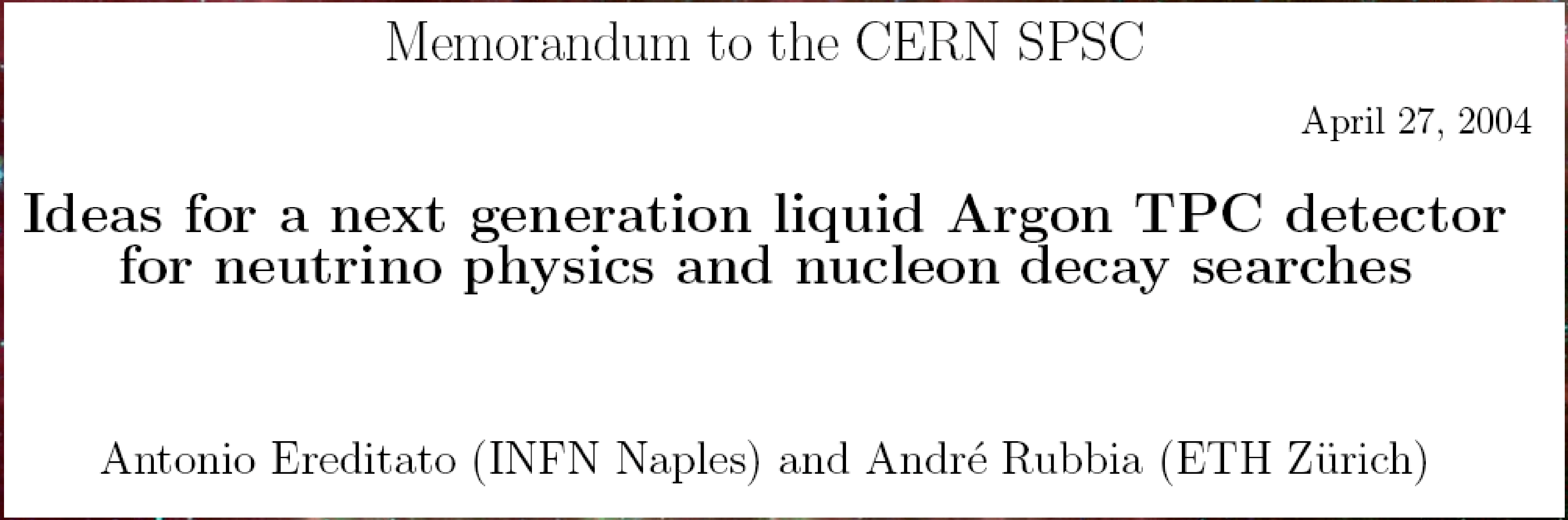


Memorandum to the CERN SPSC

April 27, 2004

Ideas for a next generation liquid Argon TPC detector for neutrino physics and nucleon decay searches

Antonio Ereditato (INFN Naples) and André Rubbia (ETH Zürich)

CERN SPSC - Villars meeting - September 2004

Abstract

- The liquid Argon TPC imaging has reached a high level of maturity thanks to many years of R&D effort conducted by the ICARUS collaboration.
- The ICARUS experiment, which acts as an observatory for the study of neutrinos and the instability of matter, is starting to come together. In the summer of 2001, the first module of the ICARUS T600 detector passed brilliantly a series of tests. The installation at the Underground Gran Sasso Laboratory is on-going.
- In this presentation, we discuss possible future and independent applications of the technique. More details can be found in the following references:

- 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, 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

Preliminary considerations

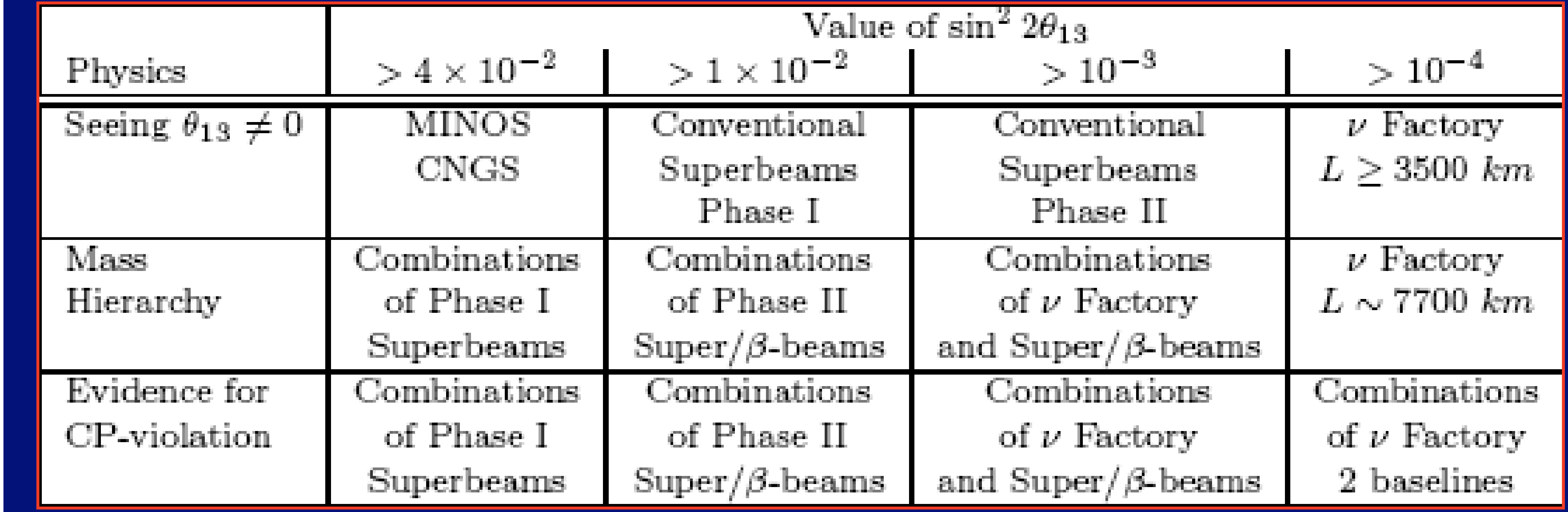
- The **evidence for neutrino oscillation** mostly built-up with **solar**, **atmospheric** and **reactor** neutrino experiments is today very robust. This has opened the way to precision studies of the mixing matrix with **accelerator** neutrino experiments, together with future projects on direct mass measurements, double-beta decay, reactor, solar and atmospheric neutrinos.

- Running and planned experiments will contribute to **narrow-down the errors** on the oscillation parameters and with some chance to prove that the mixing matrix is indeed 3 x 3. The next generation will need high intensity facilities to pin down a non vanishing value of θ_{13}. Advanced detector technique will be required to keep BG low for a real improvement of the sensitivities. This physics subject is of **outstanding importance** ‘per se’ but also because it will drive future initiatives.

- The detection of **matter** and of **CP violating effects** will likely require a further generation of experiments using high intensity (> 1 MW) neutrino facilities with more massive detectors. At present, two options are being considered: a 500-1000 kton **water Cerenkov** detectors (à la SK) and 50-100 kton **liquid Argon TPCs**. Solving degeneracies in the parameters calls for different experiments with different optimizations.

- In addition to the need of large mass, the detectors have to be **‘general purpose’** (think of tomorrow’s physics), must have good energy resolution (measure oscillation parameters), good granularity (to measure channels involving e, μ, τ,…) and adequate NC/CC separation for BG suppression. They will need to be as good for **astroparticle physics** (underground or at shallow depth) and they have to employ cost effective technical solutions/technologies.

Outstanding goals

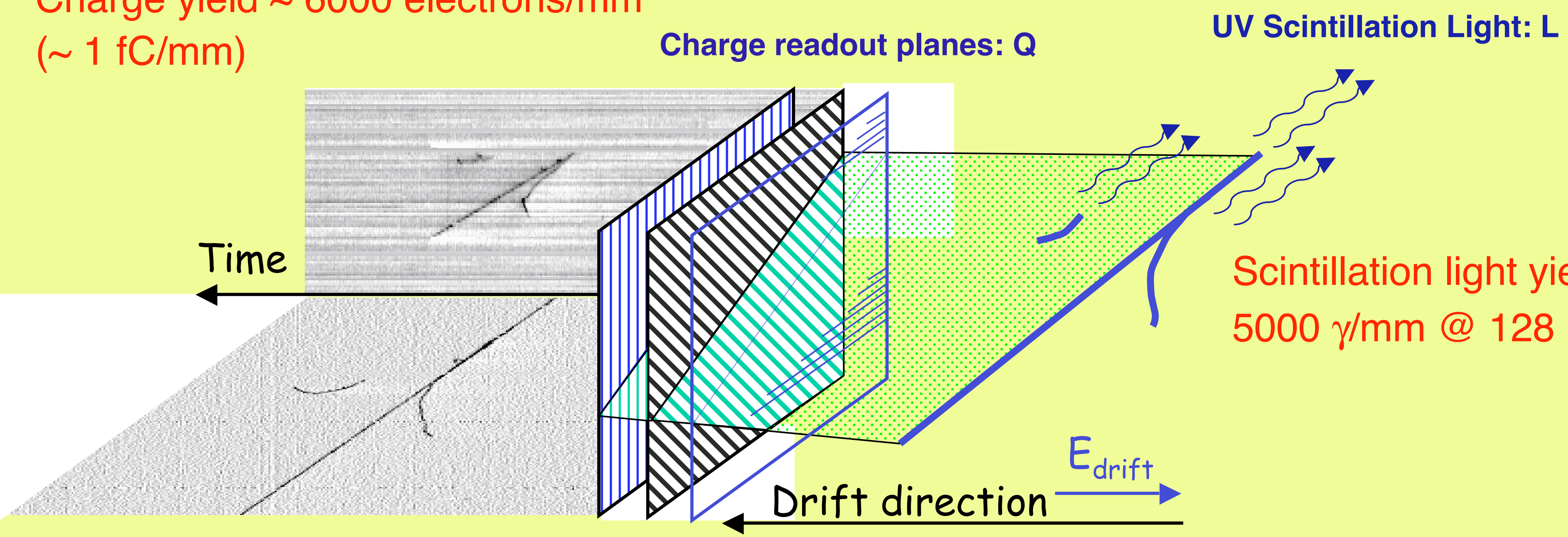


Physics	Value of $\sin^2 2\theta_{13}$			
	$> 4 \times 10^{-2}$	$> 1 \times 10^{-2}$	$> 10^{-3}$	$> 10^{-4}$
Seeing $\theta_{13} \neq 0$	MINOS CNGS	Conventional Superbeams Phase I	Conventional Superbeams Phase II	ν Factory $L \geq 3500$ km
Mass Hierarchy	Combinations of Phase I Superbeams	Combinations of Phase II Super/β-beams	Combinations of ν Factory and Super/β-beams	ν Factory $L \sim 7700$ km
Evidence for CP-violation	Combinations of Phase I Superbeams	Combinations of Phase II Super/β-beams	Combinations of ν Factory and Super/β-beams	Combinations of ν Factory 2 baselines

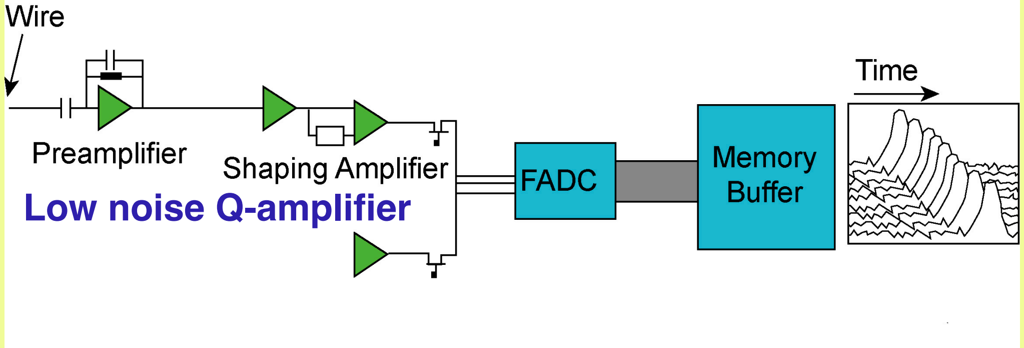
How to achieve these outstanding physics goals will depend on the value of θ_{13}, for which there is no theoretical input.

The Liquid Argon TPC principle

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



Scintillation light yield ~
5000 γ/mm @ 128 nm



Low noise Q-amplifier

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).

Liquid Argon medium properties

- A Historical View On the R&D for liquid Rare Gas detectors, T. Doke, NIM A 327 (1993) 113 and references therein.

