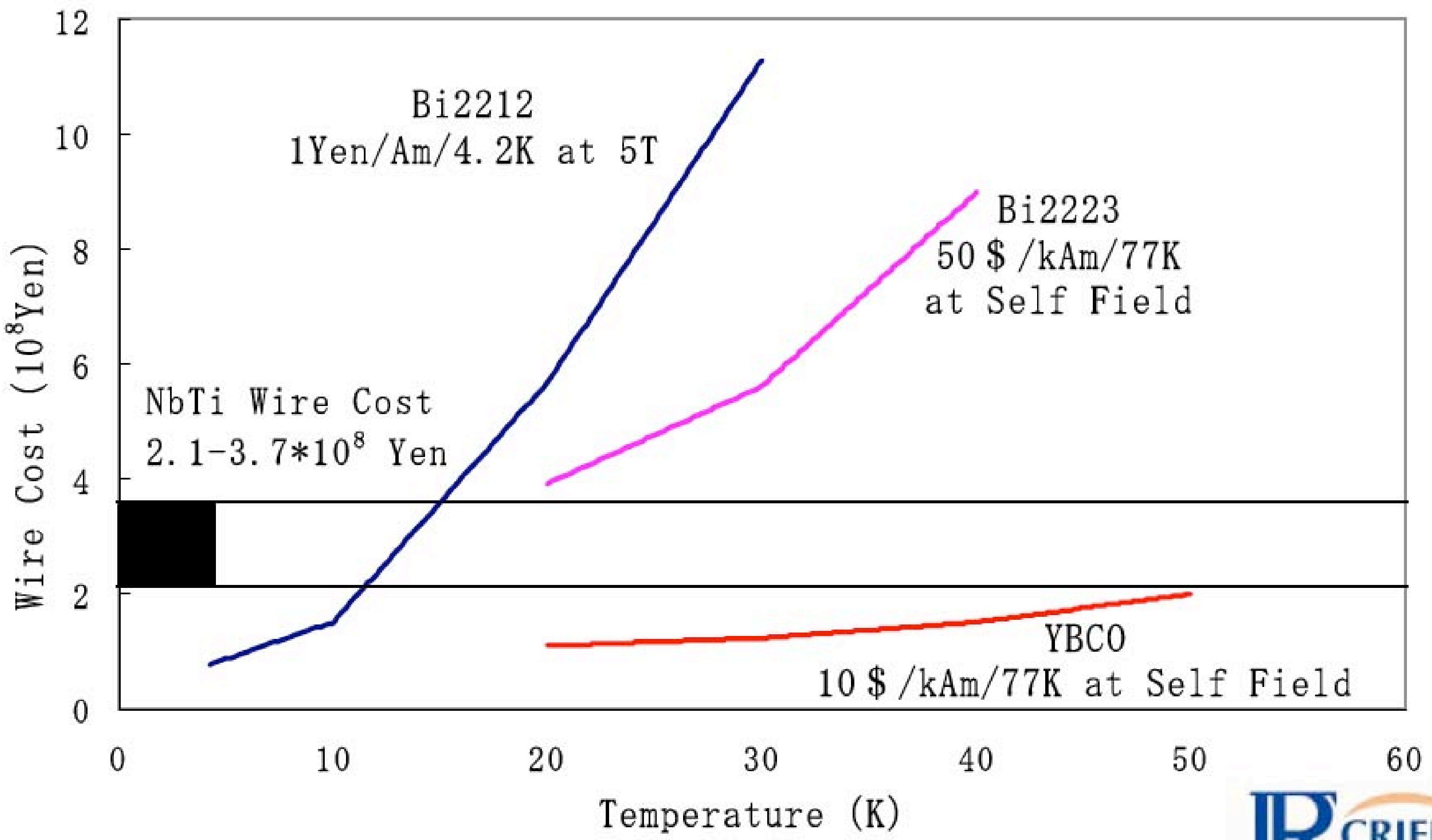
(Detailed magnetic, mechanical, thermal and quench analysis yet to be performed…)

Other challenge: High Tc superconductors ?

- A new era in superconductivity opened in 1986 when Bednorz and Mueller in Zürich discovered superconductivity at a temperature of approximately 30K. In the following years, new materials were found and currently the world record is $T_c \approx 130K$.
- HTS are fragile materials and are still at the forefront of material science research. For example, BSCCO-2212 (Bi_2-Sr_2-Ca_2-Cu_3-O_{10}) with T_c=110 K is promising. Tapes of Bi2223 or YBCO coated are promising HTS cables.
- Magnets have been constructed although HTS do not tolerate high magnetic fields.
- Massive R&D required ! See **Superconducting Magnetic Energy Storage (SMES)**

Example of BSCCO-2212 coils (Cryo department, Southampton Univ, UK)

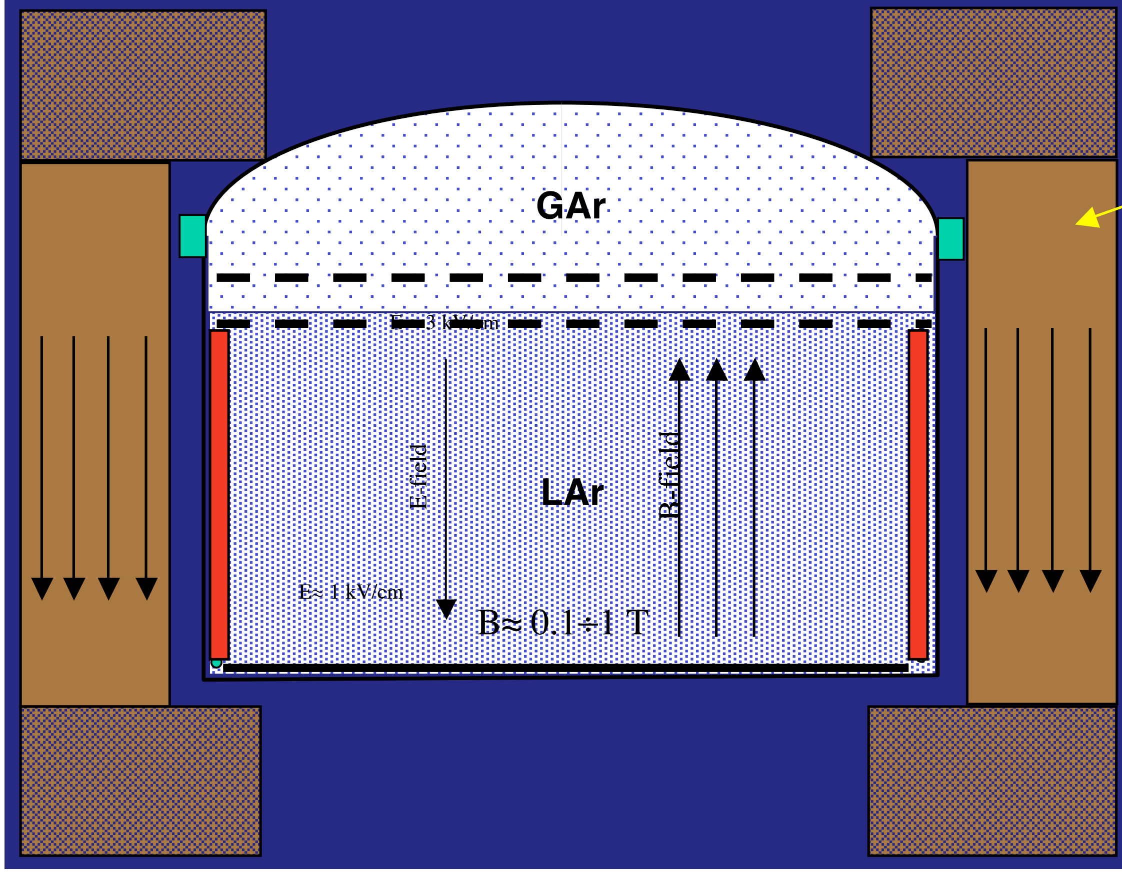
Wire Cost of 15kWh (54MJ) SMES for Power System Stabilization



From S. Akita, Central Research Institute of Electric Power Industry (Japan)

Tentative Yoke parameters

Cylindrical Fe yoke	**10 kton LAr**			**100 kton LAr**		
Magnetic induction (T)	**0.1**	**0.4**	**1.0**	**0.1**	**0.4**	**1.0**
Magnetic flux (Weber)	**70**	**280**	**710**	**385**	**1540**	**3850**
Assumed saturation field in Fe (T)	**1.8**			**1.8**		
Thickness (m)	**0.4**	**1.6**	**3.7**	**1**	**3.7**	**8.7**
Height (m)	**10**			**20**		
Mass (kton)	**6.3**	**25**	**63**	**34**	**137**	**342**



Cylindrical Fe yoke.
(Instrumented?)

NB: Superconducting Magnetic Energy Storage (SMES) systems were considered for underground storage of MJ energy without return yoke buried in tunnels in bedrock (see e.g. Eyssa and Hilal, J. Phys. D: Appl. Phys 13 (1980) 69). Avoid using a yoke?