	Water	**Liquid Argon**
Density (g/cm^3)	**1**	**1.4**
Radiation length (cm)	**36.1**	**14.0**
Interaction length (cm)	**83.6**	**83.6**
dE/dx (MeV/cm)	**1.9**	**2.1**
Refractive index (visible)	**1.33**	**1.24**
Cerenkov angle	**42°**	**36°**
Cerenkov $d^2N/dEdx$ ($\beta=1$)	**≈ 160 eV^{-1} cm^{-1}**	**≈ 130 eV^{-1} cm^{-1}**
Muon Cerenkov threshold (p in MeV/c)	**120**	**140**
Scintillation (E=0 V/cm)	**No**	**Yes** **(≈ 50000 γ/MeV** **@ λ=128nm)**
Long electron drift	**Not possible**	**Possible** **(μ = 500 cm^2/Vs)**
Boiling point @ 1 bar	**373 K**	**87 K**

When a charged particle traverses LAr:

1) Ionization process

$W_e = 23.6 \pm 0.3$ eV

2) Scintillation (luminescence)

$W_\gamma = 19.5$ eV

UV "line" (λ=128 nm ⇔ 9.7 eV)

No more ionization: Argon is transparent

Only Rayleigh-scattering

3) Cerenkov light (if relativistic particle)

☞ **Charge**

☞ **Scintillation light (VUV)**

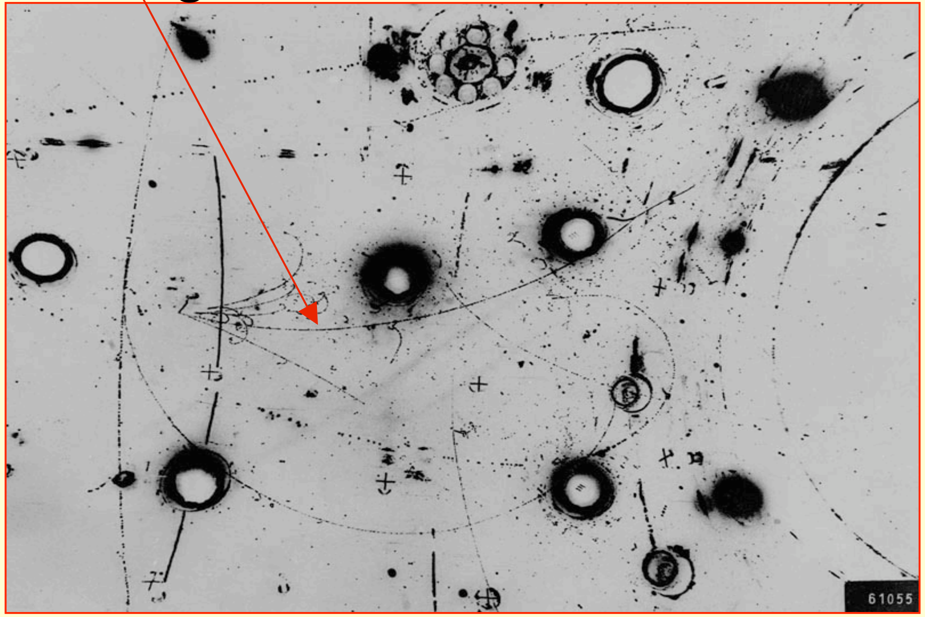
☞ **Cerenkov light (if β>1/n)**

Scintillation & Cerenkov light can be detected independently !

Liquid Argon TPC: an electronic bubble chamber

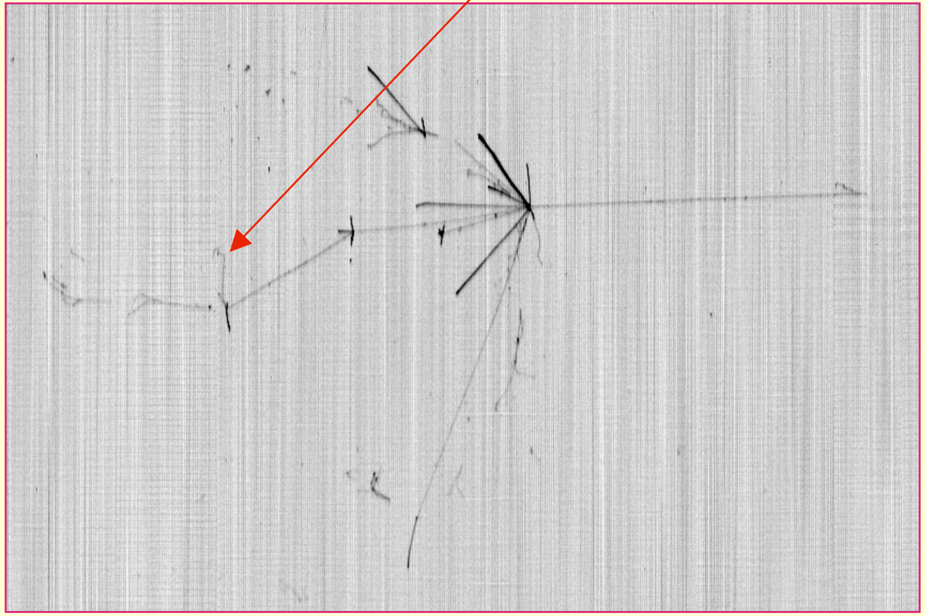
Bubble diameter ≈ 3 mm (diffraction limited)

Gargamelle bubble chamber



Bubble size ≈ 3x3x0.4 mm^3

ICARUS electronic chamber

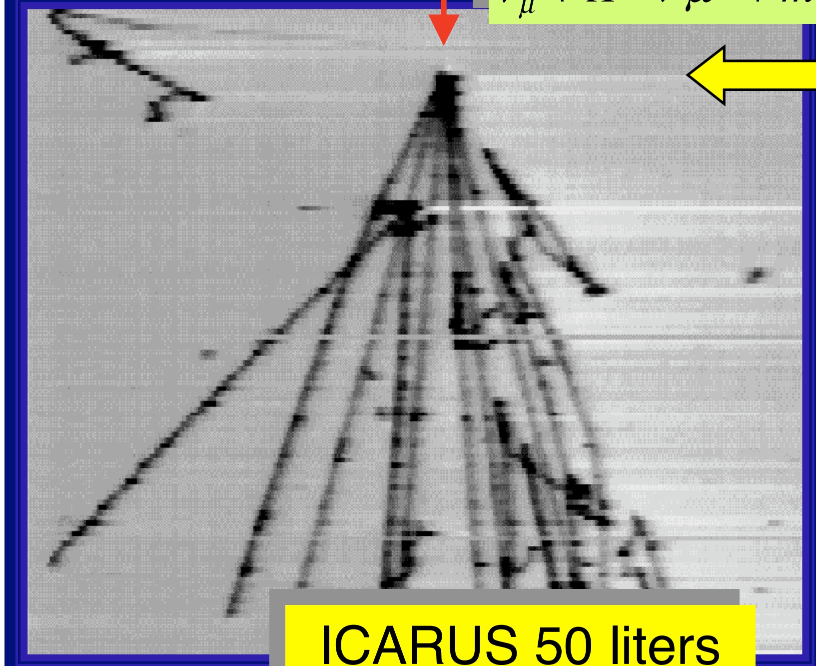


Medium	*Heavy freon*	
Sensitive mass	3.0	ton
Density	1.5	g/cm3
Radiation length	11.0	cm
Collision length	49.5	cm
dE/dx	2.3	MeV/cm

Medium	*Liquid Argon*	
Sensitive mass	Many ktons	
Density	1.4	g/cm3
Radiation length	14.0	cm
Collision length	54.8	cm
dE/dx	2.1	MeV/cm

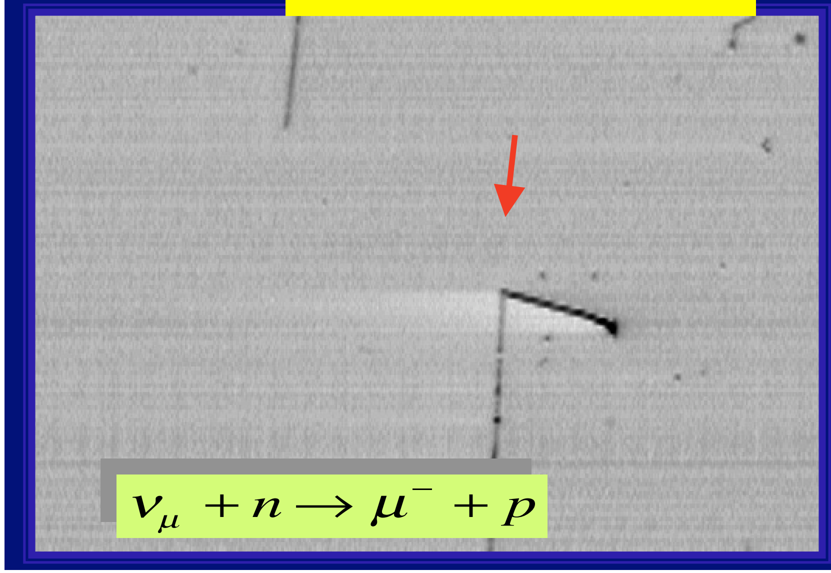
Neutrino detection: LAr TPC vs water Cerenkov

$\nu_\mu + X \rightarrow \mu^- + many\ \ prongs$



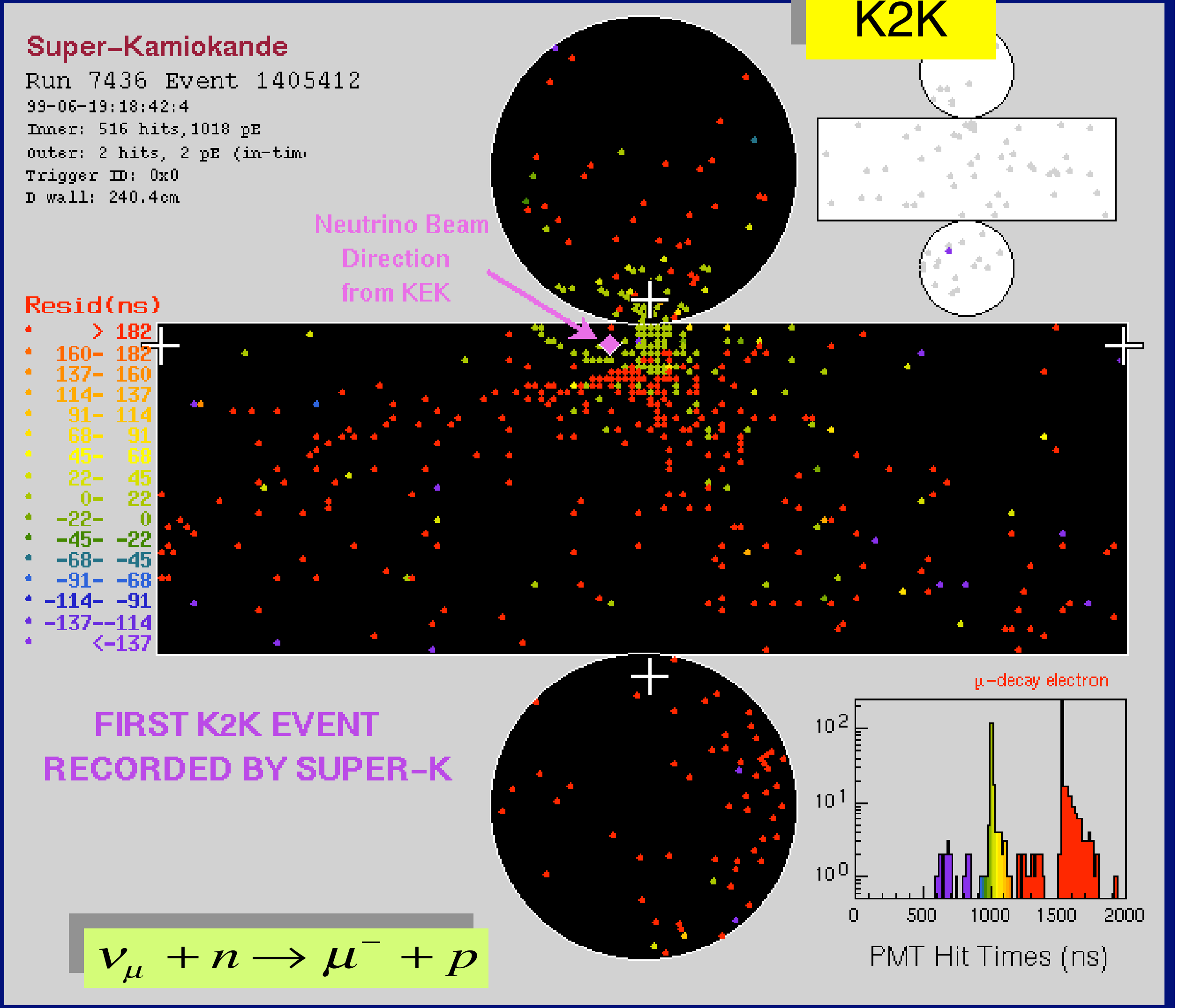
Multi prong event detection not possible with water Cerenkov