Cost estimate

Rough Cost Estimate in MEuro : 100 & 10 kton

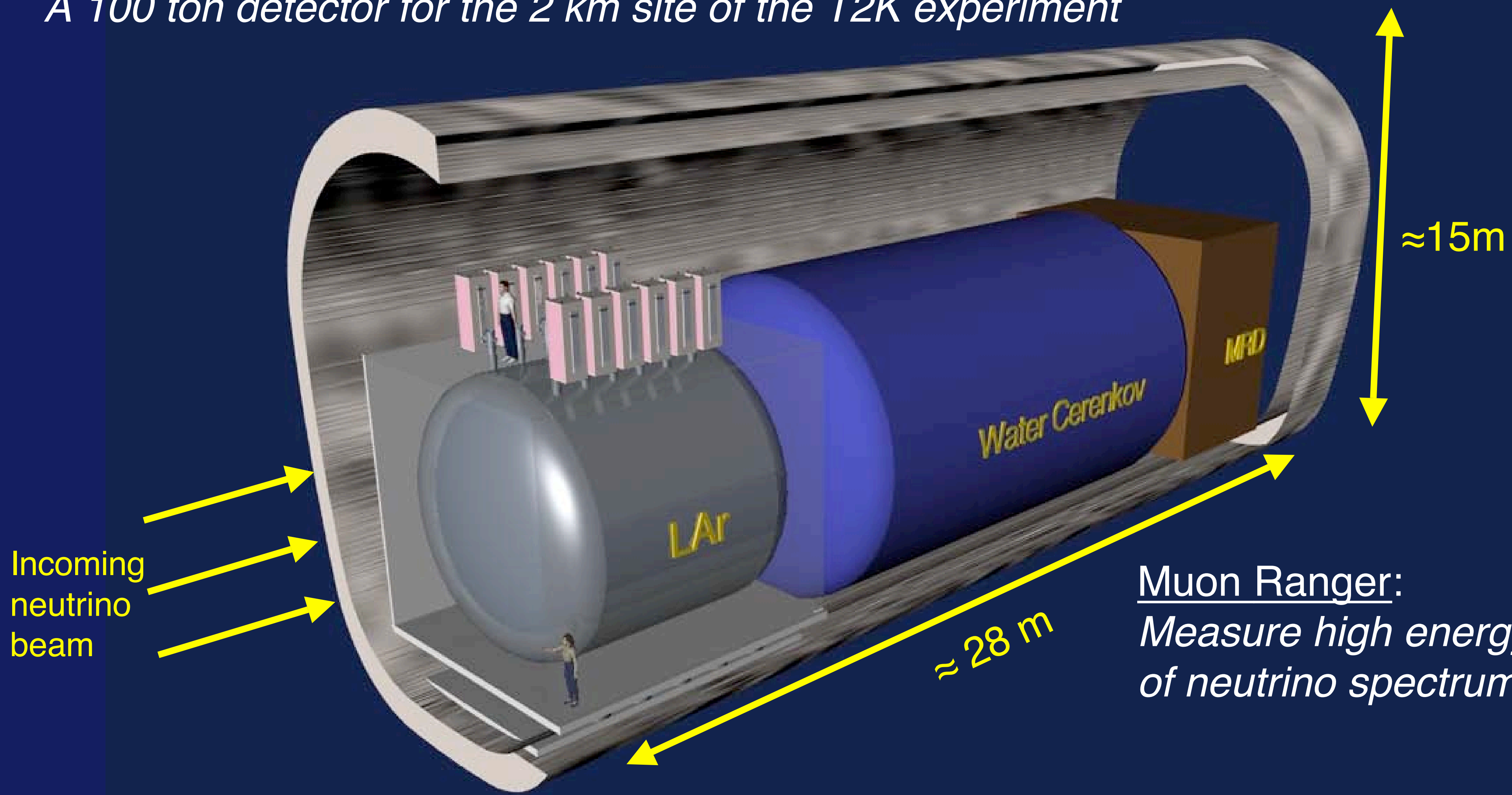
Item	100 kton	10 kton
LNG tanker (see notes 1-2)	50÷100	20 ÷ 30
Merchant cost of LAr (see note 3)	100	10
Refilling plant	25	10
Purification system	10	2
Civil engineering + excavation	30	5
Forced air ventilation	10	5
Safety system	10	5
Inner detector mechanics	10	3
Charge readout detectors	15	5
Light readout	60 (with Č)	2 (w/o Č)
Readout electronics	10	5
Miscellanea	10	5
Total	**340 ÷ 390**	**≈ 80 ÷ 90**
Magnet	**100 ? (B=0.4T)**	**100 ? (B=1T)**

Notes:
(1) Range in cost of tanker comes from site-dependence and current uncertainty in underground construction
(2) Cost of tanker already includes necessary features for LAr TPC (surface electropolishing, hard roof for instrumentation, feed-throughs,…)
(3) LAr Merchant cost ≠ production cost. Fraction will be furnished from external companies and other fraction will be produced locally (by the refilling plant)

An important milestone…

Important milestone of the LAr TPC technique for accelerator neutrino physics

A 100 ton detector for the 2 km site of the T2K experiment



Muon Ranger:
Measure high energy tail of neutrino spectrum

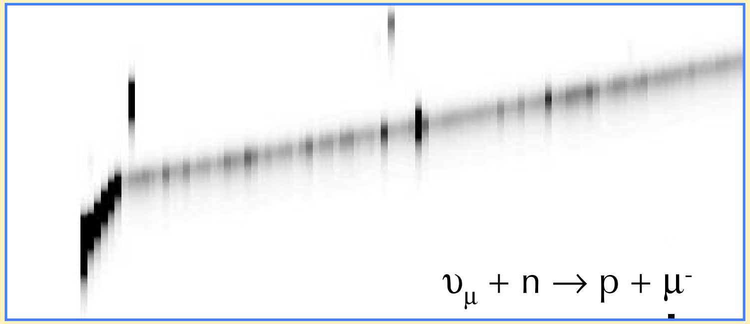
Liquid Argon detector:
Exclusive final states
Frozen water target

Water Cerenkov detector:
Same detector technology as SK
≈1 interaction/spill/kton

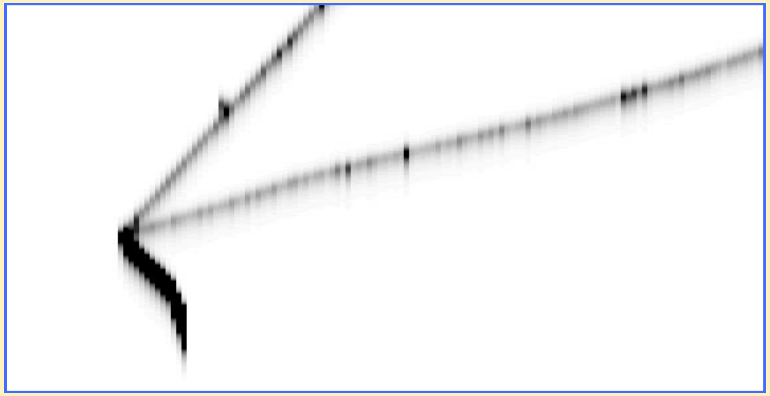
Important features provided by the LAr TPC in the context of T2K

- Fully active, homogeneous, high-resolution device ⇒ **fine grain detector and high statistics neutrino interaction studies with bubble chamber accuracy .**
- Reconstruction of **low momentum hadrons** (below Cherenkov threshold), especially recoiling protons.
- Independent measurement of off-axis flux and QE/nonQE event ratio.
- Exclusive measurement of νNC events with clean π^0 identification for an independent determination of systematic errors on the NC/CC ratio.
- Measurement of the intrinsic ν_eCC background.
- **Collection of a large statistical sample of neutrino interactions in the GeV region** for the study of the quasi-elastic, deep-inelastic and resonance modelling and of nuclear effects.

≈120'000 QE events/yr/100 ton
≈70'000 non-QE events/yr/100 ton



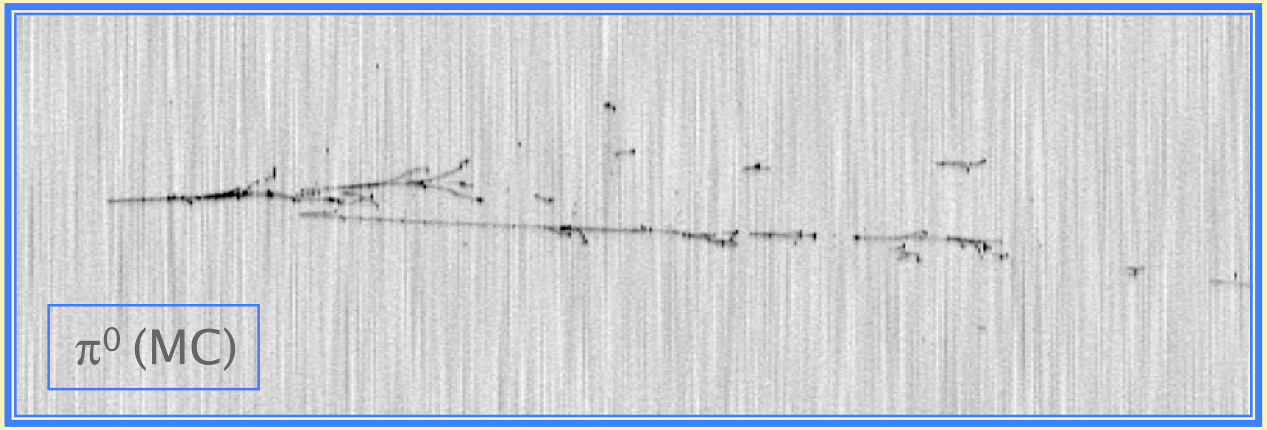
MC QE event.
Proton momentum = 490 MeV/c