ICARUS 50 liters



$\nu_\mu + n \rightarrow \mu^- + p$

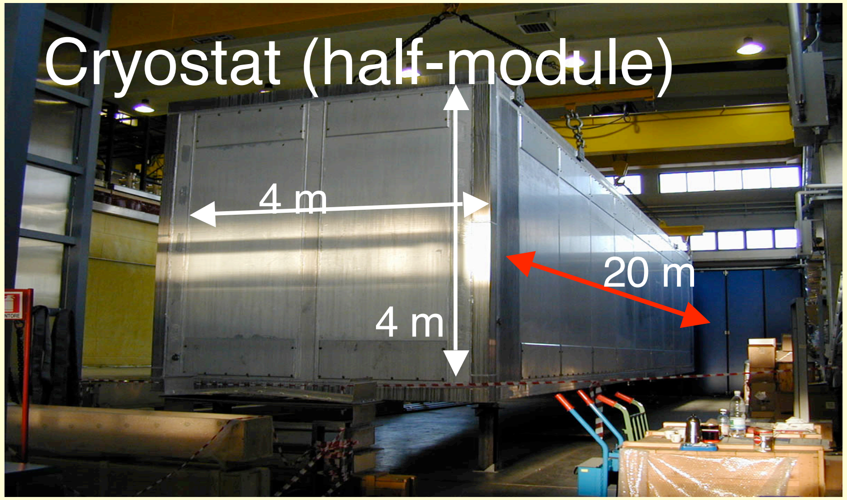
K2K

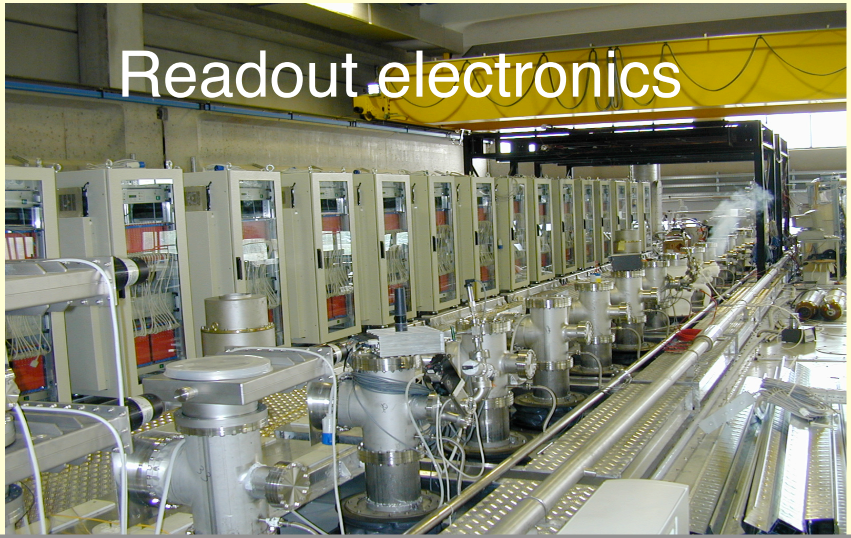


```
Super-Kamiokande
Run 7436 Event 1405412
99-06-19:18:42:4
Inner: 516 hits,1018 pE
Outer: 2 hits, 2 pE (in-tim
Trigger ID: 0x0
D wall: 240.4cm
```

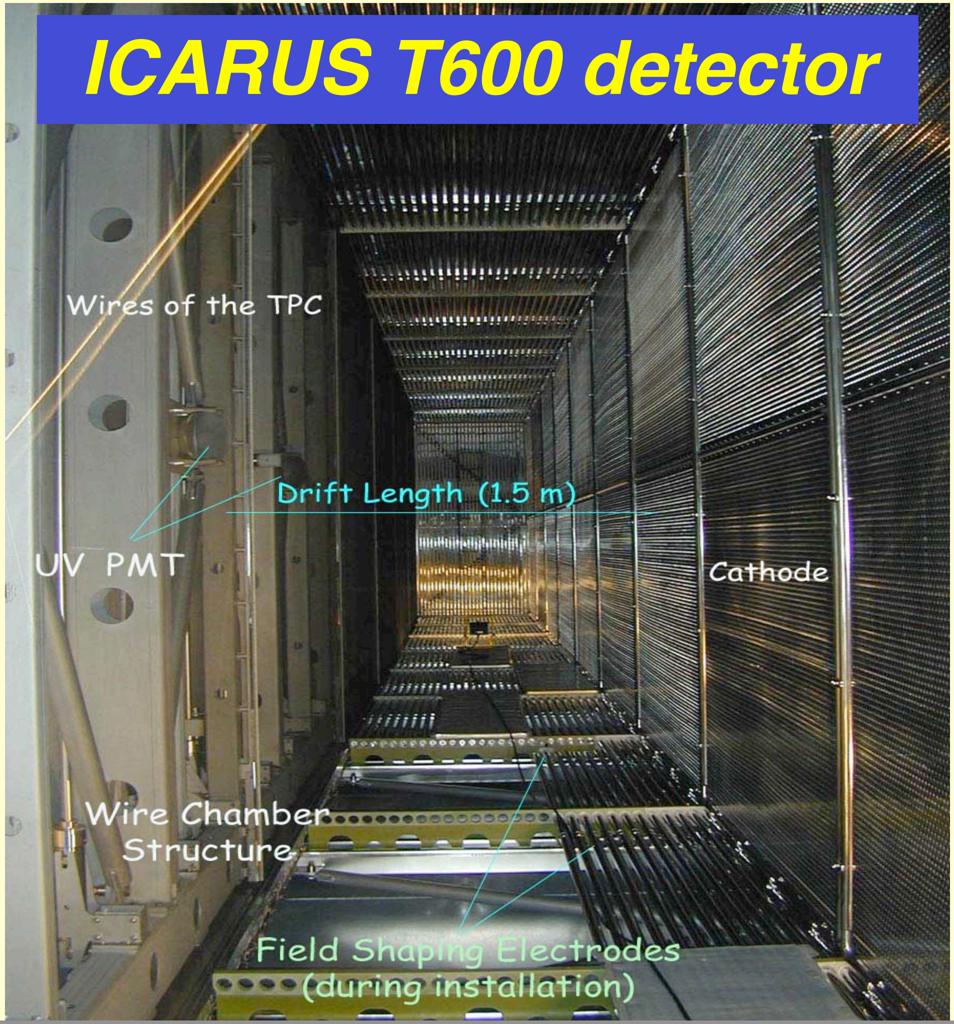
FIRST K2K EVENT RECORDED BY SUPER-K

$\nu_\mu + n \rightarrow \mu^- + p$





ICARUS T600 detector



- 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 strategy for future application of the liquid Argon TPC

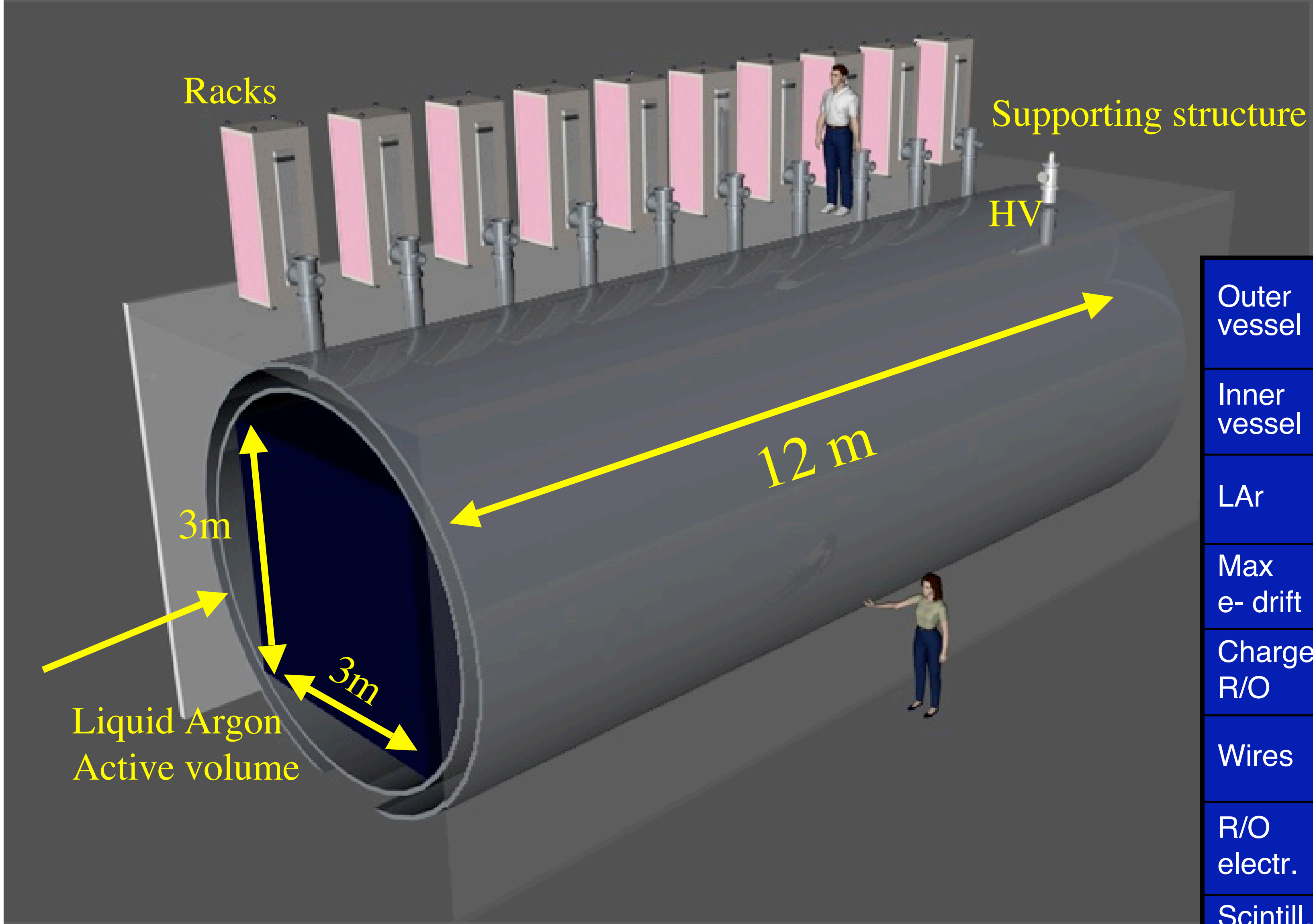
- **A 100 ton detector in a near-site of a long-baseline facility** is a straight forward and very desirable application of the technique. This is a mandatory step in order to be able to handle high statistics provided by large detectors. Detector will be a powerful tool for ultimate systematic errors in oscillation parameter determination.

- **A 100 kton liquid Argon TPC** will deliver extraordinary physics output. It will be an ideal match for a Phase-II Superbeam, Betabeam or Neutrino Factory. This program is very challenging. Tentative design and preliminary costing of such a detector are available, as shown later. R&D is in progress.
- **A 10% full-scale prototype** on the scale of 10 kton 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. This phase is relatively mature.

This strategy assumes a graded evolution of the international neutrino physics program within the next few decades.

If a potential window of opportunity is positively reviewed (e.g. CERN based options) with proper timescale, then one could envisage a prompter LOI-phase for the 100 kton.

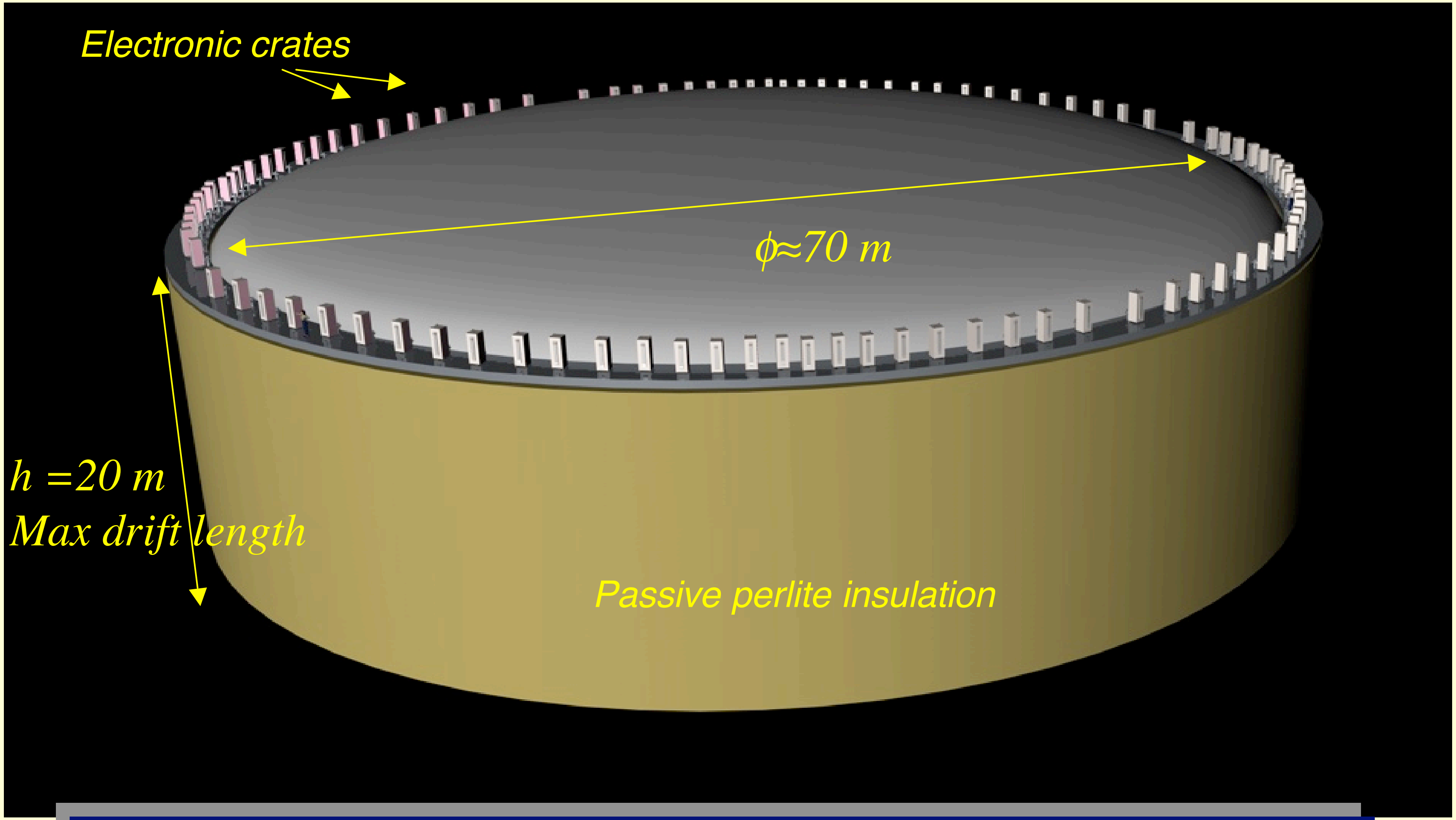
Conceptual design of a ~100 ton LAr TPC for a near station in a LBL facility:



Outer vessel	ϕ ≈ 5m, L≈13m, 15mm thick, weight ≈ 22 t
Inner vessel	ϕ ≈ 4,2 m, L ≈ 12 m, 8 mm thick, ≈ 10 t
LAr	Total ≈ 240 t Fiducial ≈ 100 t
Max e- drift	3 m @ HV=150 kV E = 500 V/cm
Charge R/O	2 views, ± 45° 2 (3) mm pitch
Wires	≈10000 (7000) $\phi = 150\ \mu m$
R/O electr.	on top of the dewar
Scintill. light	Also for triggering
B-field	possible

The approved T2K experiment in Japan could provide the ideal conditions and high statistical accuracy. Other beams elsewhere could also be considered.

A 100 kton liquid Argon TPC detector



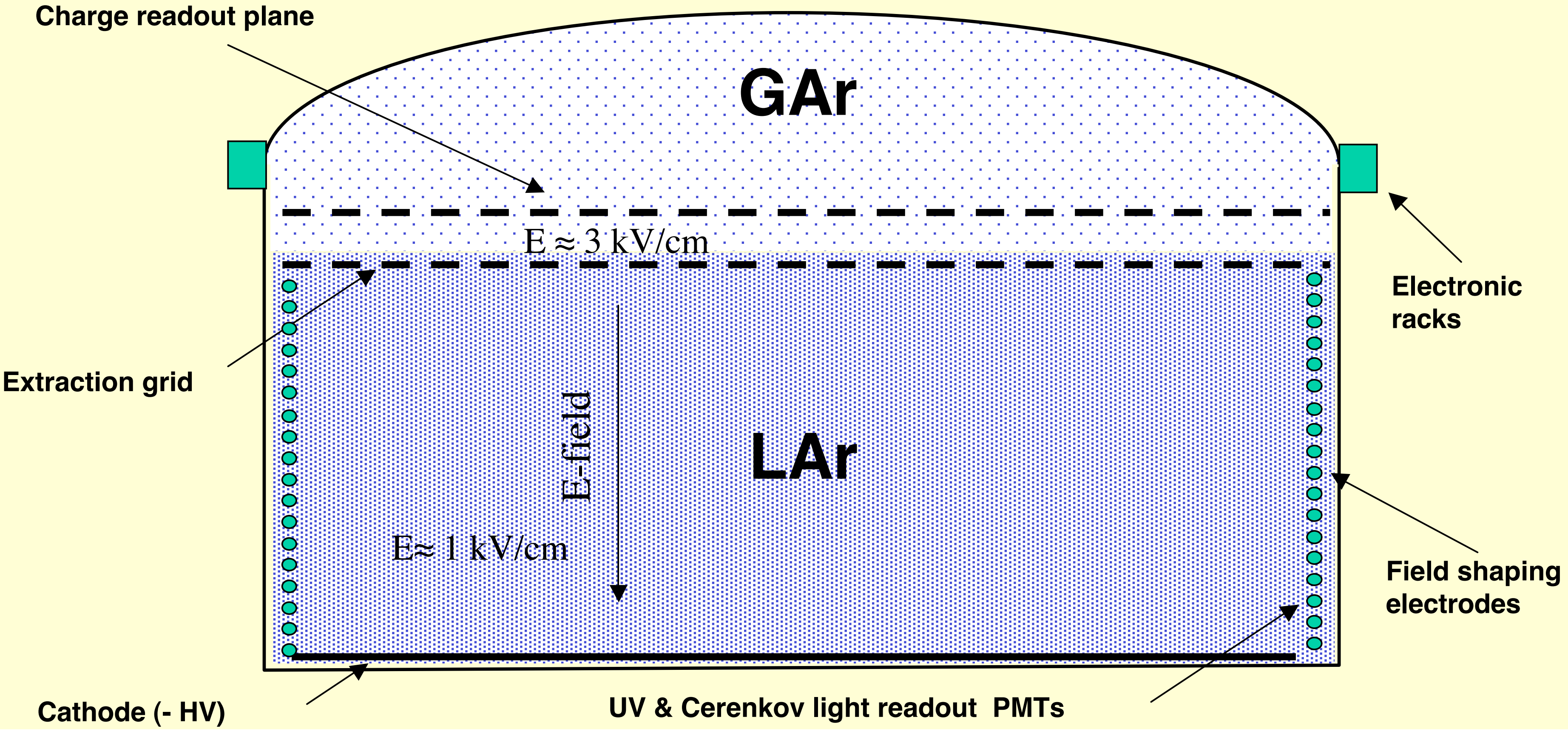
Single module cryo-tanker based on industrial LNG technology

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

A tentative detector layout

Single detector: charge imaging, scintillation, 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



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.

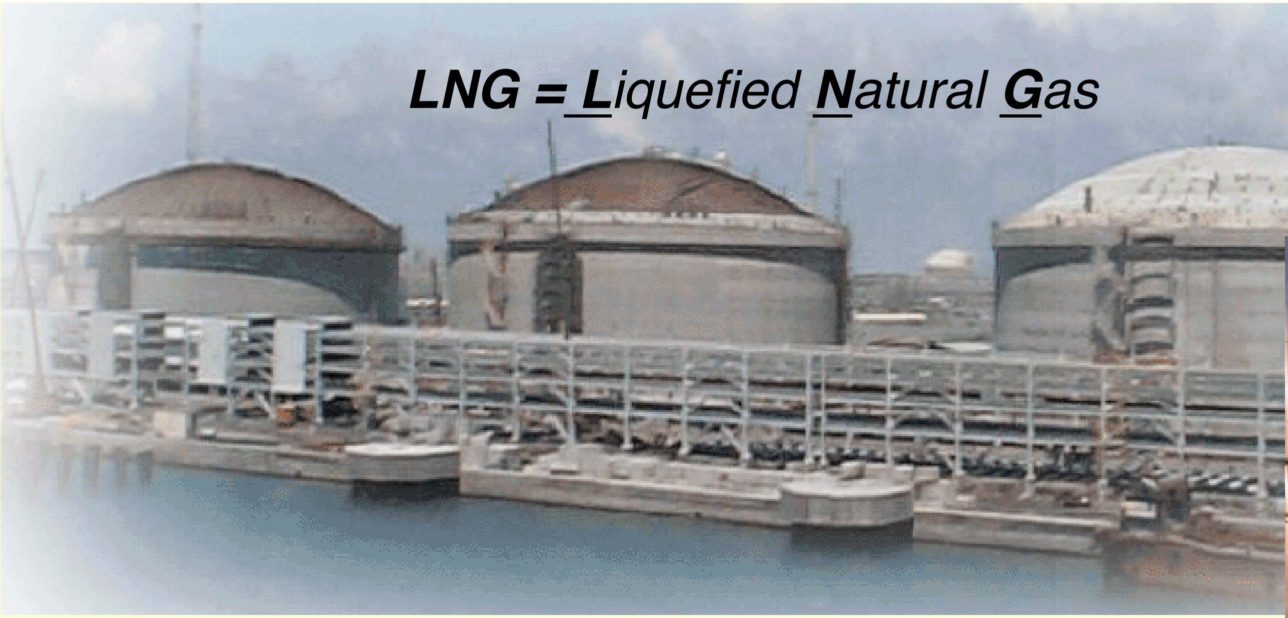
- **Charge imaging, scintillation and Cerenkov light readout for a complete (redundant) event reconstruction**. This represents a clear advantage over large mass, alternative detectors operating with only one of these readout modes. The physics benefit of the complementary charge, scintillation and Cerenkov 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 charge amplification near the anodes located in the gas phase.

- **Absence of magnetic field, although this possibility might be considered at a later stage**. R&D studies for charge imaging in a magnetic field are on-going and results are expected soon. Physics studies indicate that a magnetic field is really only necessary when the detector is coupled to a Neutrino Factory and can be avoided in the context of Superbeams and Betabeams.

Cryogenic storage tankers for LNG

LNG = Liquefied Natural Gas



"I learned a lot from the Shell training course. It was detailed, relevant to our business and moved at the right pace"

An employee, Nigeria LNG

Shell Global Solutions

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

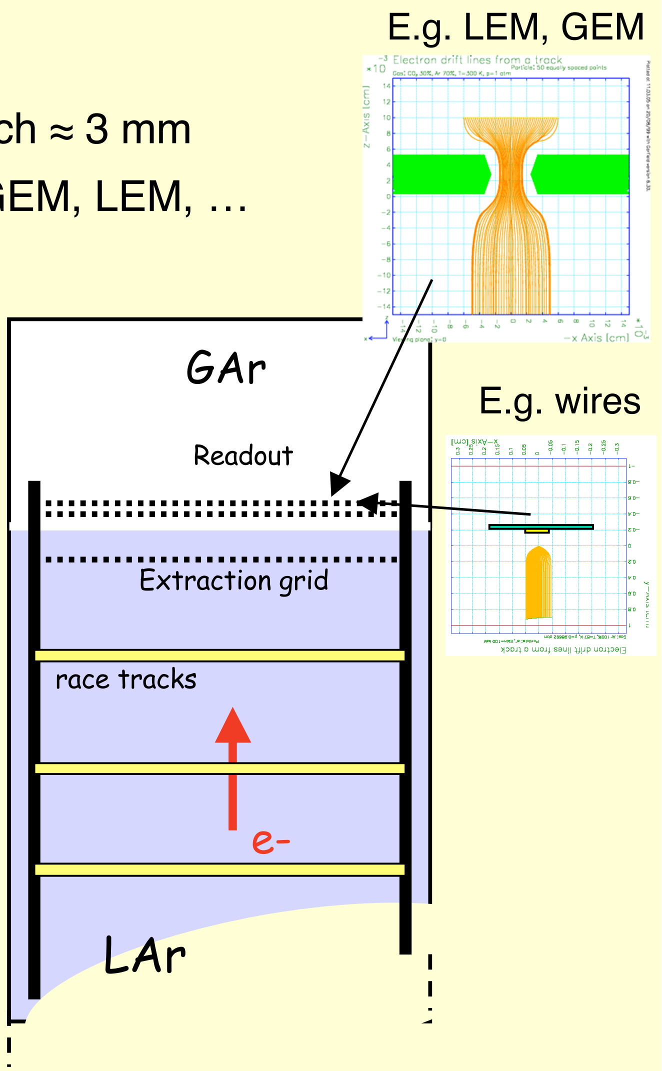
Cooling by "auto-refrigeration"

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, …

Electron drift in liquid	**20 m maximum drift, HV = 2 MV for E = 1 kV/cm, $v_d \approx 2$ 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	**$e^{-(tmax/\tau)} \approx 1/150$ for $\tau = 2$ 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, …**