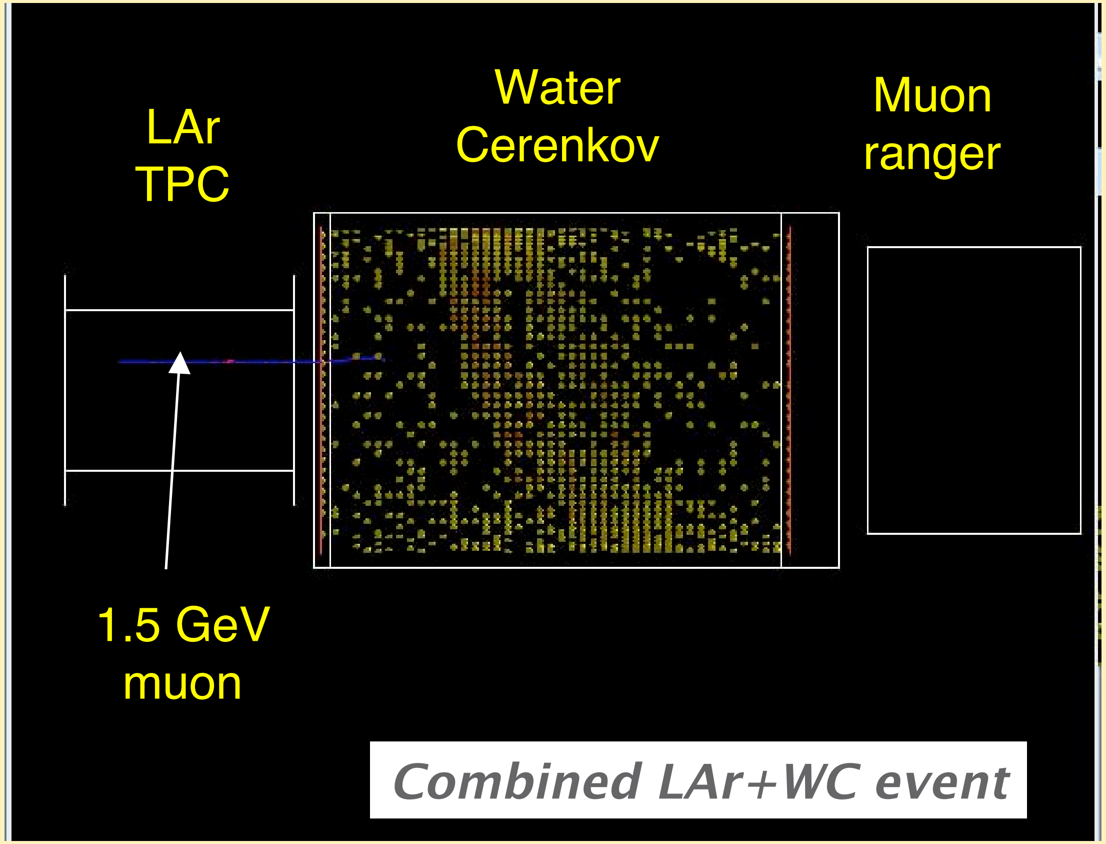
MC nQE event.
Pion+ momentum = 377 MeV/c, Proton momentum = 480 MeV/c