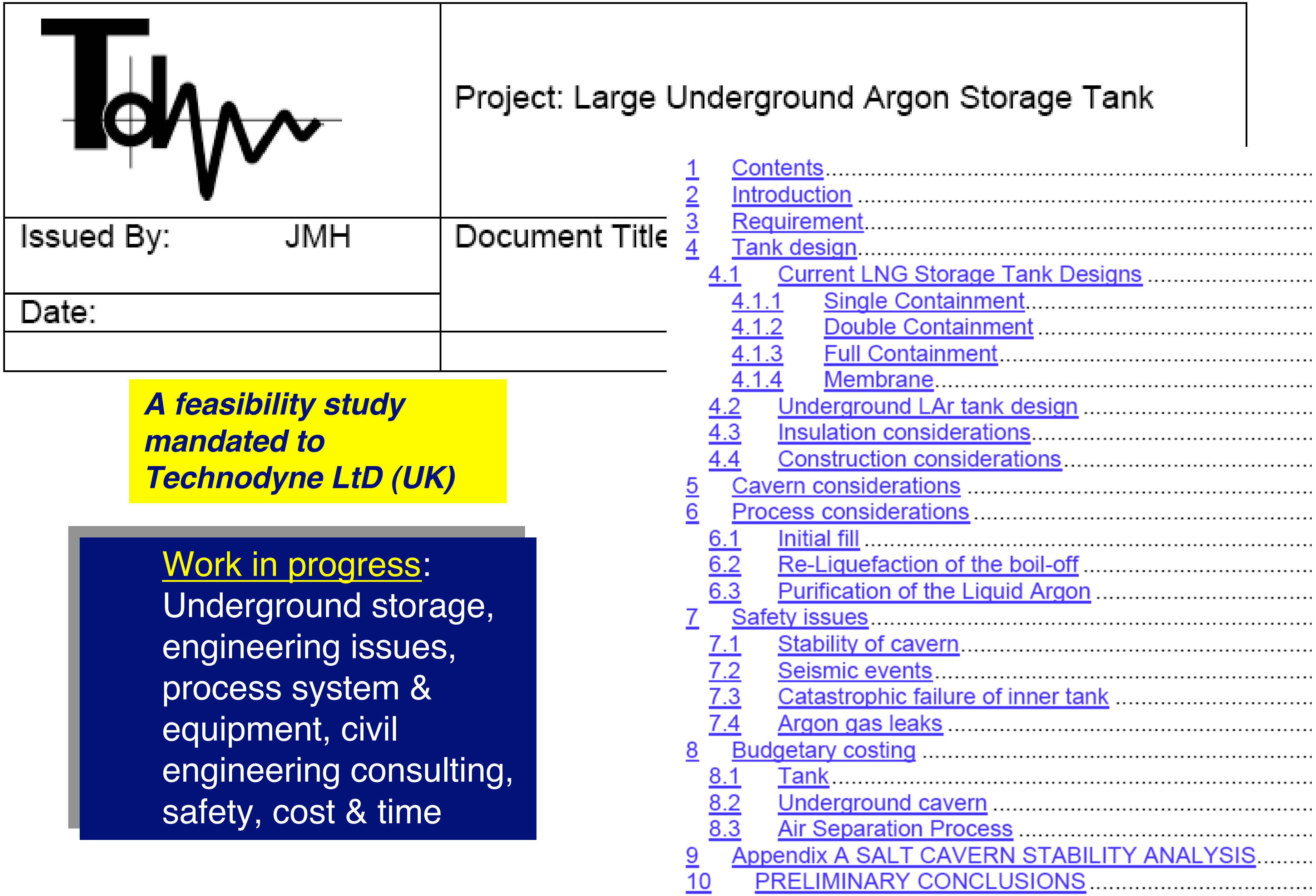
R&D strategy

Engineering studies, dedicated test measurements, detector prototyping, simulations, physics performance studies are planned and in progress:

- **Study of suitable charge extraction, amplification and imaging devices**
- **Understanding of charge collection under high pressure**
- **Realization and test of a 5 m long detector column-like prototype**
- **Study of LAr TPC prototypes immersed in a magnetic field**
- **Study of large liquid underground storage tank, costing**
- **Study of logistics, infrastructure and safety issues for underground sites**
- **Physics studies and phenomenology**

Will CERN play an important role in the R&D for the long-term future neutrino programs discussed in Villars?

Study of large underground storage tank



Project: Large Underground Argon Storage Tank

Issued By: JMH

Document Title

Date:

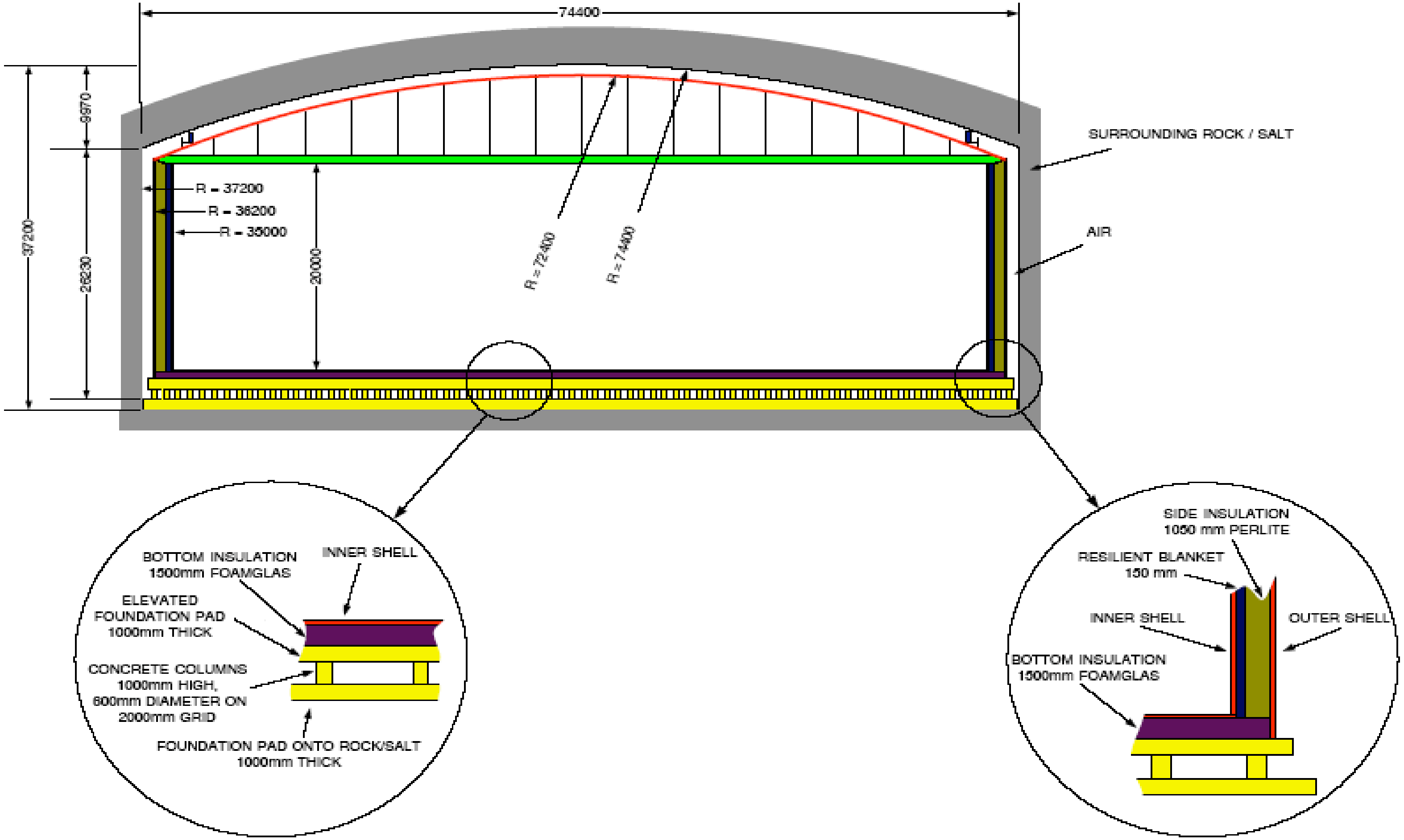
A feasibility study mandated to Technodyne LtD (UK)

Work in progress: Underground storage, engineering issues, process system & equipment, civil engineering consulting, safety, cost & time

Technodyne baseline design

TECHNODYNE INTERNATIONAL LIMITED

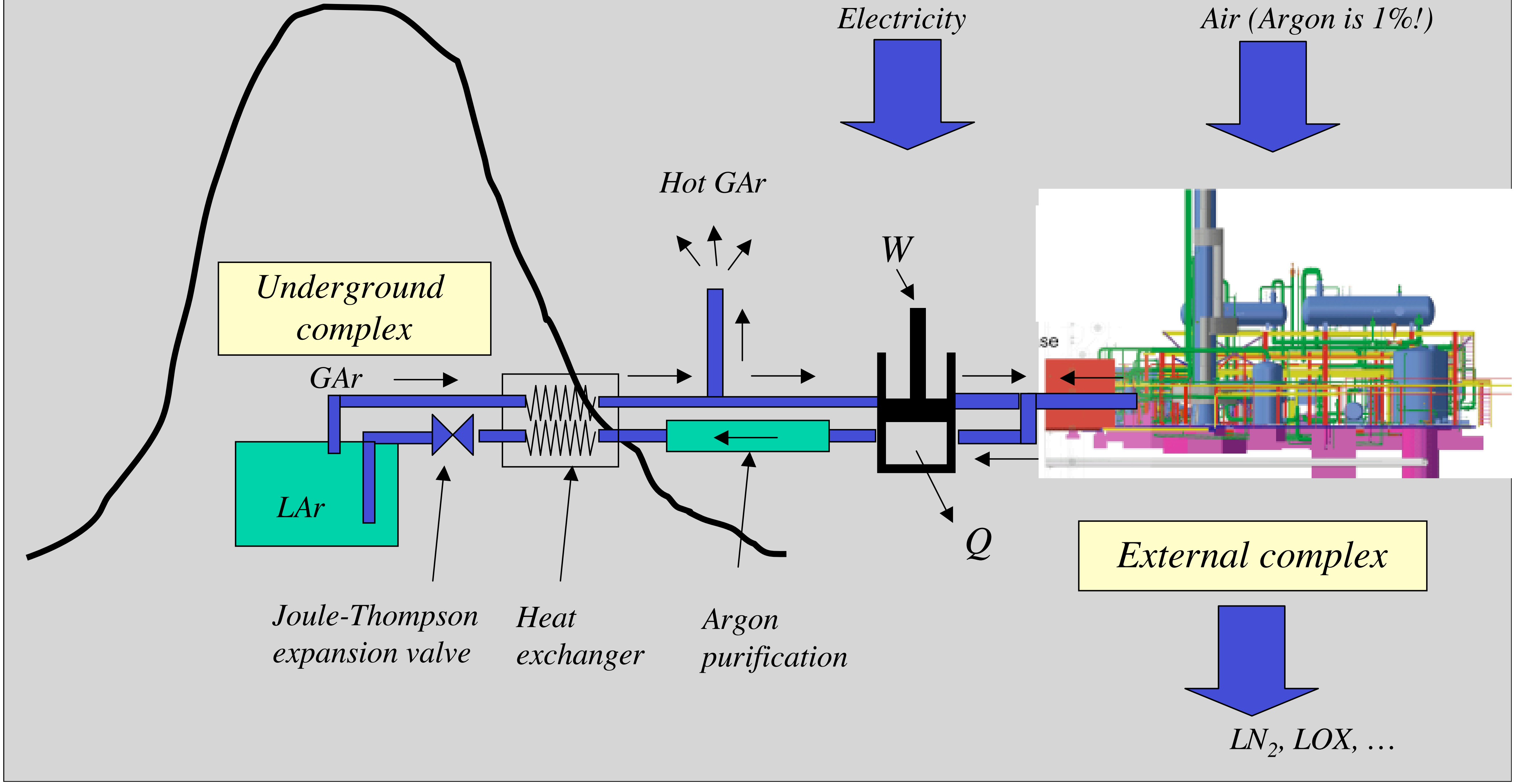
LARGE UNDERGROUND LIQUID ARGON STORAGE TANK