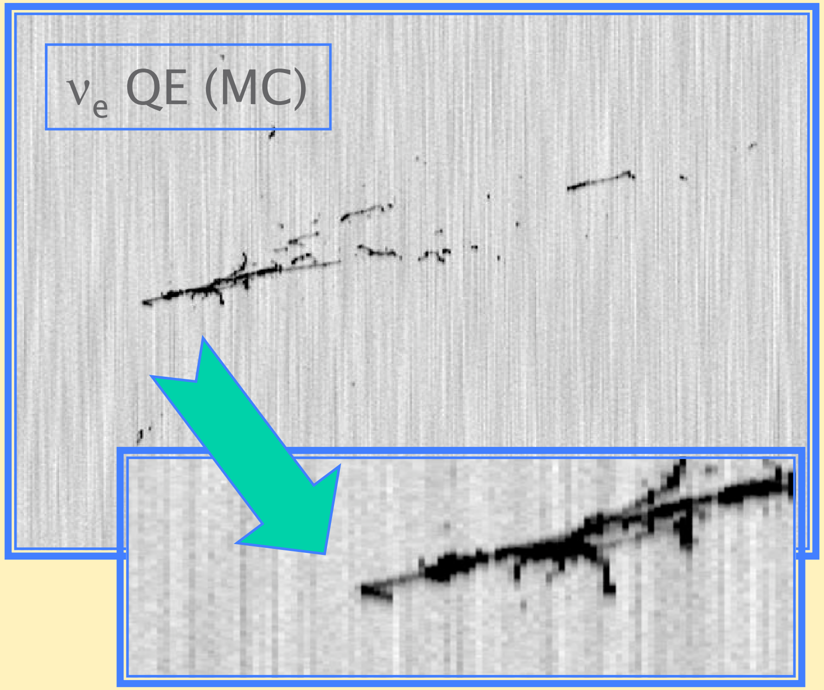
Perform physics: A fundamental milestone for the LAr TPC technique ! Extremely valuable experience for future large LAr detectors (in-situ R&D!)

Examples of application for T2K 2km site



High granularity: Sampling = 0.02 X_0





Summary

- **R&D program needed to extrapolate liquid Argon TPC concept to O(100 kton) detectors under progress**
  - ➥ Internal issues: Purification, long drift paths, magnetic field,…
  - ➥ External issues: safety, modularity (installation, access, operation, …)

- **The state of the art of our conceptual design has been presented.**

- **It relies on**
  - ➥ (a) industrial tankers developed by the petrochemical industry (no R&D required, readily available, safe) and their extrapolation to underground or shallow depth LAr storage (at this stage we do not see an extended physics program in a potential surface operation).
  - ➥ (b) improved detector performance for very long drift paths w e.g. LEM readout
  - ➥ (c) new solutions for drift very HV
  - ➥ (d) a modularity at the level of 100 kton (limited by cavern size)
  - ➥ (e) the possibility to embed the LAr in B-field (conceptually proven). Magnetic field strength to be determined by physics requirements.

Outlook - a possible roadmap

- Our roadmap considers a “graded strategy” to eventually reach the 100 kton scale.
- In the short term, ICARUS T600 at LNGS should act as the “demonstrator” for a deep underground operation of the LAr technology.
- On the mid-term, a coordinated T2K-LAr effort will be fundamental for the understanding of neutrino interactions on Argon (and possibly water) target and will represent an important and very high statistics milestone for the liquid Argon technology.
- On the medium/longer term, we think that there might be a window of opportunity to consider a ≈10kton full-scale, cost effective prototype, as an engineering design test with a physics program of its own, comparable to that of Superkamiokande. This should be discussed at the EU level (ApPEC) ?
- Eventually, the strategy of the neutrino mixing matrix studies and ultimate proton decay searches could envisage a (possibly magnetized) 100 kton liquid Argon TPC. The tentative design outlined above seems technically sound and would deliver extraordinary physics output. Such a detector could be located in Korea acting as a T2K OA and/or possibly future NF in Japan.
- Detailed design efforts must be pursued to understand precisely cost of such large detectors.