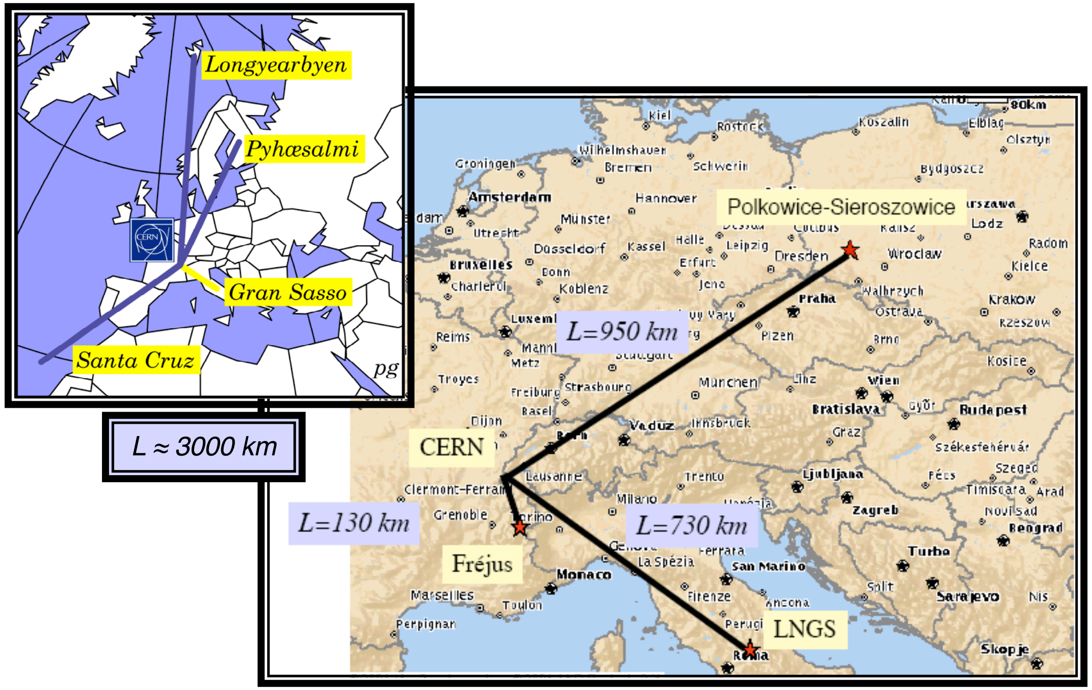
NOT TO SCALE

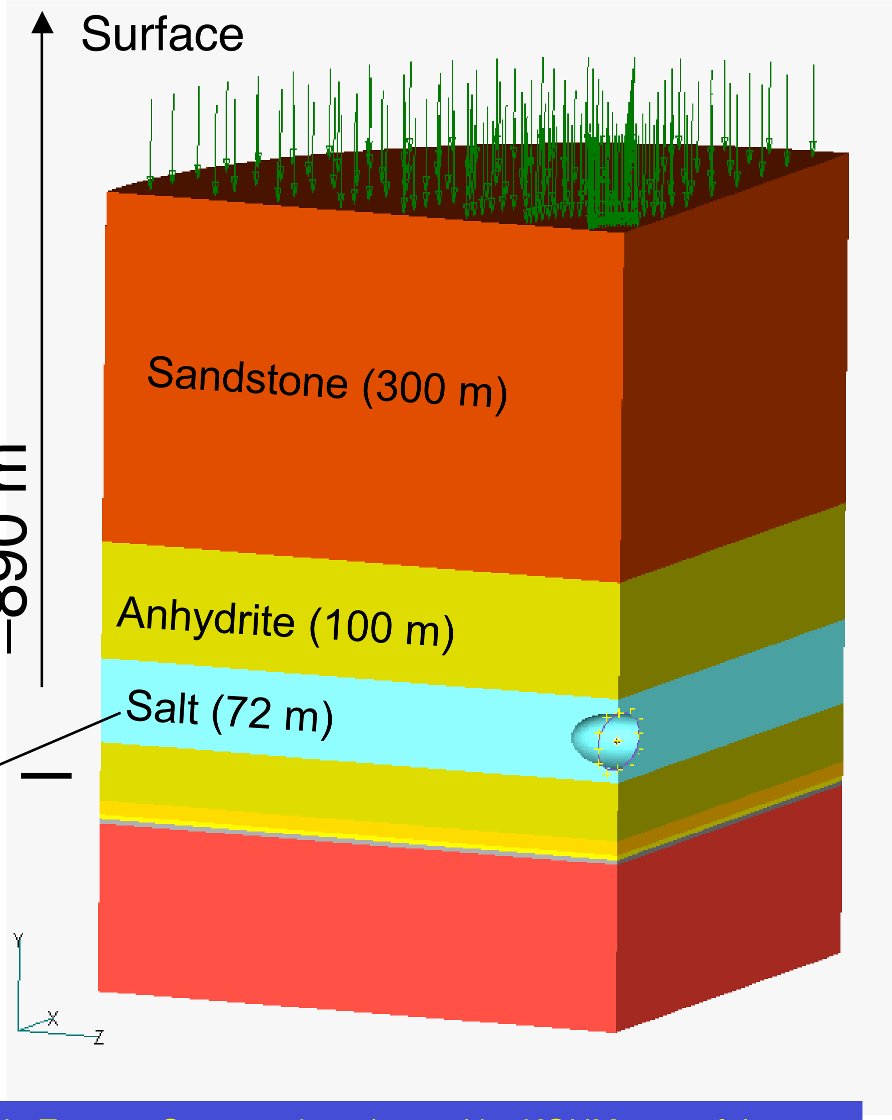
Process system & equipment

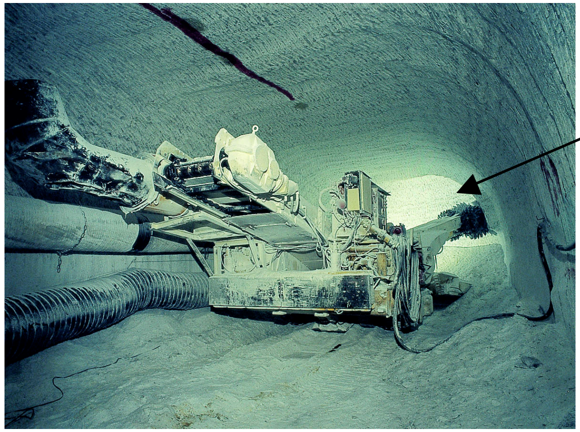
- Filling speed (100 kton): 150 ton/day → 2 years to fill, ≈10 years to evaporate !!
- Initial LAr filling: decide most convenient approach: transport LAr and/or in situ cryogenic plant
- Tanker 5 W/m^2 heat input, continuous re-circulation (purity)
- Boiling-off volume at regime: 30 ton/day: refilling



Possible European CERN-LBL sites

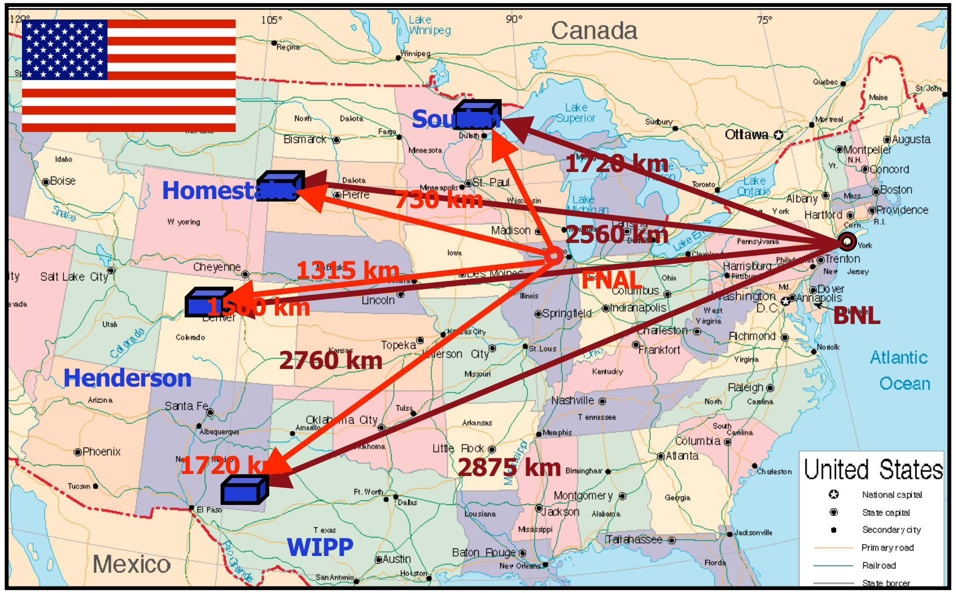


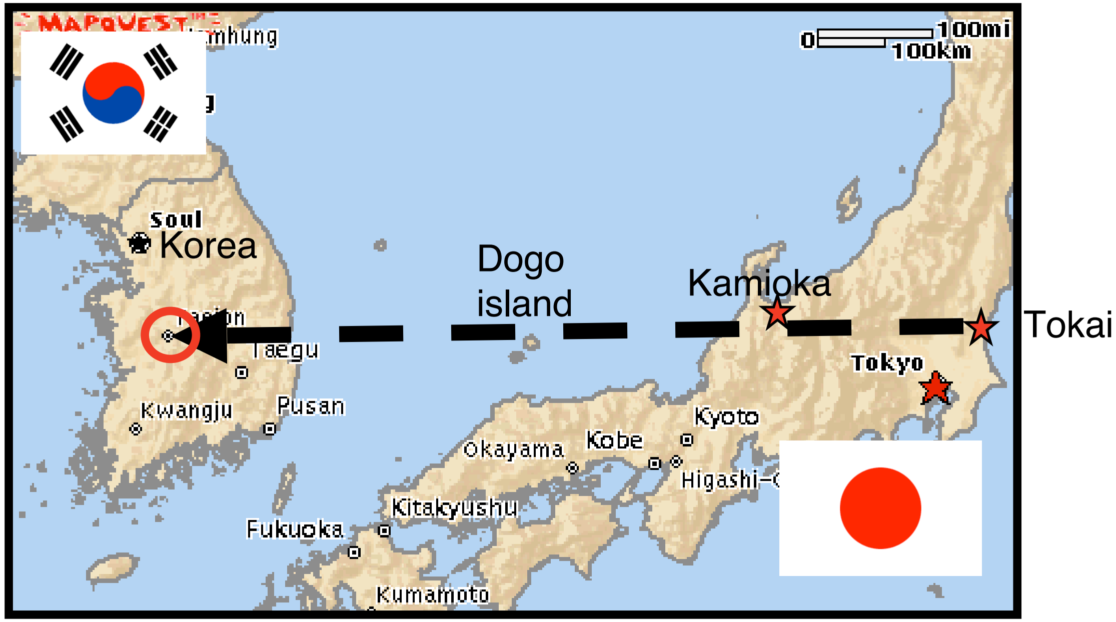




Example: Salt mine in Europe: Copper mines (owned by KGHM, one of the largest producers of copper and silver in the world). Salt layer at 1000 underground (dry) **Very large caverns already exist** (from mine exploitation). Possibility to host ≈80’000 m^3 detector in salt cavern under study.

Non-European sites for very large liquid argon TPC





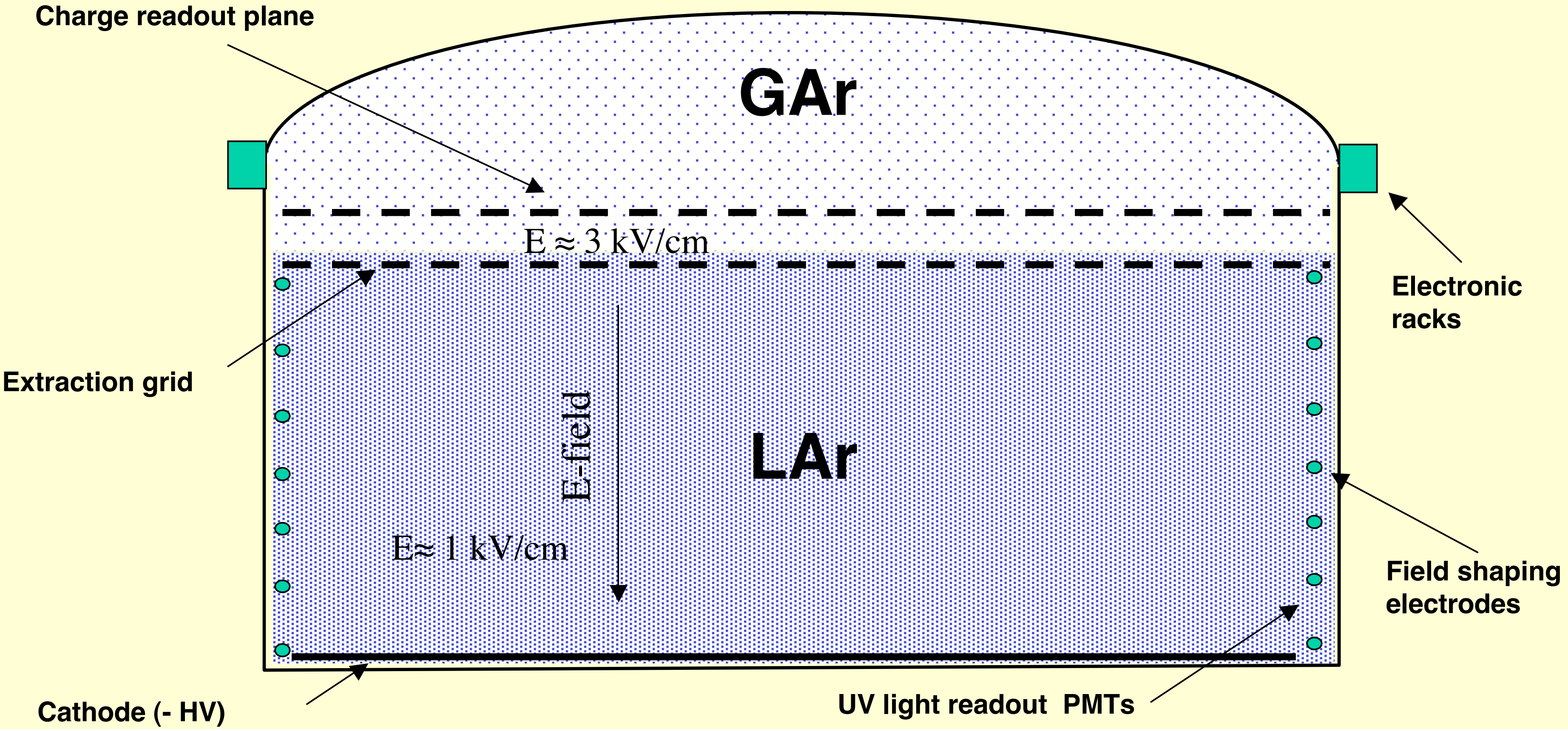
Liquid Argon TPC provides high efficiency for broad energy range: Flexibility in L & E choice

10 kton detector

- 10% full-scale prototype
- Shallow depth acceptable
- **Physics program on its own**

(e.g. sensitivity for p→νK: τ>10^{34} yrs for 10 years running)

Dewar	ϕ ≈ 30 m, height ≈10 m, perlite insulated, heat input ≈ 5 W/m^2
Argon storage	Boiling Argon, low pressure (<100 mbar overpressure)
Argon total volume	7000 m^3, ratio area/volume ≈ 33%
Argon total mass	9900 tons
Hydrostatic pressure at bottom	1.5 atmospheres
Inner detector dimensions	Disc ϕ ≈30 m located in gas phase above liquid phase
Charge readout electronics	30000 channels, 30 racks on top of the dewar
Scintillation light readout	Yes (also for triggering), 300 immersed 8" PMTs with WLS



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**

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)

Conclusions

- The liquid Argon TPC imaging has reached a high level of maturity thanks to many years of R&D effort conducted by the ICARUS collaboration.

- A 100 ton liquid Argon TPC detector in a near-site of a long-baseline facility is a straight forward and very desirable application of the technique. The approved T2K experiment in Japan is envisaged. Will be a tool for ultimate systematic errors in oscillation parameter measurements.

- The long-term strategy of the mixing angle should envisage a 100 kton liquid Argon TPC. A tentative design outlined above seems technically sound and would deliver extraordinary physics output. It would be an ideal match for a Phase-II Superbeam, Betabeam or a Neutrino Factory. A preliminary estimate of the cost has been presented. Location "hunting" is on-going.

- A 10% full-scale, cost effective prototype of the design on the scale of 10 kton could be readily envisaged as an engineering design test with a physics program of its own, directly comparable to that of Superkamiokande. This would provide a direct and probably final demonstration of the merits of a very large scale liquid Argon TPC. A preliminary cost estimate has also been presented.

- We believe that the above strategy is well matched to a potential long-term development of neutrino physics at CERN. In the meantime, a commitment of CERN in the R&D for the future neutrino programs would be very valuable.

Backup slides

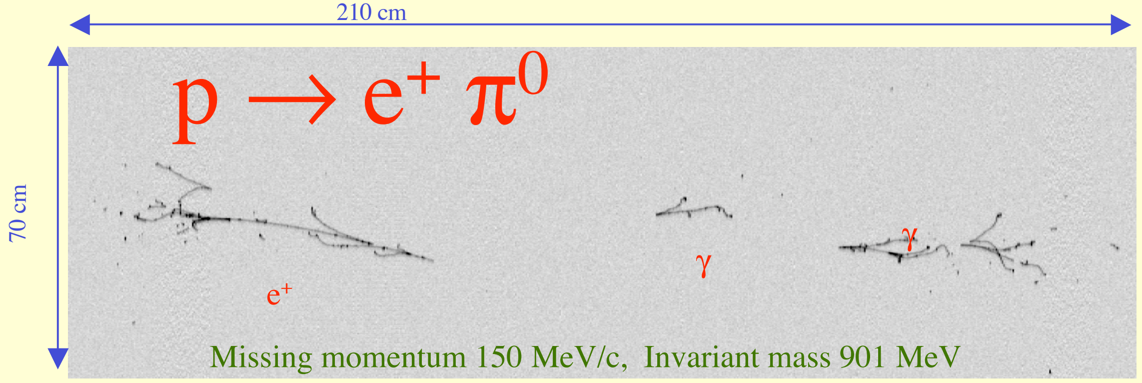
	Water Cerenkov (UNO)	Liquid Argon TPC
Total mass	650 kton	100 kton
$p \rightarrow e\,\pi^0$ in 10 years	$1.6\text{x}10^{35}$ years $\varepsilon = 17\%$, $\approx$ 1 BG event	$0.5\text{x}10^{35}$ years $\varepsilon = 45\%$, <1 BG event
$p \rightarrow \nu K$ in 10 years	$0.2\text{x}10^{35}$ years $\varepsilon = 8.6\%$, $\approx$ 37 BG events	$1.1\text{x}10^{35}$ years $\varepsilon = 97\%$, <1 BG event
$p \rightarrow \mu \pi K$ in 10 years	No	$1.1\text{x}10^{35}$ years $\varepsilon = 98\%$, <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	$\approx$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 (central module)	324000 events/year $E_e > 5$ MeV

Operation of a 100 kton LAr TPC in a future neutrino facility:

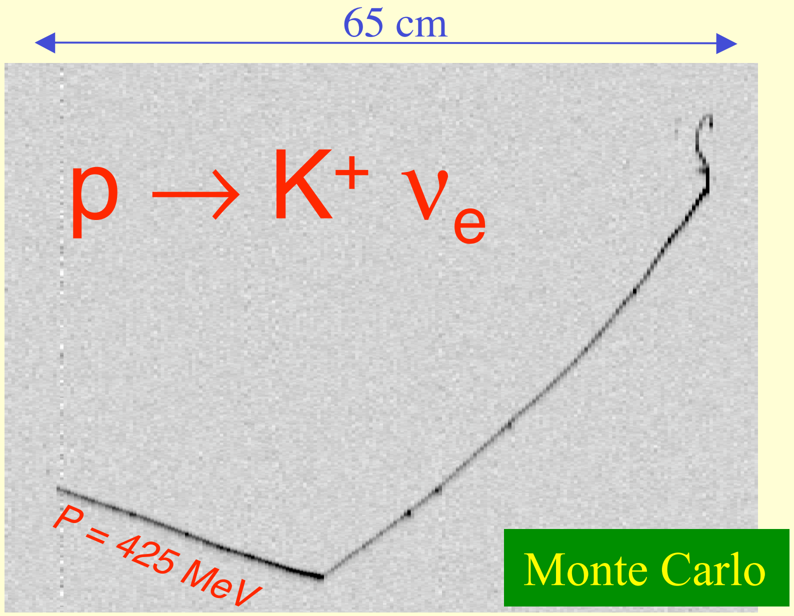
Super-Beam: 460 ν_μ CC per 10^{21} 2.2 GeV protons @ L = 130 km

Beta-Beam: 15000 ν_e CC per 10^{19} ^{18}Ne decays with $\gamma = 75$

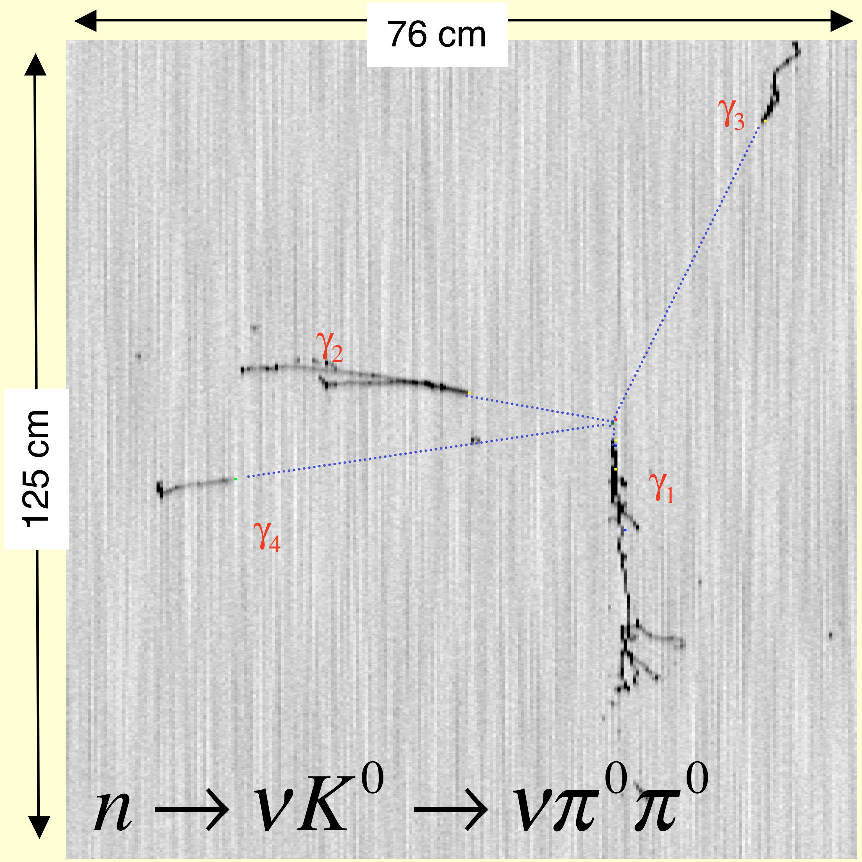
Proton decay: power of imaging



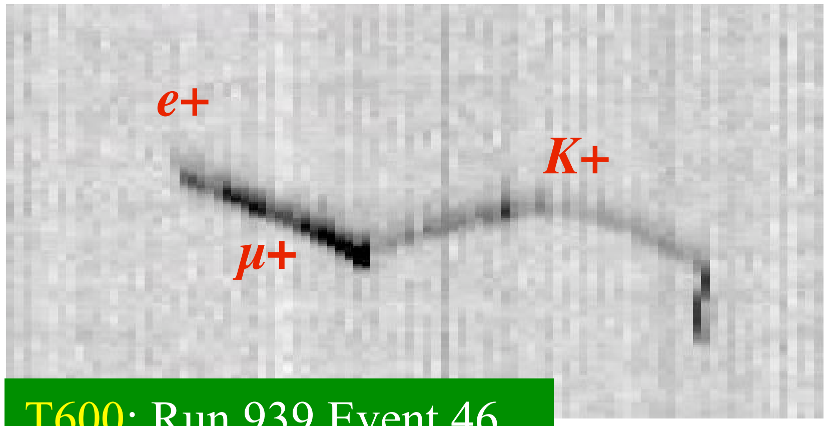
Missing momentum 150 MeV/c, Invariant mass 901 MeV



Monte Carlo



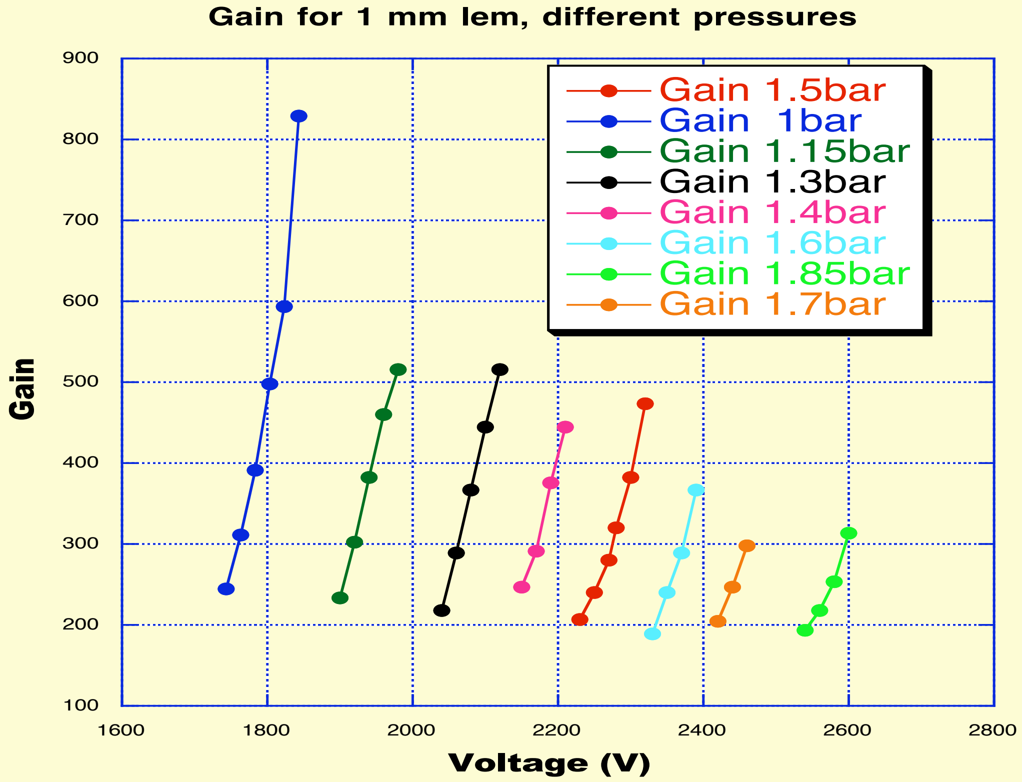
"Single" event detection capability

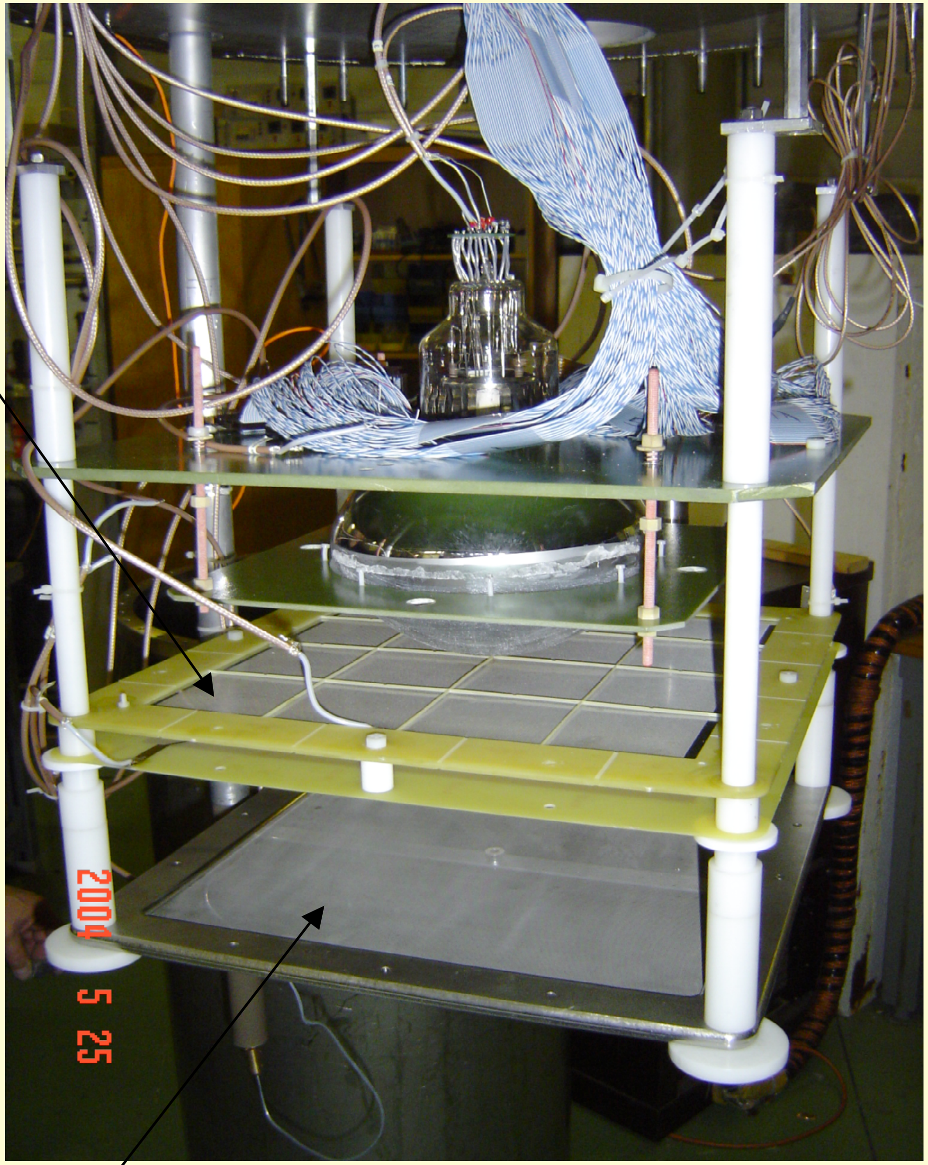


T600: Run 939 Event 46

Amplification with self-made LEMs in pure argon at high density

- Fe source (5.9 keV γ), Argon 100%
- Three LEM thicknesses: 1, 1.6 and 2.4 mm
- Varying pressures (up to 3.5 bar)
- Room temperature