감사합니다

Backup slides

Preliminary incidence on proton decay background

$$p \longrightarrow \nu K$$

$$n + N \longrightarrow K^{+} + X_{S} + \ldots.$$

$$K_{L}^{0} + N \longrightarrow K^{+} + \ldots.$$

$$\Lambda + N \longrightarrow K^{+} + \ldots.$$

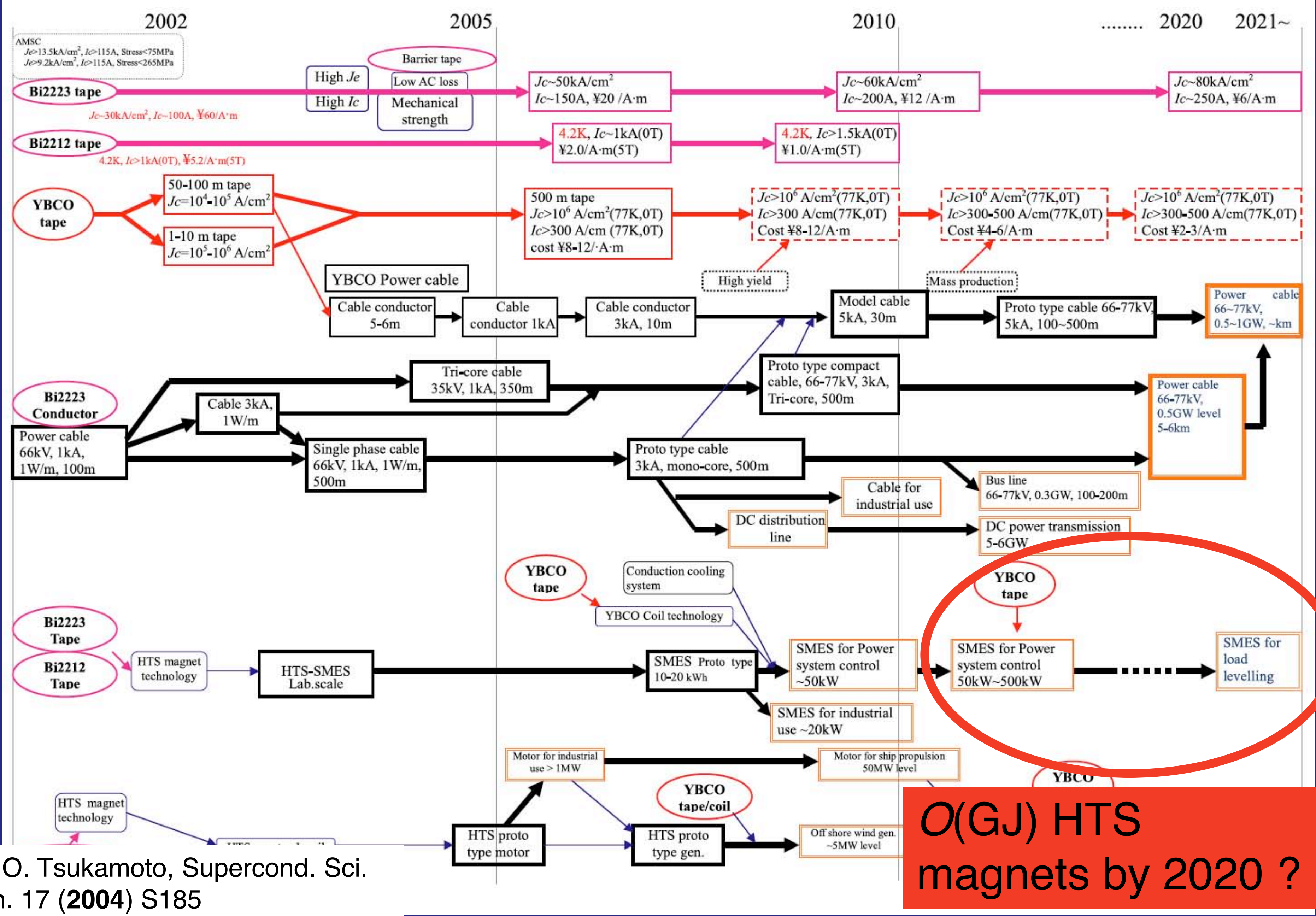
Below detection threshold (X_S)

Hadronic component can be further suppressed by hard fiducial mass cut:

Depth rock	Backgrounds for νK proton decay search in one year						
	Neutron induced		K^0_L induced			Λ^0 induced	
50 m	920	<1	36000	1200	< 1 for 60 kton	110	<1
377 m (1 km w.e)	6.7	<<1	1100	39	< 1 for 70 kton	7	<<1
1.13 km (3 km w.e)	0.2	<<1	21	<1		<1	<<1
Atmospheric neutrino	5986 ν_eCC, 1170 aν_eCC, 10688 ν_μCC, 2727 aν_μCC, 6471 ν NC, 2961 aν NC			<1			