Paper in preparation

High-pressure drift properties in liquid Argon

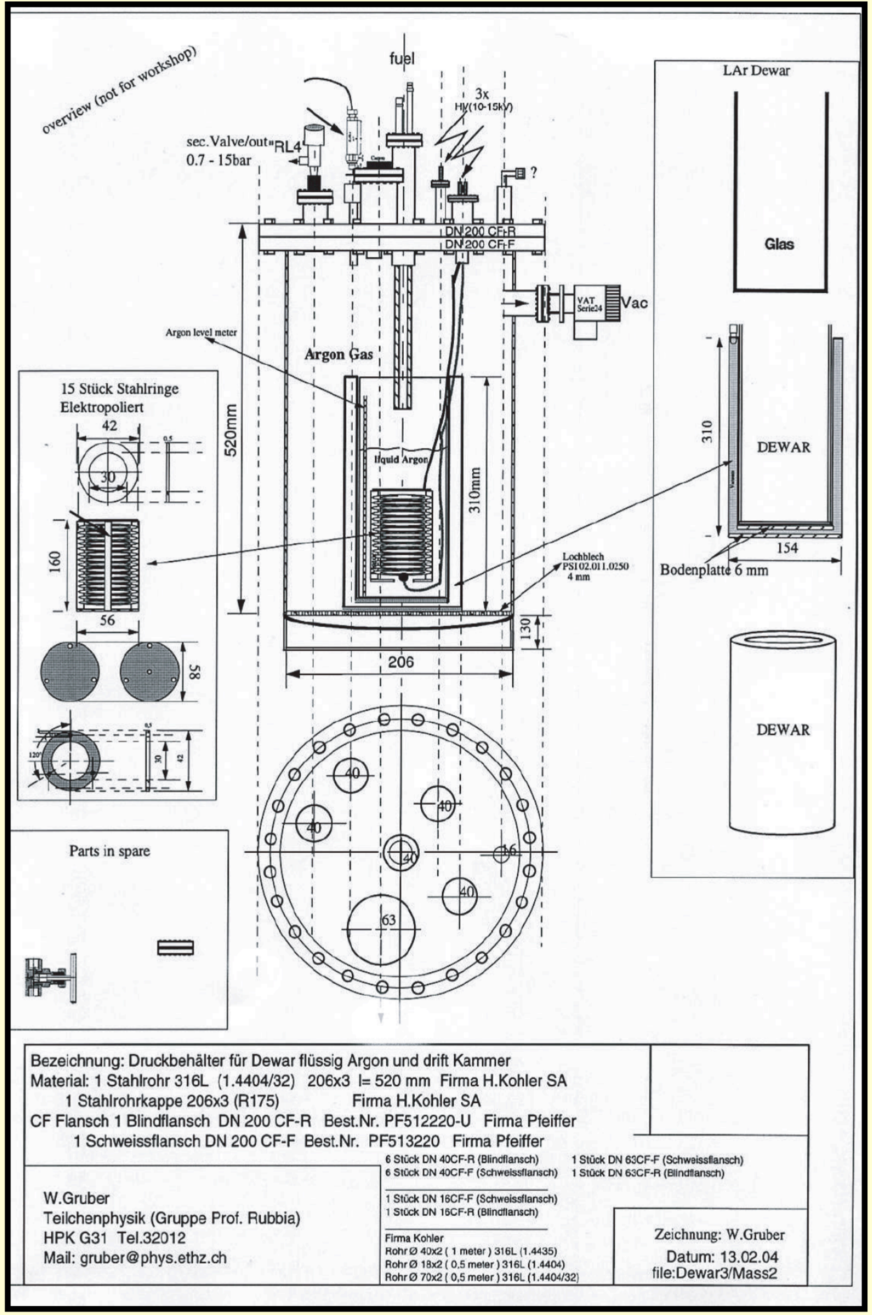
- **Future large tankers:**

  Hydrostatic pressure could be quite significant (3-4 atmosphere at the bottom of the tanker)

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

  Important to understand the electron drift properties and imaging under high pressure

- **Study in progress**
  - ✓ Prototype designed
  - ✓ Parts being assembled at PSI



Bezeichnung: Druckbehälter für Dewar flüssig Argon und drift Kammer
Material: 1 Stahlrohr 316L (1.4404/32) 206x3 l= 520 mm Firma H.Kohler SA
1 Stahlrohrkappe 206x3 (R175) Firma H.Kohler SA
CF Flansch 1 Blindflansch DN 200 CF-R Best.Nr. PF512220-U Firma Pfeiffer
1 Schweissflansch DN 200 CF-F Best.Nr. PF513220 Firma Pfeiffer

6 Stück DN 40CF-R (Blindflansch)
6 Stück DN 40CF-F (Schweissflansch)
1 Stück DN 63CF-F (Schweissflansch)
1 Stück DN 63CF-R (Blindflansch)

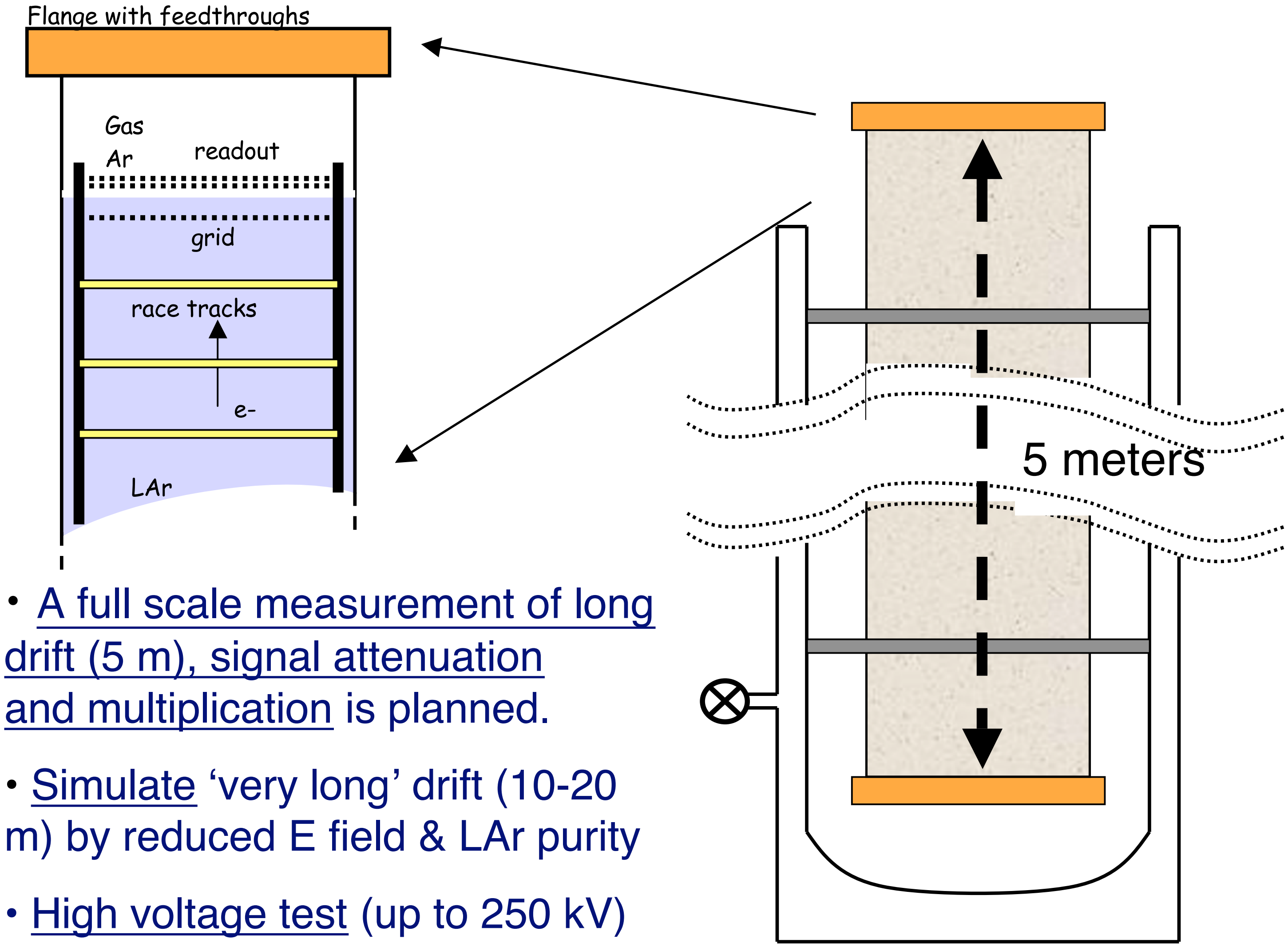
1 Stück DN 16CF-F (Schweissflansch)
1 Stück DN 16CF-R (Blindflansch)

Firma Kohler
Rohr Ø 40x2 (1 meter) 316L (1.4435)
Rohr Ø 18x2 (0,5 meter) 316L (1.4404)
Rohr Ø 70x2 (0,5 meter) 316L (1.4404/32)

W.Gruber
Teilchenphysik (Gruppe Prof. Rubbia)
HPK G31 Tel.32012
Mail: gruber@phys.ethz.ch

Zeichnung: W.Gruber
Datum: 13.02.04
file:Dewar3/Mass2

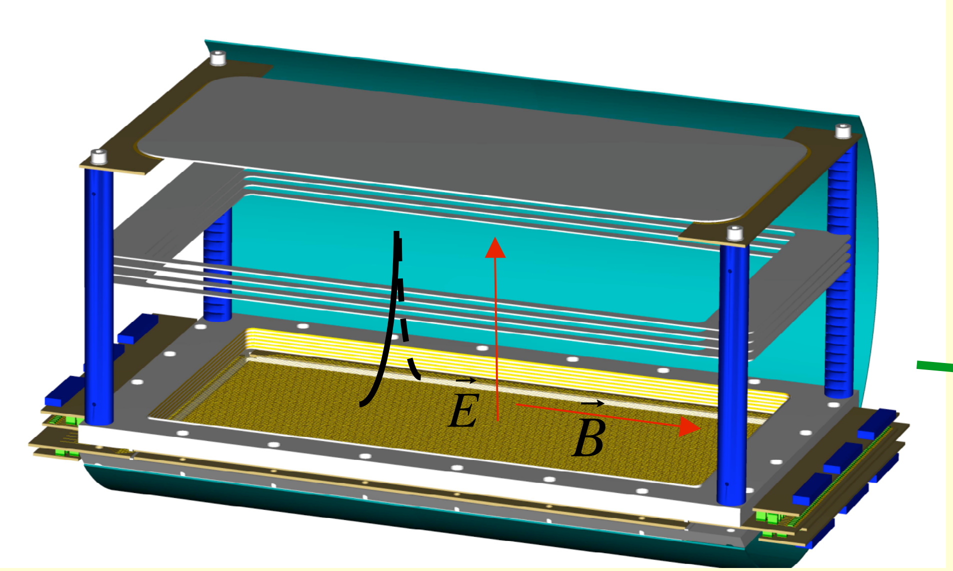
Long drift, extraction, amplification: test module



- A full scale measurement of long drift (5 m), signal attenuation and multiplication is planned.
- Simulate 'very long' drift (10-20 m) by reduced E field & LAr purity
- High voltage test (up to 250 kV)
- Design in progress: external dewar, detector container, inner detector, readout system, …

Test of liquid Argon imaging in B-field

- **Small chamber in SINDRUM-I recycled magnet up to B=0.5T (230KW) given by PSI, Villigen**
- **Test program:**
    - Check basic imaging in B-field
    - Measure traversing and stopping muons bending
    - Charge discrimination
    - Check Lorentz angle ($\alpha \approx 30$mrad @ E=500 V/cm, B=0.5T)



Width 300 mm, height 150 mm, drift length 150 mm