Standard analysis cuts: see e.g. hep-ph/0407297

Roadmap of HTS power applications

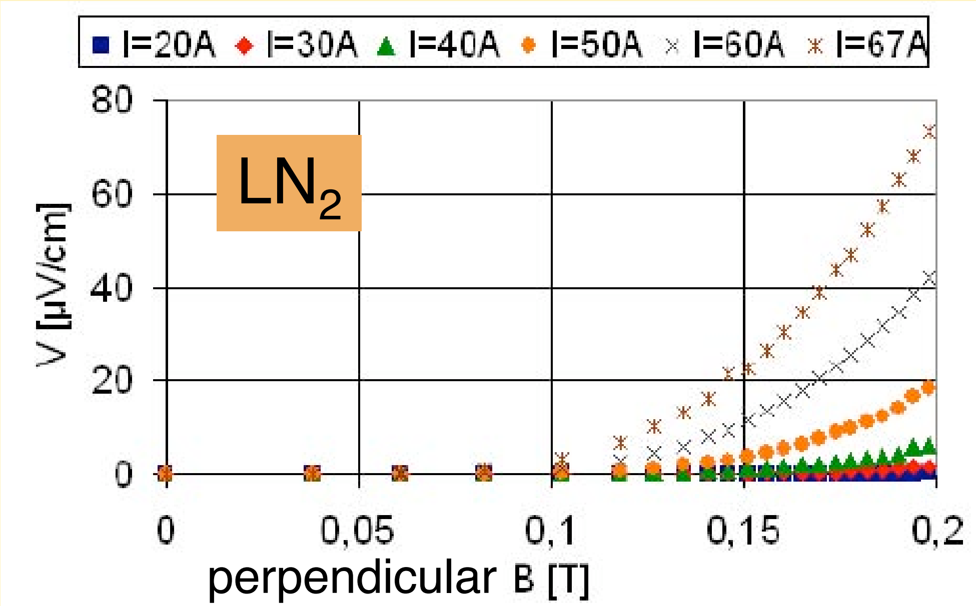


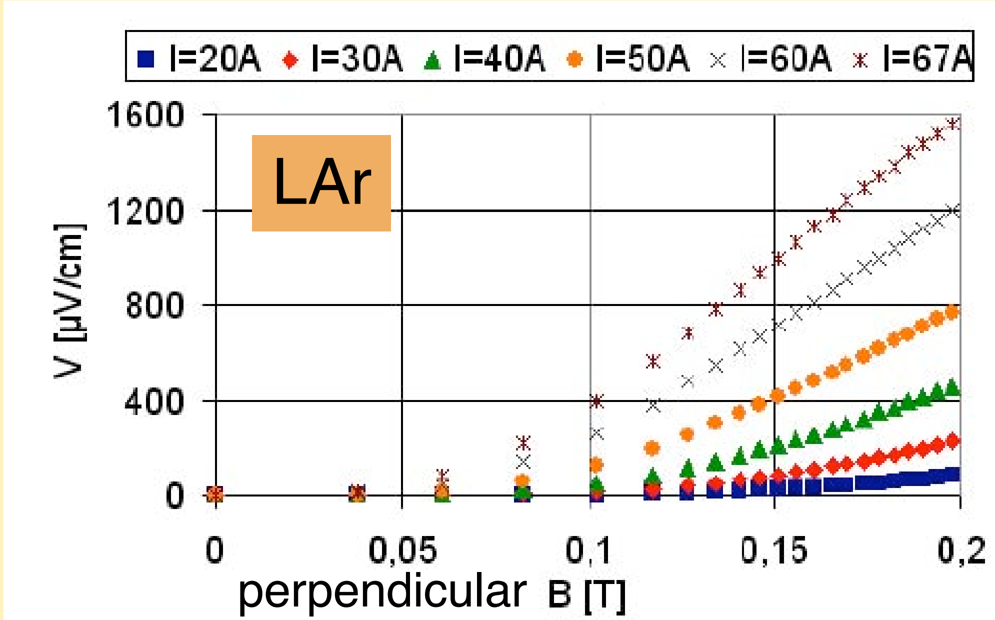
From O. Tsukamoto, Supercond. Sci. Techn. 17 (**2004**) S185

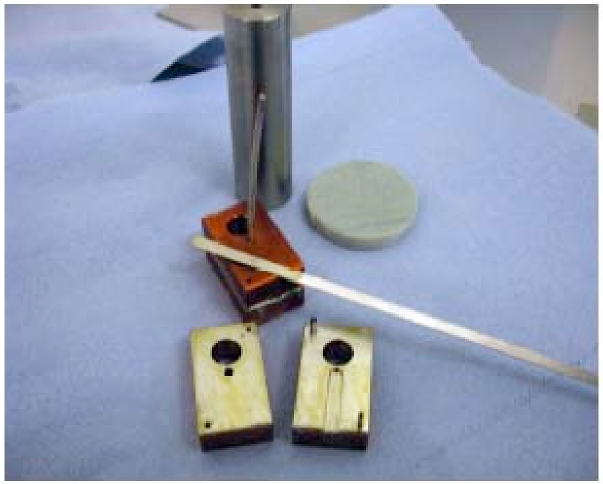
O(GJ) HTS magnets by 2020 ?

First tests of HTS conductor in Liquid Argon

- We have performed first tests with BSCCO HTS superconductor by American Superconductor (www.amsuper.com) in order to compare critical currents and influence of stray-field at LAr temperature (rather than LN_2).







Diploma student
T.Strauss

This is very preliminary…